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Central Department of Geography,
Tribhuvan University, Kathmandu, Nepal

Approach to multi-disaster risk assessment and policy recommendation for disaster resilient urban development: A study of Birgunj–Simara Corridor

Motilal Ghimire

Central Department of Geography, Tribhuvan University, Kathmandu, Nepal,
Corresponding email: moti.ghimire@cdg.tu.edu.np
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Abstract

This study identified multiple nature of disasters in Tarai in general and Birgunj - Simara Urban Corridor, one of the hotspots of urbanization in Nepal in particular. Using geospatial technology, secondary sources of information, and stakeholder's consultations, this study evaluated floods, earthquakes, windstorms, and fire impacts, identified factors contributing to vulnerability, and solutions for increasing resilience. Although rivers have limited floodplains, floods have been increased because of floodplain encroachment, improper drainage, land use changes in upper catchment, and climate change. Although the earthquake could have a high impact, the seismicity is low compared to the national context. During pre- and monsoon seasons, windstorms have a high impact over a limited area and are hard to predict. Fires are not widespread in the settlements but common during hot, dry months due to compact rural settlements, nonresilient house designs, and inadequate safety measures. Besides, lack of adaptation capacity as a result of poor awareness, widespread poverty, and poor disaster response have contributed to a high vulnerability to multihazards. Mitigation actions identified include risk-sensitive land use planning, flood control and hydraulic structure design, efficient urban drainage, waste management, resilient housing, and disaster safety plans. Local communities should be involved in developing early warning systems, disaster preparedness, and response measures.

Keywords: Multihazard, vulnerability, urban corridor, Tarai, resilience

Introduction

Disasters have increased tenfold across the globe since the 1970s (Guha-Sapir *et al.* 2011, Laframboise & Loko 2012, Panwar & Sen 2019, Rusk *et al.* 2022) Mountainous and lowland areas in Nepal have experienced severe disasters caused by earthquakes, floods due to extreme rainfall , windstorms, landslides, glacier lake outburst flood, and other events. These events have increased and are associated with increasing warming and extreme precipitation (Javadinejad *et al.* 2019, Rieger 2021, Rusk *et al.* 2022). With the expansion of human settlements, urbanization, and development infrastructure, exposure to multiple hazards as well as disaster risks have been amplified (Aksha *et al.* 2020, Van Westen 2013). Taking into account the multiple dimensions of disaster is essential to protecting the benefits of development, reducing poverty, and saving lives during shocks and stresses. Assessment of multiple hazards and disaster resilience are notable research fields worldwide, and multi-hazard approaches are increasingly incorporated in development to ensure disaster resilience. Disaster risk information should be integrated into investment decisions and development programs adapted to be disaster-resilient.

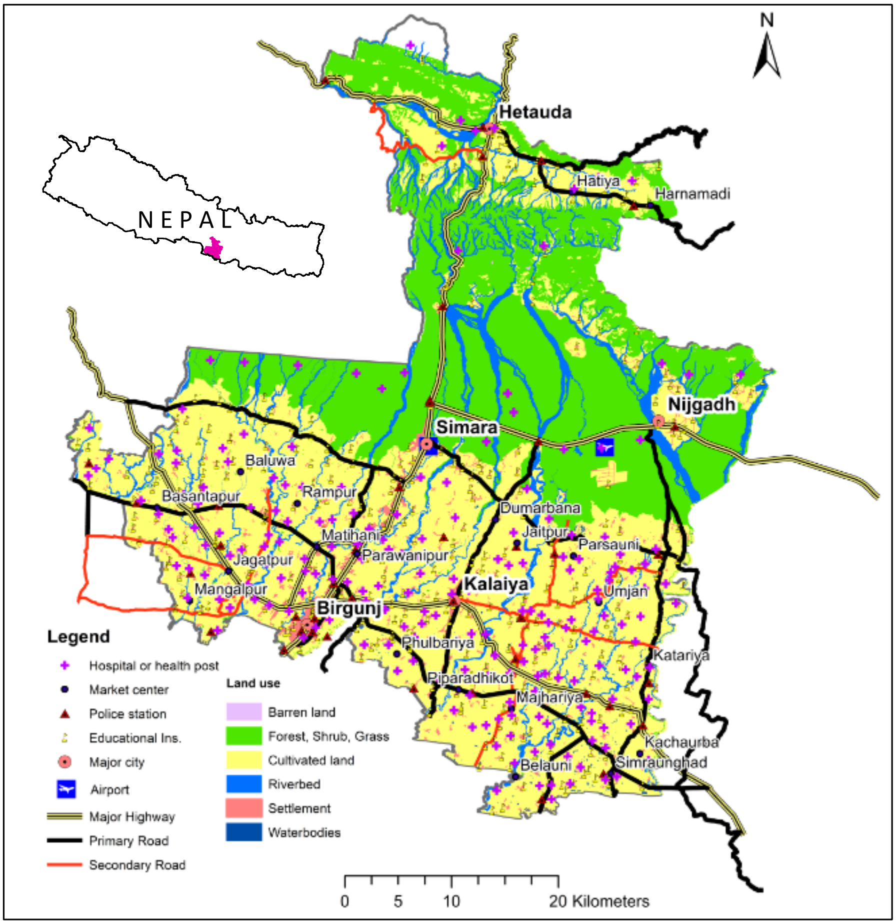

Figure 1: Study area, land use, and social infrastructure.

Tarai, part of the Indo-Gangetic plain in Nepal, has experienced rapid population growth and urbanization (15.1 % growth rate) (CBS 2014). In conjunction with climatic trends and variability, and located in seismically active zone, these changes have increased climate and seismic induced disaster risk, vulnerability, and hazard, and are likely to increase in the future. Various studies have contributed to an increased understanding of the disaster in Nepal (Aksha *et al.* 2020, Dahal *et al.* 2008, Dhital 2000, Dingle *et al.* 2020, Ghimire 2011, Ghimire 2020, Khanal *et al.* 2007, Sharma *et al.* 2019, Shrestha 2019). But these studies were mainly focused on either floods or landslides. In this study, we aim to identify the multiple nature of disasters in Tarai through a case study of the Birgunj Simara Urban Corridor, one of Nepal's most populated urban areas (Figure 1). The study also include their impacts, the factors contributing to vulnerability, and identifying solutions for increasing the disaster resilience of the corridor

Concept of multi-hazard and vulnerability

Multi-hazards

The multi-hazards approach in dealing with disaster risk reduction emerged from realizing that most parts of the world are subject to multiple natural hazards(Gill & Malamud, 2014, Liu *et al.* 2016). Interactions with other hazards often aggravate the impacts of a hazard event. One event may trigger another or a combination of events may occur in close proximity in space and time without evident shared cause (Kappes *et al.* 2012, Liu *et al.* 2016; Marzocchi *et al.* 2012). Hazard interaction is possible when two or more hazards overlap spatially and temporally, which may affect both hazard levels and vulnerability (Kappes *et al.* 2012). Single and independent multi-hazard approach potentially underestimates the risk leading to inadequate disaster risk reduction measures. And also, the interaction of different hazards can lead to an impact greater than the sum of the single hazard effects.

Disaster risk management must be viewed from a multi-hazard perspective to address the risk arising from the potentially interconnected multiple hazards. The concept of multi-hazard was referred in Agenda 21 Conference in Rio de Janeiro(UNEP 1992)followed in Johannesburg (Gallina *et al.* 2016). Likewise, the UN Sendai Framework and the recent Global Assessment Report emphasized the need for a holistic multi-hazard approach to disaster risk reduction (DRR). Various definitions are proposed for the concept of multi-hazard. According to UNDRR (2020) the multi-hazard concept refers to "(1) the selection of multiple major hazards that the country faces, and (2) the specific contexts where hazardous events may co-occur, cascading or cumulatively over time, and taking into account the potential interrelated effects." According to Gill and Malamud (2014), the multi-hazard approach considers more than one hazard concurrently or cumulatively affecting one place, including their interactions over time. The interactions between hazards may take the form of a domino effect, a cascading effect, or the influence of one hazard on another. Despite being recognized as an important research field worldwide, multi-hazard risk assessment is a relatively new approach in Nepal to identify and assess the risks arising from the cumulative effects of more than one hazard.

In this paper, "multi-hazard" means potentially disastrous events that can occur within a given spatial unit in a cascading, induced and coincident manner in varying time scales and spatial scales, in terms of magnitude, intensity, onset, extent, severity, probability, and impact. This definition facilitates a multi-risk informed approach to urban and rural settlement development to mitigate overall and potentially interacting risk.

Concept of vulnerability

The idea of vulnerability to natural hazards can be conceptualized through the equation below. Vulnerability increases with greater exposure to natural hazards and also increases with greater sensitivity of a population. While increasing adaptive capacity will reduce vulnerability (Glick *et al.* 2011).

$$\text{Vulnerability} = \frac{\text{Exposure} \times \text{Sensitivity}}{\text{Adaptive Capacity}}$$

Exposure is the presence of people, livelihood, resources or assets in areas affected by natural hazards. It is not linear, and the magnitude of exposure can vary in space e.g., based on elevation (flooding) or proximity to epicenter (earthquake). It is important to understand and map exposure to reduce the impact of hazards on populations – through planning, infrastructure design, and other measures.

Sensitivity relates to the impact of exposure to a hazard on a population. i.e., how well is the community able to cope with the physical impacts of the hazard. Socioeconomic factors such as population density, housing typology, access to services, sanitation, income level, savings, and insurance all contribute to sensitivity. Once understood, sensitivity can be reduced by addressing these factors through policy, planning and design. If available, these data can be mapped with exposure data to develop vulnerability maps.

Adaptive capacity is the ability of the community, governing bodies and other supporting agencies to manage, respond and adapt to natural hazards. Adaptive capacity can be improved by strengthening institutional capacity to plan for and respond to disaster events, preparing disaster management and response plans, community action plans, and other procedural plans; improving preparedness, including early warning systems; improved operation and maintenance of infrastructure; and other safeguarding measures.

Approaches and methods

The multi-hazard risk assessment should begin with identifying what natural hazards can be expected and how they might change in the short and medium-term due to anthropogenic activities or climate change. This could include earthquakes, floods, drought, windstorms, fire, industrial disasters and epidemics. Considering the impact and scale of the disaster events in the region, an integrated approach using a variety of assessment methodologies, including flooding, earthquake, fire, and windstorm, was employed:

- Desk study that includes the investigation and review of the available records and documents on the disaster and climate risk in the study area.
- Multihazard and risk and vulnerability mapping using GIS and remote sensing
- Preparation of case studies of recent disaster events to identify probable causes, risks, vulnerability, disaster management response, weaknesses, and lessons learned.
- Consultations with relevant stakeholders at the national level (Department of Hydrology and Meteorology, Department of Urban Development and Building Construction, Department of Water Resources and Irrigation).
- Cosultation with disaster-affected communities and local level municipalities and relevant institutions from the municipalities of Birgunj, Jitpur, Simara, Pokhariya, Kalaiya, Parwanipur, Prasauni and Pheta.
- Preparation of problem trees to identify the root cause of systemic weaknesses (natural and human processes) that create vulnerabilities.

The process involves developing a broad understanding of the vulnerability to a range of disasters to inform the development of solutions and planning recommendations. This vulnerability assessment is derived from consultations and analysis of secondary information only. It does not include any primary data collection or modeling.

Multi-hazard risk and vulnerability mapping:

Multi-hazard risk and vulnerability mapping was done using data derived from maps and satellite imageries as well as statistical records and documents from the Government of Nepal. The majority of the data has been obtained at village unit level (Village Development Committee, now corresponding to rural municipality wards) but some were available at the municipality level – municipal budget etc. Table 1 describes the unit, source and purpose of each data set.

Table 1: Data sets used in disaster risk and vulnerability mapping

Data set	Unit	Source	Purpose	Notes
Flood risk map	N/A	Prepared from time series satellite imageries (Google earth), topographic maps (Department of Survey: DoS), and field visit	For mapping exposure to flooding and preparing 'Flood' index.	Description of analysis is provided in report below this table.
Village Develoment Committee (VDC) Area (currently municipalities)	Ha	DOS	To prepare indices such as population density etc.	
VDC population	No.	Nepal Central Bureau of Statistics (CBS)	For mapping population density and preparing 'density' index – sensitivity.	2011 Census data (CBS, 2014)
VDC No. of households	No.	CBS	To prepare indices using % of households.	2011 Census data
VDC number thatched roofs	No.	CBS	To prepare 'fire' index – exposure.	Obtained from details of household construction type in the 2011 Census data.
Seismicity – ground acceleration	GAL	National Earthquake Monitoring and Research Center, Nepal	To prepare 'Seismicity' index – exposure.	Interpolated to the centroid of each VDC from contours in map, Figure 5.
VDC number of mud/ bamboo/ wood houses	No.	CBS	To prepare 'Construction' index – sensitivity.	Obtained from details of household construction type in the 2011 Census data.
Length of roads in VDC (all types)	Km	Open Street Map	To prepare 'access' index – sensitivity.	
Number of health posts in VDC	No.	DoS / Ministry of Health	To prepare 'Healthcare' index – sensitivity.	
Number of schools/ colleges in VDC	No.	DoS / Ministry of Education	To prepare 'Shelter' index – sensitivity.	
VDC poverty percent	%	CBS/World Bank[1]	To prepare 'Poverty' index – adaptive capacity.	Small Area Estimation of Poverty
Number of police stations in VDC	No.	DoS	To prepare 'Response' index – adaptive capacity.	
Literacy rate per VDC	%	CBS	To prepare 'Education' index – adaptive capacity.	2011 Census data
Disaster risk management budget allocation by municipality		Municipal budget	To prepare 'Planning' index – adaptive Capacity.	Not all municipalities have allocated budget for DRR.

[1] Small Area Estimation of Poverty, 2011, CBS/World Bank (2013) http://documents.worldbank.org/curated/en/959781468290482736/pdf/788120WP0P13300all0estimate0Poverty.pdf

Flood risk map

The flood risk map was prepared using geomorphic assessment of the river activity and flood plain through evaluation of the topography derived from digital elevation model, topograpbhic maps, and time series imageries. As there is no hydrological information or flood extents for the rivers across the study area,this requires some understanding of fluvial geomorphology and flood hydrology. Flood footprints, scroll-bars, old or recent river channels, bank erosion, and floodplains were fluvial features used for evaluating flood risk (Figure. 2)

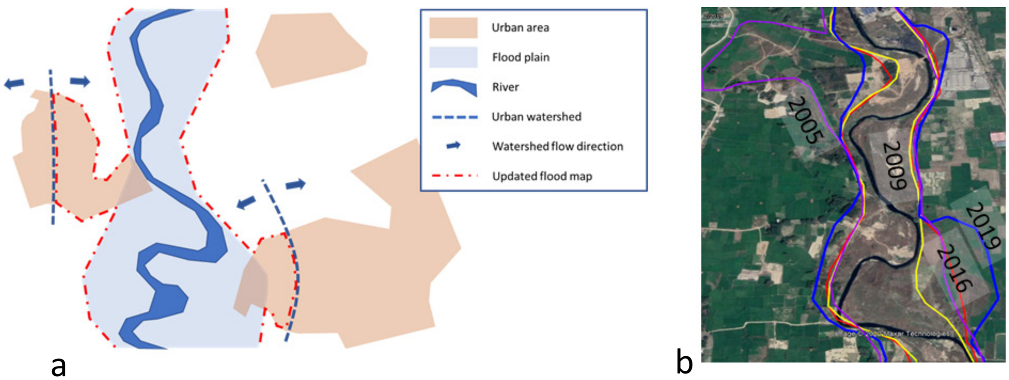

Figure 2: Approach to flood risk map delineation (a) using time series imageries (b)

To include an estimate of urban flood extent in the flood risk map, we made some assumptions based on the known issue of high river levels imparting a backwater effect on urban drainage systems. Where urban areas connect to the river floodplain, these areas we incorporated into the flood map if they drain towards the river flood extent. This required a watershed analysis in GIS to determine the extent of each 'connected' urban area which drains to the river floodplain. Figure 2 conceptually illustrates the approach to flood map delineation and updating it for urban flood risk.

The flood risk map was validated in two locations in Birgunj and one in Simara to verify a reasonable level of accuracy. The return period of the mapped flood extent along the river corridor is estimated with the help of the flood footprints of the imageries back to the 2005, which is expected to be around 15 years. Several river reaches were embanked with spurs bringing flood under control.

Relevant disasters in the study area

Through desk study and consultation, it has been determined that flood, earthquake, windstorm, and fire are the prevailing disasters relevant to this assessment.

Flood Disasters in the context of Tarai and Study area.

Floods were the main disaster affecting 68.3 percent of people affected by natural disasters between 1971 and 2022 (https://www.desinventar.net/DesInventar) if the 2015 Gorkha-Dolokha earthquake were considered exceptional. To demonstrate how frequent the problem of floods is beyond 2019, a look back at 2017 serves as an example of the widespread nature of flooding in the Tarai region of Nepal. Many districts experienced the heaviest rainfall in over 60 years. This led to the inundation of about 80 percent of the land in substantial parts of the Tarai region. The recent floods in 2017 caused damage worth USD 584.7 million. In 35 districts, over 1.7 million people were affected. The 18 'severely affected' districts were all located in the Tarai region. NCP has estimated recovery needs to be over USD 700 million.

The study area in several sites experiences high monsoon and regular flooding. According to the Ministry of Home Affairs and DWIDM (2019), Nine flood disasters have been reported since 1978, including 1978, 1980, 1993, 2002, 2004, 2008, 2011 and 2017, 2019, and 2022 in the area. Flooding events in the study area are not monitored or hydrologically analyzed, but based on extreme rain events and anecdotally, flooding is becoming increasingly frequent and severe. On July 16, 1978, August 1, 1997, July 13, 2019, and June 29 2022, Simara, 19 km north of Birgunj, recorded the highest extreme rainfall events of 266.4, 300.3, 311.9 mm, respectively. During 1985-2022, other stations near Birgunj, such as Amlekhgunj and Kolhibi, also recorded 15 extreme rainfall events (over 200 mm). On the basis of flood magnitude once every 15 years, the high flood and moderate flood risk areas were estimated as 2658 and 7157 hectares, respectively (DHM 2019a). A total of 236 of 908 settlements, including urban areas, are at risk of flood hazards (Figure 3). Similarly, about 1419 and 6366 ha of cultivated land is under high and moderate flood risk, respectively. About 76 ha of the built-up area is also at high or moderate risk for flooding. The risk would be far larger if extreme flood events were considered. Areas affected by the flood are densely populated, between 5-25 people per hectare, and have a poverty rate of 20-33% of the total population (Figure 4).

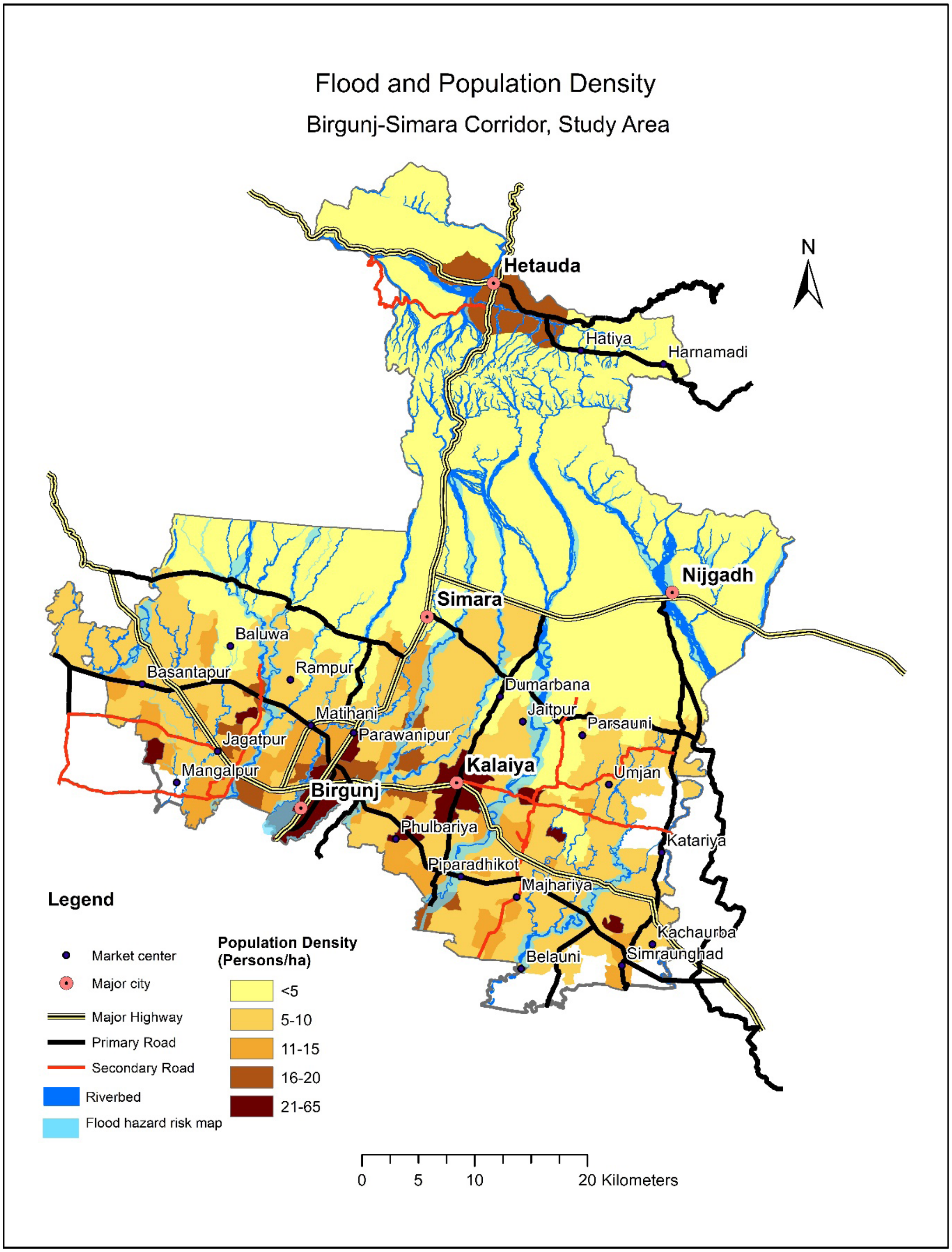

Figure 3: Flood hazard risk and population density map

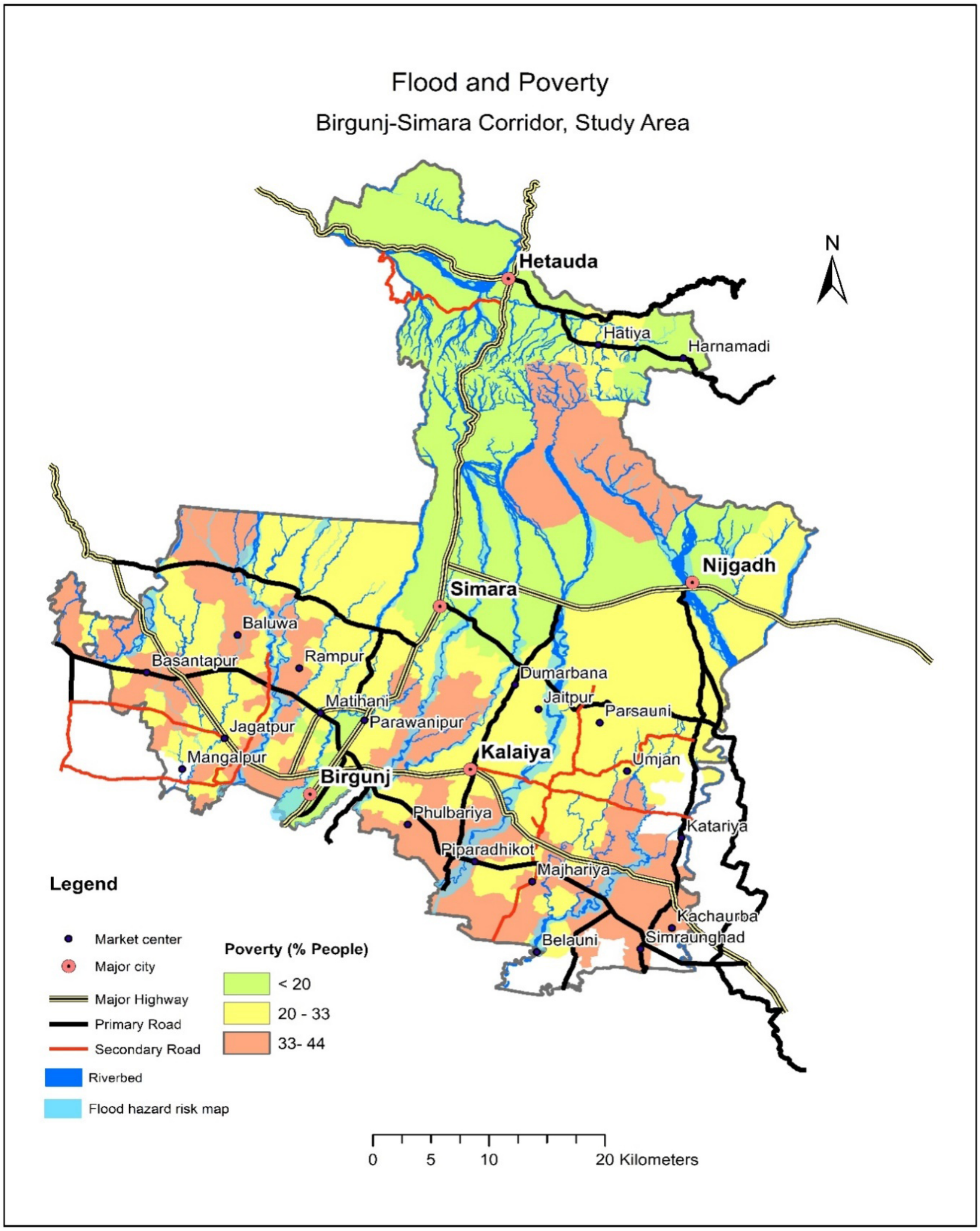

Figure 4: Flood hazard risk and poverty map

Table 2: Accumulated rainfall for Kolhbhi and Nijgadh weather stations

Events	1 hr	3 hr	6 hr	12 hr	24 hr
12 July, 2019: 8 am	3	5.6	60.8	125.8	188
13 July, 2019: 8 am	16.8	40.8	78.8	163.4	202.4
28 july, 2022: 8 am	0.2	4.4.	84	169	180
28 July, 2022 8 AM (Nijgadh)	0.4	12.4	17.2	199.8	216.4

Source: DHM 2019 and http://www.hydrology.gov.np/#/rainfall_watch?_k=x7r9kd

Incessant 48 hrs rainfall was 390 mm. Rainfall could have been higher in Birgunj. It is noted that the drainage infrastructure has been designed for 2 year return period event, and it is very likely that this was exceeded during this event. Coupled with the backwater effect caused by high river levels, widespread flooding occurred in Birgunj. The forecasted rainfall for the 11th of July was over 150 mm for 24 hr period, see image below, so some warning would have been possible to disseminate even before river levels rose.

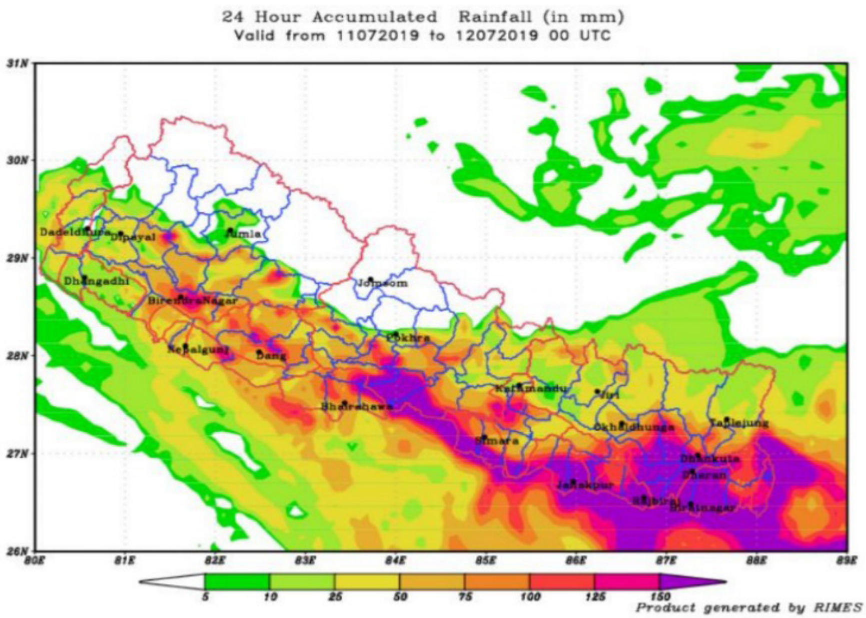

Figure 5: Twenty-four hour accumulated rainfall (in mm) (source:…..

Note: *DHM has real time telemetry-based monitoring systems on Major and Medium rivers. Alerts in these flood zones are issued for 'Alert', 'High Alert', and 'Danger' dependent upon real time monitoring and specified water levels (warning and danger) for each station coupled with a 'rising trend'. To date, flood modeling and mapping are only undertaken for Major and Medium rivers. Obtaining accurate topographic elevation has been a constraint in developing accurate flood maps.*

Case studies on flood of 2019 in Birgunj metropolitan city

This section covers case studies on floods and windstorms, where it examines hazard events and their characteristics, cause and vulnerability, and lessons learned and responses made to mitigate disasters.

Flood extent and cause

a) The floodwaters extended into floodplain areas, generally according to flood maps (estimated from geomorphic assessment of aerial imagery), except in urban areas where widespread flooding occurred as drainage infrastructure was overwhelmed.

b) The backwater effect caused by high river levels is likely to have contributed to urban flooding by compromising the urban drainage infrastructure in Birgunj. In addition to high river flows, channel constriction and encroachment reduce the hydraulic capacity of rivers, resulting in high river levels.

c) Due to the lack of gauging, the magnitude (rainfall intensity and river flow) is uncertain. According to news reports, Simara airport rain gauge received 300mm in one day. Total 48 hr rainfall was 390 mm at Kolbhi weather station (GoN 2019).

d) According to consultation, flooding is an annual problem, but it has been worse in 2019 than in previous years.

e) The community reported that the flooding problem is getting worse every year. The reason for this may be (a) higher flows due to land use changes upstream, (b) channel constriction caused by encroachment and sedimentation, (c) increased local runoff from urbanization, (d) clogging of urban drainage systems with unmanaged solid waste, or (e) residents and activities in floodplains may be more susceptible to flooding. All of these contributing factors exist, and it is likely that they all contribute to increased flood risk.

f) Bank erosion and lateral migration of rivers is high across the study area. The rivers are dynamic systems with high loads of coarse sediment and ‘flashy’ regimes causing high deposition in channel and the creation of numerous channels and bars. Sand and gravel from the Tarai floodplains have low cohesion, and agricultural land uses do not provide any additional stability. It is difficult to manage this without costly hard infrastructure solutions, so rural communities need to adapt to these risks. This can be challenging when a significant loss of land occurs.

Impact and vulnerability

a) Over 1000 households were affected, and 5 deaths were reported in Parsa and Bara districts. Irrigation canals were damaged, and local and regional transportation was disrupted. Widespread flooding in Birgunj as drainage infrastructure was overwhelmed. Food prices increased by over 100%. Water quality became poor, and the impact of the flood was exacerbated

b) Vulnerable communities on both sides of the Sirsiya river in Birgunj were affected. These communities live in informal settlements without roads and suitable infrastructure. Communities are particularly vulnerable due to poverty; they have no savings or insurance. They do not have the financial capacity to improve the quality of their housing or raise floor elevation.

c) When the water level is rising in the river it is monitored by the community. When necessary, the ward leader coordinates relocation to shelter at the local community center, which has basic facilities. Collections are made (food etc.) within the community and distributed to those in need.

d) Red Cross will come but they only record numbers; they don't provide materials, food, water, and other relief. District authority coordinated response with Police and APF for rescue efforts. Some shelter and food was distributed to those in need.

Lesson learned and response

a) The flood event was of unknown magnitude, so difficult to compare with previous subsequent annual floods and determine system deficiencies.

b) Sedimentation and encroachment are likely to cause problems, as they will raise river water levels for a given flow. Poor land use planning and human activity are directly responsible for these problems. Due to the low gradient nature of the stream (less than 0.5% slope), downstream encroachment and hydraulic constrictions may cause backwater effects upstream - i.e., channel constrictions downstream of drainage outfalls.

c) To undertake any design work, it is important to understand the river system. Hydrologic and hydraulic models of the Sirsiya River would enable the design of bridges/culverts and other hydraulic structures. This will give boundary (downstream) conditions for hydraulic calculations (models) for urban storm water design (see analysis of rainfall). This modeling would also enable better flood mapping and resilient land use planning.

d) Water quality improvement in the Sirsiya river would reduce the impact of flooding.

e) District and municipal governments are reactive, not proactive in flood disaster management. Flooding occurs annually, so the community has developed management capacity at a local level. This needs to be augmented with a coordinated response from local government and NGOs in accordance with community Disaster Risk Management Plans. Ward leaders provide good coordination during the disaster, shelter can be provided in wards, and the community responds with the distribution of local collections for food etc.

f) The community can communicate informal warning systems at a ward level.

g) The community would support projects to resolve the issue of encroachment into the river and restore its function. And would support the relocation of the most vulnerable if necessary. They mentioned that the land use maps should have a river setback.

h) In Bara/Parsa Districts, warnings are issued based on rainfall. Alerts are delivered through SMS to the population within the identified zone if rainfall exceeds 60 mm in 1hr, 80 mm in 3hr, 100 mm in 6 hr, 120 mm in 12 hr, or 140 mm in 24 hr. The Bara/Parsa flood risk zone is new to this initiative, it was established after the 11th-12th July event. To date, the population in this zone has received just one warning SMS. There is a helpline established for the community to receive clarification on the meaning of the SMS message. There are 3 automatic rain gauges in the Bara/Parsa region feeding real-time data back to DHM.

i) It was noticed that gullying is occurring in agricultural lands across the study area due to high rainfall intensity, incohesive soils and limited vegetative cover. This loss of land will be exacerbated if climate change leads to greater rainfall intensity. If present, community disaster risk management plans could be expanded to include measures to mitigate such climate change impacts.

Wind storms

Windstorm, a wind that is strong enough to cause at least light damage to trees and buildings and may or may not be accompanied by precipitation. Wind speeds during a windstorm typically exceed 55 km (34 miles) per hour. Tornadoes are very strong windstorms with a small column of violently rotating air developing within a convective cloud and in contact with the ground (Fujita 1989). Tornadoes occur most often in association with thunderstorms or hailstorms during the spring or summer. Nepal is exposed to moderate levels of wind in the spring, and storms with wind speeds strong enough to damage buildings are extremely rare. In recent years, there has been an increase in windstorm and cloudburst events before the onset of monsoon as well as cyclone formations over the region as a result of some unexpected abnormalities of thermodynamic surface characteristics both on land and in the ocean (Chhetri *et al.* 2020).

The strong winds and hailstorms that hit Bara and Parsa districts on 31 March 2019 killed 30, injured more than 1150 people and left more than 2890 families homeless. Several mosques, schools, businesses, industries, agricultural lands, and utilities, such as water supply and electricity, were damaged.

After undertaking a reconnaissance survey and assessing other available information, DHM classified the storm as a tornado. Due to the absence of previous tornadoes in Nepal, the DHM evaluation team coined "Ghumrapaat" as a Nepali name for tornadoes (DHM 2019b). Based on the destruction, the strength of Bara-Parsa tornado was estimated by DHM to be of EF3 category (Enhanced Fujita scale number 3 category) with the wind speed between 180 to 265 km/h. The tornado travel speed was estimated to be 157mph (70m/s) and up to 182mph (82 m/s).

Affected communities and relevant authorities were consulted in the field to understand this event better, which are presented in Tables 3 and 4.

The key observations made in preparing the case study are summarized in Table 3 and 4:

Table 3: Case study of windstorm disaster, impact and response in Birgunj Metropolitan City

Windstorm disaster	**Impacts**
The width of the severe storm was limited to approximately 250m. Wind speed is estimated at around 157mph (70m/s) and 182mph (82 m/s). The length of the storm affected area was around 25km. Anecdotally, this has been described as a 1 in 50 year event.	27 People killed. 668 People injured. Around 1,500 houses damaged. 122 houses completely destroyed. 1,500 electricity poles damaged including regional 33kv transmission lines. Thousands of trees have been uprooted, obstructing roads and highways.
Community's reponse and preparedness	**Government response**
The majority of affected people were Muslim minority, generally poor with poor quality housing and limited land. Communities suggested they have never experienced such strong winds and were unprepared to respond to such severe events. They were satisfied with the response from community, local, provincial and national government. Damage of transmission lines created a hazard, falling on people and homes. Most of their homes are still poorly constructed, so we fear another event would affect us again.	A national response was coordinated through federal task force (cabinet level) coordinating with Province 2 officials and local government. Security forces (Nepal Army, Armed Police Force and Nepal Police) mobilized for the relief and rehabilitation effort. Medical officers of Nepal Army were mobilized. Tents were distributed and assembled as temporary shelter for affected households. Nepal Army completed construction of replacement (concrete block) housing for affected households by 4th September 2019. National government committed to bear all costs. Provincial government provided compensation to deceased family members.

Table 4: Lessons learned from the windstorm

Experiencing disaster	Preparedness and response to disaster
Such high windspeeds are rare – 1 in 50 years. The location of such wind storms are very difficult to predict; they rapidly evolve based on atmospheric pressure and heat, and create high levels of devastation over a small path. Even with advanced radar technology (currently unavailable to DHM), warning times would only be 15-30 minutes before the event. With such short warning lead times communication channels would have to be excellent, and it is unlikely the community can take many protective measures. Widespread resilient housing would be a better focus than advanced warning systems for such rare and focused events. 'Safe rooms' could be a cheaper alternative than fully resilient housing. If it proves difficult to implement full build out of resilient housing, a number of resilient buildings should be identified in each village within disaster management plans coupled with a storm action/ evacuation plan. In this way, resilient schools and other community centres could provide shelter for communities. In the Tarai region, the building code is designed for 47 m/s, top estimates for wind speed during the storm were up to 70 m/s.	National provincial and district level response was timely and appropriate. All political parties made contributions to the recovery effort. Whilst the event had significant impacts, it can be easier to respond to a focused disaster (in time and space) where the affected area is well constrained and impacts can be well defined, recorded and reconstructed and/ or compensated. The hazard was not long lasting or widespread. International assistance was coordinated in the provision of temporary shelter. Reconstruction efforts are already underway, implemented by the armed forces. Always 'build back better'.

Earthquake

Nepal is a seismically active region located at the boundary between the Indian and Tibetan tectonic plates. Historical data show that highly destructive earthquakes have occurred in the past. Nepal is the 11th most earthquake-prone country in the world and has experienced a major earthquake every few generations. According to Nepal's National Seismological Centre (NSC), Department of Mines and Geology an earthquake of 7.6 magnitude occurred about 76 km northwest of Kathmandu in April 2015. Nepal had not faced a natural shock of comparable magnitude for over 80 years (Chaulagain et al., 2018).

The catastrophic earthquake was followed by more than 300 aftershocks greater than magnitude 4.0 (as of 7 June 2015). Four aftershocks were greater than magnitude 6.0, including one measuring 6.8 which struck 17 days after the first big one with the epicentre near Mount Everest. To date, there are over 8,790 casualties and 22,300 injuries. It is estimated that the lives of eight million people, almost one-third of the population of Nepal, have been impacted by these earthquakes (NPC, 2015)

Since 1978, the NSC has monitored earthquakes on a network of 21 short period seismic stations and 7 accelerometer stations. NSC has also prepared a ground Peak acceleration contour maps, which is a measure of the intensity of an earthquake and is often used to evaluate the potential damage that an earthquake may cause to buildings and infrastructure (Figure 6 and 7).

As shown in Figures 6 , Nepal is a country at high earthquake risk, but only one earthquake greater than 5 magnitude has occurred near the Birgunj-Jitpur-Simara corridor. From a national perspective, seismic risks in the study area are relatively low. Consultations with local stakeholders revealed no concerns about earthquake risks. It is estimated that 15-40% of the houses in the corridor are earthquake-resilient. Some small towns and Birgunj Metropolitan City are the only places with relatively more resilient houses based on construction material and design (Figure 7).

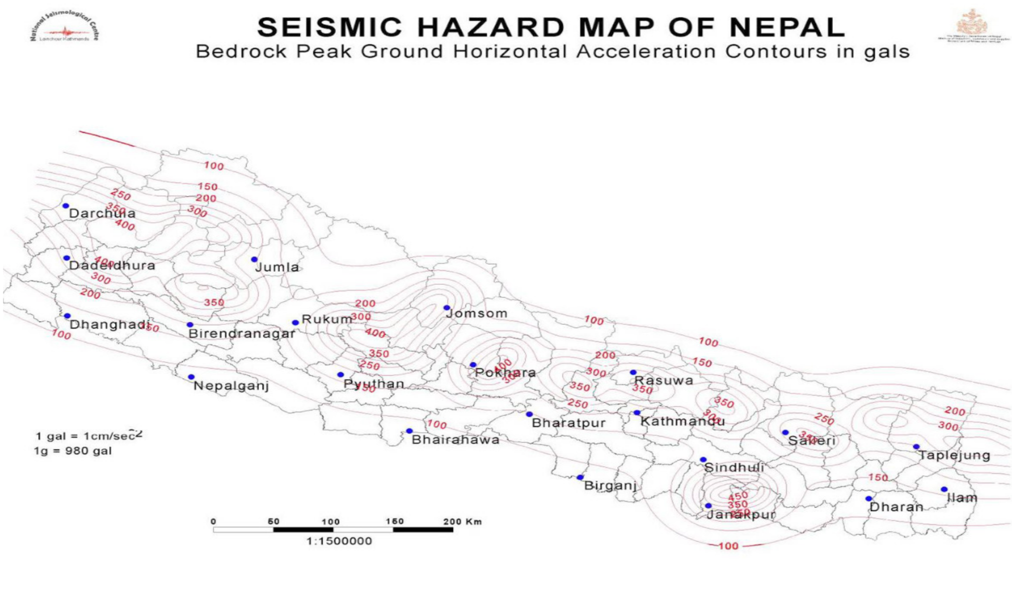

Figure 6: Seismic hazard map of Nepal - bedrock peak horizontal acceleration in gals. Source: NSC

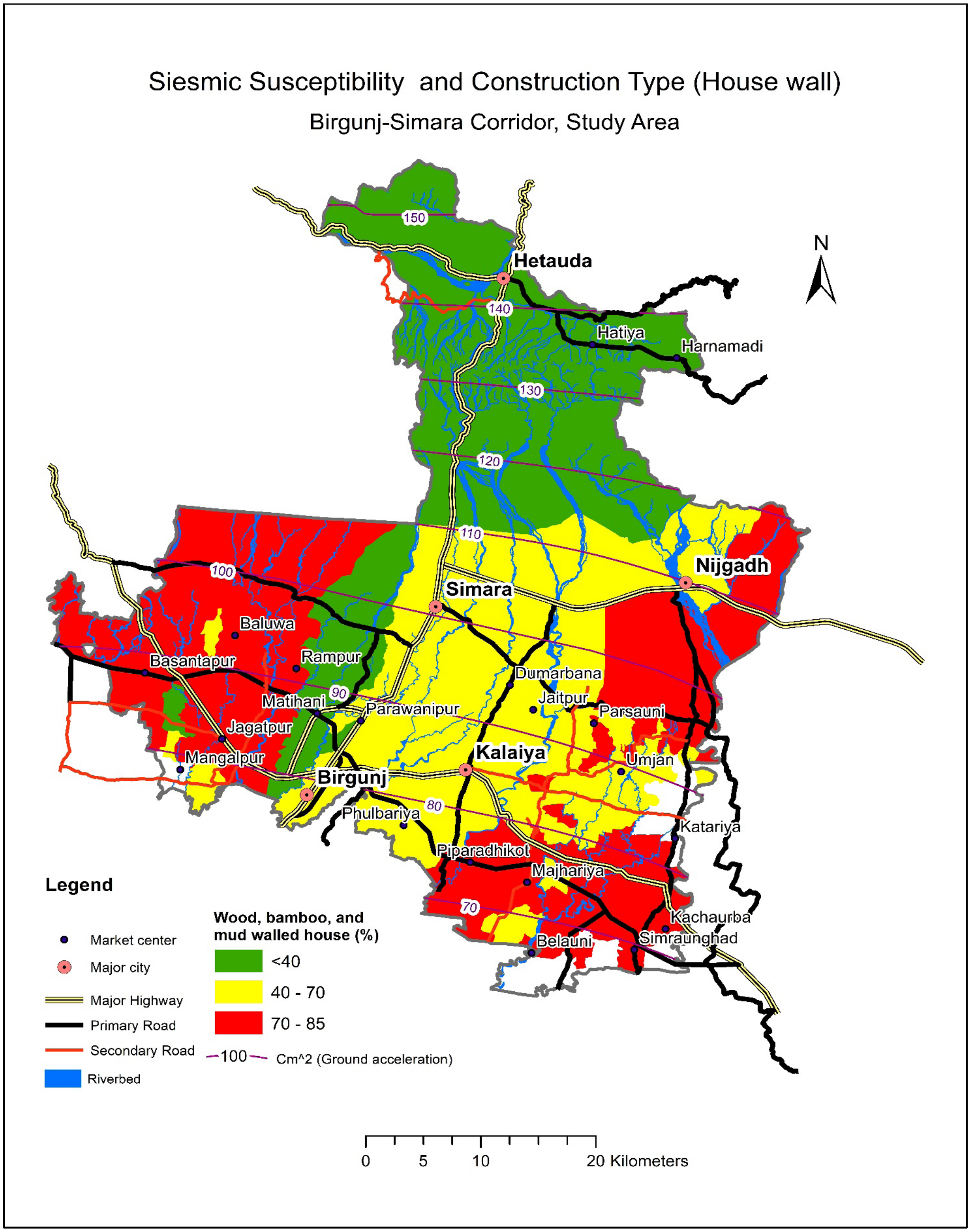

Figure 7: Earthquake vulnerability - Seismicity (GALs) and % mud/bamboo/wood house.

Fire

The Tarai region suffers fire outbreaks in the dry and windy season between April and June. Over the last two decades, the total fire incidents in the rural and urban parts of the corridor were 1358, i.e., an annual average of 61 fire incidences and 206 families affected. During this period, an overall increase in fire incidents and families affected in the corridor was observed (Figure 8).

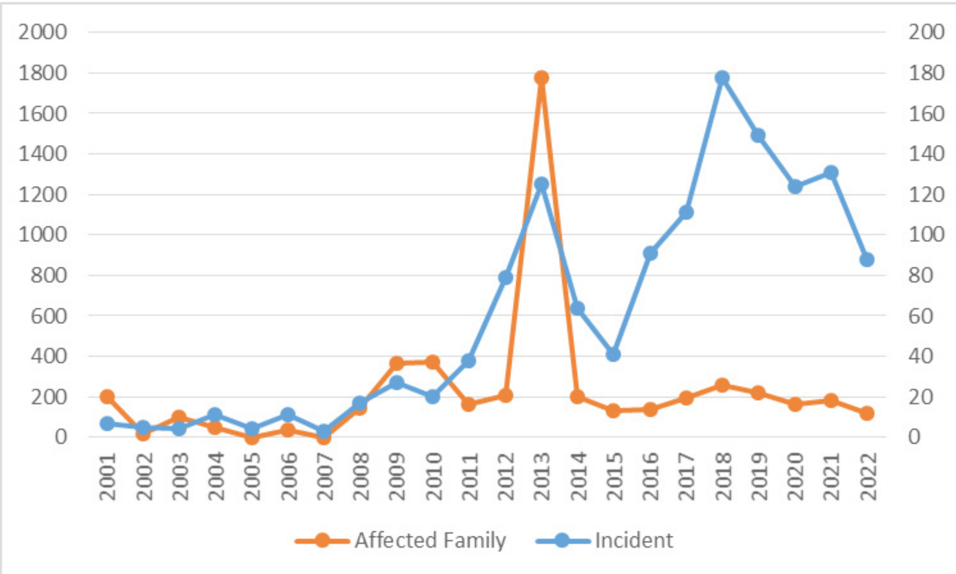

Figure 8: Trend of fire incidents in the study area. Source MoHA 2022

As forest cover is limited, fires are not usually extensive,so hazard risk is generally assumed low. Fires are caused by a lightning strike, poor handling of fire during cooking,bad electrical installation,and handling of gas cylinders. Fires are also connected with festivities and crop harvesting. Much of the housing stock is not resilient to fires (Figure 9). From the observation and consultation, the causes of the fire outbreak can be classified into the two categories:

1. Natural factors: excessive hot temperature, prolonged dryness, and strong winds.

2. Conditioning factors include: a. Inflammable construction materials such as houses comprising thatch or straw covered roofs, mud bonded straw, wood or bamboo fenced wall, etc. b. Settlement pattern: compact or agglomerated settlement. C. Unsafe Inflammable materials such as agriculture residues, storage of hay or straw

close to houses or sheds, unsafe storage of liquid fuels such as kerosene, diesel or petrol, and D. The practice of burning fire outside the courtyard for keeping warm.

Fire-fighting capacity is limited to major urban centers and is under-resourced so response times to rural areas can be extended.

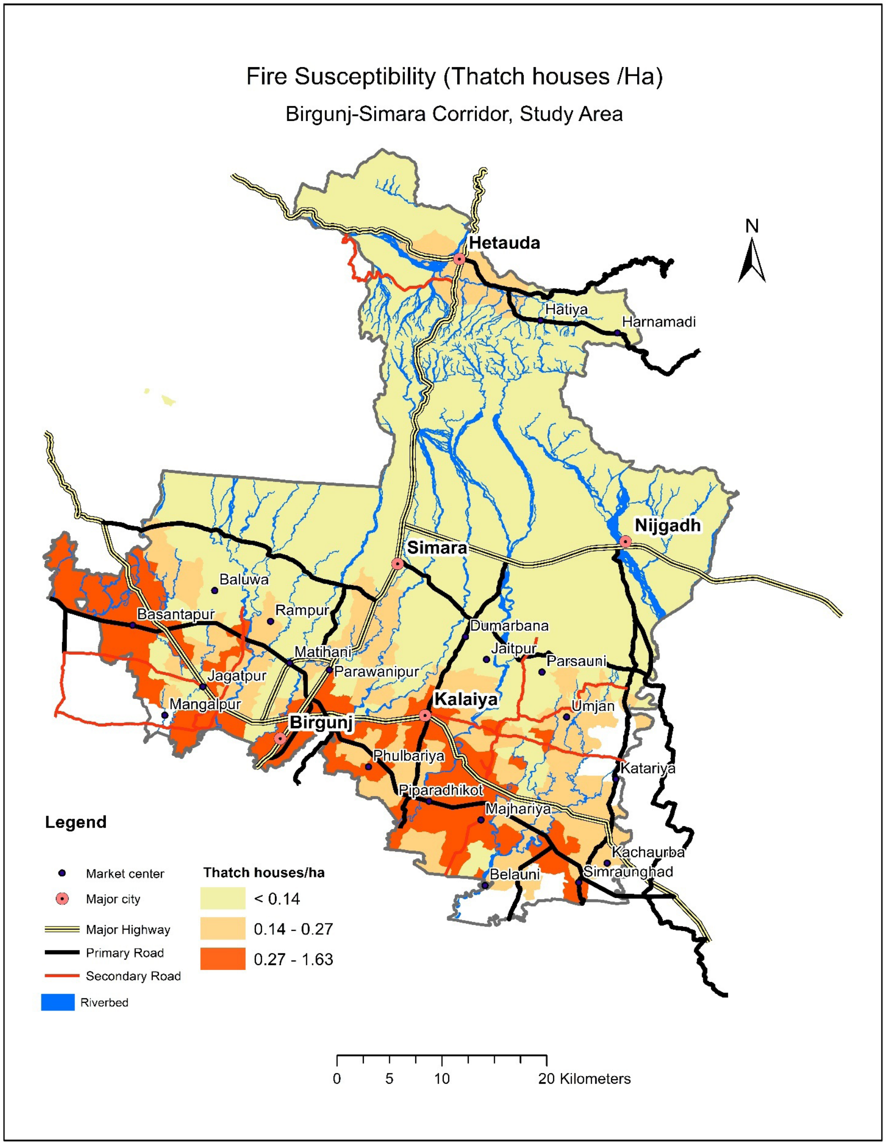

Figure 9: Fire vulnerability: density of the thatch houses

Multi hazard vulnerability assessment

A simple multi-hazard vulnerability index tool was developed to prepare a single map that describes the most vulnerable populations to disaster risk (Figure 10). The tool combines a number of exposure, sensitivity, and adaptive capacity indices developed for each VDC to deliver a weighted disaster vulnerability index score for each VDC. The method of calculating indices and weights assigned are described in Table 5. List of indices used in multi-hazard vulnerability analysis

Table 5: Method describing calculation of index value and weight

Index	Vulnerability factor	Measures (Municipality)	Index value	Weight
Flood	Exposure	% of VDC area in flood risk zone	Flood %/100	3
Seismicity	Exposure	Ground acceleration at centroid of VDC	Seismicity at VDC/500 Gal (Maximum in country)	1
Fire	Exposure	Thatched roofs per hectare in a VDC	Thatched per hectare in village or /Maximum	1
Density	Sensitivity	Population density	Population density/ Maximum	2
Construction	Sensitivity	% houses poor construction (mud/wood/bamboo)	Poor construction / Maximum	1
Shelter	Sensitivity	Schools per population	Schools per 1000 population/Maximum	1
Healthcare	Sensitivity	Health posts per 1000 population	Health posts /per 1000 population /Maximum	1
Education	Adapt. Cap.	Literacy rate	Literacy rate /Maximum	1
Poverty	Adapt. Cap.	Poverty rate	Poverty rate /Maximum	1
Response	Adapt. Cap.	Police stations per population	Police stations per 1000 population/Maximum	1
Planning	Adapt. Cap.	Municipal DRR budget	Municipal DRR budget per/1000 persons/ Maximum	1

Each index was normalized to one (1) based on mean or distribution as most appropriate. And weightings were assigned as per Table 5. Table 6 is a screenshot of the spreadsheet-based index calculator. The range in the calculated vulnerability index 0.58 to 0.14, and the mean is 0.30. Due to the selection of indices the most vulnerable places are the most poor, densely populated areas which are underserved and exposed to flooding. Note that Birgunj sub-metropolitan area has the greatest vulnerability. Figure 10 presents the calculated multi-hazard vulnerability index spatially across the study area.

Table 6. Screenshot of index calculator

		Exposure			Sensitivity				Adaptive Capacity				
	weighting	3	1	1	2	1	1	1	1	1	1	1	
Municipality	VDC	Flood index	Seismicity index	Fire index	Density index	Construction index	Shelter index	Healthcare index	Education index	Poverty index	Response index	Planning index	INDEX
ADARSHKOTW.	Enarwamal	0.04	0.18	0.15	0.12	0.79	0.56	0.84	0.31	0.62	0.52	0.00	0.39
ADARSHKOTW.	LakshmipurKotw	0.31	0.17	0.17	0.15	0.79	0.63	0.59	0.39	0.61	0.00	0.00	0.40
ADARSHKOTW.	Paterwa	0.00	0.17	0.11	0.09	0.79	0.72	0.70	0.44	0.62	1.00	0.00	0.27
BAHUDARAMA	Bahauri Pidari	0.28	0.18	0.19	0.24	0.74	0.43	0.79	0.43	0.66	0.00	0.28	0.39
BAHUDARAMA	BairiyaBirta(Nau	0.25	0.17	0.14	0.17	0.74	0.36	0.53	0.46	0.64	0.00	0.31	0.32
BAHUDARAMA	Bhauaratar	0.04	0.18	0.11	0.14	0.74	0.76	0.74	0.46	0.67	0.43	0.18	0.30
BAHUDARAMA	Bisrampur	0.01	0.17	0.18	0.24	0.74	0.68	0.83	0.42	0.69	0.00	0.23	0.33
BAHUDARAMA	Gamhariya	0.00	0.18	0.32	0.41	0.74	1.00	1.00	0.41	0.64	0.00	0.39	0.43
BAHUDARAMA	Nagardaha	0.20	0.18	0.09	0.13	0.74	1.00	0.32	0.47	0.69	0.00	0.45	0.33
BAHUDARAMA	Ramnagari	0.01	0.17	0.18	0.22	0.74	0.33	1.00	0.52	0.68	0.00	0.49	0.30
BARAGADHI	Gadhahal	0.02	0.18	0.22	0.19	0.66	1.00	0.62	0.45	0.67	0.00	0.00	0.34
BARAGADHI	Khopuwa	0.10	0.18	0.12	0.11	0.66	0.56	0.76	0.40	0.62	0.00	0.00	0.31
BARAGADHI	Mahendra	0.23	0.18	0.11	0.09	0.79	0.13	0.29	0.44	0.61	0.00	0.00	0.26
BARAGADHI	Pathara	0.23	0.18	0.12	0.09	0.79	0.55	0.76	0.42	0.66	0.80	0.00	0.33
BARAGADHI	PipraBasatpur	0.01	0.18	0.13	0.12	0.66	0.74	0.44	0.48	0.66	0.00	0.00	0.27
BINDABASINI	JhauwaGuthi	0.07	0.16	0.26	0.19	0.67	1.00	0.81	0.49	0.67	0.00	0.00	0.38
BINDABASINI	Amarpatti	0.04	0.16	0.20	0.16	0.67	0.32	0.02	0.51	0.62	0.80	0.00	0.18
BINDABASINI	Bahuarwa Bhath	0.08	0.17	0.09	0.11	0.74	1.00	0.83	0.54	0.67	0.00	0.00	0.36
BINDABASINI	Patwaritolabarw	0.04	0.17	0.03	0.09	0.24	0.48	0.63	0.44	0.61	0.62	0.00	0.19
BIRGUNJ	Harpatgunj	0.00	0.17	0.07	0.22	0.24	0.75	1.00	0.59	0.70	0.00	0.26	0.28
BIRGUNJ	Rampur (Tokani)	0.05	0.18	0.08	0.13	0.56	0.53	0.49	0.55	0.73	0.00	0.16	0.24
BIRGUNJ	Alau	0.12	0.16	0.20	0.26	0.74	0.87	0.72	0.51	0.63	0.00	0.14	0.38
BIRGUNJ	Bagahi	0.05	0.18	0.05	0.14	0.24	0.83	0.45	0.46	0.67	0.00	0.18	0.23
BIRGUNJ	Basadilwa	0.05	0.19	0.05	0.15	0.24	0.48	0.81	0.41	0.68	0.00	0.18	0.24
BIRGUNJ	Belwa Parsene	0.10	0.22	0.02	0.05	0.24	0.52	0.74	0.47	0.74	0.00	0.13	0.23
BIRGUNJ	Bhawanipur	0.06	0.17	0.06	0.18	0.24	0.64	0.22	0.64	0.82	0.00	0.19	0.19
BIRGUNJ	Bindabasini	0.21	0.16	0.18	0.23	0.74	1.00	1.00	0.52	0.56	0.77	0.22	0.41
BIRGUNJ	Birgunj Sub Metr	0.05	0.17	1.00	1.00	0.42	0.87	0.96	0.77	0.86	0.15	0.01	0.57
BIRGUNJ	Chorni	0.03	0.20	0.09	0.15	0.56	0.64	0.74	0.54	0.77	0.00	0.12	0.28

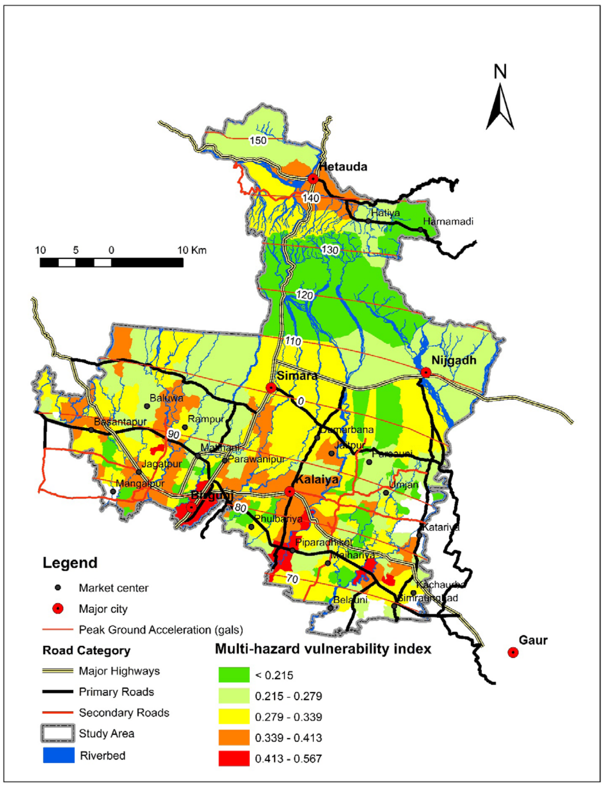

Figure 10: Map of multi-hazard vulnerability index

Disaster exposure and identification of focus area

In recent years, the greatest and most frequent impact on the population in the study area is from flooding. There is an underlying risk of earthquakes, windstorms, and fire disasters, as well as industrial accidents, but the frequency is uncertain and the sensitivity is not so great. In the corridor, disaster risk reduction efforts should focus on flood risk management, but earthquake, wind, fire, and industrial accident risks should also be considered. Several simpler interventions may be able to mitigate these risks, such as improving land use planning, providing resilient buildings, and improving disaster response and planning.

The hazard matrix below Table 7 was used to describe the greatest hazard risks to the study area and provide further focus for areas of intervention.

Table 7: Hazard matrix: identify focus areas for intervention

Disaster	Exposure		Sensitivity	Focus
	Impact	Frequency		
Flood	Complex. Not well identified. Widespread. Limited death toll but high impact in terms of economic disruption and public health (sanitation, dengue, etc).	Annual	Very complex	HIGH
Earthquake	Impact could be high but seismicity (potential ground acceleration) in the region is low in the National Context.	Medium/Low in the Tarai region	Can be resolved through resilient buildings.	MEDIUM
Wind	High impact over a limited area. Difficult to predict location, very low lead time for warning.	Very low. Could be increasing.	Can be resolved through resilient buildings.	MEDIUM
Fire	Unlikely that widespread fires occur outside of forested areas.	Assumed low frequency as no forest. Thatch density can be high. Electric maintenance is poor.	Road density is reasonable, but fire-fighting Capacity is poor.	LOW
Industrial accidents	Could have a high impact but confined to a very small area resulting in low impact relative to other hazards.	Medium frequency, possibly 5 years, caused by poor industrial health and safety practices.	Requires land use planning and industrial H&S enforcement.	MEDIUM

Identifying Problems and priorities

Based on an assessment of disaster risks and vulnerability across the study area, with reference to Figure 6, the priorities identified for mitigating disaster risk in the study area include:

i. Flood risk reduction, with a particular focus on the Sirsiya river which floods annually affecting some of the most vulnerable people in the study area, the densely populated peri-urban settlements, and causes major economic disruption and damage to infrastructure.

ii. Reducing the sensitivity of the population to all disasters by implementing improved land use planning, resilient housing, and community disaster risk management planning, and response capacity.

Problem trees (Figure 11 and 12) were prepared for both of these priorities to examine the issue's root causes and ensure that any recommendations address these issues. The issues fall under the following categories:

- Land: land availability and land use planning.
- Capacity: technical and budgetary Capacity to design, implement, and maintain infrastructure and disaster risk management systems/services.
- Socio-economic: linked to the regional economy, job security and poverty.

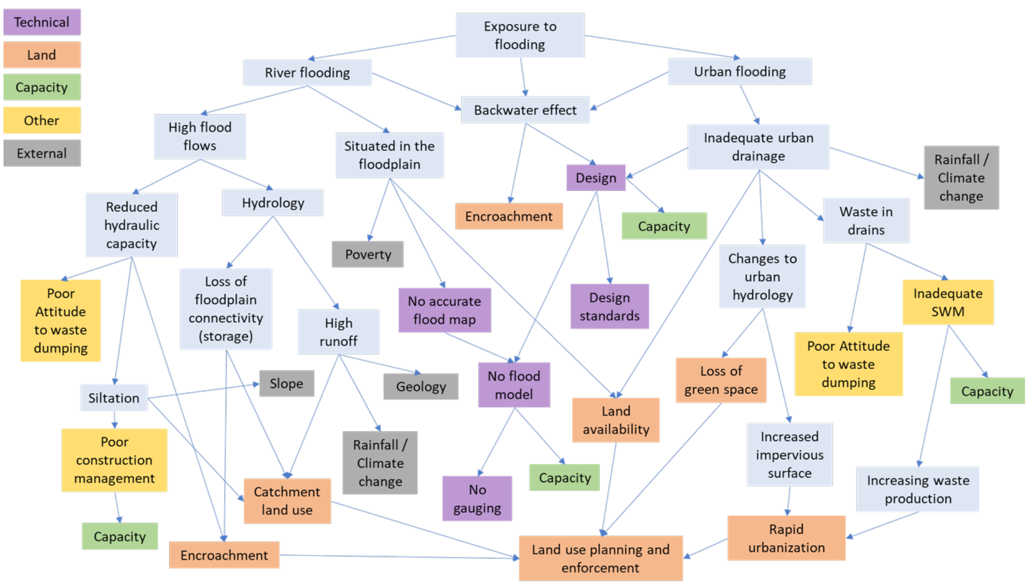

Figure 11: Exposure to flooding, problem tree

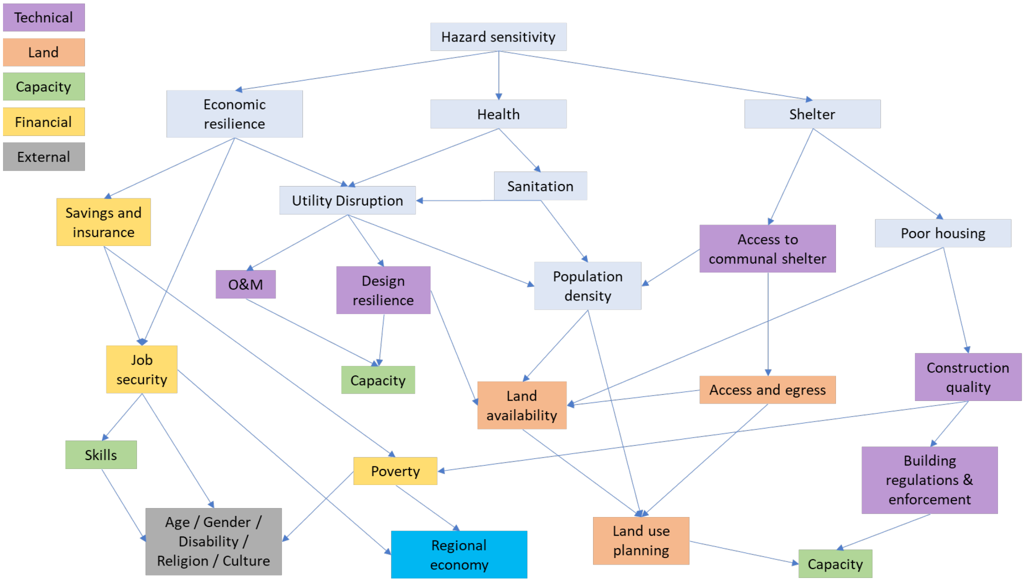

Figure 12: Sensitivity to disasters, problem tree

Discussions: Issues and approach to reduce vulnerability

Multi-hazard risk and vulnerability have been examined. Flooding occurs annually,and the recurrence interval of high magnitude flood is low. The impact of the flood is complex and not well identified. The death toll is limited but has a high impact in terms of economic disruption and public health (sanitation, epidemics, etc.), a common problem in Tarai and other lowland areas in south Asia (Adhikari 2013, Bhatt & Rao 2016, Kale 2003). Flood frequency in the study area is reportedly increasing as result : (a) higher flows as a result of human encroachment on forest, and flood prone areas, and increase in built-environment upstream, (b) river channel constriction through encroachment and sedimentation, (c) increased local runoff from urbanization, (d) clogging of urban drainage systems with unmanaged solid waste, (e) greater exposure to flooding as increased residents and activity are situated in the floodplain, and (f) climate change. Climate and land use change and human activity-induced flood disaster in Tarai in Nepal has been substantially documented (Devkota & Gyawali 2015, Devkota *et al.* 2014, Dewan 2015, Dulal *et al.* 2010, Ghimire 2020, Kaphle *et al.* 2008, Khanal *et al.* 2007, Mirza 2011, Sharma *et al.* 2019).

Recently, some studies (Chhetri *et al.* 2020 Karki *et al.* 2017)concluded that generally, extreme precipitations were obtained in the major rainy period, but pre-monsoon cloud burst events are also observed due to some unexpected abnormality of the thermodynamic surface characteristics over both the land and oceans before the onset of monsoon in Nepal.

Encroachment and sedimentation are likely to be key issues, as these will increase river water level for a given flow These are a direct result of human activity and poor land use planning. Due to the low gradient nature of the stream (less than 0.5% slope), downstream encroachment and hydraulic constrictions can produce backwater effects (elevated river water levels) upstream – i.e., channel constrictions downstream of drainage outfalls can create these backwater effects.

Development is uncontrolled. There is no clear zoning strategy, land use policy, or enforcement. Flood risk zones should be allocated for green space, agriculture or where necessary, critical infrastructure (appropriately designed for resilience). The poorest, most vulnerable sectors of the population often move to cheaper marginal land which is at risk of flooding. What remains of the forests to the north of the corridor should be strictly protected to maintain its capacity to attenuate runoff and reduce further impacts on the, already flashy, hydrological regime.

Undertaking any design work, it is essential to understand the river system. Hydrologic and hydraulic models of the Sirsiya River would enable the design of bridges/culverts and other hydraulic structures and give boundary (downstream) conditions for hydraulic calculations (models) for urban storm water design. This modeling would also enable better flood mapping and resilient land use planning(El Kadi Abderrezzak *et al.* 2009, Paquier *et al.* 2015, Rangari *et al.* 2019, Yin *et al.* 2015).The development plan should ensure no increase in urban storm flood. A sustainable urban drainage system should be included in development to attenuate storm water attenuation or infiltration.

Due to waste disposal from urban or rural areas into the rivers, the impact of flooding aggravates (Dewan 2015, Nepal *et al.* 2022, Rai *et al.* 2019). Waste management in the Sirsiya river and water quality improvement would reduce the impact of flooding. Communities need to develop flood management capacity at a local level. This needs to be augmented with a coordinated response from local government and NGOs following community Disaster Risk Management Plans. Communities acknowledge the issue of encroachment human activity into the river and disrupting hydraulic function of the river is prevalent. Communities can be motivated to resolve the issue of encroachment through appropriate plans and projects, which has been affirmed in studies of Dewan (2015), Gautam and Phaiju (2013), and Smith et al. (2017)and citations therein. They would support the relocation of the most vulnerable if necessary. They mentioned that the land use maps should have a river set back.

Tarai is close to high concentration of the epicenters located at Main Central Thrust (~100-150 km) and moderate concentration at Main Frontal Thrust at the northern edge of the Tarai (Styron *et al.* 2010, Thapa 2018). Hence, it is a seismically active zone; big earthquakes are inevitable although earthquakes are less predictable. Most buildings before the earthquake 2015 are vulnerable as they were poorly constructed and can be collapsed or damaged easily. Disaster resilient urban corridor planning with the enactment of earthquake-resilient building code is necessary.

Minor to moderate windstorm annually occur, but strong windstorm like tornadoes are rare–1 in 50 years. The location of such wind storms is very difficult to predict. They rapidly evolve based on atmospheric pressure and heat and create high levels of devastation over a small path. Even with advanced radar technology (currently not available to DHM), warning times would only be 15-30 minutes before an event. With such short warning lead times, communication channels would have to be excellent, and it is unlikely the community can take many protective measures(Gautam & Phaiju 2013, Smith *et al.* 2017, Toolkit 2002). Housing construction is often mud and bamboo with thatched roof. Widespread resilient housing would be a better focus than advanced warning systems for such rare and focused events. 'Safe rooms' could be a cheaper alternative than fully resilient housing (Toolkit 2002).

At the initial stage, a number of resilient buildings should be identified in each village within disaster management plans coupled with a storm action/evacuation plan. In this way, resilient schools and other community centers could provide shelter for communities. In the Tarai region, the building code is designed for 47 m/s, top estimates for wind speed during the storm were up to 70 m/s. The response to wind disaster from the national provincial and district level response was timely and appropriate. International assistance was coordinated in the provision of temporary shelter. Reconstruction efforts are already underway, implemented by the armed forces.

The 2017 Disaster Risk Reduction and Management Act following the Constitution of Nepal, 2015, has provisioned new legal and institutional framework for disaster risk management. This framework is comprehensive and sets out roles and responsibilities through all levels of governance, from federal, provincial, district to local. Disaster risk management is a shared responsibility through every layer of governance system, but gives particular importance to the lower governance levels as planning for disaster risk and mitigating vulnerability is area specific. There is a clear provision for Disaster Management funds at the federal, provincial and local levels. However, there is a less clarity on role, responsibility, and coordination on planning and implementation of disaster risk reduction and management at all tiers of governance.

Sharing roles and responsibilities between federal levels according to the nature, intensity, and effect of disastrous events is also indecisive (Bhandari *et al.* 2020). Response to disaster in the study area is varied. Where disasters are well constrained, (in space and time) such as the Bara-Parsa 2019 tornado, national and provincial level response is rapid and appropriate with declaration of emergency and coordination of international and national response, support and recovery occurring rapidly after the Bara-Parsa tornado. But for widespread disasters like floods, the national response is sluggish, mainly carried out by community and ward leaders. District, municipality and community are reactive in response not proactive, and mostly limited to relief, shelter and rescue operation. Local government have limited Capacity on rehabilitation and reconstruction and maintenance operations. Local capacity is currently weak, training will be required to develop Capacity to implement the plans. Disaster response and resilient shelter centres are not clearly defined, but should be in disaster risk management plans. Disaster risk reduction fund is allotted upto 15 % of total municipality budget, is still scarce, particularly in flood prone parts. Much of the fund is initially allocated for spurs and embankment construction and maintenance, apart from relief and rescue responses. Ward leaders provide good coordination during disaster, shelter can be provided in wards, and the community responds by distributing local collections for food etc.

These should outline responsibilities, communications plans, and resources for disaster preparedness, warning systems, disaster response, rescue, and recovery. The plan should include temporary shelter, search and rescue, food and other relief assistance details. Identifying the most vulnerable sites and settlements should form a core part of the District Disaster Management Plan. These most vulnerable communities should then be supported to prepare their disaster risk management plans with responsibilities, establish community early warning systems, and identify resilient temporary shelter locations.

Conclusions

The accumulative effects of multi-disasters are complex. The death toll is limited but has a high impact– loss of property, economic disruption, and public health. The natural flood potential of small rivers is low, but flood disasters have increased due to channel constriction by encroachment, improper drainage, and land use change in the upper catchments. The earthquake's impact could be high, but seismicity is low compared to the national context. Windstorms during pre or monsoon onset are challenging to predict, and their impact is high over a limited area. A fire disaster is not widespread but frequently occurs during hot and dry months due to compact rural settlements, nonresilient houses, and lack of fire safety measures. Industrial disasters are confined to some locations but can have a high impact due to poor industrial health and precautionary measures.

Exposure to flood, seismicity, and fire; high sensitivity due to dense population, poverty, poor construction, inadequate shelter, and health care; and low adaptation capacity owing to lack of awareness, widespread poverty, poor disaster preparedness, response and planning have contributed to high vulnerability of the multi-hazards. Efforts must be made to mitigate disasters through resilient land use planning, appropriate flood control and hydraulic structure design, sustainable urban drainage, waste management, and resilient housing. It is imperative to enhance and develop early flood warning systems and disaster preparedness and response at all tiers of governance in conjunction with the local community through the activation of relevant statutes and institutions.

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