Coalition for Disaster Resilient Infrastructure

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COHORT 2021-22

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Abstract

The Eastern Economic Corridor (EEC) is a special invent zone situated in the coastal area of Chonburi, Rayong and Chachoengsao provinces of Thailand. The EEC has several major infrastructures and is poised to attract multiple infrastructure development projects. The coastal provinces of Thailand are prone to various hazards that include flood, cyclone, tsunami and coastal erosion. These hazards pose a serious threat to the existing infrastructures including critical infrastructure in the coastal areas mostly along the Chonburi and Rayong provinces of Thailand.

A risk management exercise in the EEC area is critical to safeguard the existing infrastructure and the ones being developed in the near future from hazards. This study is a unique step to perform risk assessment of critical infrastructures with a focus on transport, health and education sectors with reference to natural hazards of flood, cyclone and coastal erosion. The methodology employs the identification of key critical infrastructures and indicators of hazard, exposure, sensitivity and capacity. Further, secondary data is gathered from national and global data sources to analyse hazards, exposure, sensitivity and finally risk of critical infrastructures in the EEC.

The result shows districts that come under very high-risk level are Si Racha (Chonburi) and Ban Chang (Rayong). Muang Chonburi (Chonburi) and Muang Rayong (Rayong) are high-risk-level areas. Under moderate risk level is Klaeng (Rayong) district, while Ko Sichang (Chonburi) and Sattahip (Chonburi) are considered low risk. It must be remembered that Laem Chabang Port and U-Tapao Airport are located in very high-risk zones. Similarly, Map Taphut Port, situated in Muang Rayong, is also a high risk-level zone. On the basis of this knowledge, priority should be given to Chonburi and Rayong districts while allocating resources. Additionally, for future studies baseline research for the development of database is highly recommended. Accessibility to such database will ensure a more accurate and comprehensive risk assessment in the future.

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1. Introduction

Asian countries have been encountering natural hazards in terms of both frequency and severity. These disasters have been causing damage to infrastructure and especially to critical infrastructures. Therefore, understanding current situation of hazards and the probable impact on these critical infrastructures becomes important. In many industrialized countries, especially in Southeast Asia, infrastructure has become a crucial key to reduce physical and economic losses. Over the past few decades South Asia, East Asia and Pacific regions have been facing inadequacy of critical infrastructure to minimize the mentioned losses and support development goals.

Critical infrastructure can be defined as assets and services that offer essential resources related to the physical structures, which enable the economy and society to function. According to the World Bank Group, inaccessibility to critical infrastructure, particularly electricity, water supply, transportation or sanitation services, increases the pressure on people health, quality of life, education, employment and economics (Marcelo et al., 2020). Even though definitions and categorizations of critical infrastructure differ among countries, their role are important for running societies and economy. Moreover, in terms of industrialized societies they rely heavily on the functioning of infrastructure services, especially, telecommunication technology, power supply or water supply. These services help to accommodate other operations such as health system, drainage system, sanitation system and so on. Mohanty et. al. (2020) said the term 'critical infrastructure' has diverse connotations, depending on the context of its use. They believe that the simplest way to identify vital infrastructure is to determine what is essential to the society's normal operations. Systems, assets, buildings and networks that offer essential services for an economy's operation as well as safety and well-being of the population are referred to as critical infrastructure.

However, critical infrastructure can get damaged or interrupted by natural hazards, disasters or other threats (e.g., anthropogenic activities, terror, human failure). There are past examples of events such as 2004 Indian Tsunami, 2008 Cyclone Nargis, 2011 Thailand Flood, 2012 Hurricane Sandy, that had intensive impact on the critical infrastructure. Therefore, having sustainable infrastructure can reduce disruptions from any threats. Asia and the Pacific confront significant constraints, determined by the scarcity of infrastructure investment. To have stable infrastructure, targeted policy reforms, improved planning, management and operation are important to reduce essential infrastructure-service scarcity and issues related to both quality and quantity (Marcelo et al., 2020).

In Asian countries, electricity, water supply, transportation and sanitation services are critical infrastructures and a reflection of the smooth functioning of a society. Therefore, many industrialized countries in the regions may have to invest US$26 trillion in critical infrastructure by 2030 (ADB, 2017) in order to maintain the growth momentum and tackle climate change.

Thailand is placed as a centre of economic growth in Southeast Asian region. The economic growth of the country is propelled by export-oriented manufacturing and tourism. However, the region is prone to natural hazards such as cyclone, flood, storm surge and tsunami. Thailand flood of 2011 alone caused damage and loss to the tune of US$46.5 billion to various sectors (Haraguchi and Lall, 2015). In recent times, Thailand has become an upper middle-income country and second largest economy in Southeast Asia. It transformed from a rural economy to urban agglomeration where more people live in urban areas as compared to rural areas. This transformation has put pressure on the existing infrastructure. The country has to invest in making these infrastructures resilient. The breakdown of these systems may incur devastating impact on public functioning, safety and resilience. A clear understanding of different degrees of risks to critical infrastructure and investment decisions by investors, multilateral funding agencies, businesses and national governments in the region is paramount for the sustainable development of the region. Therefore, it is important to identify the risks to critical infrastructure and address them to build long-term resilience in the system.

This study aims to assess current situation of hazards in coastal areas of Thailand. The chief focus will be on Easter Economic Corridor (EEC) that falls in the Chonburi and Rayong provinces of the country. We will determine the level or potential risk of coastal critical infrastructure by establishing risk maps. By doing this, we will assist in choosing the direction of investment.

2. Statement of Problem, Objectives and Scope of the Study

2.1 Statement of the problem

As mentioned above, there are several hazards that pose threat to critical infrastructure, especially in coastal areas and EEC of the country. These are mostly along coastal areas in Chonburi and Rayong provinces. These two provinces have the two most important seaports that are usually affected by hydrological hazards such as coastal flood, coastal erosion and coastal erosion.

According to Thailand's Infrastructure Development Action Plan (2017), attempts are being made to construct and develop comprehensive transportation and logistics systems to increase the investment value and competitiveness, such as high-speed train connecting three airports, U-Tapao Airport and Eastern Aviation City, Laem Chabang Port Phase 3, Map Ta Phut Industrial Port Phase 3 and digital infrastructure. These infrastructures will assist in reducing travel time, save shipping cost and connect and support business and trade from neighbouring regions. This will reflect the country's economy in the long run.

However, the mentioned infrastructures are prone to coastal hazards, particularly, flooding, cyclone and coastal erosion leading to disruption of economic activities and impacting human lives. There are very few studies about assessing multi-hazard vulnerability, especially in coastal areas in Thailand, and very little to identify the potential risk, whereas extreme hazards have increased every year. Developing suitable methods/tools for risk assessment is still an existing gap in this research area.

2.2 Objectives of the study

The main objective of this research study is to review hazard profile, coastal critical infrastructure and risk index in the coastal area of Chonburi and Rayong provinces, Thailand. The main objective is further divided into three sub-objectives mentioned here:

1. To evaluate the hazard profile in the coastal area of Chonburi and Rayong provinces.
2. To review the typology of various coastal critical infrastructure in Chonburi and Rayong provinces.
3. To assess the risk of critical infrastructure from different hazards in the coastal areas.

2.3 Scope of the study

This special study focuses on risk indexing of critical infrastructure. The scope of the study is as follows:

1. To study the historic hazard statistics and previous research.
2. To focus only on coastal district of Chonburi and Rayong provinces.
3. To provide hazard, exposure and risk maps by using QGIS and other software.

3. Methodology

Multi-hazard risk assessment of coastal critical infrastructure is an effort to identify key risks of important infrastructure of a country that is prone to different hazards. The multi-hazard risk assessment efforts for critical infrastructure involve identification of different hazards, exposure, vulnerability and risk parameters. The risk assessment process for critical infrastructure quantifies and locates the multi-hazard risk and facilitates integration of risk information in the decision-making process for long-term development of the society and economy as a whole. Therefore, multi-hazard risk can be read as the reflection of hazards posing risk to a certain area under consideration. It is taken to determine the risk based on hazard and risk assessment. It takes into account the hazard assessment index that focusses on multi-hazards which potentially impact the most to EEC, particularly floodings, cyclones and coastal erosions. At the same time, the risk index is developed by analysing the relationship between exposure index, sensitivity index and adaptive capacity index in order to locate where the existing critical infrastructures are and assesses what levels of the risk the EEC is prone to.

Selection of Chonburi and Rayong provinces as study areas

The study areas (Figure 1) are concentrated in coastal areas of Chonburi and Rayong provinces and spread across eight districts: Muang Chon Buri, Si racha, Ko Sichang, Bang Lamung Sattahip (Chonburi province), and BanChang, Muang Rayong, Klaeng (Rayong province). Chonburi and Rayong are located in the country's eastern Gulf of Thailand coast and have coastal distance of 225 km, accounting for 130 km and 95 km, respectively.

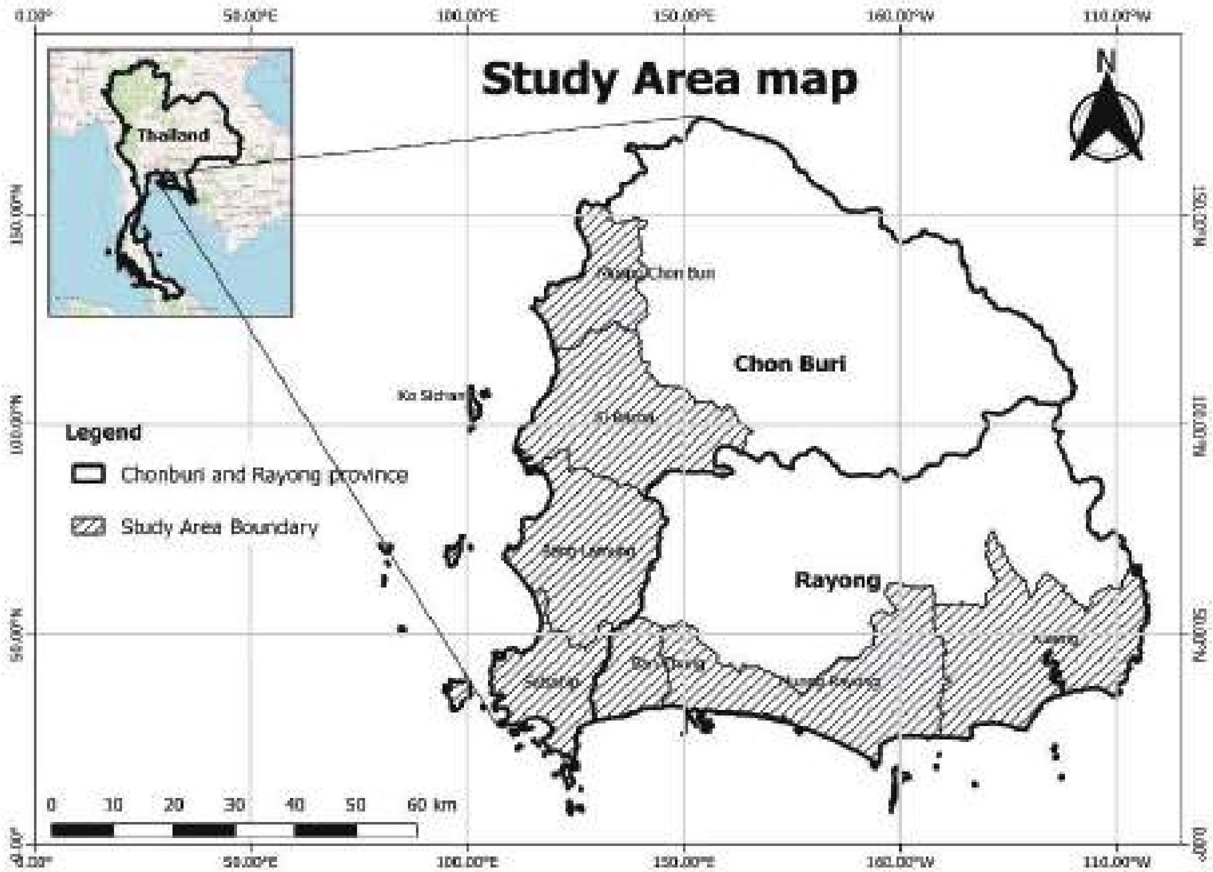

Figure 1. Study area (eight districts of Chonburi and Rayong provinces)

Source: Project Team

Chonburi and Rayong are the main two provinces that will be the centre of gateway as per the Thailand government plan. According to the information currently available, the coastal flood hazard in the area is assessed as high. This suggests that the shoreline is likely to be flooded by potentially damaging waves at least once in the next 10 years (ThinkHazard, 2020). Based on this information, the risk of coastal flooding on any activity along the coast must be evaluated at various stages of the project. As the result, it is crucial that the Thai government carefully considers project planning decisions, project design and construction procedures while making the EEC development plan strategy.

Table 1. Area of coastal district and total coastal distance

Provinces	Coastal Districts	Coastal District Area (km^2)	Total Coastal Distance (km)
Chonburi	Mueang Chon Buri	228.791	130
	Si Racha	616.434	
	Bang Lamung	469.021	
	Ko Sichang	17.239	
	Sattahip	333.422	
Rayong	Ban Chang	238.372	95
	Muang Rayong	514.547	
	Klaeng	788.463	

Source: e-report.energy.go.th

3.1 Methods and analysis

The approach and formula have been used to perform multi-hazard risk assessment of coastal critical infrastructure, which is defined as the probability of harmful consequences or expected losses resulting from interactions between multi-hazard and vulnerable conditions of critical infrastructures. The study employs a relative risk assessment than an absolute risk assessment method for critical infrastructure risk calculation. Risk assessment is performed for different districts of two provinces: Chonburi and Rayong. It compares composite risk of districts within these provinces.

Risk is considered as the product of probability of an event and its consequences. Further, risk is the product of hazard and vulnerability, and inversely related to coping capacity, where vulnerability comprise exposure and sensitivity (Rana and Routray, 2018)current focus is on risk assessment of hazard-prone communities. Risk measurement is complex as scholars engaged in disaster science and management use different quantitative models with diverse interpretations. This study tries to provide clarity in conceptualizing disaster risk and proposes a risk assessment methodology with constituent components such as hazard, vulnerability (exposure and sensitivity. The following formula was used to determine risk index:

$$R_i = H_i \times V_i$$

where R_i is Risk index, H_i is hazard index and V_i is vulnerability index

The indicators were based on polygons related to political-administrative areas, which are mostly at the district level. Each indicator was processed, analysed and standardized according to its contribution to hazard and vulnerability. The indicators were weighted using neutral to obtain the multi-hazard risk index map. The vulnerability assessment of coastal critical infrastructure was considered further and the following formula was used.

$$V_i = \frac{Ex_i \times S_i}{AC_i}$$

where V_i is vulnerability index, Ex_i is exposure index, S_i is sensitivity index and AC_i is adaptive capacity index.

The coastal critical infrastructure vulnerability was computed based on coastal facilities vulnerability of the U.S. National Park Service, adapted from IPCC (2001, 2007) and NPS (2022). It provides a more holistic approach in computing vulnerability as it accounts for not only exposure and sensitivity, but also adaptive capacity.

$$Normalized\ Value = \frac{X_i - X_{min}}{X_{max} - X_{min}}$$

Moreover, in order to compare the variables for each indicator, a normalization formula was used. A normalization approach with weighting was used as reflected by the normalized value formula (Mullick et al., 2019)sea level rise, increased tropical cyclone occurrence etc. To understand the problem followed by necessary coastal management recommendation, an integrated coastal vulnerability index i.e., Composite Vulnerability Index (CVI. The values for each component were combined to produce a composite map that exhibited the vulnerability for each district based on the collective normalized data of all the variables and indicators used. The spatial distribution mapping was done in QGIS3 using an administrative boundary map from ArcGIS Hub and a base map from Google Earth. Figure 2 shows the detailed methodological approach adopted for this study.

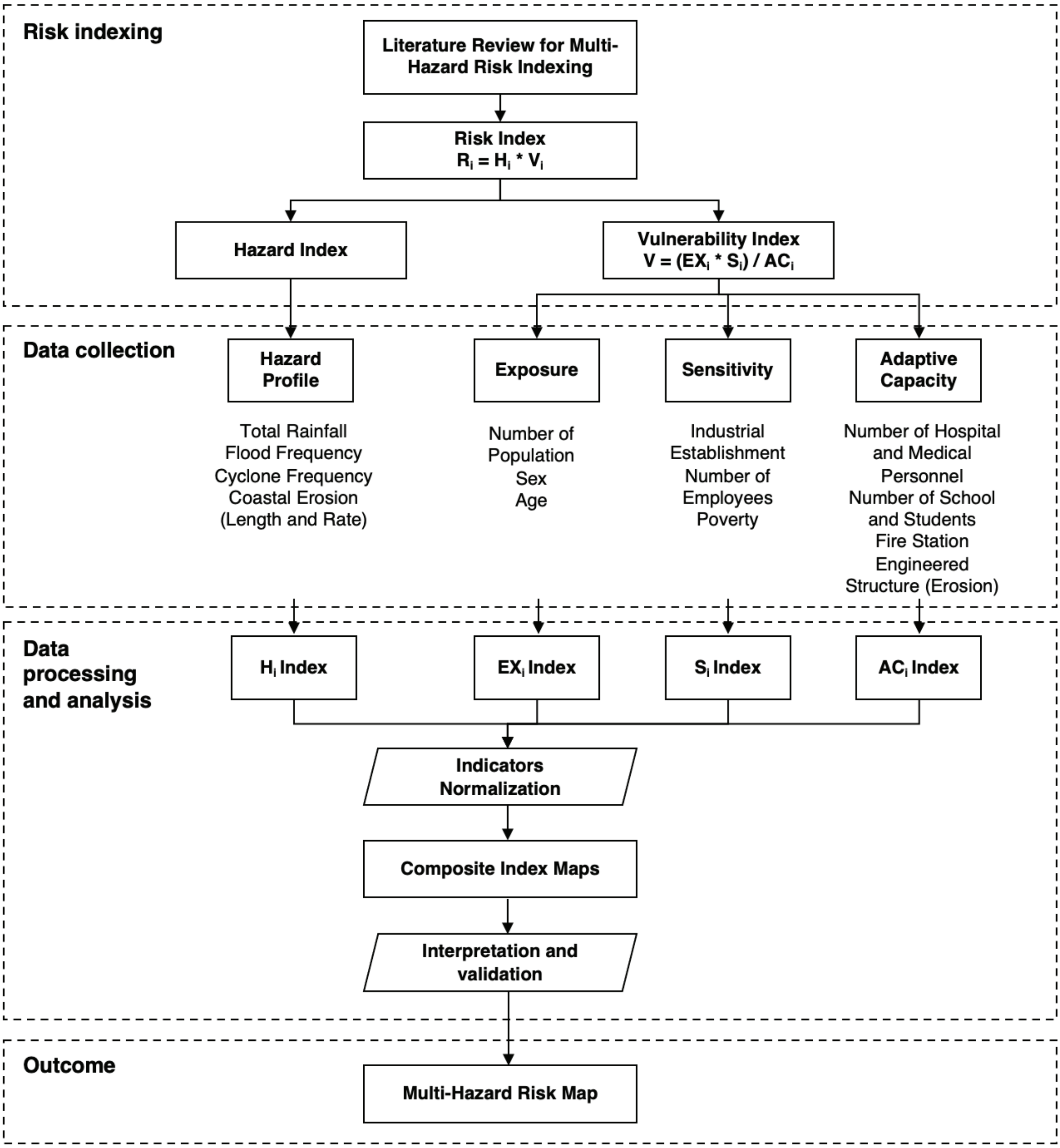

Figure 2. Methodology of risk assessment of Chonburi and Rayong coastline

3.2 Data source

The data set used for the research involved secondary quantitative data with the sources identified and provided from the Thailand government. These included census statistics (population, age, sex, number of hospitals and medical personnel) and climatic data. Once indicators normalization is utilized in the phase of data processing and analysis, maps of each component (exposure, sensitivity and adaptive capacity) present the composite index map. After that a map of risk assessment is presented, which leads to the development of a combination map of critical infrastructure risk.

The rainfall data and occurrence frequency are presented as a variable of flood hazard indicator. The occurrence frequency of cyclones is presented as a variable of cyclone hazard indicator and the length and area of coastal erosion over the decade are presented as a variable of coastal erosion hazard indicator. Along with population, age and sex stand for exposure component. Industrial establishment and the number of employees will be calculated to see the sensitivity index because the area of Chonburi and Rayong is a part of the EEC project and reflects the entire Thailand's economy. Lastly, adaptive capacity indicators consist of a number of hospitals and medical personnel to see the capacity to tackle climatic hazards, as well as education indicators that allow knowing the access to education for the local's awareness to hazard.

This study is based on secondary data, collected from multiple reliable sources. As shown in Table 2, indicators for the hazard component include flood hazard (return period from 2003 to 2015), cyclone hazard (the number of occurrences by district recorded by the department of disaster prevention and management of Chonburi and Rayong) and coastal erosion hazard (the length and area of coastal erosion by district recorded by the department of marine and coastal resources). The vulnerability component includes the exposure component and demography. The sensitivity component is economic, presented by industrial establishment and number of employments. Meanwhile, adaptive capacity is composed of the number of hospitals and medical personnel, fire stations that work as response activities and engineering structure that aim against erosion. Moreover, education is considered an indicator of adaptive capacity. This indicator is to view people's awareness. The greater the number of schools, the higher the awareness of hazards. All these indicator descriptions and data sources are provided in Table 2.

Table 2. Risk assessment indicators and variables

Risk Components	Indicators	Variables	Description and Justification	Spatial Scale	Time Scale	Data Source	Reference
Hazard	*FloodHazard*	Total rainfall	The maximum recorder precipitation from 2003 to 2015. Higher amount of rainfall means a greater possibility of the hazard leading to higher vulnerability.	mm	2003 - 2015	Meteorological Department, Ministry of Information and Communication Technology	Mandal and Choudhury (2015), Ali et al. (2019), (Ghosh and Mistri (2021)
		Number of flood occurrences	The recorded number of flood occurrences by districts during 2017-20. It depicts the greater possibility of flood hazard, which means higher vulnerability.	Number	2017-2020	Department of Disaster Prevention and Management, Chonburi and Rayong office	(Rana & Routray, 2018)
	Cyclone Hazard	Number of cyclone occurrences	The recorded number of cyclones occurrences in 2017-20 by districts depicts the greater possibility of cyclone hazard, which means higher vulnerability.	Number	2017-2020	Department of Disaster Prevention and Management, Chonburi and Rayong office	Hoque et. al., 2019
	Coastal Erosion Hazard	The ratio of coastal erosion by length	The recorded coastal erosion in Chonburi and Rayong over decades. The longer the length, the higher the hazard.	District ratio	2020	Department of Marine and Coastal Resources	Hoque et. al., 2019
		The ratio of coastal erosion by area	The recorded coastal erosion in Chonburi and Rayong over decades by area. The greater the area, the higher the hazard.	District ratio	2020	Department of Marine and Coastal Resources	Hoque et. al., 2019

Risk Components	Indicators	Variables	Description and Justification	Spatial Scale	Time Scale	Data Source	Reference
Exposure	*Demography*	Population	Refers to the number of people living within a specific unit of measurement. The higher the population density, the higher the vulnerability.	Person	2008-20	Department of Provincial Administration, Ministry of Interior	Ali et al. (2019), Das et al. (2020)
		Sex	Male and female refer ratio of number of men and women in the area.	Person	2015	Department of Provincial Administration, Ministry of Interior	Rufat et al. (2015), Das et al. (2020)
		Age Group	Children aged < 18 years old and senior citizens aged 19 - 100 years old	Person	2015	Department of Provincial Administration, Ministry of Interior	Rufat et al. (2015), Sahana and Sajjad (2019)
Sensitivity	*Economic*	Employment	Number of employees	Person	2015	Chonburi and Rayong Provincial Industrial Office	Qasim et al. (2017)
		Industrial Establishment	Number of established industries in the area	Place	2015	Chonburi and Rayong Provincial Industrial Office	Qasim et al. (2017)

Risk Components	Indicators	Variables	Description and Justification	Spatial Scale	Time Scale	Data Source	Reference
Adaptive Capacity	*Hospital and Health Centre*	Number of Hospitals and Health Centres	Refer to the capability to reduce loss and mortality of climatic hazards. The higher the number of hospitals, the less the physical loss.	Place	2015	Chonburi and Rayong Provincial Health Office	Yoo et al. (2011), Das et al. (2020)
		Number of Medical Personnel	The ability to support a large number of patients, the higher number of medical personnel, the higher number of thorough cares to patients.	Person	2015	Chonburi and Rayong Provincial Health Office	Yoo et al. (2011), Das et al. (2020)
	Education	Number of Student	Refers to accessibility to education in the area. The higher the number of student, the higher the population awareness to climatic hazards.	Person (student/total population by district)	2015	Educational Service, Chonburi and Rayong Provincial Office of Local Administration	(Fekete, 2011)
	Fire Stations	Number of Fire Station	Refers to capability to response to emergency incidents. As fire fighting personnel are trained to response appropriately. The higher the number of fire stations, the more the coping capacity.	Place	2020	Department of Disaster Prevention and Management, Chonburi and Rayong office	
	Engineered Structures for Coastal Erosion	Number of Construction Length	Chonburi and Rayong have been exposed to coastal hazards over long decades. They are protected and readdressed by constructing engineered structure. The more the coverage, the more the rate of adaptive capacity.	Length	2020	Department of Marine and Coastal Resources	

4. Results and Discussion

The multi-hazard risk assessment index will be discussed in this section.

4.1 Multi-hazard index

This study focuses on the three main hazards that affect the performance and serviceability of critical infrastructure: floods, cyclones and coastal erosion. This is consistent with the Inform Risk Index (Table 3) stats, where Thailand ranked 81st out of 191 countries at a high risk to natural hazards by 2019. Further, it provides risk index for different hazards, vulnerability and coping capacity at a scale of 0–10. Floods caused 58% of all disasters. Storms (29%) and droughts (37%) are the other two major disasters that affect most people. On the other hand, earthquakes are responsible for 65% of all deaths, owing to the tsunami triggered by the Sumatra Earthquake in 2004. Coastal erosion is yet another threat that severely damages coastal areas.

Table 3. The INFORM 2019 index for risk management for Thailand

Flood (0–10)	Tropical Cyclone (0–10)	Drought (0–10)	Vulnerability (0–10)	Lack of Coping Capacity (0–10)	Overall Inform Risk Level (0–10)	Rank (1–191)
8.8	4.9	5.7	3.1	3.9	4.1	81

Flood hazard

Floods are by far the most common and damaging natural hazard in Thailand. The country ranks in the top 10 flood-prone countries in the world. Flooding is triggered by heavy rains during the rainy season, resulting in irregular riverbank overflow, flash floods in urban areas and landslides and flash floods in mountain areas. Coastal communities are also more prone to be flooded when sea levels rise (World Bank and ADB, 2021). Prolonged floods result in human and economic losses. For instance, 13 million people were affected by the 2011 flood. The entire property loss was estimated to be US$ 46.5 billion in 2011, with the private sector accounting for almost 90% of the total damage (Singkran, 2017). Furthermore, Thailand's average yearly loss from floods is roughly US$ 2.6 billion, accounting for nearly all of the country's disaster costs. As mentioned above, floods have been affecting Thailand's economy regularly. Understanding flood risk would allow sustainable development likelihood and land use in the floodplain, and will be helpful in preparing certain measures or policies to manage future flood risks (Singkran, 2017).

Even though coastal floods occur owing to seasonal climate and location, Chonburi and Rayong provinces are not particularly vulnerable to them. Chonburi and Rayong do not experience major flooding. Generally, water was found on the road's surface at a height of about 1 foot, and it took not more than an hour for it to drain. This natural hazard occurs once a year, between November and December, according to the area's historical records. It causes traffic congestion and inconvenience to local people, but does not result in any substantial infrastructural damage. As per EM-DAT declared by Thailand government, floods have occurred only four times in the past 20 years (Table 4).

Table 4. Summary of flood occurrences in Chonburi and Rayong

Province	Year	Disaster Subtype	Duration (month)	Total Death (no.)	Total Affected (no.)	Total Damages ('000 US)
Chonburi	2006	Riverine flood	4	164	2,212,413	9,940
	2012	Riverine flood	2	-	235,545	N/A
Rayong	2012	Riverine flood	2	-	N/A	N/A
	2021	Riverine flood	1	-	325,400	N/A

Source: EM-DAT

As shown in Table 4, coastal flooding was not severe in these areas, but the riverine floods were declared over 20 years' time period. In 2006, a major flood affected more than 2,000,000 people in the area, costing about US$ 10 million in total damage. However, the coastline of Chonburi and Rayong was very less damaged because not many main rivers, waterbodies and steams are there. Additionally, the inner parts of Chonburi and Rayong was more impacted than its shoreline. According to local interviews, coastal floodings are not severe but happen frequently. Sometimes sea-level rise makes it difficult to drain the water into the sea, resulting in inundation period and taking a longer time to be back to normal situation. Figure 3 shows the flood hazard map of Chonburi and Rayong provinces.

Figure 3. Flood hazard map of the Chonburi and Rayong provinces
Source: Project Team

Furthermore, cyclones are usually a reason for flooding in Chonburi and Rayong. These two hazards have compound effects on the areas and aggravate poor drainage system because of the location morphology. Heavy rain and sea-level rise are the chief causes of the aforementioned problem. Consequently, coastal critical infrastructures tend to be more affected due to massive inundation.

4.1.1 Cyclone hazard

Cyclone risk in Thailand is considered high, and cyclonic storms have wreaked havoc on the country. Damages can occur not just as a result of wind, but also as a result of cyclone-induced severe rainfall and consequent flooding and coastal floods in offshore areas (ThinkHazard, 2020). In the last three decades, there have been approximately 30 storm occurrences all over the country, which have killed 1696 people, impacted over 3.2 million people and resulted in a total economic loss of US$ 911 million. Meanwhile, Chonburi and Rayong provinces were impacted by only one cyclone event in the past 30 years (EM-DAT). This proves that Chonburi and Rayong are not prone to meteorological hazards, especially cyclones. Only small storms occur regularly, affecting the marine sailing of fishing boats.

Table 5. Summary of cyclone occurrences in Chonburi and Rayong

Province	Year	Disaster Subtype	Duration (days)	Total Death (no.)	Total Affected (no.)	Total Damages ('000 US)
Chonburi / Rayong	2015	Tropical cyclone	10	3	N/A	561

Source: Project Team

In September 2015, a tropical cyclone that weakened from the South China Sea passed into the Gulf of Thailand. Even though the tropical cyclone did not cause a lot of casualty, there were damage due to strong winds and storm that surged at about 1 m in height. Again, annual tropical cyclones are a major cause of failure in fishing because the upper Gulf of Thailand is a habitat and an economically valuable food and refuge for marine life. Figure 4 shows cyclone hazard map of study area.

Figure 4. Cyclone hazard map of the Chonburi and Rayong provinces
Source: Project Team

Coastal Erosion

When the net or relative rate of sea-level rise is considered, a combination of rising seas and falling land, as well as probable cyclone-induced storm surge, place many cities along the coastline at risk. Sea-level rise will also have an impact on sustainable land use for economic activities such as tourism, import and export and commercial areas. The Thailand coastline stretches for 2815 km along the Gulf of Thailand and the Andaman Sea. Thailand's total oceanic area is around 400,000 km^2 in 23 provinces (Paphavasit et al., n.d.). Sea-level rise poses a serious physical threat to Thailand's coastal zones, resulting in considerable land subsidence. In 2013, the Gulf of Thailand experienced a modest sea-level rise, averaging 1.4–12.7 mm per year from 1985 to 2009, with land subsidence around river mouths accounting for majority of this rise (World Bank, 2013).

A significant amount of critical infrastructure is cited in coastal places that will be exposed as a result of global climatic events. By 2070–2100, up to 2.5 million people in Thailand could be flooded as a result of rising sea levels. The government will have to invest in efficient adaptation and balance trade-offs between physical infrastructures, including dykes, concrete blook or seawalls, and nature-based measures, particularly mangrove forests. By doing this, the annual casualty due to coastal hazards will steadily decrease (World Bank and ADB, 2021). The erosion severity has been recorded as 1 m to 5 m per year, and it damaged more shoreline in Chonburi than in Rayong, such as Banglamung municipal district, Sansuk municipality and Pattaya city. Rayong city has more constructed barriers to restore beach nourishment, including offshore breakwaters (Saengsupavanich, 2020). In 2017, there was a small erosion of about 0.40 km in the Chonburi coastline while 3.7 km coastal erosion in Rayong, accounting for 0.16 km and 3.54 km in severe erosion and moderate erosion, respectively (DMCR, 2017).

The erosion situation in Chonburi has improved in recent times because of several measures taken by local administration. These include constructing 64 different coastal erosion prevention structures, such as riprap, breakwater, bamboo embroidery. This is 65.96 km along the coastline. On the other hand, 22 erosion prevention structures were built, representing 22.87 km along the coastline of Rayong. However, there are issues that need to be considered, such as various structures that invade the sea creating problems with coastal erosion or maintenance of bamboo embroidery, and so on. Figure 5 shows the coastal erosion map of Chonburi and Rayong provinces.

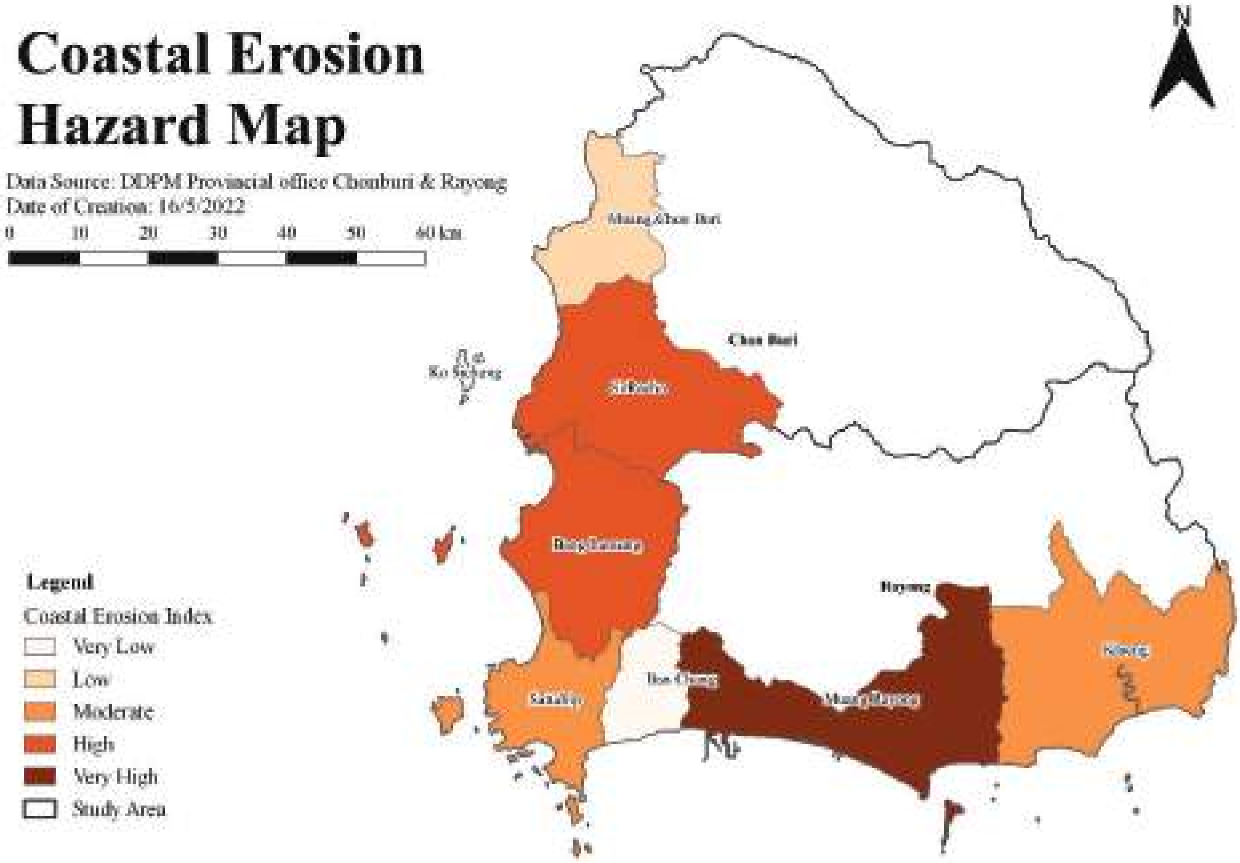

Figure 5. Coastal erosion hazard map of Chonburi and Rayong provinces
Source: Project Team

4.1.2 Multi-hazard in EEC

Considering the sectoral hazard discussed above, a multi-hazard index has been created to understand and find the hazard level of each district. This section discusses multiple hazards considered for this study: flood, cyclone and coastal erosion. A composite multi-hazard risk index is developed based on the hazard index developed in the previous sections. It was found that Mueang Rayong and Kleang have the highest risk. This is because they are most exposed to floods, storms and coastal erosion, while Sri Racha, Mueang Chonburi and Baan Chang have the least risk. In this regard, the index was considered as detailed in Table 6 and multi-hazard map developed based on these indices is depicted in Figure 6.

Table 6. Multi-hazard index

Province	District	Normalized Erosion Rate	Normalized Erosion Length	Normalized Cyclone Occurrence	Rainfall Normalized	Normalized Flood Occurrence	Hazard INDEX
Chonburi	Mueang Chon Buri	0.40	0.14	0.07	0.87	0.18	0.33
	Bang Lamung District	1.00	0.13	0.07	0.39	0.00	0.32
	Si Racha District	1.00	0.15	1.00	0.33	0.27	0.55
	Ko Sichang District	0.00	0.00	0.00	0.41	0.00	0.08
	Sattahip District	1.00	0.05	0.14	0.00	0.09	0.26
Rayong	Mueang Rayong	0.34	1.00	0.71	1.00	1.00	0.81
	Ban Chang	0.31	0.17	0.71	1.00	0.27	0.49
	Klaeng	0.33	0.34	0.71	1.00	1.00	0.68

Source: Project Team

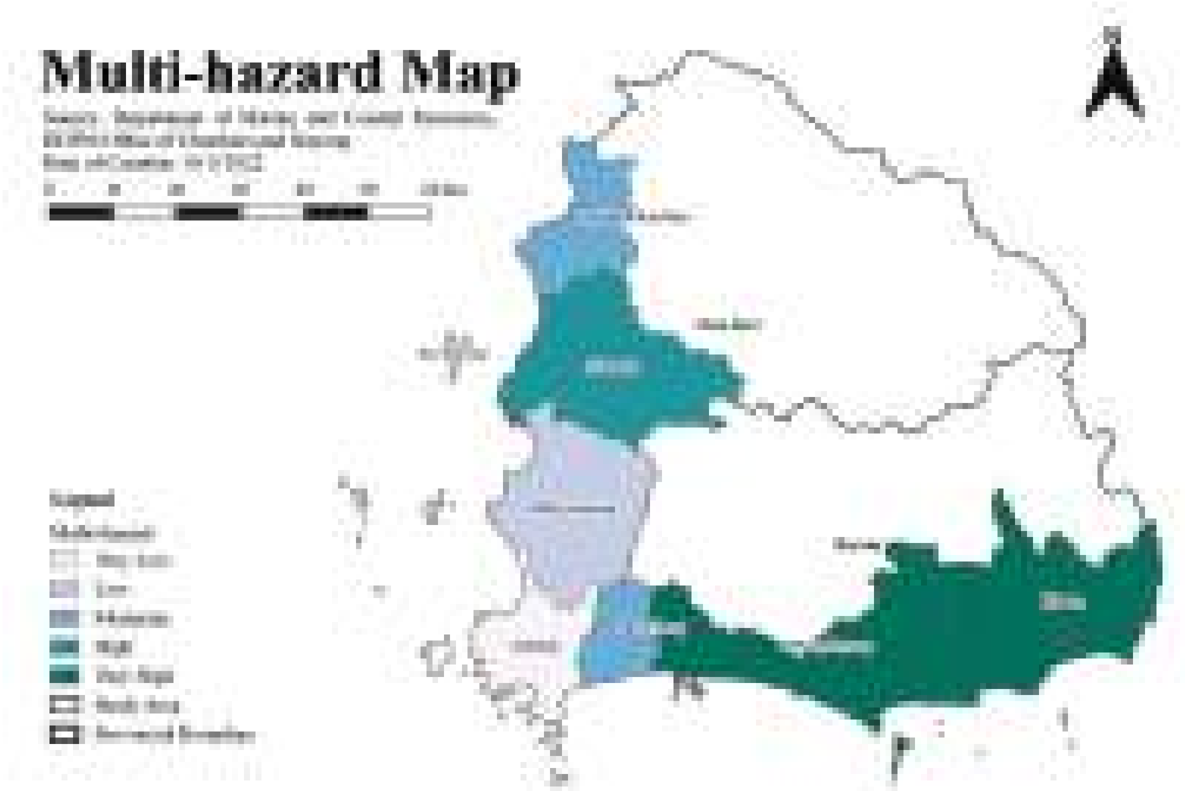

Figure 6. Multi-hazard map of the Chonburi and Rayong provinces

Source: Project Team

Coastal Critical Infrastructure

Thailand is a Southeast Asian country bordered by the Andaman Sea and the Gulf of Thailand. Its location is well situated to fulfil Asia's financial, manufacturing, tourist and service demands. Moreover, Thailand is suitable for producing a high degree of agricultural products and merchandise, as well as inexpensive and educated workers. The manufacturing sector in Thailand is the second-largest economy in ASEAN and has become the centre for regional supply chains. For instance, the Laem Chabang Port is one of the largest shifting ports in Southeast Asia. The region also attracts huge number of tourists (OBG, 2017).

4.1.3 Road and railway infrastructure in Chonburi and Rayong

Road and railway infrastructure are part of the transport infrastructure. Thailand has achieved the necessary basic infrastructure in terms of well-connected road and highway networks across the country. The government of Thailand has constructed 4150 km of toll-ways across the country, linking the North–South and East–West economic corridors. Along the coastline of Chonburi, the special highway number 7 (Bangkok–Ban Chang) and the national highway number 3 (Sukhumvit road) are the main road networks. The special highway number 7 stretches for 125.865 km, while the national highway number 3 runs from Bangkok through the Chonburi and Rayong coastline, that is 65.24 km and 63.38 km, respectively. On the other hand, the vast majority of roads in Chonburi and Rayong are local highways, which branch off from special highway number 7 and national highway number 3. Figure 7 shows the road and railways network in Chonburi and Rayong provinces.

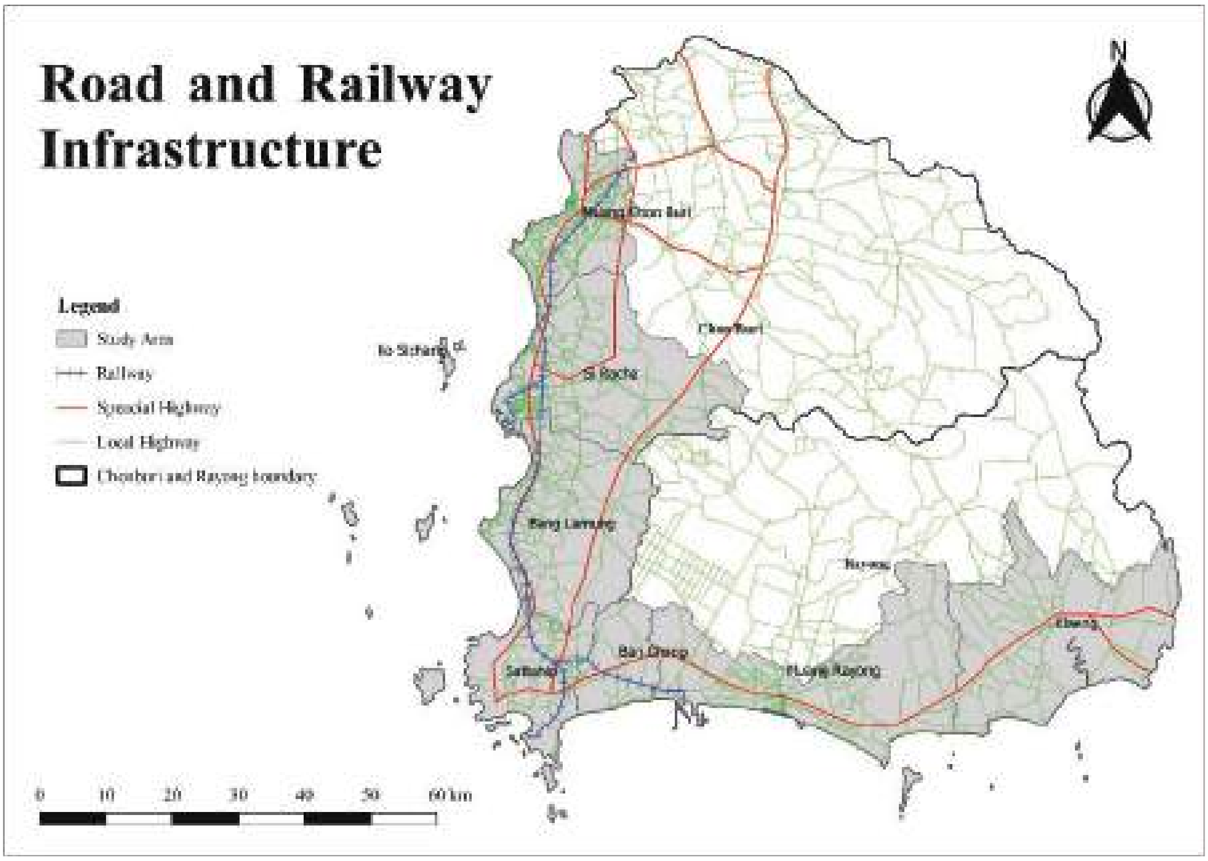

Figure 7. Road and railway infrastructure in Chonburi and Rayong provinces
Source: Project Team

In terms of road quality, Thailand has improved road infrastructure. However the quality of rural road remains in poor condition and needs to be developed. According to Thailand's road statistics, the country achieved 4.4 out of 7 in terms of road quality (Marcelo et al., 2020). Chonburi and Rayong are known as industrial estate provinces, therefore the road transportation must be in good condition. The majority of roads in the area are reinforced concrete due to huge transportations, which has a useful life of approximately 25 years. Railway transportation in Chonburi and Rayong rely on only one inter-city rail, called Eastern Coast Railway or Chachoengsao-Sattahip Railway. The track is 269.38 km long and supports the transportation of goods from the Sattahip deep seaport, Deep-Sea Port Laem Chabang Industrial Estate and the Deep-Sea Port of Map Ta Phut Industrial Estate. Figure 8 shows field photographs of various roads typologies observed in Chonburi province.

Figure 8. Coastal Highway, Chonburi

Source: Project Team

4.1.4 Seaport and airport infrastructure in Chonburi and Rayong

Laem Chabang Port is the main deep seaport for international cargo transportation. It is located in the eastern part of Thailand. It has an area of 14 km^2, divided into 10.145 km^2 (land area) and 3.857 km^2 (water area). The port consists of 7 container berths, 1 multipurpose berth, 1 roll-on roll-off berth, 1 passenger berth, 1 general bulk cargo and 1 shipyard and repair. Laem Chabang Seaport is a very important seaport because of its location. The port is prepared in terms of infrastructure and modern facilities that meet international standards and can accept the largest cargo ship, well-known as Post Panamax. Moreover, the attempt is to make it a world-class port, which will lead to Laem Chabang becoming developed with more supporting areas and capacity, such as truck terminals, free trade areas and Fire Damage Prevention Training Centre. Laem Chabang has gone through two stages of development and the third phase of Laem Chabang's development is expected to boost the facility's capacity to a maximum of 18 million TEUs. The expansion is part of the government's plan to reduce the country's logistic costs by 20% by 2020. According to the port statistics, Laem Chabang Seaport handles up to 11.8 million TEU per year, representing 54% of Thailand's overall exports and imports. The number of containers (TEU) and product volume (in tonnes) have increased from 2013 to 2020, before dropping in 2021 due to COVID-19 outbreak. This reflected that Laem Chabang Seaport is a critical infrastructure to the country. Figure 9 shows the field photographs of Laem Chabang port of Thailand situated in the Chonburi province.

Figure 9. Laem Chabang Port

Source: Project Team)

Map Ta Phut port is part of Map Ta Phut Industrial Estate. The main duty of Map Ta Phut port is to support the logistics of natural gas loading and unloading and liquid raw materials for the petrochemical industry. The port's capacity is 16 million tonne a year of unloading natural gas and liquid products. This makes Map Ta Phut Industrial Port the largest industrial port in Thailand. Similar to Laem Chabang, the expansion of Map Ta Phut in Phase 3 with 1.6 km^2, classified as improvement of infrastructure and port construction, allows for an increased capacity of up to 31 million tonne a year.

U-Tapao Airport is an international airport, located in Ban Chang district, Rayong province. U-Tapao is the main commercial airline in the Eastern part of Thailand. With 3500 m long standard runway, which is 60 m wide, it is able to accommodate 52 aircraft landing holes. If the runway is used to its full potential, it will accommodate 20 million passengers per year. Currently, only passenger Terminal 1 accommodates both domestic and international passengers. It receives about 700,000 people per year. Approximately 3 million passengers can be received if both Terminals 1 and 2 are enabled. From 2016 to 2021, there were about 1.5 million passengers per year.

4.1.5 Hospital and health centre

Government hospitals, private hospitals, health-promoting hospitals and clinics were categorized in Chonburi and Rayong provinces. Being a bigger province, Chonburi has more health centres that Rayong. There are 13 government hospitals, 11 private hospitals, 49 health-promoting hospitals and 747 clinics in Chonburi, while Rayong has 4 government hospitals, 4 private hospitals, 52 health-promoting hospitals and 223 clinics. This significantly reflects that Chonburi has a higher medical capacity to handle coastal hazards than Rayong. Table 7 list the number of government and private hospitals in Chonburi and Rayong provinces.

Table 7. Summary of hospital types in Chonburi and Rayong

Province	District	Government Hospitals	Private Hospitals	Health-promoting Hospitals	Clinics
Chonburi	Mueang Chonburi	5	4	17	264
	Bang Lamung	2	3	14	265
	Si Racha	2	4	12	182
	Ko Sichang	1	-	-	-
	Sattahip	3	-	6	36
	Total	**13**	**11**	**49**	**747**
Rayong	Mueang Rayong	2	4	20	150
	Ban Chang	1	0	9	21
	Klaeng	1	0	23	52
	Total	**4**	**4**	**52**	**223**

Source: Government of Thailand

Although there are 283 hospitals, health centres and clinics in the coastal areas of Chonburi and Rayong provinces, they are not up to the standard in terms of disaster preparedness. Inadequacy in supplies and equipment are found to be in place, and many of them lack implementation to meet the set standards (Rattanakanlaya et al., 2016). In addition, the scarcity of hospitals and medical equipment on islands, particularly Ko Sichang, led to the construction berth in order to reduce the transferring time of patients to a bigger hospital. Figure 10 shows location of hospitals and health centres in Chonburi and Rayong provinces.

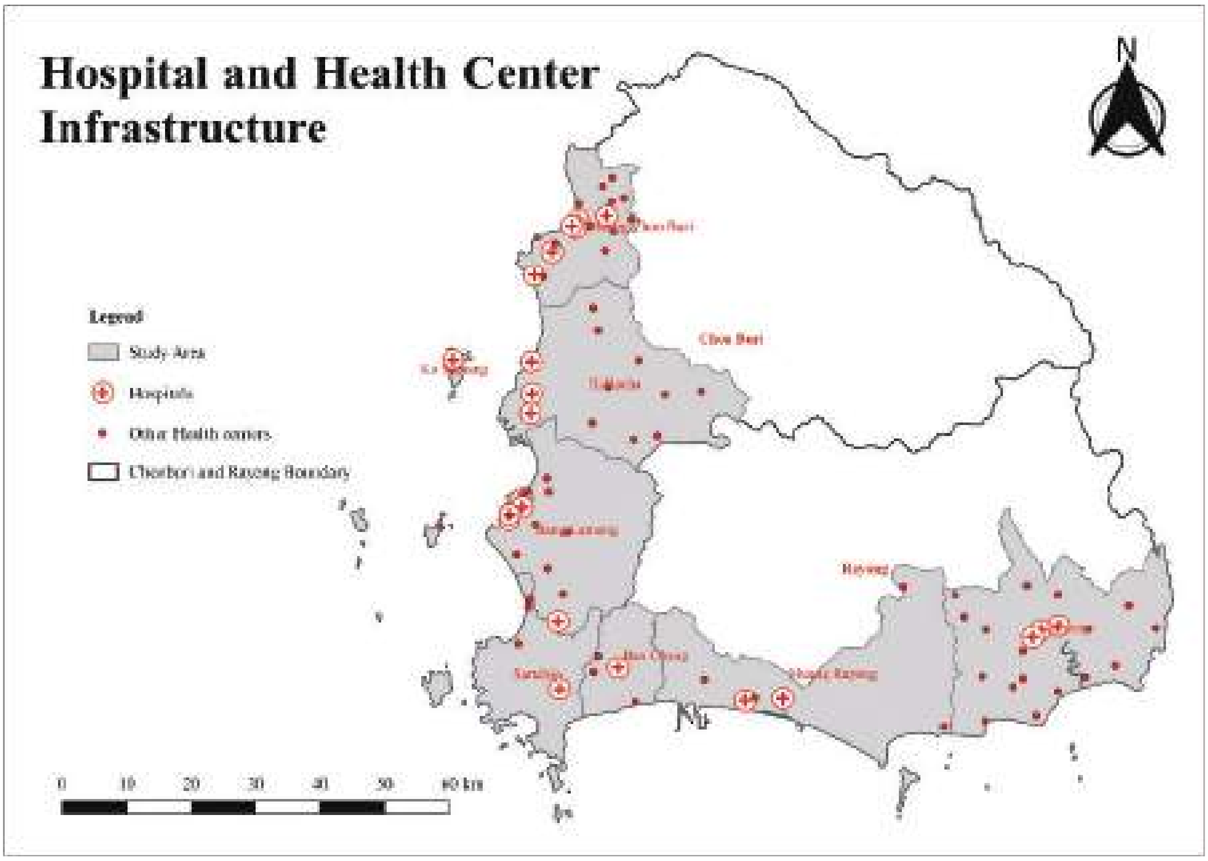

Figure 10. Location of Hospitals and Health Centres in Chonburi and Rayong Province
Source: *Project Team*

4.2 Vulnerability Index

The Vulnerability Index is determined by three components: Exposure Index, Sensitivity Index, and Adaptive Capacity Index, which are discussed in detail in the next paragraphs. Table 8 shows components of vulnerability comprising hazard, sensitivity and adaptive capacity indices calculated for vulnerability index for different districts of Chonburi and Rayong provinces.

Table 8. Vulnerability index

Province	District	Hazard INDEX	Sensitivity INDEX	Adaptive Capacity INDEX	Vulnerability Index
Chonburi	Mueang Chon Buri	0.33	0.76	0.67	0.66
	Bang Lamung District	0.32	0.26	0.54	0.23
	Si Racha District	0.55	0.85	0.44	1.16
	Ko Sichang District	0.08	0.33	0.00	0.00
	Sattahip District	0.26	0.03	0.25	0.07
Rayong	Mueang Rayong	0.81	0.38	0.62	0.48
	Ban Chang	0.49	0.35	0.16	1.05
	Klaeng	0.68	0.18	0.39	0.14

Source: Project Team

4.3 Exposure index

According to the calculation of exposure index, all the three components index are represented in Table 9, which focuses on population, age and gender of EEC residents according to the population register.

Table 9. Exposure Index

Province	District	Population Normalized Mean	Age Normalized	Sex Normalized	Exposure INDEX
Chonburi	Mueang Chon Buri	0.92	0.54	0.28	0.58
	Bang Lamung District	0.87	0.56	0.00	0.48
	Si Racha District	0.84	0.64	0.33	0.60
	Ko Sichang District	0.00	0.00	0.44	0.15
	Sattahip District	0.43	0.22	1.00	0.55
Rayong	Mueang Rayong	1.00	1.00	0.36	0.79
	Ban Chang	0.25	0.72	0.48	0.48
	Klaeng	0.49	0.16	0.26	0.30

Source: Project Team

Figure 11 illustrates information about the exposure level of the coastal area of Chonburi and Rayong. To analyse the exposure level, population, gender and age were used as demographic indicators. Generally, there were distributions of the exposure level and both the provinces showed various levels of exposure. According to Figure 13, Si Racha (Chonburi) and Muang Rayong (Rayong) were in class 5, that is very high exposure, while Ko Sichang and Klaeng had low exposure.

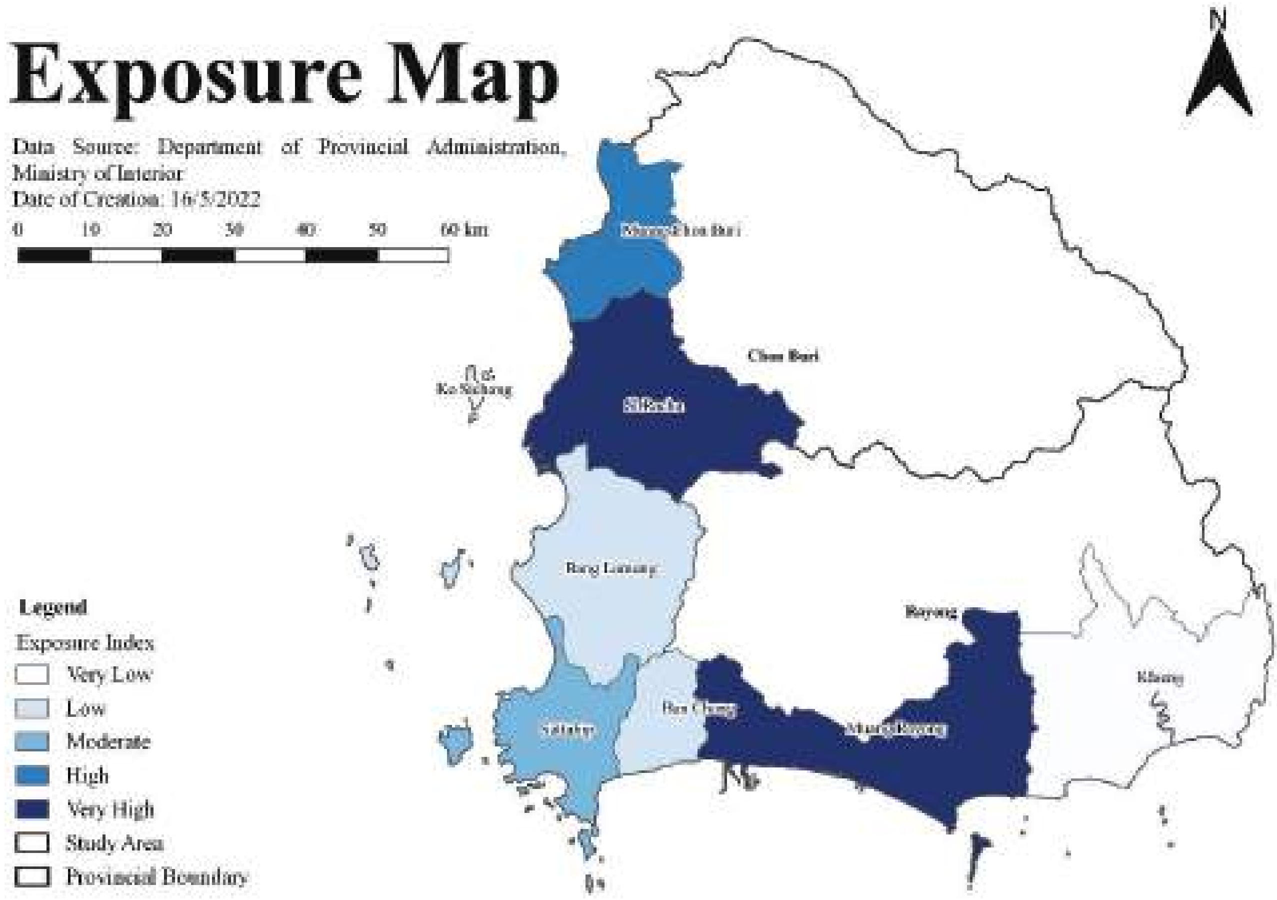

Figure 11. Exposure map
Source: Project Team

4.4 Sensitivity index

According to the calculation of sensitivity index, all three components index are represented in Table 10, which focuses on the number of employees, industrial establishment and poverty of EEC residents according Chonburi and Rayong reported statistics.

Table 10. Sensitivity index

Province	District	Employees Normalized	Industrial Establishment normalized	Poverty normalized	Sensitivity INDEX
Chonburi	Mueang Chon Buri	0.87	0.92	0.48	0.76
	Bang Lamung District	0.10	0.23	0.46	0.26
	Si Racha District	1.00	1.00	0.54	0.85
	Ko Sichang District	0.00	0.00	1.00	0.33
	Sattahip District	0.03	0.06	0.00	0.03
Rayong	Mueang Rayong	0.47	0.46	0.20	0.38
	Ban Chang	0.61	0.35	0.08	0.35
	Klaeng	0.14	0.20	0.21	0.18

Source: Project Team

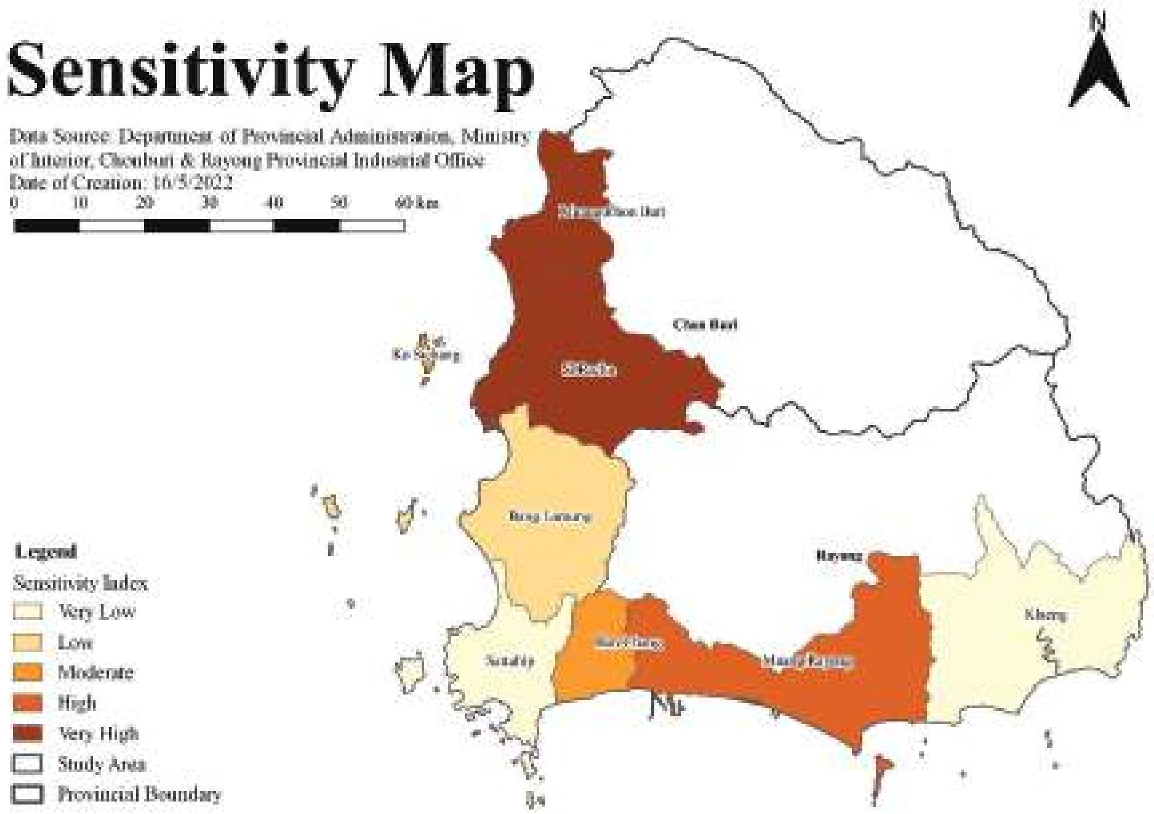

Figure 12. Sensitivity map
Source: Project Team

Figure 12 presents the sensitivity of Chonburi and Rayong by districts. From the figure it can be clearly seen that Muang Chonburi and Si Racha (Chonburi) had the highest sensitivity because in the area Laem Chabang is a very important seaport to Thailand's economy. Moreover, Muang Rayong (Rayong) reflected high sensitivity in terms of existing critical infrastructure, particularly U-Tapao airport and Map Taphut seaport.

4.5 Adaptive capacity index

According to the calculation of adaptive capacity index, all six components index are represented in Table 11, which focusses on the number of school and students, hospital and medical personnel, fire station and engineered structure construction for reducing the impact of coastal erosion.

Table 11. Adaptive Capacity Index

Province	District	School Normalized	Hospital Normalized	Medical Personnel Normalized	Normalized Student	Fire Station Normalized	Normalized Engineering Structure	AC INDEX
Chonburi	Mueang Chon Buri	0.02	1.00	0.65	0.86	1.00	0.46	0.67
	Bang Lamung District	0.00	0.98	0.18	0.74	0.33	1.00	0.54
	Si Racha District	0.07	0.69	0.10	0.91	0.58	0.27	0.44
	Ko Sichang District	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Sattahip District	0.03	0.15	0.07	0.46	0.58	0.18	0.25
Rayong	Mueang Rayong	0.14	0.61	1.00	1.00	0.75	0.22	0.62
	Ban Chang	0.06	0.10	0.05	0.20	0.17	0.37	0.16
	Klaeng	1.00	0.26	0.11	0.39	0.42	0.15	0.39

Source: Project Team

The adaptive capacity provides information about how each district adjusts itself to be more resilient to climatic hazards by analysing accessibility to education and health centre statistics. Undoubtedly districts that have a seaport and airport tend to have moderate to very high adaptive capacity, while Ko Sichang (Chonburi) and Ban Chang (Rayong) showed the least adaptive capacity. Figure 13 shows the adaptive capacity of Chonburi and Rayong provinces.

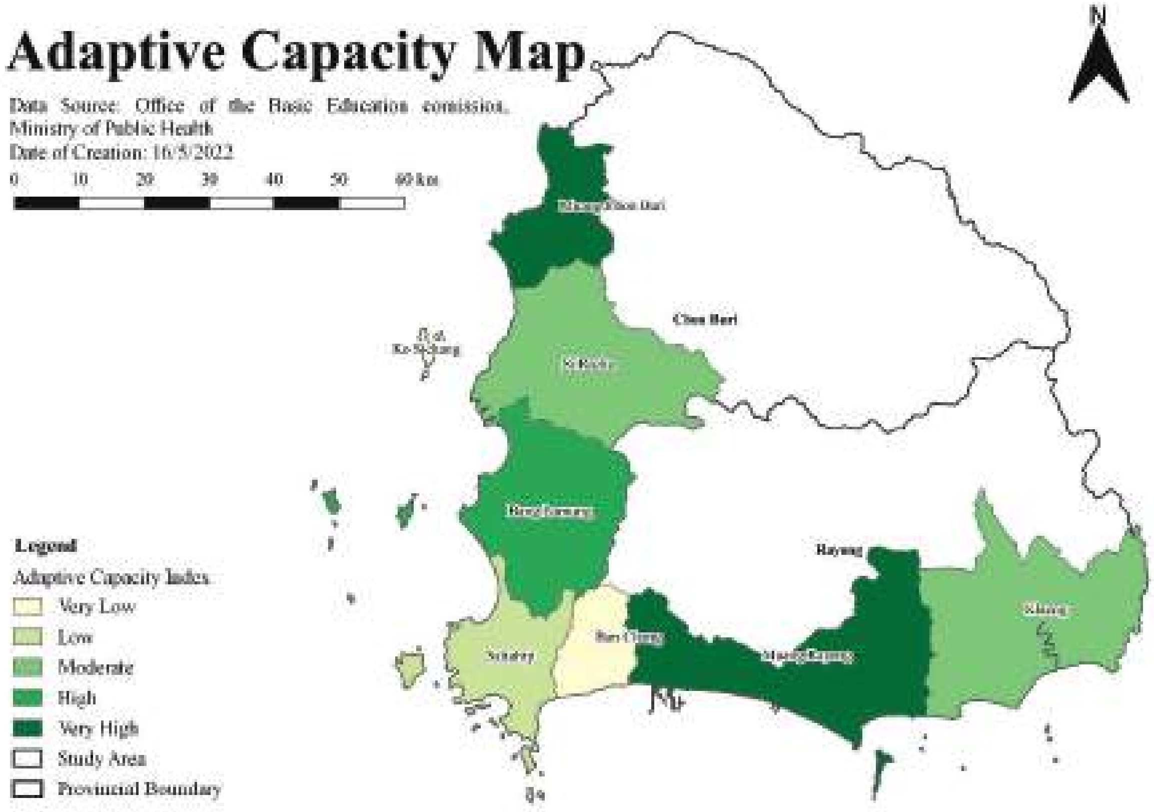

Figure 13. Adaptive capacity map
Source: Project Team

4.6 Risk index

The risk index is determined by two components: Hazard Index and Vulnerability Index, which are represented in Table 12.

Table 12. Risk index

Province	District	Hazard INDEX	Vulnerability Index (Ex * S / AC)	Risk Index (H * V)
Chonburi	Mueang Chon Buri	0.33	0.66	0.22
	Bang Lamung District	0.32	0.23	0.07
	Si Racha District	0.55	1.16	0.64
	Ko Sichang District	0.08	0.00	0.00
	Sattahip District	0.26	0.07	0.02
Rayong	Mueang Rayong	0.81	0.48	0.39
	Ban Chang	0.49	1.05	0.52
	Klaeng	0.68	0.14	0.10

Source: Project Team

4.6.1 Flood risk index

Figure 14 presents the flood risk of Chonburi and Rayong by districts. From the figure it can be clearly seen that Muang Rayong and Ban Chang (Rayong) were the highest risk as the locations are home to U-Tapao airport and Map Taphut seaport, which are very important to Thailand's economy. Muang Rayong and Ban Chang experience high frequency of flood occurrences compared to the rest of the region. Muang Chonburi and Si Racha (Chonburi) and Klaeng (Rayong) reflect moderate risk, respectively.

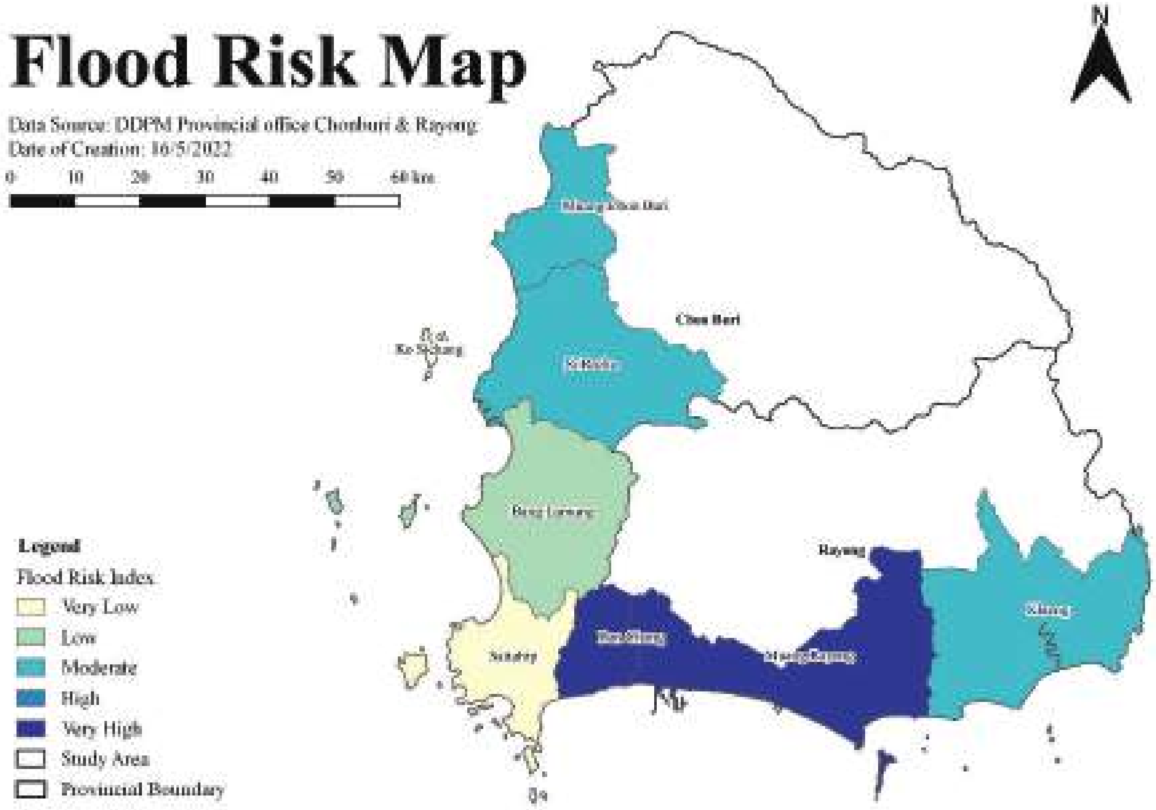

Figure 14. Flood risk map
Source: Project Team

Cyclone risk index

Figure 15 presents the cyclone risk of Chonburi and Rayong by districts. Si Racha (Chonburi) and Ban Chang (Rayong) have the highest risk as they are the biggest critical infrastructure agglomeration. At the same time, they also experience high frequency of cyclone occurrences compared to the rest of the region. Muang Rayong (Rayong) is high risk region and Muang Chonburi (Chonburi) and Klaeng (Rayong) are moderate risk regions, respectively.

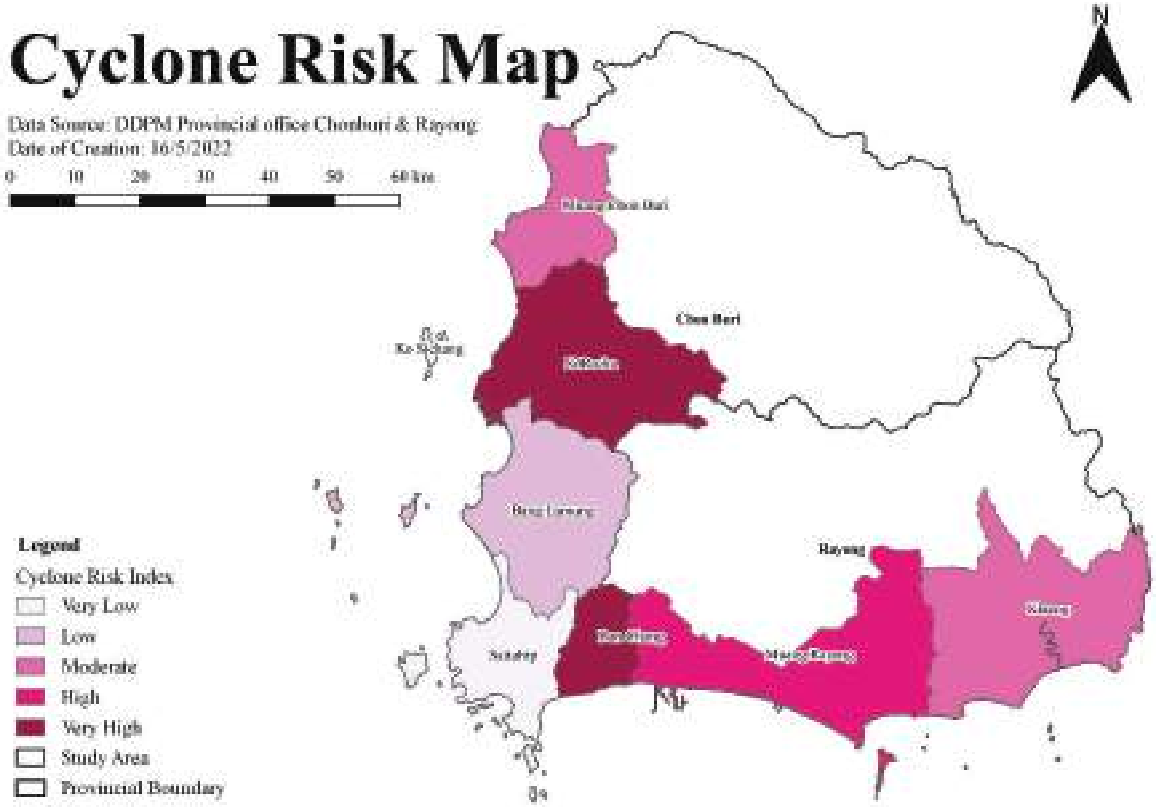

Figure 15. Cyclone risk map
Source: Project Team

Coastal erosion risk index

The coastal erosion risk map presents (Figure 16) the risk of Chonburi and Rayong by districts. It is seen that Si Racha (Chonburi) and Muang Rayong (Rayong) were the highest risk as they have the biggest agglomeration of population, economic activities and most importantly home to expensive national-wise infrastructure. Moreover, they were reported as the high affected area of coastal erosion. Ban Chang (Rayong) reflected high risk and Muang Chonburi and Bang Lamung (Chonburi) were of moderate risk.

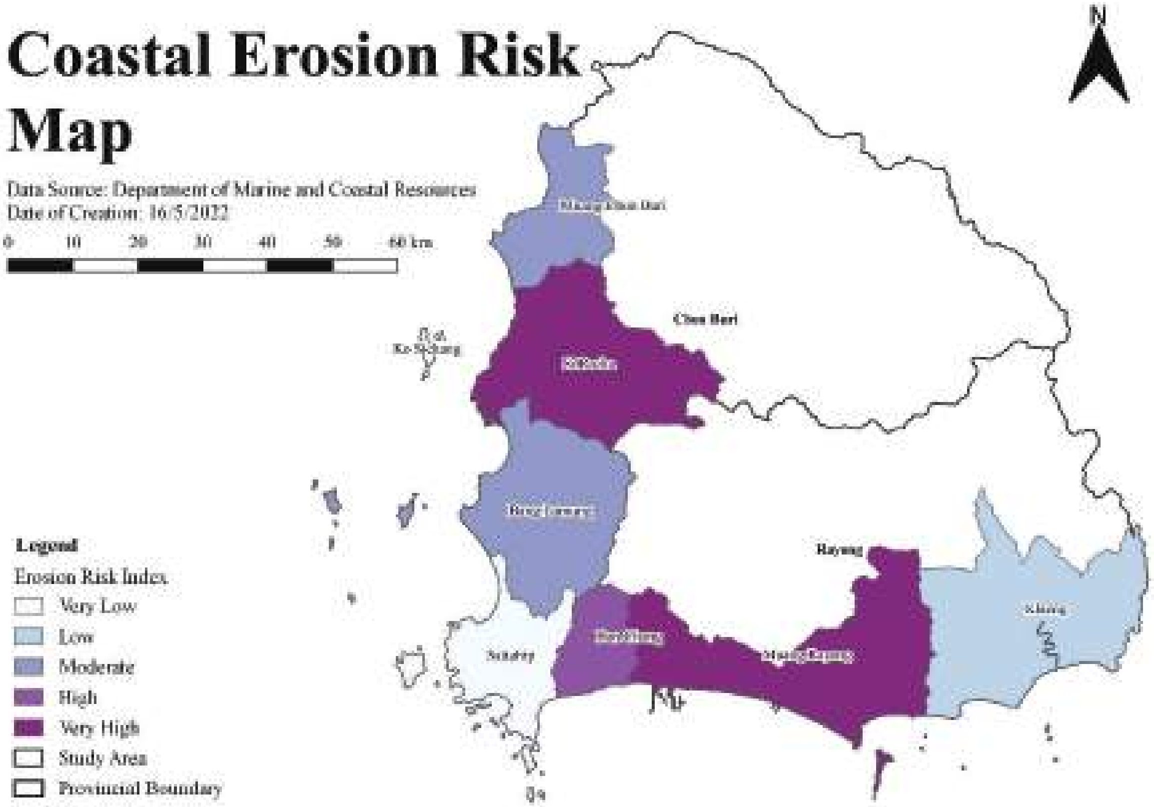

Figure 16. Coastal erosion risk map
Source: Project Team

4.6.2 Multi-hazard risk index

The multi-hazard risk map (Figure 17) presents the total risk of Chonburi and Rayong by districts. Si Racha (Chonburi) and Ban Chang (Rayong) are the highest risk whereas Muang Rayong (Rayong) is high risk and Muang Chonburi and Klaeng (Rayong) are moderate risk, respectively.

Figure 17. Multi-hazard risk map
Source: Project Team

4.6.3 Multi-hazard and coastal Critical infrastructure risk

Figure 20 illustrates information about the location of critical infrastructures that are in place of different multi-hazard risk levels. It is clear from the map that Ta Phut Port and Laem Chabang Port are situated at very high- and high-risk levels, respectively. Similarly, U-Tapao Airport is operated at a very high-risk level. This reflects that Si Racha (Chonburi) and Ban Chang (Rayong) need to reduce their vulnerability by improving or providing stronger adaptive capacity in order to tackle climatic hazards and support the functioning of these critical infrastructures.

Some districts of Chonburi and Rayong do not have adequate healthcare centres. For instance, Ban Chang and Muang Rayong lack hospitals and health-promoting centres, compared to other districts, especially Klaeng. This leads to difficulty for the locals to access healthcare. However, the catchment area or service radius should be considered in order to reflect the current situation in an appropriate way.

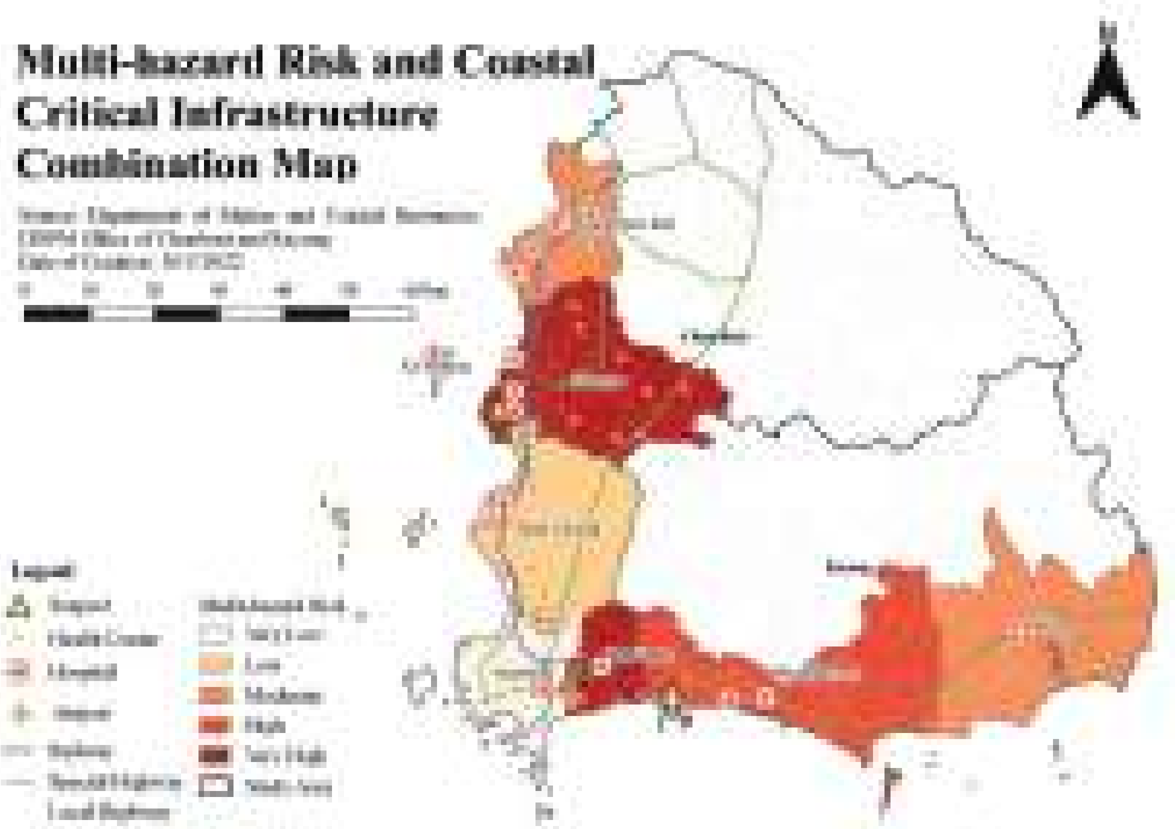

Figure 18. Multi-hazard risk and coastal critical infrastructure map
Source: Project Team

Coastal Critical Infrastructure Risk Assessment Matrix (CCIRAM) Toolkit

4.7 Features of the CCIRAM toolkit

Several recent events have highlighted the potential catastrophic impact on critical infrastructure induced by natural hazards that pose serious consequences from health impacts, environmental degradation to economic loss due to damage to assets and business interruption. Multi-hazard risk assessment of coastal critical infrastructure is an effort to identify key risks of important infrastructure of a country that is prone to different hazards. The multi-hazard risk assessment efforts for critical infrastructure involve identification of different hazards, exposure and vulnerability parameters.

The proposed toolkit will provide first-hand assessment of the risk of vital critical infrastructure from natural hazards. This simple yet sophisticated toolkit uses questionnaire to screen and assess risks of the infrastructure facility. The result obtained from facility risk assessment is used in comprehensive risk assessment of the area. The toolkit provides ease in data collection, data analysis and a source for comprehensive risk assessment.

4.8 Existing Risk Assessment Toolkits

Efforts have been made to develop multi-hazard risk assessment tools for various sectors. A number of multi-hazards risk assessment tools are available in the literature and also adopted for practical usage. Some of the important risk assessment toolkits considered for detailed review in this study are listed here.

4.8.1 RAIN—Risk Analysis of Infrastructure Networks in response to extreme weather

RAIN is a risk management framework that considers impact of extreme weather events on critical infrastructure in Europe. It also provides a number of mitigation tools to enhance the resilience of infrastructure network. The risk assessment process of the framework involves hazard identification and system vulnerability assessment by assessing frequency of weather hazards. Identification of extreme weather events is analysed by defining appropriate intensity thresholds and by taking into account regional differences in vulnerability and climate. Further, it considers risk assessment and mitigation measures for transportation, energy and telecom sectors. Analysis of transportation sector vulnerability identifies critical transport infrastructure, its failure and protection measures. Risk of energy and telecommunication sectors are assessed by analysing failure case studies, protection measures and its effect on the society.

4.8.2 INFRARISK

INFRARISK is a framework that analyses risk to critical road and rail infrastructure networks due to extreme natural hazard events in Europe. The framework considers spatial-temporal processes associated with multi-hazard and cascading extreme events and their impacts on transportation infrastructure. It also analyses response of networks to extreme hazard events for critical transport infrastructure and provides an online decision support tool for decision-making approaches for better protection of transportation infrastructure.

The framework assesses the risk from flood considering the potential for bridge-scour, road inundation and track blockages due to rainfall-triggered landslides. A qualitative risk assessment was performed through Objective Ranking Tool method for determining the rail sections along the network where risk was the most substantial.

Vulnerability of road network was considered based on the seismic vulnerability of road-bridges and tunnels, and vulnerability of road sections to earthquake-triggered landslides. The landslide triggered by earthquake was assessed as per the determined values of landslide yield acceleration for the region.

4.8.3 STREST—Harmonized approach to stress tests for critical infrastructures against natural hazards

The STREST is a framework to test stress of non-nuclear critical infrastructures in Europe. The framework assesses risk and resilience of low-probability high-consequence extreme events for six critical infrastructures (Clarke and Obrien, 2016). The STREST framework designs scenario-based models for hazard, risk and resilience assessment of extreme events with a focus on earthquakes, tsunamis, geotechnical effects and floods. Further, STREST framework tries to improve the resilience of critical infrastructures against low-probability high-consequence natural hazards, in support of the implementation of the European policies for disaster-risk reduction and protection of critical infrastructures.

4.9 Framework for CCIRAM toolkit development

Meyer et al. (2013) has given a detailed review of the risk assessment from natural hazards-affecting infrastructure. There are several ways to classify levels and scopes for risk assessment of infrastructure. Bouchon (2006) divided this into three levels:

(i) Level of the infrastructure (component level and network level)

(ii) Level of the interdependent infrastructures

(iii) Level of dependent territorial, socio-economic, politically dependent sub-systems

The toolkit uses Bouchon classification and level (i) and level (iii) in risk assessment. The toolkit uses an indicator-based approach to assess critical infrastructure risk. The risk assessment is performed in three steps. First step involves assessment of screening and risk of the infrastructure facility. Second step involves detailed and comprehensive risk assessment of the area where facility is located considering different aspects of hazard, exposure and vulnerability. Third step involves assessing risk through indicators. The methodology framework involves the following major steps:

a) Step 1: Defining context and scope of CCIRAM

There are very limited efforts and resources available in the area of critical infrastructure risk assessment and resilience building measures for Thailand. At the beginning, it is important to define the context and scope of the framework. The framework covers key critical infrastructures, namely transportation, seaport, education, and health as well as some of the pressing hazards of Thailand. A detailed literature review was performed to review some of the best suited approaches and toolkits for critical infrastructure risk assessment. A summary of review approaches is discussed in Section 3.2.

b) Step 2: Criticality assessment

Criticality is the overall importance of an asset or system. Criticality can be assessed in two ways:

i) Criticality screening: To identify the most critical facilities or components within a system.

ii) Criticality assessment: To quantify or assess criticality of an individual facility, in order to determine potential consequences of disruption.

This framework focuses on the criticality assessment. The criticality assessment is further integrated in the comprehensive multi-hazard risk indexing. The toolkit summarizes a set of criticality indicators for initial screening of infrastructure to be considered as critical. All the indicators are categorized into four categories: facility operations, economic contributions, health or safety implications of facility and interconnectivity. Table 13 shows the list of category-wise criticality criteria considered for the study.

Table 13. Criticality criteria for assessment

Category	Criticality Criteria
Facility operations	Volume of passengers (daily, monthly or annual)
	Number of movements (daily, monthly or annual)
	Value of cargo transported
Economic contributions	People employed at the facility
	Contribution of facility to GDP
Health/safety implications of facility	Whether facility is necessary for emergency management
	Whether facility is necessary for access to hospital or healthcare
Interconnectivity	Whether facility provides access to economic centres
	Whether facility provides access to other modes of transport
	Whether facility provides access to employment centres
	Whether facility is necessary for roads to operate
	Whether facility is necessary to provide fuel supplies
	Whether facility is necessary for power systems to operate
	Whether facility is necessary for communications systems to operate
	Whether facility is necessary to maintain access to water supplies
	Whether facility is necessary to maintain access to food supplies
	Whether facility is necessary to maintain access to basic goods
	Whether facility is necessary to maintain operations of waste services

Source: U.S. DOT (2014) and Cox et. al. (2013)

c) Step 3: Assessing risk through indicators

The indicators selected for the exercise are most important for the scope, and it is based on generic indicators from the literature. The indicators are relevant for assessing the exposure and vulnerability levels and for the resulting risk level. Risk indictor identification involves physical and socio-economic indicator identification.

The vulnerability assessment is performed through indicator-based approach. The indicators are grouped into physical vulnerability indicators and socio-economic vulnerability indicators. Three indicators have been selected for both physical and socio-economic vulnerability. Tables 14 and 15 show the physical and socio-economic indicators selected for the toolkit.

Table 14. Physical vulnerability indicators and their ranking score

Physical Vulnerability Indicator	Criteria for Choice of Score Value (1–5)	Score Value
Robustness and buffer capacity	The infrastructure is robust towards the natural event and/or could withstand the natural event for a duration more than two times the median duration of the natural event.	1
	The infrastructure is quite robust towards the natural event and/or could withstand the natural event for 1–2 times the median duration of the natural event.	2
	The infrastructure could withstand the natural event if the intensity is low–medium and/or the duration is 0.5–1 time the median duration of the natural event.	3
	The infrastructure could only withstand the natural event if the intensity is low and the duration is less than 0.5 times the median duration of the natural event.	4
	The infrastructure is fragile to natural event.	5
Level of protection (including physical mitigation measures and exposure)	Infrastructure is not exposed to, or well protected from, the natural event. It is well adapted both to the current and to the future climate.	1
	Infrastructure has a low exposure to or protected from the natural event in the study. Well adapted to current climate and partially adapted to future climate.	2
	Partially protected from the natural event in the study. Well adapted to current climate, but not to future climate.	3
	To a large extent, exposed to the natural event and insufficiently adapted to current climate.	4
	To a large extent, exposed to the natural event and infrastructure is not adapted to current climate.	5
Quality level/age/level of maintenance and	Well maintained or age is <15% of expected lifetime.	1
	Generally, well maintained or age is 15–30% of expected lifetime.	2
	Some planning of renewal and maintenance.	3
	Scarce planning of renewal and maintenance. Shortage of resources.	4
	Corrective maintenance only and ageing infrastructure.	5

Source: Norwegian Directorate for Civil Protection (DSB, 2014)

Table 15. Socio-economic vulnerability indicators and their ranking score

Socio-economic Vulnerability Indicator	Criteria for Choice of Score Value (1–5)	Score Value
Redundancy/substitutes	There are adequate alternatives or back-up systems for the infrastructure with sufficient capacity.	1
	There are alternatives or back-up systems for the infrastructure, which implies a few disadvantages for the users.	2
	There are alternatives or back-up systems for the infrastructure, but with limited capacity or which implies disadvantages for the users.	3
	There exist alternatives, but with low (insufficient) capacity or which imply major disadvantages to the users.	4
	There are no back-up systems or practical alternatives.	5
Cascading effects and dependencies	The exposed infrastructure is of negligible importance for societal functions, with no potential cascading effects.	1
	The exposed infrastructure has little importance for societal functions, with potentially small cascading effects.	2
	The exposed infrastructure has moderate importance for societal functions, with potentially moderate cascading effects.	3
	The exposed infrastructure has considerable importance for societal functions, with potentially considerable cascading effects.	4
	Important societal functions depend on the exposed infrastructure. Malfunctioning of the infrastructure would potentially have large cascading effects.	5
Preparedness	Very high-risk awareness regarding the natural event, exhaustive emergency response plans are available and frequent targeted drills.	1
	High risk awareness regarding the natural event, emergency response plans are available and targeted drills are performed.	2
	Some risk awareness regarding the natural event and simple emergency response plans are available.	3
	Low risk awareness and insufficient emergency response plans.	4
	Lack of risk awareness and knowledge about the natural event, with no explicit emergency response plans.	5

Source: Norwegian Directorate for Civil Protection (DSB, 2014)

4.10 Site Selection and interview with the stakeholders for testing of the CCIRAM toolkit

Site visits at affected facilities and interview with facility managers and other stakeholders to test the toolkit are important parts of this development. Site visits can allow visual understanding of site conditions and potential vulnerabilities, and provide an opportunity to gather information about the facility from those who know it best. One infrastructure facility under each category is selected for site visit and interview.

4.11 Toolkit data analysis

The method adopted for data analysis involves risk identification and risk assessment. A semi-quantitative analysis to rank the risk, i.e., screening of the scenarios of hazards threatening the infrastructures with their probability of occurrence is performed. Table 16 shows the category of hazard occurrence assessment.

Table 16. Categorization of the probability of occurrence of hazards

Category	Frequency of Natural Event	Annual Probability of Natural Event	Weightage
E	Higher than once every 10th year	≥ 10%	5
D	Once per 10–50 years	≥2, <10%	4
C	Once per 50–100 years	≥1, <2%	3
B	Once per 100–1000 years	≥0.1, <1%	2
A	Lower than once per 1000 years	<0.1%	1

Source: Norwegian Directorate for Civil Protection (DSB, 2014)

Table 17. Categorization of consequence based on the number of infrastructure users and duration of the outage

No. of Infrastructure Users/ Duration of the Outage/ Infrastructure Loss	<50 Persons	50–199 Persons	200–999 Persons	≥1000 Persons
≥7 days	3	4	5	5
≥2 days, <7 days	2	3	4	5
≥1 day, <2 days	1	2	3	4
<1 day	1	1	2	3

Source: Norwegian Directorate for Civil Protection (DSB, 2014)

4.12 Risk categorization based on hazard and vulnerability assessment

The probability ranking of hazards is carried out into one of five. The categories range from an annual probability lower than 0.1% to an annual probability higher than 10%. Further, each of the vulnerability indicators are assigned an integer score value on the scale 1–5, with 1 meaning the lowest vulnerability and 5 meaning the highest vulnerability. Second, estimation of one aggregated physical vulnerability score and one aggregated socio-economic vulnerability score are assessed.

5. Enablers and Barriers

There are several enablers for this research. One of the main enablers of this research is the availability and access of open data-source. As COVID-19 pandemic continued to delay the process of field visits and primary data collection, research methodology modified to adopt secondary data sources. Secondary data sources especially open data sources became a key enabler in the research. Hazard and infrastructure information were obtained from secondary and open data sources.

COVID-19 situation was a continued barrier in this research especially in the first and second quarters of the research. The situation hindered field visit and face-to-face interactions among stakeholders. However, as COVID-19 situation started to ease out in Quarter 3 and Quarter 4, field visit for data collection and interaction with stakeholders were made possible.

6. Conclusion and Way Forward

Based on the results, it is true that there is higher risk for areas that have experienced more rainfall in a season. Furthermore, the exposure and sensitivity proved to increase the vulnerability that further led to higher risk as well. In the results of this study, it shows that the adaptive capacity has greatly affected the risk levels of each district. By identifying the high risk and low risk districts, a more efficient and effective resource allocation can be done among the districts. Critical infrastructure can be better built-in districts where high risk is present. Likewise, the adaptive capacity can be better improved in these districts. Furthermore, the Thailand government is investing and setting up the EEC project in Chonburi and Rayong, acknowledging risk of the coastal areas. For a worthwhile investment, vulnerability assessment and risk assessment need to be done.

Coastal Critical Infrastructure Risk Assessment Matrix (CCIRAM) is a powerful tool that can identify the highest risk areas and districts that have the highest potential of losses. In this study, Si Racha and Ban Chang have the highest vulnerability level. Being an industrial province, they have major exposure in terms of population density. However, Ko Sichang as an island has low risk because of low population density, which leads to low exposure. Similarly, Klaeng has a low vulnerability as a big city in Rayong but the district itself has less exposure in terms of population, age, sex and hazards, but high adaptive capacity.

The current baseline research could be used as a starting point for a more detailed area- specific risk assessment with the interactive dashboard with simulated data for future climate scenario. The indicator list for the Coastal Critical Infrastructure Risk Assessment (CCIRA) can be standardized as CDRI assessment tools after validation with other coastal infrastructures. The study broadly proposed the following future research directions in line with the targets of CDRI in the region:

1) Scaling up of the current CCIRAM through digital and special techniques. Interactive and near-real time dashboard can be created for the coastal critical infrastructure monitoring and decision-making.
2) Comprehensive digital database for coastal critical infrastructures can be developed keeping in mind the “Systemic Risk Assessment” for climate hazards.
3) Assessment of “Cascading impacts of climate hazards on coastal infrastructures” for resilience building and sustainable development.
4) Policy analysis for coastal critical infrastructure development and achieving sustainable development goals.
5) Coastal infrastructure development, livelihoods and vulnerability nexus and resilience pathways.

References

1. ADB. (2017). *Meeting Asia's Infrastructure Needs*. https://doi.org/http://dx.doi.org/10.22617/FLS168388-2
2. ADB. (2021). *Six ways Southeast Asia strengthened disaster risk management*. https://www.adb.org/news/features/six-ways-southeast-asia-strengthened-disasterrisk-management
3. Ali, S. A., Khatun, R., Ahmad, A., & Ahmad, S. N. (2019). Application of GIS-based analytic hierarchy process and frequency ratio model to flood vulnerable mapping and risk area estimation at Sundarban region, India. *Modeling Earth Systems and Environment*, 5(3), 1083–1102.
4. Alisjahbana, A. S., Zahedi, K., & Bonapace, T. (2021). *Resilience in a Riskier World*. https://www.unescap.org/kp/2021/asia-pacific-disaster-report-2021
5. Andrew, J., Cooper, G., & Pilkey, O. H. (2012). *Pitfalls of Shoreline Stabilization (Vol. 3)*. Springer. https://doi.org/10.1007/978-94-007-4123-2
6. Angeli, S. De. (2021). *Natural Hazards and Multi-hazards*. EGU Blogs. https://blogs.egu.eu/divisions/nh/2021/10/04/natural-hazards-101-multi-hazards-andmulti-hazard-risk/
7. Arslan, A., & Bibigul, Z. (n.d.). *Natural disasters in South and Southeast Asia*. Retrieved August 19, 2021, from https://www.arcgis.com/apps/Cascade/index.html?appid=bf261f8ff42640ecaadf27ca1cdb8dc4
8. Birkmann, J., Cardona, O. D., Carreño, M. L., Barbat, A. H., Pelling, M., Schneiderbauer, S., Kienberger, S., Keiler, M., Alexander, D., Zeil, P., & Welle, T. (2013). Framing vulnerability, risk and societal responses: The MOVE framework. *Natural Hazards*, 67(2), 193–211. https://doi.org/10.1007/s11069-013-0558-5
9. BOI. (2020). The Board of Investment of Thailand: Airports. *Thailand Board of Investment*, 1–5. https://www.boi.go.th/index.php?page=airports
10. Bouchon, S. (2006). The Vulnerability of interdependent Critical Infrastructures Systems: Epistemological and Conceptual State of the Art. *Institute for the Protection and Security of the Citizen*, ..., 99. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:The+Vulnerability+of±interdependent+Critical+Infrastructures+Systems+:+Epistemological+and+Conceptual+State-#0%5Cnhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:The+Vulnerability
11. Cardona, O. D., Van Aalst, M. K., Birkmann, J., Fordham, M., Mc Gregor, G., Rosa, P., Pulwarty, R. S., Schipper, E. L. F., Sinh, B. T., Décamps, H., Keim, M., Davis, I., Ebi, K. L., Lavell, A., Mechler, R., Murray, V., Pelling, M., Pohl, J., Smith, A. O., & Thomalla, F. (2012). *Determinants of risk: Exposure and vulnerability. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*, 9781107025, 65–108. https://doi.org/10.1017/CBO9781139177245.005
12. CBO.MOHP. (n.d.). ส ำนักงำนสำธำรณสุขจังหวัด.. Retrieved March 30, 2022, from http://www.cbo.moph.go.th/cbo/
13. Chao-Amonphat, S. (2020). *Assessment of Multiple Water-Related Hazard Under Changing Climate In An Urbanized Sub-Region Of Yom River Basin, Thailand*. Asian Institute of Technology.
14. Clarke, J., & Obrien, E. (2016). A Multi-hazard Risk Assessment Methodology, Stress Test Framework and Decision Support Tool for Transport Infrastructure Networks. *Transportation Research Procedia*, 14, 1355–1363. https://doi.org/10.1016/j.trpro.2016.05.208
15. Das, S., Pradhan, B., Shit, P. K., & Alamri, A. M. (2020). Assessment of wetland ecosystem health using the pressure–state–response (PSR) model: A case study of mursidabad district of West Bengal (India). *Sustainability*, 12(15), 5932.

16. DMCR. (2017). *The state of marine and coastal resources and coastal erosion 2017*. https://www.dmcr.go.th/downloadLib/?file=qTMcMUujpP5gAap3GQMgYJp5qQqcZKtlpQqgZUpk-GQEgAJpkqP1cZKtkpQSgZUp4GQSgZTplqP1cMKufpTygMapiGTIgoTqcqTMcY3u0pTEgY3qx-GTSgo2qfqUOcqKtipUWgL3qgGTEgY2qyqTAcpau1pT9gp3qyGUWgY2qbqUEcYauipTqgYaqlG-TAgoJqxqP5cMKuwpUWgqKqiGUAgMJ
17. DOH. (n.d.). *Department of Highway*. Retrieved March 6, 2022, from http://www.doh.go.th/content/page/page/118#
18. EEC. (2019). U-tapao Airport and Eastern Aviation City. *EEC*. https://www.eeco.or.th/th/utapao-airport-and-the-eastern-aviation-city
19. EU. (2017). *Commission Regulation (EU)*. https://competitioncooperation.eu/wpcontent/uploads/2018/07/COMMISSION-REGULATION-EU-No-651-2014.pdf
20. Ghosh, S., & Mistri, B. (2021). Assessing coastal vulnerability to environmental hazards of Indian Sundarban delta using multi-criteria decision-making approaches. *Ocean & Coastal Management*, 209, 105641.
21. Gupta, S. (2010). Synthesis Report on Ten ASEAN Countries Disaster Risks Assessment. Hoque, M. A. A., Pradhan, B., Ahmed, N., & Roy, S. (2019). Tropical cyclone risk assessment using geospatial techniques for the eastern coastal region of Bangladesh. *Science of the Total Environment*, 692, 10-22.
22. Huynh, M. (2021). The Impact of Southeast Asia Floods. The Seasonal Natural Disaster, 1–15. https://storymaps.arcgis.com/stories/3eba8ddb266d46678dc1443e8ff504f7/print JCI. (n.d.). Joint Commission International. *Joint Commission International*. Retrieved February 13, 2022, from https://www.jointcommissioninternational.org/search/#q=Bumrungrad&t=_Tab_All&sort=relevancy&f:_SitesOrganizations=[Joint Commission International]
23. Kappes, M. S., Papathoma-Köhle, M., & Keiler, M. (2012). Assessing physical vulnerability for multi-hazards using an indicator-based methodology. *Applied Geography*, 32(2), 577–590. https://doi.org/10.1016/j.apgeog.2011.07.002
24. Konno, A., Kato, H., Takeuchi, W., & Kiguchi, R. (2021). Global evidence on productivity effects of road infrastructure incorporating spatial spillover effects. *Transport Policy*, 103(January), 167–182. https://doi.org/10.1016/j.tranpol.2021.02.007
25. Laitae, C., Praneetvatakul, S., & Vijitsrikamol, K. (2014). Assessment of vulnerability index on climate variability in Eastern Thailand. *Kasetsart Journal - Natural Science*, 35(3), 432–446.
26. Lam, J. S. L., Liu, C., & Gou, X. (2017). Cyclone risk mapping for critical coastal infrastructure: Cases of East Asian seaports. *Ocean and Coastal Management*, 141, 43–54. https://doi.org/10.1016/j.ocecoaman.2017.02.015
27. Mandal, S., & Choudhury, B. U. (2015). Estimation and prediction of maximum daily rainfall at Sagar Island using best fit probability models. *Theoretical and Applied Climatology*, 121(1), 87–97.
28. Marcelo, D., Raina, A., Houser, S., Saha, D., Partap Singh Bhatia, H., Suzuki, K., Phan Dai Trang, N., Kishwar Ashraf, R., Gillen, M., Mikou, M., Rozenberg, J., Koks, E., Fox, C., Quiros, T. P., Khalil, A. F., Olivier, G. P., Khosla, S. K., Vangelova, L., & Adams-Kotsch, V. (2020). *Infrastructure in Asia and the Pacific*. www.worldbank.org
29. MCE. (2016). *Glossary of Flood Terms*. https://moenvironment.org/wpcontent/uploads/2016/04/Glossary-of-Flood-Terms-MCE-4-16.pdf
30. Meyer, V., Becker, N., Markantonis, V., Schwarze, R., Van Den Bergh, J. C. J. M., Bouwer, L. M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E., Pfurtscheller, C., Poussin, J., Przyluski, V., Thieken, A. H., & Viavattene, C. (2013). Review article: Assessing the costs of natural hazards – state of the art and knowledge gaps. *Natural Hazards and Earth System Sciences*, 13(5), 1351–1373. https://doi.org/10.5194/NHESS-13-1351-2013

31. MIP. (2022). Duties & services of Maptaphut. *MIP*. https://www.maptaphutport.com/maptaphut/index.php/th/about-6/about-12
32. Mohanty, S. K., Chatterjee, R., & Shaw, R. (2020). Building resilience of critical infrastructure: A case of impacts of cyclones on the power sector in Odisha. *Climate*, 8(6). https://doi.org/10.3390/CLI8060073
33. Mullick, M. R. A., Tanim, A. H., & Islam, S. M. S. (2019). Coastal vulnerability analysis of Bangladesh coast using fuzzy logic based geospatial techniques. *Ocean and Coastal Management*, 174, 154–169. https://doi.org/10.1016/j.ocecoaman.2019.03.010
34. NOAA. (2015). *What is the difference between a hurricane and a typhoon?* https://oceanservice.noaa.gov/facts/cyclone.html
35. NPS. (2022). *Coastal Facilities Vulnerability Assessments - Climate Change (U.S. National Park Service)*. https://www.nps.gov/subjects/climatechange/vulnerabilityandadaptation.htm
36. OBG. (2017). *Infrastructure improvements aim to connect Thailand with the rest of Asia*. https://oxfordbusinessgroup.com/overview/path-prosperity-infrastructureimprovements-are-heart-plans-connect-thailand-rest-asia-0
37. Otto, A., Kellermann, P., Thieken, A. H., Máñez Costa, M., Carmona, M., & Bubeck, P. (2019). Risk reduction partnerships in railway transport infrastructure in an alpine environment. *International Journal of Disaster Risk Reduction*, 33(July 2018), 385–397. https://doi.org/10.1016/j.ijdrr.2018.10.025
38. Paphavasit, N., Chotiyaputta, C., & Siriboon, S. (n.d.). *Pre-and post-tsunami coastal planning and land-use policies and issues in Thailand*.
39. PAT. (2018). Laemchabang Port. PAT. http://lcp.port.co.th/cs/internet/lcp/ขอัมูลทวั่ ไป.html
PEMSEA. (2020). *Integrated Coastal Management*. http://pemsea.org/ourwork/integrated-coastal-management.
40. Peterson, J. (2019). Coastal Storm and Sea Level Rise Risks to Critical Infrastructure. *A New Coast*, 57–69. https://doi.org/10.5822/978-1-64283-013-2_6
41. Pootrakool, K. (2016). Eastern Economic Corridor. *Bnagkokbiznews*. https://www.bangkokbiznews.com/blog/detail/638337
42. Rana, I. A., & Routray, J. K. (2018). Integrated methodology for flood risk assessment and application in urban communities of Pakistan. *Natural Hazards*, 91(1), 239–266. https://doi.org/10.1007/s11069-017-3124-8
43. Rattanakanlaya, K., Sukonthasarn, A., Wangsrikhun, S., & Chanprasit, C. (2016). A survey of flood disaster preparedness among hospitals in the central region of Thailand. *Australasian Emergency Nursing Journal*, 19(4), 191–197. https://doi.org/10.1016/j.aenj.2016.07.003
44. Rattharangsri, T., Ariffin, E. H., Awang, N. A., & Hongshuai, Q. (2020). Roughness coefficient of polyurethane-bonded revetment. *Maritime Technology and Research*, 2(1), 19–32. https://doi.org/10.33175/mtr.2019.177366
45. Rufat, S., Tate, E., Burton, C. G., & Maroof, A. S. (2015). Social vulnerability to floods: Review of case studies and implications for measurement. *International Journal of Disaster Risk Reduction*, 14, 470–486.
46. Saengsupavanich, C. (2020). The 2018-Coastal Problems in Thailand’s Second Largest Coastal City. In Apac 2019 (Issue October 2019). *Springer Singapore*. https://doi.org/10.1007/978-981-15-0291-0
47. Sahana, M., & Sajjad, H. (2019). Vulnerability to storm surge flood using remote sensing and GIS techniques: a study on Sundarban Biosphere Reserve, India. *Remote Sensing Applications: Society and Environment*, 13, 106–120.

48. Salika. (2018). Necessity and Opportunity for Thailand. *Salika Knowledge and Sharing Space*. https://www.salika.co/2018/06/08/eec-for-the-future/
49. Singkran, N. (2017). Flood risk management in Thailand: Shifting from a passive to a progressive paradigm. *International Journal of Disaster Risk Reduction*, 25(May), 92–100. https://doi.org/10.1016/j.ijdrr.2017.08.003
50. SRT. (n.d.). Types of Railway. *State Railway of Thailand*. Retrieved March 6, 2022, from https://www.railway.co.th/Service/Passenger_detail?value1=00DE5502B5AA7B42A92BE9FF953D8EBD01000000BED881B1555F65E17EAE15973C141176893D35DDAE4C9194A4946BCBFD2C7BF2&value2=00DE5502B5AA7B42A92BE9FF953D8EBD010000000E4C39DCA67B1347F2E7ED304B7952E4DFA76714AD292
51. Taylor, M. A. P. (2017). Critical Infrastructure , Services , and Lo- Road Network. *Vulnerability Analysis for Transportation Networks*. https://www.sciencedirect.com/topics/socialsciences/road-network
52. The World Bank, & ADB. (2021). *Climate Risk Country Profile: Thailand*. www.worldbank.org
53. ThinkHazard! (2020). *ThinkHazard! Thailand*. https://thinkhazard.org/en/report/240-thailand
54. UKABC. (2019). *Thailand's Key Infrastructure Sectors*. https://ukabc.org.uk/news/thailands-key-infrastructure-sectors/
55. UNDRR. (2020). Hazard Definition & classification review: Technical Report. *Hazard Definition & Classification Reviewazard Definition & Classification Review*, 1–88. https://www.undrr.org/publication/hazard-definition-and-classification-reviewFdi
56. UNISDR. (2009). Terminology for disaster risk reduction. *United Nations International Strategy for Disaster Reduction (UNISDR)*. In UNISDR. *UNISDR*.
57. https://www.undrr.org/publication/2009-unisdr-terminology-disaster-riskreduction#:~:text=The UNISDR Terminology aims to,authorities%2C practitioners and the public.
58. UNISDR. (2017). Flood Hazard and Risk Assessment. *National Disaster Risk Assessment*. https://www.preventionweb.net/files/52828_04floodhazardandriskassessment.pdf
59. Woolfe, M., & Baldock, T. (2017). Coastal Erosion Hazard and Risk Assessment. *Words into Action Guidelines*, 1–13. https://www.undrr.org/publication/coastal-erosion-hazardand-risk-assessment

Integrating Plans and Strengthening Communications Through Artificial Intelligence and Machine Learning

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Abstract

Plan integration is currently performed manually and it is met with several challenges, obstacles, and inconsistencies, and the current way is often ineffective. The problem that arises is that hazard mitigation is often forgotten about during other community planning initiatives, resulting in a lack of integration of hazard mitigation and risk reduction principles into other important planning initiatives. This research project aims to reduce these problems by employing Artificial Intelligence (AI) and Machine Learning (ML) for the automated integrated planning of hazard mitigation principles. Our team built an automated AI application that utilizes the concept of ML to reduce the current challenges associated with manually performing plan integration, and to provide an automated platform to for communities to integrate hazard mitigation principles into other community planning initiatives and documents. Application development is completed through a two-phase process: Phase 1: Build the Brain and Phase 2: Process the Plans. Ultimately, this project strengthens the resilience of policy and governance infrastructure by providing a central online location to view potential gaps in planning initiatives, for intergovernmental coordination and for identifying recommendations to fill gaps and challenges. The end product is a new automated AI application that will help align existing plans, goals, visions, policies, actions and help increase hazard mitigation and coordination and communications during hazard events.

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1. Introduction

Natural disasters have been increasing in frequency and magnitude throughout the world in recent years, and hence there is an ever-growing need to integrate hazard mitigation and risk reduction principles into plans and policies, both at the local level and into the wide array of local community planning initiatives. While many planning documents may have been written within a jurisdictional planning framework, it has been observed that possible contradictions or gaps exist between them regarding hazard mitigation and other emergency management functions.

vMoreover, doing a plan review and integrating these plans manually is a challenge because of many issues, obstacles and inconsistencies in relation to a large number of planning documents, inadequate manpower to perform the task and varying plan update schedules. Additionally, a single department or agency is not designated responsible for developing all the plans. Different departments are tasked with developing the plans in which they are the experts. Different plans also mean different update and maintenance cycles, making the manual integration task a never-ending process. Currently, the manner in which a manual plan integration is performed, it is nearly impossible that all the plans are aligned and have no inconsistencies, gaps or errors.

An additional problem that arises within the manual plan integration process is that hazard mitigation is often forgotten about during other community planning initiatives. This results in a lack of integration of hazard mitigation and risk reduction principles into other important planning initiatives. For example, during a master planning development project, developers often take into account other community planning aspects, such as transportation, land use, housing, natural resources, etc. The master plan will likely and inevitably include hazard mitigation/public safety-related factors, but often times, not derived from the actual hazard mitigation plan.

The primary objective of this research, through the Coalition for Disaster Resilient Infrastructure 2020 Fellowship programme, is to explore the use of technologies such as ML and AI within the framework of integrated planning of hazard mitigation and risk reduction principles, and how these principles can be more effectively integrated into existing jurisd ictional planning frameworks and documents through automation.

1.1 Plan integration

1.1.1 What is Plan Review? Why do Plans Need to be Integrated?

Figure 1. Plan Integration Process Model

Plan review and integration is the process by which communities look critically at their existing planning framework and align efforts, including goals, objectives, policies, and projects, with the goal of building a safer, smarter and more resilient community.[1] Plan review and plan integration is a two-way exchange of information[2], and for the purposes of this project, we have incorporated concepts from hazard mitigation plans (state and local) and other community plans. For example, a comprehensive plan, an emergency operations plan and/or local zoning ordinance as illustrated in Figure 1.

The overall goal of plan review and integration is to effectively link plans and policies across disciplines and agencies within a community by considering the potential of hazards as one of the key factors in future development of the community. There are three primary objectives to plan integration: the first of which is to integrate hazard mitigation principles into all community planning initiatives. The second objective of plan integration is to better define roles of and improve interdepartmental coordination among community planners, emergency managers and risk reduction specialists, engineers, local stakeholders and organizations, other local governmental staff and regional partners in improving disaster resiliency. An additional objective of plan integration is to develop harmony between the hazard mitigation plan and other local planning mechanisms by identifying gaps and inconsistencies between policies, plans and ordinances.

1 https://www.fema.gov/sites/default/files/2020-06/fema-plan-integration_7-1-2015.pdf

2 https://www.fema.gov/sites/default/files/2020-06/fema-plan-integration_7-1-2015.pdf

Within the field of emergency management, there are examples of different types of plans that contain emergency-related information and direction (Table 1).

Table 1: Plan Types

Plan Title	
Comprehensive Plans	Hazard Mitigation Plan
Land Use Plans	Emergency Operations Plan
Economic Development Plans	Disaster Recovery Plan
Revitalization Plans	Community Risk Assessment
Capital Improvements Plan	Continuity of Operations Plan
Subdivision and Land Use Development Ordinance	Long Range Transportation/ Infrastructure Plan
Zoning Ordinance	Floodplain Ordinance

1.1.2 How can plans be integrated?

There are two primary approaches to manually performing plan review and integration. The first approach is to integrate hazard information and mitigation strategies, policies and principles into already existing local planning mechanisms, and vice versa. This can involve integration of different pieces of hazard information embedded within different plans.

A second approach to plan review and integration is through inter-agency planning and inter-agency coordination. This involves horizontal integration or collaboration between key staff across departments and agencies to help share knowledge and build relationships. A list of local/state departments where horizontal integration would be effective is included in Table 2.

Table 2. Integration across Agencies/Departments

Agencies/Departments	
Public Safety	Public Information
Planning and Urban Development	Land Conservation/Natural Resources/Sustainability
Public Works	Buildings and Infrastructure
Land Use and Development	Transportation
Police	Information Technology
Forestry and Wildlife	Mayor’s Office
Health and Family Welfare	Housing
Historic Preservation	Environment

2. Research Problem

2.1 Why is Manual Integration Inefficient? What Are The Challenges of Manual Plan Integration?

Manual integration comes with many challenges and is inefficient for a wide variety of reasons. In each jurisdiction, especially large jurisdictions, typically a large number of planning documents are available that need to be reviewed. Many of these documents are stored across a variety of mediums (paper copies, CDs, PDFs, etc.), which makes finding, searching, or interacting with these documents a major challenge of manual plan integration. When documents are improperly stored, named or catalogued, and/or stored across various locations or platforms (external drives, discs, networks, or desktops), it creates a lack of ownership and responsibility for document maintenance and updates. When documents are stored on or within different mediums, it is quite difficult to find information when what is needed is actually separately stored with a multitude of separate and especially when on different maintenance cycles as it is highly unlikely that these different documents actually “speak to” each other.

The length of plans also makes manual integration inefficient. Manually reviewing each of the pages is time consuming and rather difficult, and also opens up the likelihood of human error. In addition to the long timeframe to review the plans, there is also often inadequate workforce to perform the manual plan integration task.

A primary challenge of manual plan integration is that there may be various interpretations of the purpose and intent of specific planning products. In addition to various interpretations, another challenge is that there may be limited or lack of communication between different community departments. Often times, there is no proper inter-agency and inter-departmental communication in most government agencies.

Departmental budget constraint is another challenge that makes manual plan integration inefficient. Developing countries and a lot of rural communities face budget crunches and tend to prioritize their resources on other pressing issues. Additionally, there is no systematic way to complete the process, i.e., the methodology may vary from person to person and from department to department. There would be lack of consistency between reviews based on the person performing the review, which would lead to errors in the process.

A final challenge is the increased chances of error associated with manual plan integration. When there are many plans and many people involved in the process, there are bound to be errors in the process.

2.2 Solution to Manual Plan Integration

Our solution to tedious manual plan integration is to develop a process to automate through ML to save time, improve efficiencies and eliminate some of the major challenges and inconsistencies. Automating this process will successfully and effectively enable community plans to talk and learn from one another, reduce the workforce and the time needed to integrate the plans, eliminate the potential for human error and lack of consistency between reviews, regardless of the total number and length of plans or varying plan update cycles and eliminate the potential for complete knowledge loss. We have investigated a web application to perform tasks that normally require complex reasoning and/or human intelligence, and in this case, perform searches of relevant concepts in community plans and documents.

ML is an application that provides systems the ability to automatically learn and improve from experience, without being explicitly programmed, and focuses on the development of computer programmes that can access data and use it to learn. The primary aim of ML is to allow the computers to learn automatically without human intervention or assistance and to adjust future actions accordingly.

The ideal solution is to use ML to perform plan integration through an automated process by developing a comprehensive, smart, game-changing application that addresses the daily barriers and challenges of integration through automated searches of specific concepts that are informed by an ontology, which is discussed later in this report.

2.3 What is the proposed solution to the problem?

Our initial proposed solution was to develop a software that uses ML concepts such as Natural Language Processing (NLP) that can assist the process of planning and integration by helping the user search for a concept or an idea and be able to pull information on how this concept is addressed in various plans.

This application allows us to build a repository of Disaster Management Plans of any type that can be used to search for classifiable and searchable functions for specific disaster data and plans, including best practices, case studies and success stories etc.

Using ML for the advanced searching of hazard mitigation and emergency management (EM) plans is a process to help governments examine existing planning frameworks, and align plans, goals, visions, policies and actions, reduce contradictions, eliminate the potential for human error, save time for planners as they would not have to physically review large documents and capture and retain knowledge that has been gained through performing advanced searches.

2.4 Features

Our application utilizes Alfresco, which is an advanced Enterprise Content Management (ECM) software. There are several benefits that Alfresco offers and many of these benefits and features have also been incorporated and are offered by our application. Special features include:

- Tailored Document Storage Without Limits
- Intelligent Document Classification/Tagging
- Prevent Accidental Deletion
- File Sharing and Permission Management
- Semantic Search/Advanced Search
- Conflict Detection
- Robust Industry-Specific Ontology

3. Aim, Objectives and Scope of the Research Study

The primary objective of this research through the CDRI 2021 Fellowship Programme is to explore the use of technologies like ML and AI within the framework of integrated planning of hazard mitigation and risk reduction principles, and how those principles can be more effectively integrated into existing jurisdictional planning frameworks and documents by using automation.

3.1 How will this solution help integrate plans?

Our application offers a tailored document storage feature that has no limits and allows the user to build a plan repository that is tailored to their specific jurisdiction. The user can further categorize and tailor their 'plan repository' by type of plan and specific plans by agency/department.

With the assistance of our hazard mitigation-specific ontology, our solution offers the advanced search feature that will help the user search for important information, and/or compare information within different plans from any plan that is uploaded. Once the search is complete, the application will provide results through which the user can compare and contrast different plans and identify specific inconsistencies, contradictions, challenges and gaps.

3.2 Audience and Case Uses

This software and automated plan integration process will mostly help planners. It will also offer some help to public officials and some benefits to the public.

For planners, the software can be used to identify conflicts and/or discrepancies in areas that are ripe for future development, for example, differences or comparisons between similar compliance regulations. Additionally, planners can use the software to compare planning measures adopted by different states and cities. This will allow planners them to quickly identify best and recommended practices, past case studies, past success and failure stories, etc.

This solution will also offer benefits to public officials. Our application can help public officials to view and compare the details of grant funding that has been distributed to different regions/states/counties. Ultimately this software can help public officials identify measures to further aid inequitable or underprivileged areas, and in turn, improve resilience for all people and places.

This solution will not only make the plan integration process easier and more efficient, but can also be used for other uses, which can benefit a wide array of audiences. Table 3 identifies some additional potential use case scenarios that are possible to compare by using this application.

Table 3. Potential Use Case Scenarios

Use Cases
Compare data from all 50 states or East coast vs West coast, etc.
Compare how counties monitor, evaluate, and update different plans.
Compare 5 different types of plans for a city, ex. Transportation plan, Hazard mitigation plan, etc. and see how each plan is addressing a specific issue (ex. flooding)

3.3 Application development schedule and progress

Our research team completed the desired goals within the expected period of performance. The project had several different milestones that were broken down into quarterly progress milestones. Our research was completed within one year. Table 4 identifies the progress that was made during each quarter over the course of the project year.

Table 4. Quarterly Progress Updates

Quarter	Tasks Completed
Q1	Evaluated various plans and ordinances like Emergency Operations Plans, Hazard Mitigation Plans etc., to choose the best plans to test the software.
	Determined various classifications required to sort the Plan into various categories to be used for tagging.
	Developed custom algorithms for fragmenting the Plan and tagging it appropriately. This will help in the semantic search function.
	Presented preliminary results from a pilot study.
Q2	Ontology of key terms relating to disasters and hazards was developed and deployed into the application.
	Various plans and ordinances such as emergency operations plans, hazard mitigation plans, district disaster management plans, etc., were selected as the best plans to test the software.
	Various classifications were required to sort the Plan into various categories to be used for tagging have been determined.
	Custom algorithms for fragmenting the Plan and tagging it appropriately were developed to help the semantic search function.
	Accurate descriptions of each Concept were researched and incorporated into the Ontology. Relationships between Concepts were discussed and debated within the team. Relationships related to Hazard Mitigation were identified and configured.
	The ML component is being programmed to use the Hazard Mitigation segment of the Ontology.
	An uploaded Plan document was fragmented into pages and each page was tagged using the ML feature, then indexed for Search. This approach was revisited, and it was decided that fragmenting the document by topics and headings was more appropriate.
	The database store was changed from Apache Jena to neo4j because its features and performance are better for this purpose.
	The layout and formatting of the Search results page were completed.
	Automatic fragmenting of a document and indexing was completed.
	The user interfaces for the proposed software tool and the back-end processes for the Machine Learning and NLP algorithms were worked out. Short plans were pieced together to test the software.

Quarter	Tasks Completed
Q3	The Ontology of key terms was been deployed into the software.
	Research for accurate descriptions of each concept was completed and all descriptions were incorporated into the Ontology.
	Relationships between all concepts were discussed and debated between the research team. Hazard Mitigation-related relationships for all concepts was identified and incorporated.
	The Ontology was incorporated into the recommendation engine. The final product was able to pull a comprehensive list of key terms and phrases from a desired list of Plans. The Ontology was integrated into the software application and the system has been trained.
	The user interfaces for the software tool and the back-end processes for the Machine Learning and NLP algorithms was completed. Short plans were then pieced together, and the software was tested.
	Search feature that shows the results from fragments and the ability to click open the document via the Search page. Search is working to show the results from the fragments.
	The system was trained using the Ontology as a training set.
	The Code to process the uploaded documents into individual pages and scan them to detect matching Concepts in the Ontology was completed.
Q4	The application tested various concepts – various plans from different countries were uploaded onto the portal and the search was run.
	Tests were run to check for code optimization and for algorithm performance.
	The final report was developed.

4. Methodology

4.1 Application development schedule and progress

The process of developing the application was split into two distinct phases. The first phase, Build the Brain (BEB), consisted of preparing and developing a hazard mitigation specific ontology, which also included defining those hazard mitigation-specific terms within the ontology and identifying specific relationships between the different terms within the ontology. The second phase, Process the Plans (PEP), consisted of natural language processing, indexing/document tagging and generation of recommendations.

4.2 Phase 1: Build the Brain (BEB): develop ontology, define terms, develop knowledge base

The first step of Phase 1 was to prepare a common, hazard mitigation-specific ontology which included defining domain-specific terms or concepts. An ontology is a formal, explicit description of concepts in a domain of discourse, topics and sub-topics of each concept describing various features and attributes of the concept and restrictions on those properties.[3] At the basic level, an ontology is a set of concepts and categories in a specific subject area or domain, much like a glossary or index, which identifies their properties, definitions and most importantly, the relationships between them.[4]

Hazard mitigation can be connected to all other community planning disciplines. We developed our own ontology through the process illustrated in Figure 2.

We developed a hazard mitigation-specific ontology that contains over 200 terms that have an associated with the concept or field of hazard mitigation.

Each term identified was then entered into an Excel spreadsheet (Figure 3) for further analysis, before being entered into the online ontology application. Within the Excel spreadsheet, definitions were developed for each term. Each definition was informed by no less than three different reliable sources. Additionally, specific relationship types were developed, and then using those relationship types, specific relationships were established between different terms, such that at least one relationship was associated with each term.

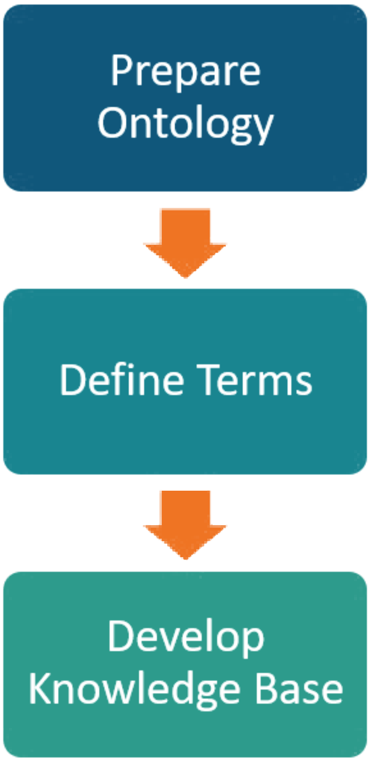

Figure 2. Build the Brain

[3] https://protege.stanford.edu/publications/ontology_development/ontology101-noy-mcguinness.html

[4] https://protege.stanford.edu/publications/ontology_development/ontology101-noy-mcguinness.html

Hazard Mitigation Plan	Hazard mitigation planning reduces loss of life and property by minimizing the impact of disasters. It begins with state, tribal and local governments identifying natural disaster risks and vulnerabilities that are common in their area. After identifying these risks, they develop long-term strategies for protecting people and property from similar events. Mitigation plans are key to breaking the cycle of disaster damage and reconstruction. Hazard mitigation plans are prepared and adopted by communities with the primary purpose of identifying, assessing, and reducing the long-term risk to life and property from hazard events. Effective mitigation planning can break the cycle of disaster damage, reconstruction, and repeated damage. Hazard mitigation plans can address a range of natural and human-caused hazards. They typically include four key elements: 1) a risk assessment, 2) capability assessment, 3) mitigation strategy, and 4) plan maintenance procedures. Plans can be developed for a single community or as a multi-jurisdictional plan that includes multiple communities across a county or larger multi-county planning region. Hazard mitigation describes actions taken to help reduce or eliminate long-term risks caused by hazards or disasters, such as flooding, earthquakes, wildfires, landslides, or dam failure. Hazard mitigation planning reduces the risk to people and property, and reduces the cost of recovering from a disaster. A hazard mitigation plan can help communities become more sustainable and disaster-resistant by focusing efforts on the hazards, disaster-prone areas and identifying appropriate mitigation actions. Effective mitigation planning and efforts can break the cycle of disaster damage, reconstruction, and repeated damage.	Is comprised of: Capability Assessment Is comprised of: Hazard ID and Profiling Is comprised of: Implementation Strategy Is comprised of: Mitigation Strategy Is comprised of: Risk Assessment May be integrated with: Comprehensive Plan May be managed by: Planning Department May be managed by: Public Safety Department May improve: Resilience
Capability Assessment	A review of a jurisdiction or community's set of capabilities, including authorities, policies, programs, staff, funding, and other resources available to accomplish mitigation and reduce long-term vulnerability. A capability assessment allows the planning team to identify capabilities that currently reduce disaster losses or could be used to reduce losses in the future, as well as capabilities that inadvertently increase risks in the community. Capabilities are analyzed by reviewing existing plans, reports, and information and interviewing local departments and agencies to gain a better understanding of relevant programs, regulations, resources, and practices. The Capability Assessment describes the tools in the city's toolbox for implementing mitigation actions to reduce disaster losses. These tools can be grouped into the following categories: planning and regulatory, administrative and technical, financial, and education and outreach. The capability assessment evaluates the capabilities and resources that are already in place in a community to reduce hazard risks. The capability assessment looks at the resources in place at the municipal, county, state and federal levels. The assessment also identifies where improvements can be made to increase disaster resistance in the community.	Is a component of: Hazard Mitigation Plan
Plan Integration	The process by which communities look critically at their existing planning framework and align efforts with the goal of building a safer, smarter community. The goal of plan integration is to effectively integrate plans and policies across disciplines and agencies by considering the potential of hazards as one of the key factors in true development. Plan integration involves a two-way exchange of information and incorporation of ideas and concepts between hazard mitigation plans and other community plans. Community-wide plan integration supports risk reduction through various planning and development measures.	Is a component of: Capability Assessment
Hazard Identification and Profiling	The comprehensive identification and description of all potential threats and local hazards to a specific jurisdiction through extensive research and analysis. Comprehensive identification of hazards must include both primary and secondary hazards, as well as both natural, man-made, and technological hazards. For each hazard, there must be a description of the type of hazard, the location and extent of the hazard, previous occurrences of the type of hazard, and probability of future hazard events. Hazard identification is part of the process used to evaluate if any particular situation, item, thing, etc. may have the potential to cause harm. The term often used to describe the full process is risk assessment: Identify hazards and risk factors that have the potential to cause harm. Hazard profiling is a process of describing the hazard in its local context, which includes a general description of the hazard, a local historical background of the hazard, local vulnerability, possible consequences, and estimated likelihood.	Is a component of: Hazard Mitigation Plan Comprises: Natural Hazards, Technological Hazards,

Figure 3. Excel Spreadsheet Ontology Development

By developing this ontology, like a human, we have taught the machine to learn and understand several hundred hazard mitigation-specific terms, definitions and concepts. The system is like us, it will read and understand just like us, as the system trained through a machine learning algorithm to extract key concepts, classify them and tag documents appropriately.[5]

Once all terms were included and defined, and all relationships developed and connected within the Excel spreadsheet, as shown in Figure 3, the ontology was then entered into electronically using an Ontology Editor, called Protégé, and the ontology was stored in an application such as Apache Jena.

5 https://protege.stanford.edu/publications/ontology_development/ontology101-noy-mcguinness.html

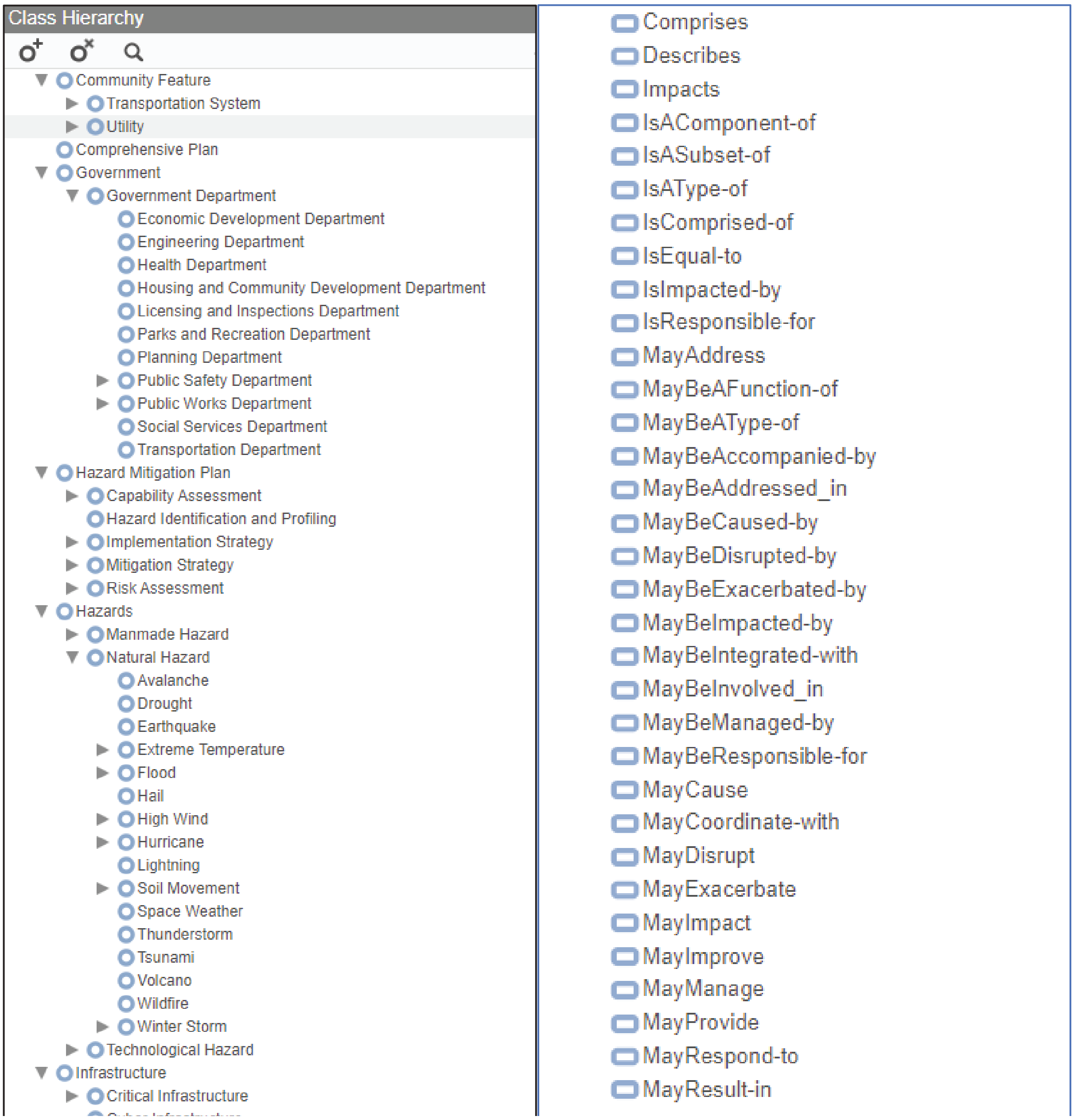

Figure 4. Hazard Mitigation Ontology Terms/Concepts and Relationship Types

Our ontology is shown in Figures 4 to 6, and shows examples of specific terms, associated definitions and relationships/connections established. Figure 4 shows the hierarchy of terms and relationship types included in our hazard mitigation-specific ontology. Figure 5 presents an example of a defined term, and the relationships established between that term and other terms included. Figure 6 illustrates the web of relationships within the entire ontology.

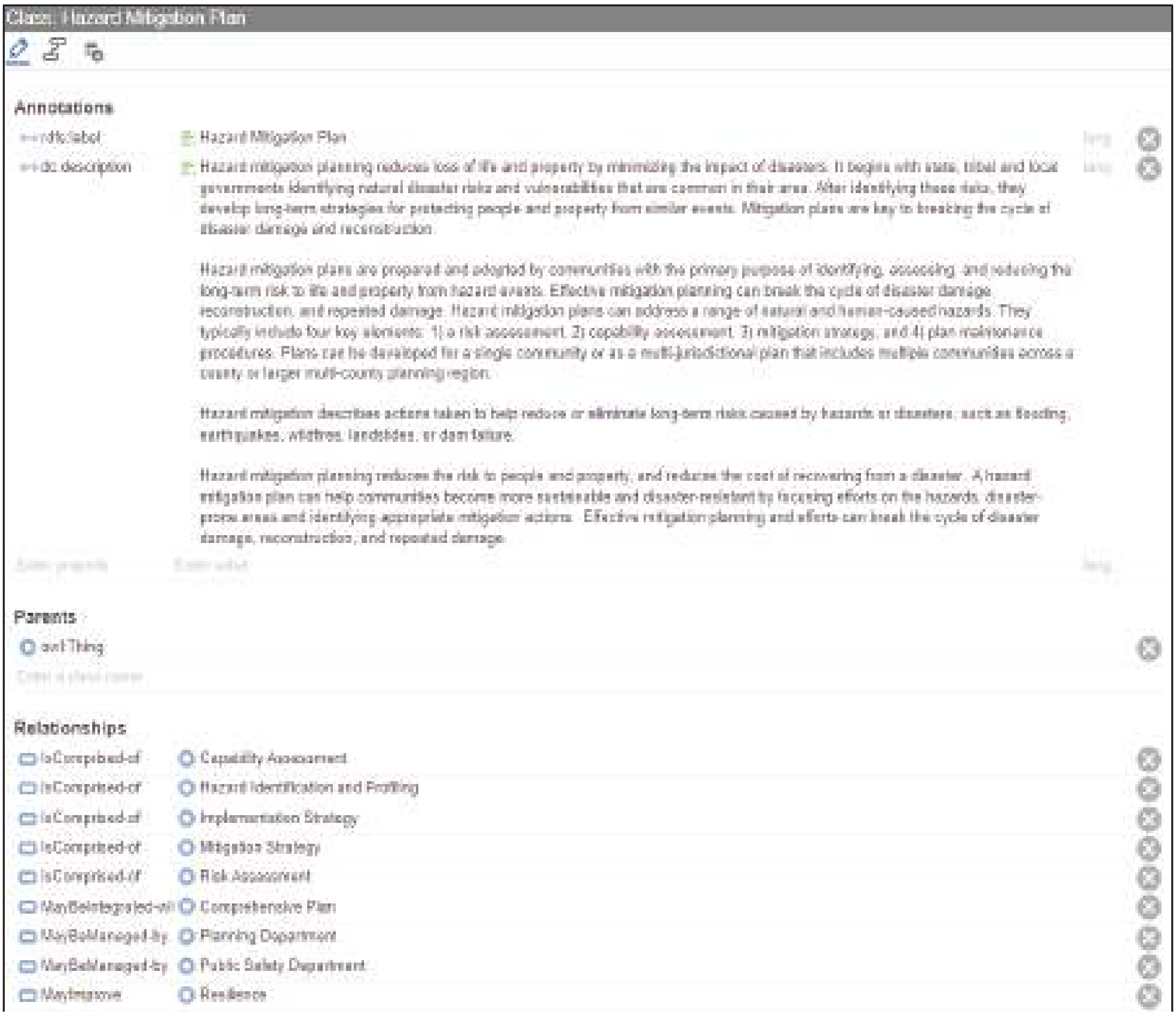

Figure 5. Ontology Definition and Relationship Example

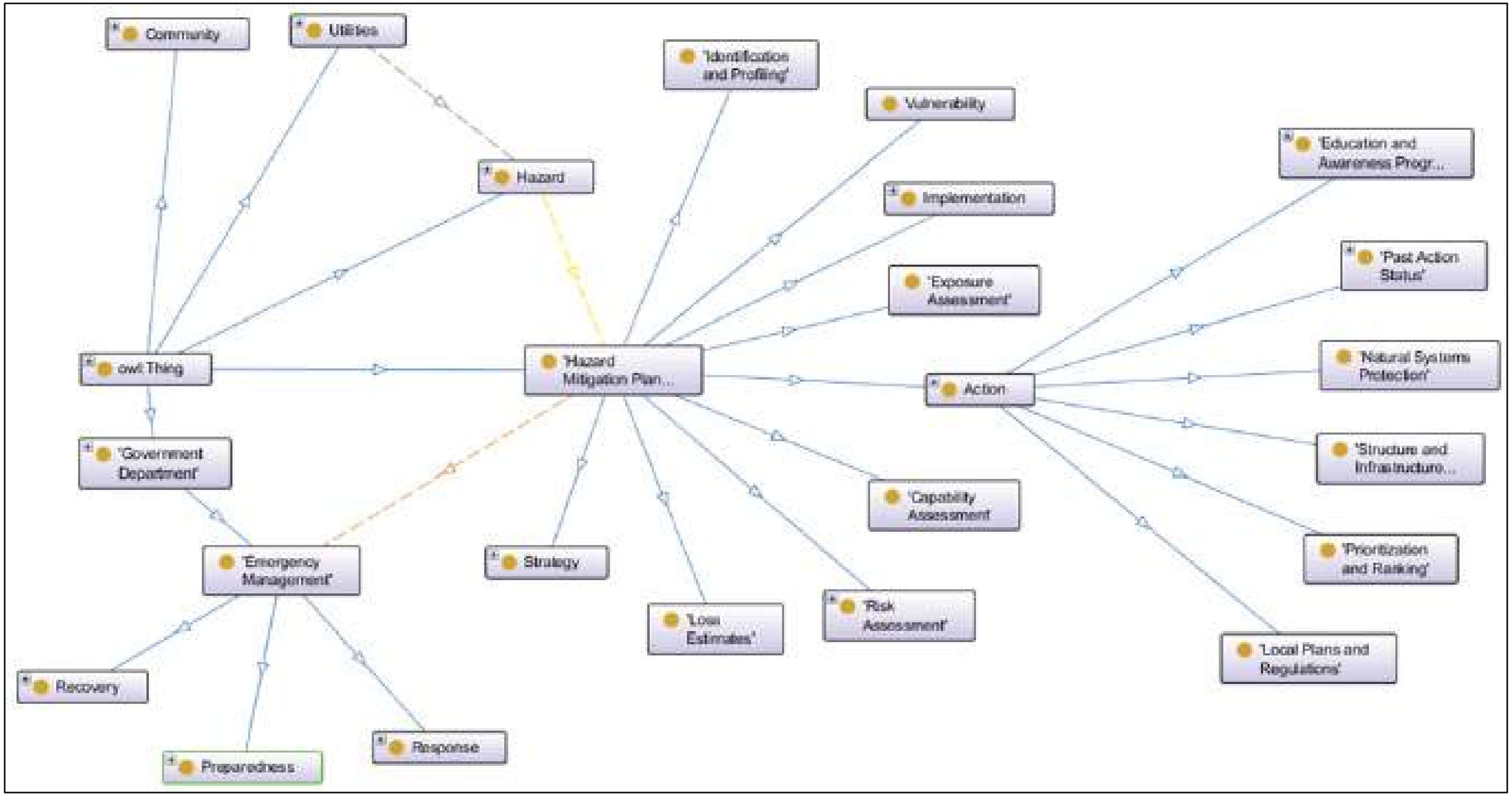

Figure 6. Example of Identified Relationships

We also implemented a storage function in the proposed software that can store any number of plans. With the storage function available and the ontology completely developed, the knowledge base of useful data is now available to the user for utilization. The user can now perform a desired advanced search

Phase 2: Process the Plans (PEP): Google NLP, Indexing, Recommendations

Phase 2 consisted of three tasks: Natural Language Processing, Indexing/Tagging, and generation of recommendations as illustrated in Figure 7. The first step in Phase 2 was NLP, which strives to build machines that understand and respond to text or voice data—and respond with text or speech of their own—in much the same way as humans do.[6] NLP is the ability of a computer program to understand human language as it is spoken and written.

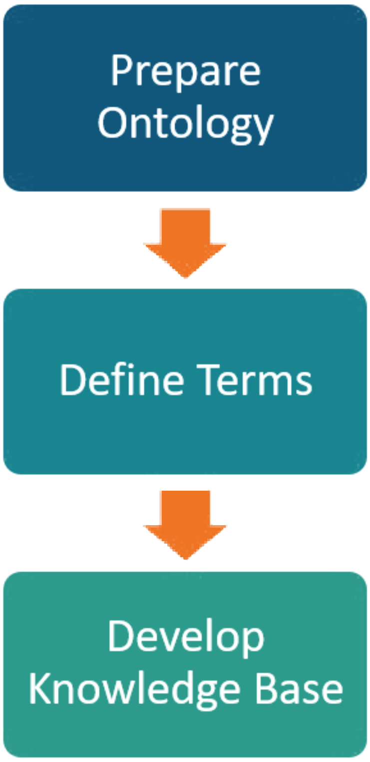

Figure 7. Phase 2: Process the Plans

It tries to understand the uploaded plan from parts of speech that are used and then extract relevant information from the plan.[7] This extraction happens by digesting the document (understanding), ignoring the small words and pulling the main entities i.e., the main parts of a sentence that are used in the Plan[8] – for example, all terms related to disaster management. The process of how NLP works is shown in Figure 8.

[6] https://www.ibm.com/cloud/learn/natural-language-processing

[7] https://www.techtarget.com/searchenterpriseai/definition/natural-language-processing-NLP

[8] https://www.techtarget.com/searchenterpriseai/definition/natural-language-processing-NLP

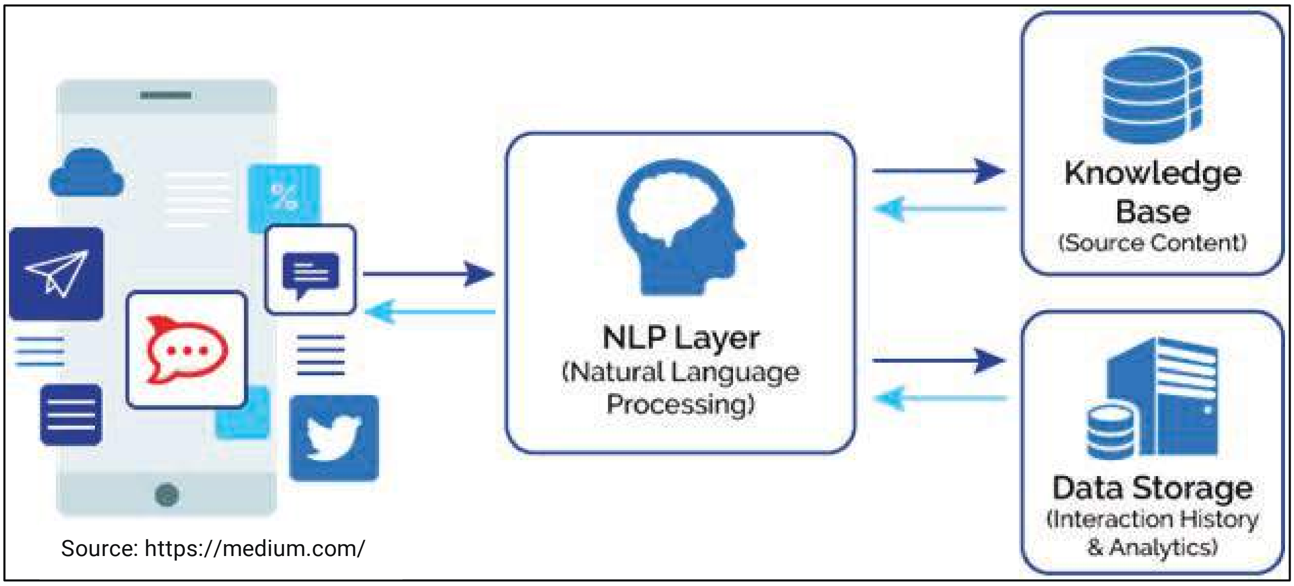

Figure 8. Natural Language Processing Flow

Step 2 in Phase 2 required indexing, which is also referred to as document tagging. This process included identifying a piece of information based on a set of characteristic information. Document indexing is the identification of specific attributes of a document to simplify and expedite accurate retrieval of a document.[9] It is important that document indexing is done accurately, else it will be difficult, if not impossible, to retrieve a scanned document.[10] Indexing identifies a specific document or paragraph based on the information it contains, which then helps the processer in future searches.

The final step in Phase 2 involved a recommendation engine, which is derived from a number of moving parts in the software. If something conflicting is detected in two plans, then the software will throw an error. This is called conflict detection and is accomplished by a combination of NLP, Indexing and searching in the Triple store database. It is at this point that results are provided back to the user.

Overall, the whole process is remarkably simple. A document is uploaded to the platform by a user. The document system then fragments the document into individual pages. Using natural language processing and machine learning, the pages are analysed and then tagged with the matching concepts from the ontology. When a user searches for a specific term, the search engine returns the results in a categorized form using the tags. The user can then drill down into the results by clicking on the appropriate category and, thus, quickly narrow down the most appropriate and desired result.

4.3 Front-end of the application (user interface)

Figure 9 presents the front end of the application, also called the user interface, i.e., what the user sees and experiences while using the application. This is the process of how a user would

[9] https://www.metasource.com/document-management-workflow-blog/document-indexing-basics/

[10] https://www.metasource.com/document-management-workflow-blog/document-indexing-basics/

upload a plan into certain folders, create new folders or even search for a particular plan using certain keywords.

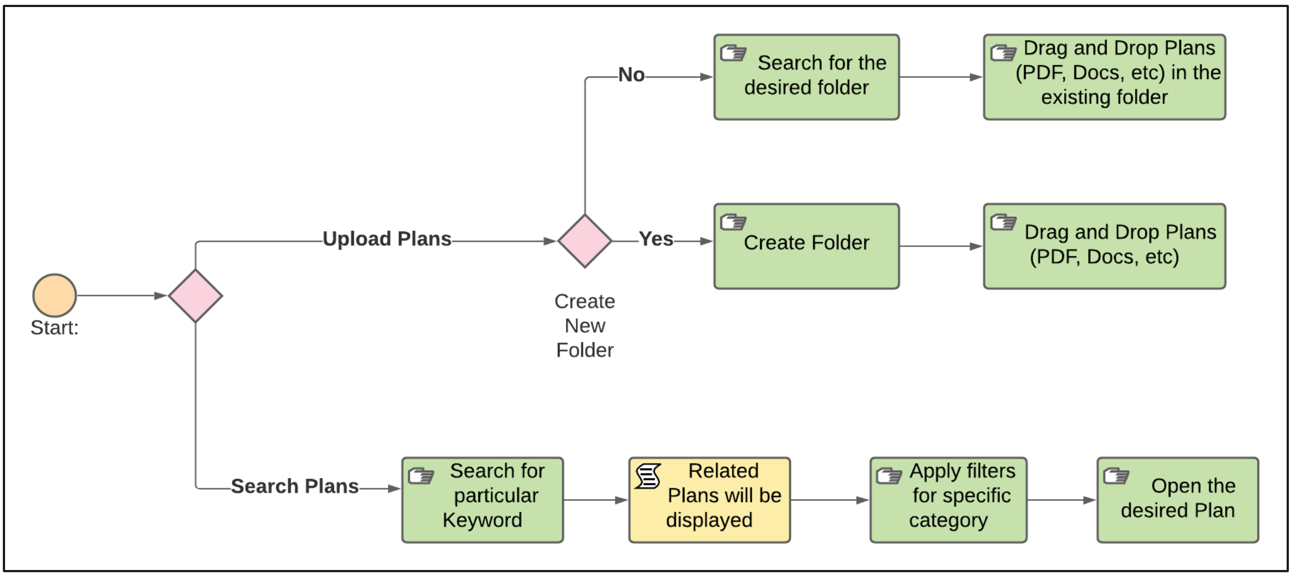

Figure 9. User Interface

The user can also create folders to manage the plans that they have uploaded and processed to organize them neatly and efficiently. This helps in creating a proper knowledge base and searching for best practices from plans of other states, counties, etc., as and when required.

4.4 Back-end of the software

Figure 10 presents the back-end of the application, and a flowchart showing the solution schematic for the application. This shows how the plans are being processed. The first step in the back-end processing of plans is for the user to upload the plan into the application. The application then takes this document and fragments it into smaller paragraphs, while paragraph tagging happens simultaneously. Fragmenting of the plan is the process of splitting the plan into smaller paragraphs, so it is easier for the software to process the Plan and retrieve the correct information when required. This process reduces the size of the data the computer handles, making the overall process more time efficient.

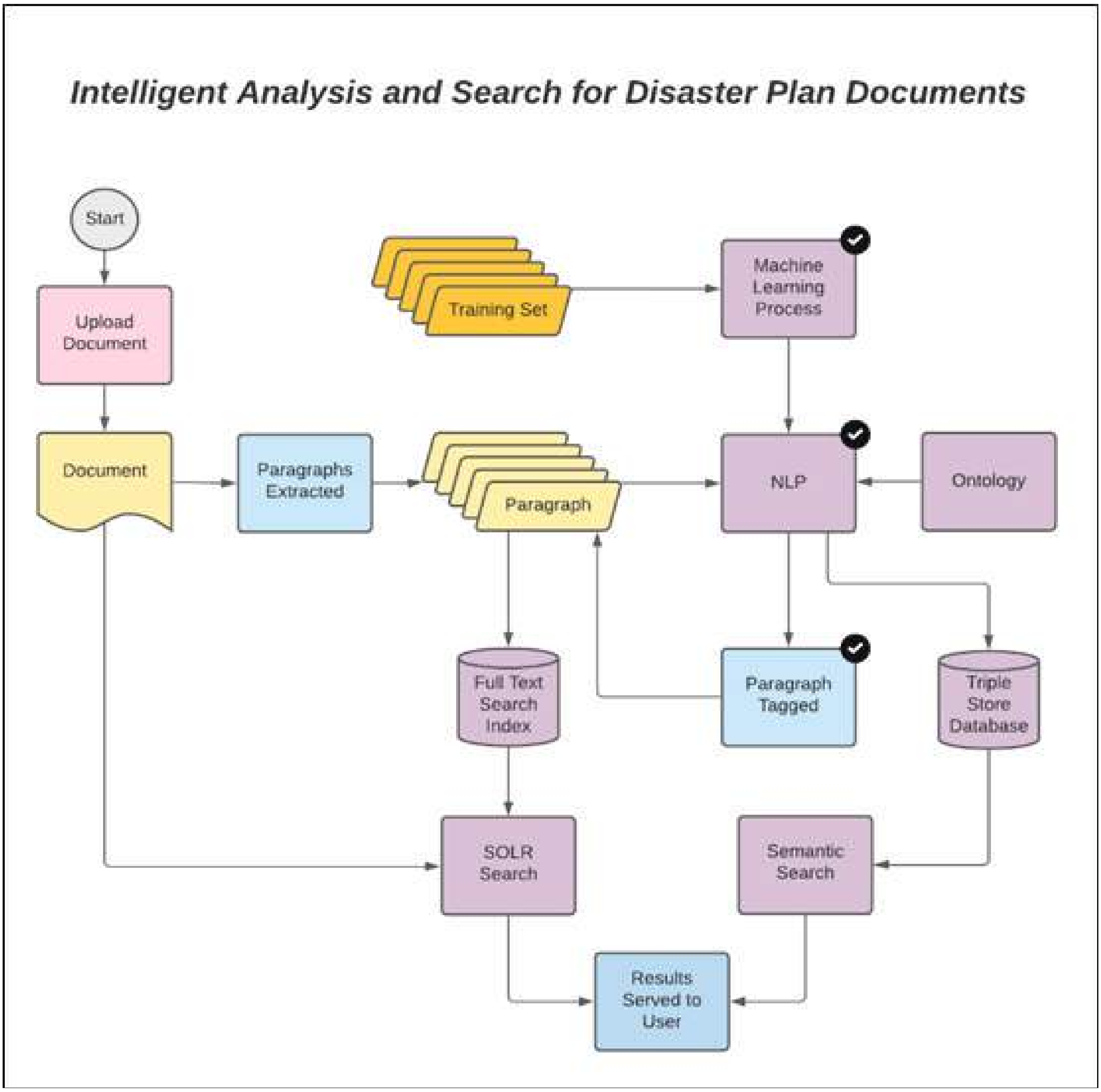

Figure 10. Back-end Processing of Plans

While one paragraph is put through a basic search algorithm (called the full text search and SOLR search), concurrently another paragraph is run through the NLP, powered by the ML algorithm. This makes the application efficient in terms of processing speed and reduces the time taken to process a plan to minutes, as even a large 300-to-600-page plan can be processed within a minute or two.

When a search is conducted by the user, the answer is retrieved from the results obtained from the NLP from the triple store database. A triple is of the form of subject–predicate–object. This is how the semantic search extracts data from paragraphs of text.

As seen in Figure 10, the ontology (on the right-hand side) feeds into the NLP as and when required. It is not a major player in the software and acts as a secondary resource. As there are two levels of searching, one by a basic search and one by an advanced NLP processor, there is very low chance of error.

5. Results and Discussion

Our software team ran our application through its automated process, using documents from Howard County, Maryland, United States, as a case study. For this case study, three Howard County plans were input into the application. These plans were the Howard County Hazard Mitigation Plan, The Howard County Master Plan and the Emergency Operations Plan. Each of these plans were written by three different departments and is likely that vertical integration across documents did not occur. Each of these plans are also very lengthy, making the manual integration process burdensome in terms of time and human power devoted to completing the task.

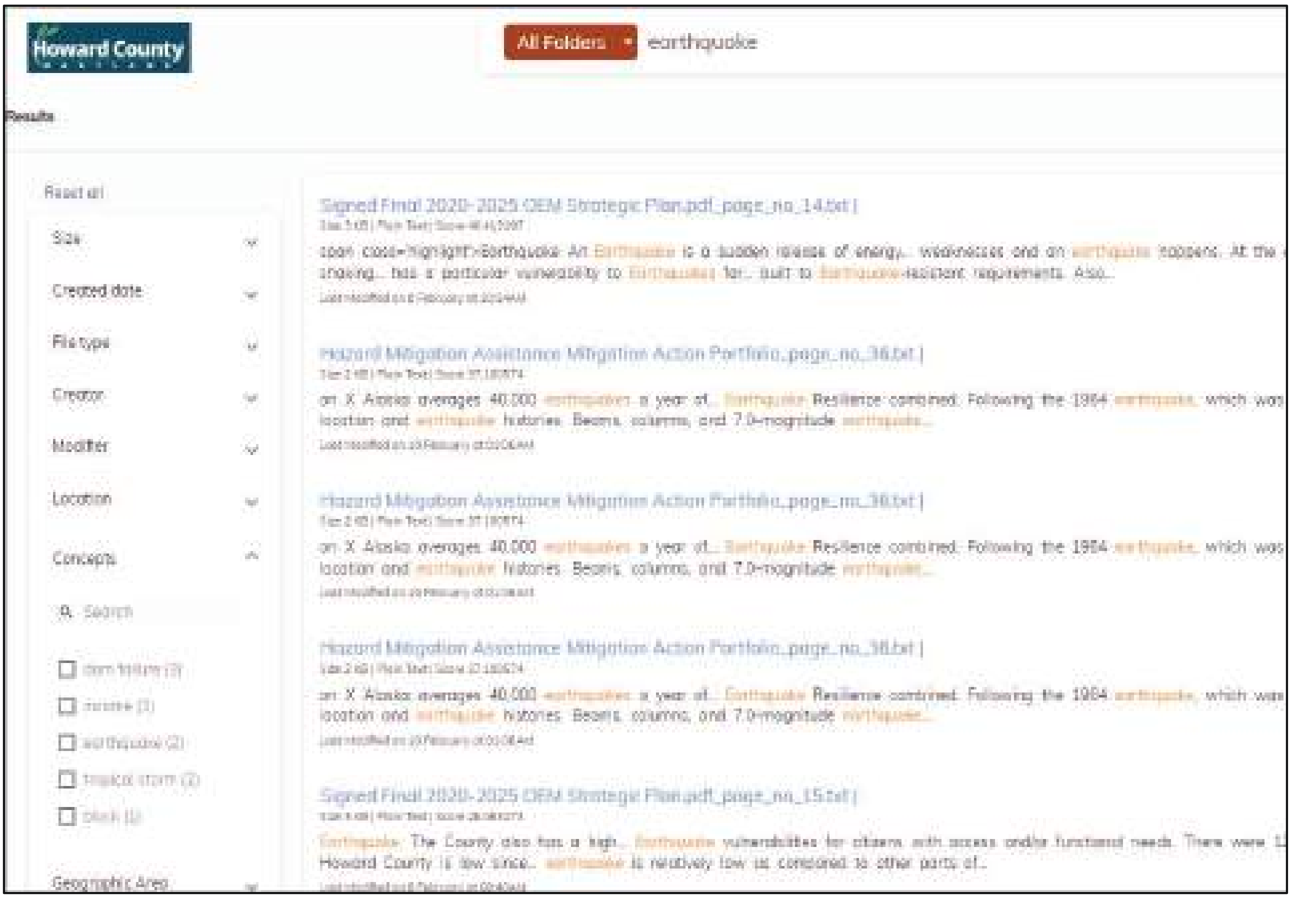

Figure 11. Howard County Earthquake Results

Once all desired Howard County plans were uploaded, an advanced search for any use of the term 'earthquake' was performed. The process was performed effectively, returning a list, location and link to where anything related to an earthquake was included within any of the documents included in the plan repository. Figure 11 shows a sample of the results returned when performing a search for an earthquake within Howard County documents.

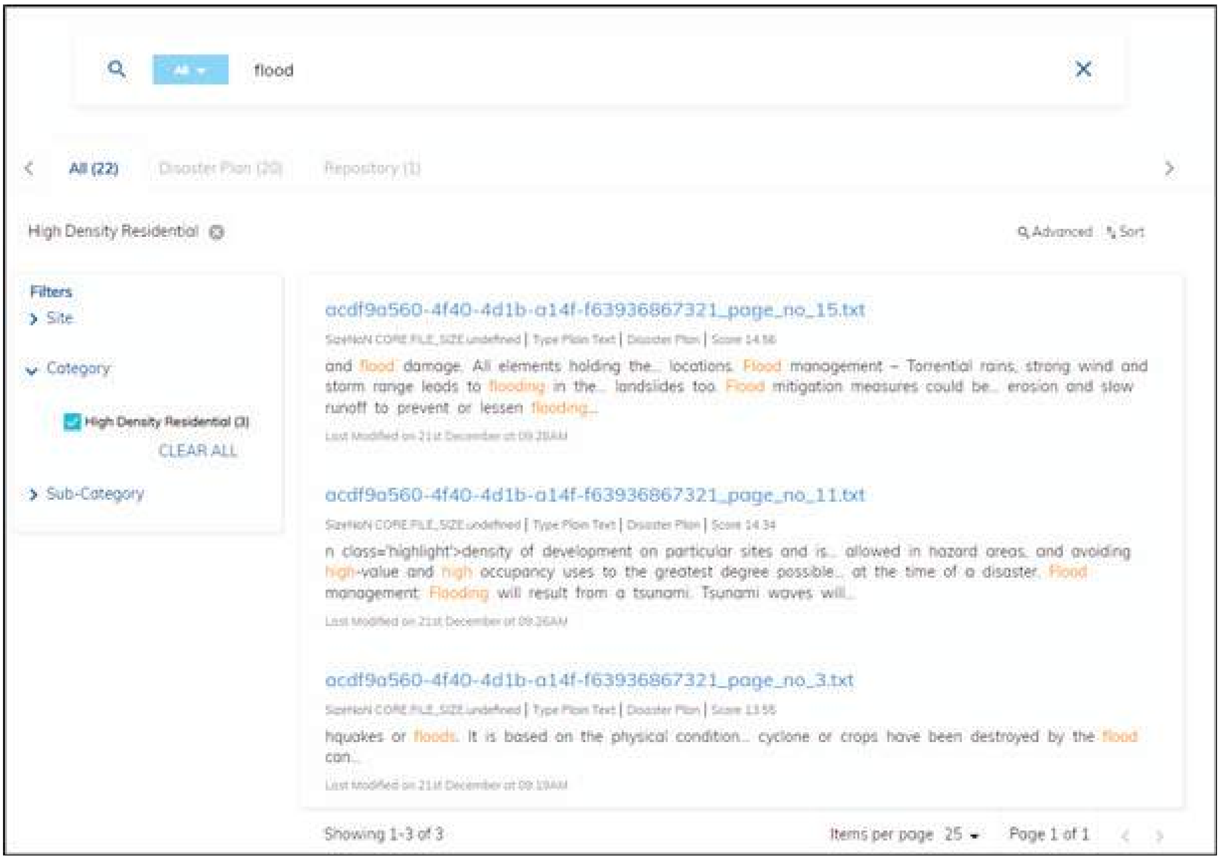

Figure 12. Howard County Flood Results (using Filter Feature)

Our research team then performed another advanced search within Howard County planning mechanisms, this time searching for anything related to flood.

Flood is a very broad topic and is a hazard of major concern in Howard County, and therefore it is likely that there is a lot of information and data regarding flood embedded within a range of different planning documents. During this performance of our application, we introduced the filter feature, in which we can identify different categories of flood-related information. For this search, our team filtered by high-density residential development, and the system returned a list of three specific plans that included information related to flooding in high-density residential development. These results are shown in Figure 12.

6. Enablers and Barriers

Although this application is a recommended solution to improve the process of integrating plans and other policy documents, it does not come without limitations.

One limitation is that the application cannot process images and maps at this time, which are very important in the field of planning and hazard mitigation. The ML algorithms at this stage are not able to process information that are contained in images and maps and draw conclusions.

Another further limitation is that there would be a special infrastructure requirement in terms of hardware in order for the application to function effectively. Plans are often large documents running upwards of 600 pages in some cases. The processing power required to process these plans would be substantial and would incur substantial costs. If this is taking place for a jurisdiction with many different planning documents, it is likely that special hardware infrastructure will be required for our application to operate smoothly and perform effectively.

An additional limitation is that the software currently can only cope with documents in English.

A final limitation is that the user would have to create their own database of Plans. This can also be viewed as a positive as the user will have the opportunity to create a database that caters exactly to what they are trying to determine an answer to.

Even though there are limitations with this solution to plan integration, it still can effectively eliminate the need to integrate plans manually, which is very time consuming, while the human power to complete this manually is most often lacking.

7. Key Takeaways from CDRI Fellowship Programme

After testing the Howard County, MD plans and completing an advanced search for two separate terms/phrases, our team identified two major key takeaways. The first key takeaway is our algorithm does indeed work as designed and as expected, with even a large set of documents in a controlled environment. Our second key takeaway is that extensive testing will continue to be conducted with larger data sets to see the accuracy of the results and improve the algorithm.

Through working with the CDRI Fellow Programme, our research project has addressed five of CDRI's eight thematic areas. This research addresses CDRI's thematic areas in the following ways:

7.1 Governance & Policy

CDRI's emphasis on governance and policy is to explore innovative concepts and tools required to bridge the information, policy and fiscal gaps across different levels of government.[11] This software is an innovative concept that helps bridge the information gap present across different levels of the government. It helps in inter-departmental co-ordination by flagging conflicts in various planning documents across departments.

7.2 Risk Identification & Estimation

CDRI believes that understanding and measuring disaster risk to infrastructure systems is instrumental in designing resilience plans.[12] Planners can use the software as a research tool to research best practices that are being followed across various countries and cities. Urban and city planners can look at the building codes of various cities and compare the laws and regulations that are present and develop a robust infrastructure resilience plan for the future.

7.3 Innovation & Emerging Technology

CDRI has a strong belief that in facing the unprecedented challenges of intense disasters, breakthrough innovations and adoption of new technologies can be our saviour. By using ML, we are innovating in the

[11] https://fellowship.cdri.world/

[12] https://fellowship.cdri.world/

field of disaster resilient infrastructure and creating a product that can actually help planners, public officials and the public, and help save lives and improve overall disaster resilience.

7.4 Community-based Approaches

CDRI believes in building the capacities of local communities to participate in the process of creating and sustaining small- and large-scale infrastructure, so as to enhance disaster and climate resilience of the community and its surrounding infrastructure.[13] Our software addresses this by providing an option for the user to look for disaster-related information about the area they are currently residing in, or they are about to reside in. Using this tool, property owners or potential buyers can see information about previous disasters in the area, zoning classifications, design guidelines, building codes, flood zonation, etc.

7.5 Recovery & Reconstruction

CDRI aims to support countries in developing and adopting mechanisms for assessing losses, estimating needs, prioritizing recovery and reconstruction activities and channelling adequate funds to disaster-affected areas in a timely manner.[14] By using this software, a city official can research how much aid and relief material was consumed in the previous disasters in the city. Using this data, the official can be better informed and prepared to make decisions in asking for funding, arranging emergency stockpiles for use during post-disaster phases.

8. Conclusion and Way Forward

Our software will continue to be developed in the future in order to create a product that is useful and effective not only for emergency planners, but also for planners across the wide range of planning disciplines. Our team will continue to develop our software based on the latest trends and technologies in order to have maps and images included in this automated integration. Our software development team will also continue to attempt to address the limitation of additional hardware infrastructure requirements, as this can become very costly.

There are also specific adjustments and/or additional features that our team would like to incorporate during the future development of our application. Within Phase 1 of the process, our team desires to provide the ability to export required search results in word/PDF and email to another person; annotate within the document and export annotations; write comments in the document and export them; highlight text and export highlighted text; and compile all annotations, comments and highlights into a word/PDF file and email. We will continue to make the following future developments as part of Phase 2 of the automated process: Cloning a document; updating a document; and creating a worldwide database of already processed documents and enable sharing of documents across users from different organizations. As we continue to develop this software into a knowledge management system, we can continue to share periodic updates and when ready, make the software available to CDRI.

[13] https://fellowship.cdri.world/

[14] https://fellowship.cdri.world/

References

1. Coalition for Disaster Resilient Infrastructure. (2022). *CDRI Fellowship Programme*. Details available at https://fellowship.cdri.world/
2. Deccan Herald. (2021). Airport metro to undo all the hard and costly work of white-topping ORR. Details available at https://www.deccanherald.com/city/airport-metro-to-undo-all-the-hard-and-costly-work-of-white-topping-orr-1022245.html
3. Hyland. (2022). *Enterprise Content Management System (ECM).* Details available at https://www.alfresco.com/ecm-software.
4. IBM. (2022). Natural Language Processing (NLP). Details available at https://www.ibm.com/cloud/learn/natural-language-processing
5. Metasource. (2015). *Let's Learn: Document Indexing*. Details available at https://www.meta-source.com/document-management-workflow-blog/document-indexing-basics/
6. Noy, N.F & McGuiness, D.L. (N.D.). Ontology Development 101: A Guide to Creating Your First Ontology. Details available at https://protege.stanford.edu/publications/ontology_development/ontology101-noy-mcguinness.html
7. TechTarget, Lutkevich, Ben. (2022). *Natural Language Processing*. Details available at https://www.techtarget.com/searchenterpriseai/definition/natural-language-processing-NLP
8. United States Federal Emergency Management Agency. (2015). Plan Integration: Linking Local Planning Efforts. Details available at https://www.fema.gov/sites/default/files/2020-06/fema-plan-integration_7-1-2015.pdf

Integrating Machine Learning in Disaster Resilience through Employing Rule-Based Verification on Aerial Imagery for Damages Assessment and Evacuation

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Abstract

Currently, flood risk management focuses on predicting floods, managing land systems and creating maps for areas prone to disaster. However, there is a lack of a smart and intelligent system that manages responses in flood-like situations. There is no automated land-based recognition method which can pinpoint the disaster-prone areas in need of help when telecommunication systems dysfunction. Recent studies have pointed towards the possibility of gathering image data to determine the digital elevation model (DEM) water levels and use it to carry out a future flood risk analysis. However, these methods are not tested or implemented for real-time flood detection. Timely detection of a flood is crucial to initiate flood relief services by identifying available routes within the limited time frame. The proposed approach targets the shortcomings of the Global Positioning System (GPS) such as variance in location coordinates and delayed information processing by using an Unmanned Aerial Vehicle (UAV)-based imaging framework.

One of the aftermaths of a natural disaster such as flood is a complete collapse or destruction of bridges, buildings and other infrastructure. Infrastructure components can sometimes be severely damaged, thus jeopardizing their structural integrity, resulting in fatalities and economic loss. In disaster-prone areas, many infrastructure elements are to be checked for defects. Manual detection of these defects is not feasible as it will require human resources and extended periods to thoroughly check each component. This may also result in some defects going undetected. This calls for the need to perform automatic defect detection to ensure reliability and precision. Using image processing and machine learning techniques, the captured or scanned images of the infrastructures can be analyzed to identify any defects.

Therefore, this project will focus on using state-of-the-art technology to facilitate disaster response. This project aims to build resilience to disasters by using a combination of machine learning and image processing-based methods. The major problems to be solved are detecting flood-affected areas from input aerial imagery in the post-disaster phase. From these areas, infrastructure components such as bridges are to be detected to perform damage assessment on them, focusing on the detection of cracks from input images of bridges. Also, it will assist in detection of entire road network from aerial imagery for disaster victim evacuation planning.

Acknowledgements

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1. Introduction

Flood risk management focuses on predicting floods, managing land systems and creating maps for areas prone to disaster. However, there is a lack of a smart and intelligent system that can manage responses in flood-like situations, coupled with the clear lack of an automated land-based recognition method which can pinpoint the disaster-prone areas in need of help when telecommunication systems dysfunction. Recent studies have pointed towards the possibility of gathering image data to determine the digital elevation model (DEM) water levels and use it to carry out a future flood risk analysis. However, these methods have neither been tested nor implemented for real-time flood detection. Timely detection of a flood is crucial to initiate flood relief services by identifying available routes within the limited time frame. The proposed approach targets the shortcomings of the Global Positioning System (GPS) such as variance in location coordinates and delayed information processing by using an Unmanned Aerial Vehicle (UAV)-based imaging framework.

This project aims to build resilience to disasters by using a combination of machine learning and image processing-based methods. One of the major problems that needs to be solved is detecting flood-affected areas from input aerial imagery in the post-disaster phase. From these areas, infrastructure components such as bridges are to be detected to perform damage assessment on them and the focus will be on the detection of cracks from input images of bridges. Also, the project will assist in the detection of the entire road network from aerial imagery to enable disaster victim evacuation planning.

Table 1 summarizes the existing techniques being used for disaster resilience and their limitations.

Table 1. Existing techniques for disaster response tools and their limitations

SR	Technique	Method	Limitation
1	GIS	To determine exit routes and transport facilities	Many cases of destruction of telecommunication system during floods
2	GPS	For flood risk management to carry out guided evacuation and rescue activities	Ambiguity in mapping the exact position; unavailability of Internet during the flood crisis
3	Remote Sensing	To gather data and provide a comprehensive characteristic of objects without direct contact; to forecast flood	Expensive; requires special training to analyze the images
4	Optical and Specific Absorption Rate	To gather knowledge about the location of water bodies and water levels; facilitates a real-time assessment of flood-affected areas	Less number of algorithms for real-time flood risk management; increased need for satellite programming and training
5	Hyperion Imaging	Narrow spectral bands used for classification; data is compared to known flooding data to reduce false detections	Lack of recent research based on this technology

2. Research Problem

One of the aftermaths of a natural disaster like a flood is a complete collapse or destruction of bridges, buildings, and other infrastructure. Infrastructure components can sometimes be severely damaged, thus jeopardizing their structural integrity, resulting in fatalities and economic loss. In disaster-prone areas, many infrastructure elements are to be checked for defects. Manual detection of these defects is not feasible as it will require human resources and extended periods to thoroughly check each component. This may also result in some defects going undetected. This calls for the need to perform automatic defect detection to ensure reliability and precision.

There is a need to detect infrastructure components like bridges/buildings to be detected to perform their damage assessment. Also, for the detection of entire road network from aerial imagery for disaster victim evacuation planning.

3. Aim, Objectives and Scope of the Research Study

This project aims to bring innovation in various aspects of disaster resilience by focusing particularly on efficient disaster response. The acquisition of aerial imagery from affected regions will be automated and improved using UAVs. The detection of flooded regions and bridges along with damage estimation from the infrastructure images will be programmed by using machine learning models.

The solution system will consist of an imaging method using an Unmanned Aerial Vehicle (UAV) that will capture multispectral aerial images of the flood-hit area. In the first stage of the project, the inundated areas from these images will be determined using machine learning. In the second stage, image processing methods such as noise reduction, Region of Interest (ROI) determination, edge detection, and isotropic surround suppression will be used to detect bridges. In the third stage, the bridge images will be processed using a deep learning model to detect damaged areas like cracks. Timely detection of flooded areas and landmark objects like bridges will assist in the quick provision of relief and aid to the affected people. It will also facilitate the initiation of evacuation operations to rescue stranded people from flooded regions by finding safe rescue routes. Detection of infrastructure components like bridges and performing damage assessment on them will help in preventing future fatalities that may occur due to the collapse of infrastructure.

The motivation for using UAVs for capturing aerial images of the disaster-hit region comes from the fact that they can capture high-resolution images of land in a short period without requiring human assistance. This makes them safe to investigate high-risk areas during disaster events, which are unreachable by humans. These factors make them ideal to be used in acquiring image data in the post-disaster circumstances. The idea of integrating machine learning along with image processing for flood detection and damage assessment originated from the fact that machine learning algorithms give results in the least amount of time, which are accurate and precise without relying on human intervention.

3.1 Proposed solution

The proposed solution for the identified research problem will comprise four stages. The first stage will map flooded regions from input aerial imagery, the second will detect bridges from the images, third will conduct damage assessment on the input bridge images and the fourth will find the optimized evacuation routes to disaster victims. All these modules will leverage novel machine learning models and will be optimized to achieve their specific goals.

Figure 1 shows the proposed solution framework. Through the research project, innovative technology will be fostered to create value by achieving the following:

- Real-time data collected from drones during flood situations will be used to feed machine learning algorithms designed as predictive models for determining inundated areas.
- A rule-based verification framework will be developed to recognize and identify key infrastructures that are prone to severe damages during floods such as bridges over water, using machine learning algorithms that support multispectral imagery.
- Image processing techniques will be embedded in the framework, including Edge detection through Robert, Prewitt, Sobel and Canny while optimizing computational efficiency.
- Mathematical programming models (based on non-linear programming) will be incorporated in the framework to optimize the routes utilized for disaster relief operations once key impacted infrastructures are pinpointed by the machine learning algorithms.
- The framework will allow the detection of critical infrastructure that are vulnerable during disaster events. The proposed approach for conducting damage assessment from input bridge images is shown in Figures 2 and 3. This information will be utilized for route optimization to access vulnerable populations and deliver aid.

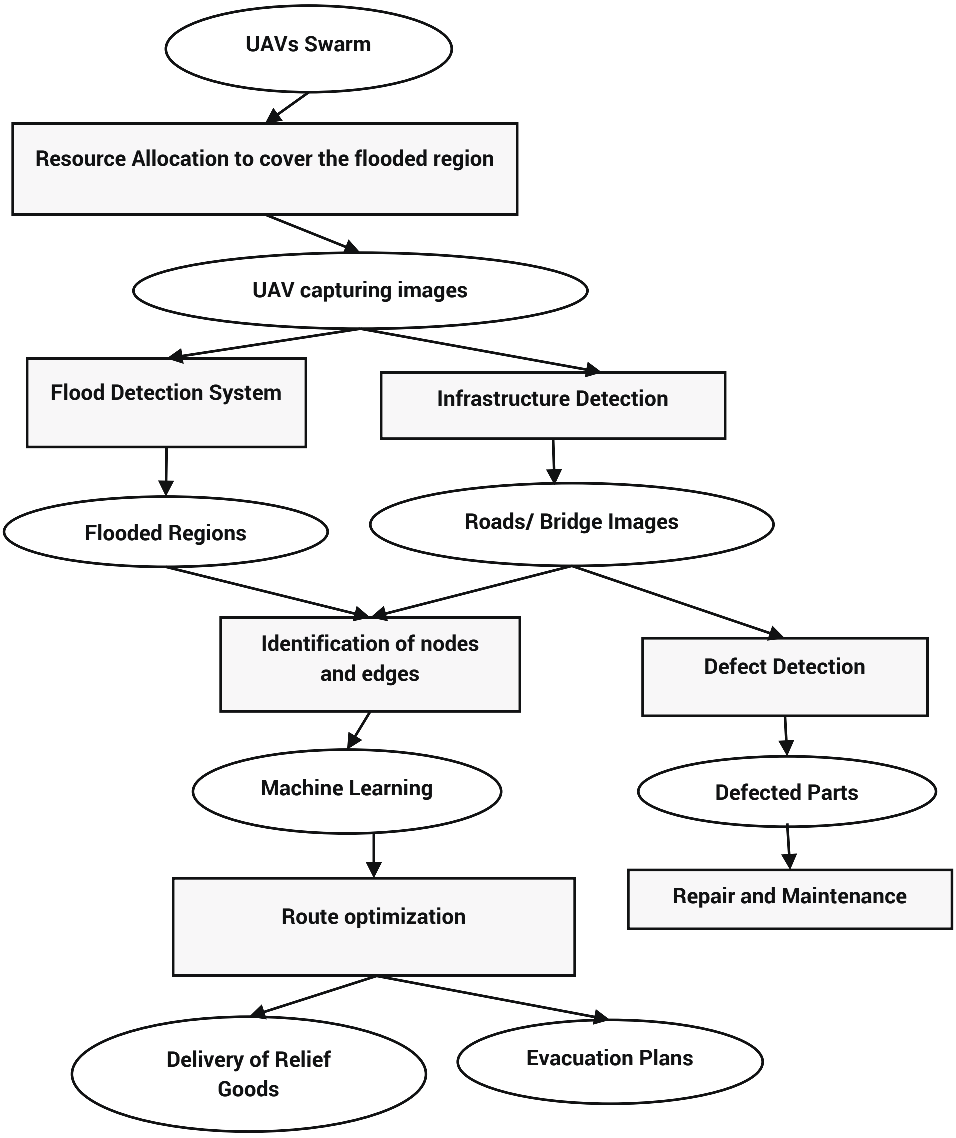


Figure 1. Proposed Framework for Disaster Resilience

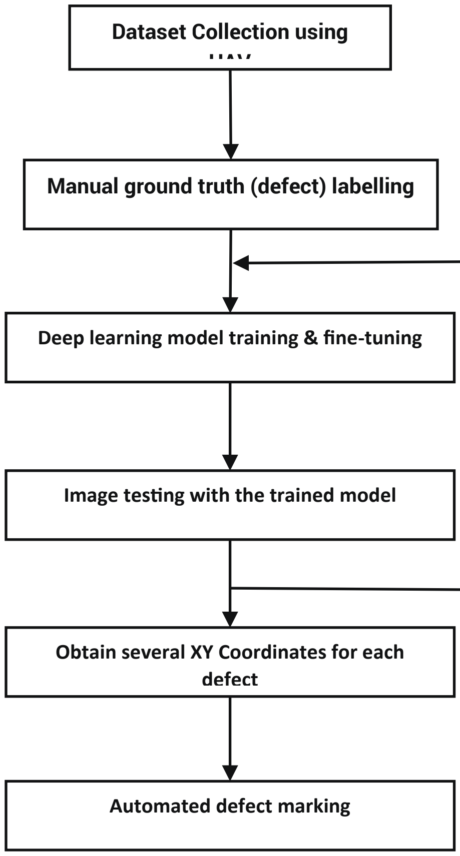


Figure 2. Damage Assessment from Bridge Images using Machine Learning

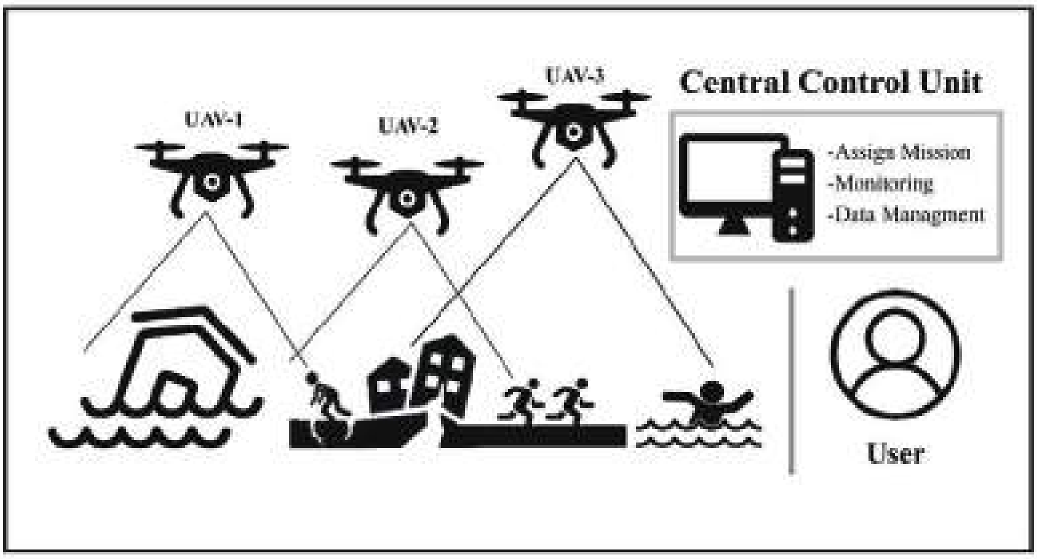


Figure 3. UAV's Swarm Covering the Flooded Region

3.2 Scope

The system is designed to provide disaster response during flood events. The system will only support multispectral aerial images. It is aimed to detect damages on bridges and other infrastructure components like roads; buildings are not in the scope of this project. The scope of damage estimation is limited to detecting cracks from input bridge images.

The scope and limitations of the proposed system concerning each module are listed below:

- The proposed system is aimed towards assisting disaster response and ensuring disaster resilience by building a complete framework that targets multiple existing problems in this area. The proposed research focuses only on floods as they are the most frequently occurring natural disasters in the world, representing 40 percent of global natural disasters (CDC, 2017).
- This system focuses only on building resilience in the post-disaster phase of the disaster management process as it carries out tasks such as flood mapping, rescue vehicle routing, identification of infrastructure components and damage assessment from infrastructure which comes under disaster response and recovery. Hence, the tasks like flood prediction, forecasting and risk assessment are not within the scope of this system.
- This system targets specifically the detection of bridges and identifying defects from them. Hence, damage assessment from other infrastructure elements like buildings, roads and houses are outside the scope of this research.
- Each module in the system will be built to work on multispectral aerial images only. Unlike traditional straight-down aerial imaging (orthogonal views), the focus is on images captured from an angle, i.e., low and high oblique images.

4. Methodology

The image data collected will be processed to remove any noise and redundant information. A system will be designed, implemented and tested on a specified framework to generate results and finally, documents will be prepared including reports, research articles and manuals.

Figure 4 depicts a research methodology flow chart that will be followed. In the first step, a comprehensive literature review will be conducted for each module of the system. Recent research papers, book chapters, abstracts and letters published by leading journals and conferences related to image processing and machine learning will be reviewed. The chosen platforms include Web of Science, Elsevier, MDPI and Google Scholar. A thorough literature review will evaluate existing techniques of disaster response and resilience and their shortcomings will be analyzed to identify research gaps. These research gaps will be addressed in the proposed study. The problem definition will specify the issues to be targeted by the proposed system. In the second step, multispectral aerial images of a flood-hit area will be captured using a swarm of UAVs as shown in Figure 5. The images will contain both flooded and non-flooded areas along with images of key infrastructure such as bridges. In the third step, these images will be pre-processed in MATLAB framework to discard redundant data, adjust brightness, remove noise and crop unnecessary regions. The cleaned data will then be divided into training and testing datasets. In the fourth step, a system will be designed by defining modules that are to be built, their sequence and flow of data between them. In the fifth step, the designed system will be implemented on PyTorch framework using the python programming language. This involves building each module of the system in its defined sequence. The modules using machine learning models will be trained using images from the training dataset. In the sixth step, the developed system will be validated using images from the testing dataset. During the testing phase, each module of the system will be assessed by giving inputs from the testing dataset. Finally, a project report will be written for the developed system along with research papers and manuals.

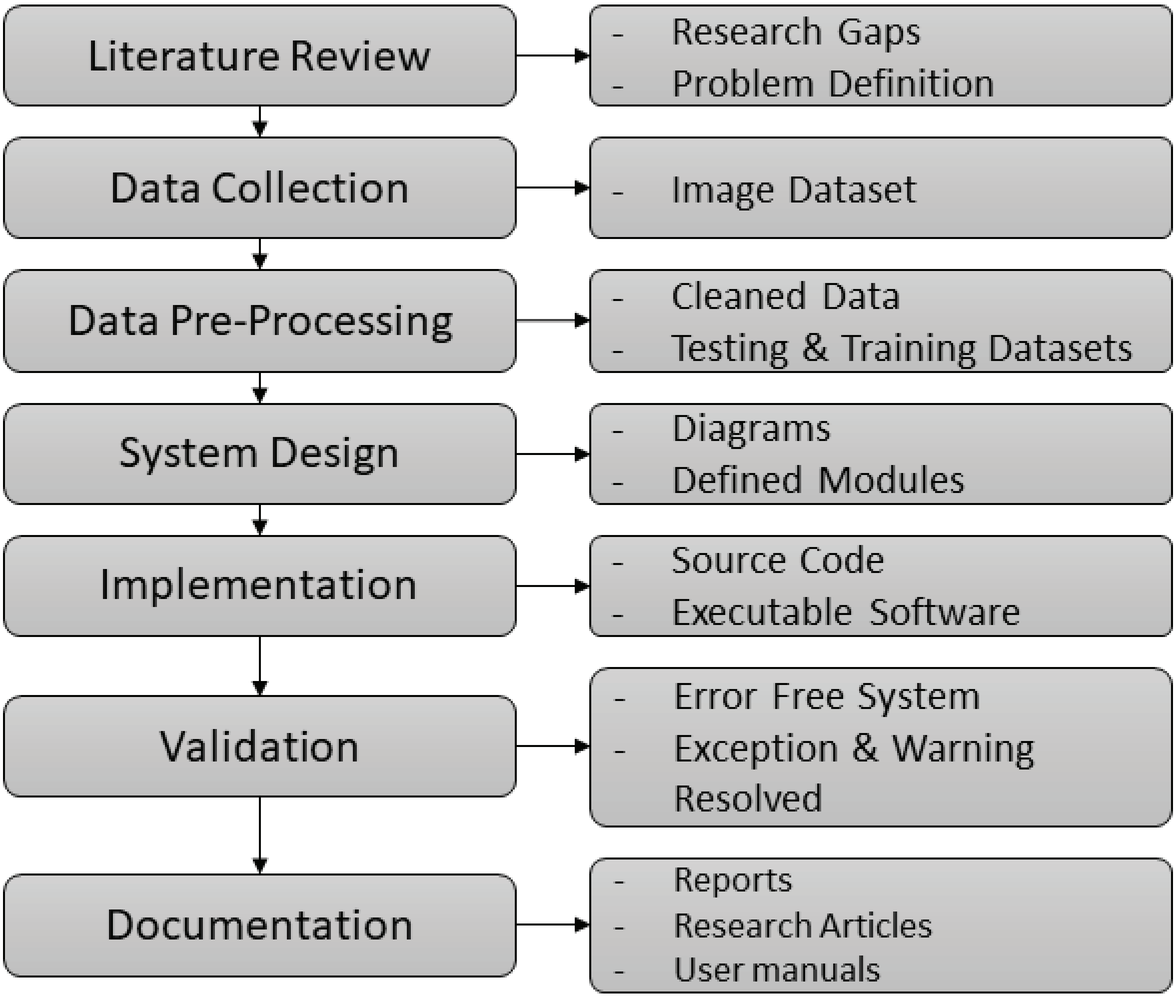


Figure 4. Research Methodology for the Proposed System

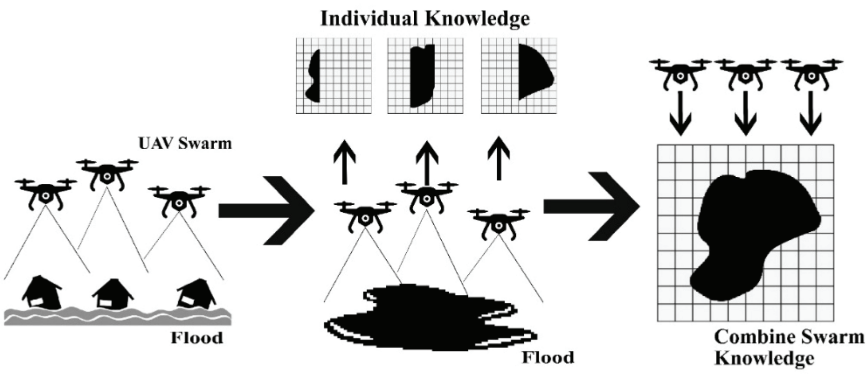


Figure 5. How an Individual UAV can Participate to Generate Combined Swarm Knowledge

Floods cause widespread damages to infrastructure including roads, bridges, water plants along the rivers etc. Identifying critical infrastructure and fortifying them before the oncoming of extreme weather events will protect the community from huge losses. Failure of multiple infrastructures has been known to escalate the impacts on the region (Karbhari & Ansari, 2009). Critical infrastructure must be maintained to minimize the losses of disasters. Infrastructure networks are essential to carry out various activities and are interdependent. Hence, the failure of one infrastructure may lead to widespread impacts on the whole network. Failure of infrastructure also has dire physical, social and economic impacts.

An alarming and frequently occurring infrastructural damage is the appearance of cracks. Generally, cracks initiate on the surfaces of the concrete structures mainly due to stress, fatigue, cyclic loading, poor construction, deterioration/corrosion, moisture, temperature effects, shrinkage and the use of incongruous construction materials and strategies (Gibb, La, & Louis, 2018; Han, Liang, Chen, Zhang, & Ge, 2021; Hoang, 2018). Various structures including bridges, tunnels, railway tracks, roads, buildings, pavements, aircrafts and automobiles are prone to cracks (Krizhevsky, Sutskever & Hinton, 2017). Cracks are the earliest signs of degradation that can lead to serious damage if allowed to penetrate or left unmaintained or unrectified (Krizhevsky et al., 2017; Mohtasham Khani et al., 2020).

Case study

For the case study, the Bolte Bridge in Melbourne, Australia (Figure 6a) was selected. Bolte Bridge is a large twin cantilever road bridge carrying a total of eight lanes of traffic. It is present on the west side of central business district, spanning over the Yarra River and Victoria Harbour (Figure 6b). The total length of the bridge is 490 m and comprises four spans, two sides of which are 72 m long and the main measure is 173 m. The data was collected by VERIS, a leading company for providing spatial data services (Figure 7a). VERIS provides an integrated approach for the project lifecycle starting from the planning phase to the final delivery phase. It uses innovative technologies to conduct surveys and damage assessments of the infrastructures such as railways, bridges, roads, buildings etc. Aerial imagery of the Bolte Bridge was carried out using UAVs.

A DJI M200 UAV was used for surveying the region (Figure 7b). A machine learning-based algorithm was developed for crack detection. Images were typically obtained from drones in cases where access is limited (e.g., due to span of the bridge, presence of traffic or in cases of floods), by automatically identifying cracks and vulnerabilities in the bridge infrastructure.

Figure 6a & b. (a) The Bolte Bridge, Melbourne, Victoria (b) Geographical location of the Bolte Bridge

(b)

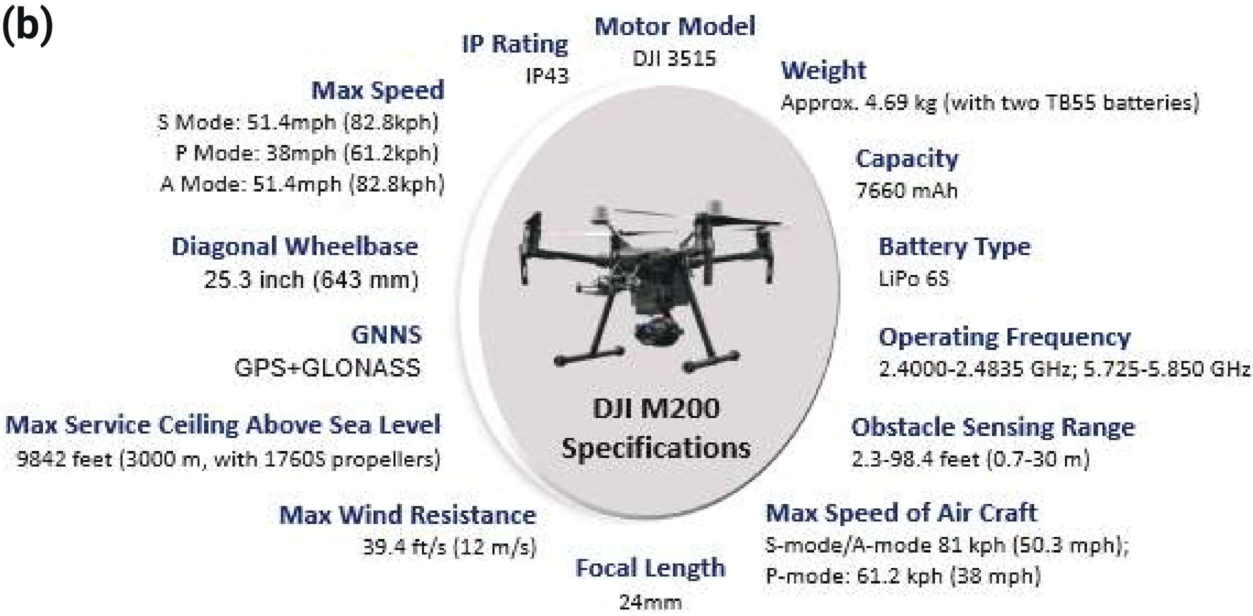


Figure 7a & b. (a) Field sampling day (b) Specification of DJI M200

4.1 Data collection and pre-processing of images

The overall workflow of the current research study is presented in Figure 7a. The crack detection procedure was initiated by the collection of 2D images that form the needed dataset (Figure 8a). The images of the bridge were obtained using a UAV carrying a digital camera onboard (Figure 7b). A total of 1980 images were captured. Images processed by deep learning are augmented through cropping, colour modification, geometric transformation, noise injection and flipping. The images included in the dataset had three main types of cracks that can be classified into simple cracks, hairline cracks and artificial marking cracks as shown in Figure 8b. Simple cracks usually result from infrastructure settling onto its foundation however, in comparison, the hairline cracks are very small and shallow that mainly emerge due to plastic shrinkages about 0.003 inches in width (Su, 2013).

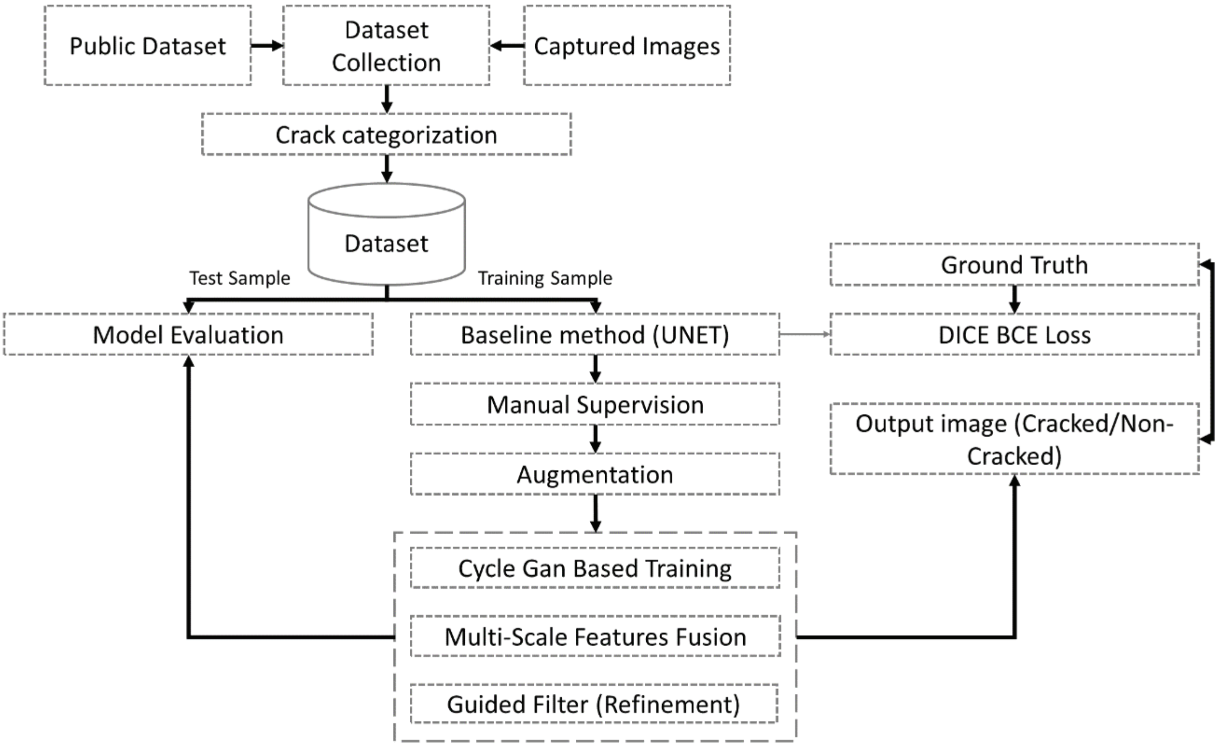


Figure 8a. Holistic View of the Proposed Framework

After finalizing the dataset, the collected crack images were pre-processed to remove any noise or undesirable background. Following this step, an image brightness adjustment was carried out. Cropping was performed on the images to remove any unwanted background such as grass, water, sky, building, trees etc. Particularly, for the crack images, the data set was divided into two types of levels including the crack and structures without cracks (non-crack) levels, respectively. The overall percentages of the pixels for all images (with or without crack) are shown in Table 2 which indicate that a lower percentage of the crack regions are included in the complete dataset.

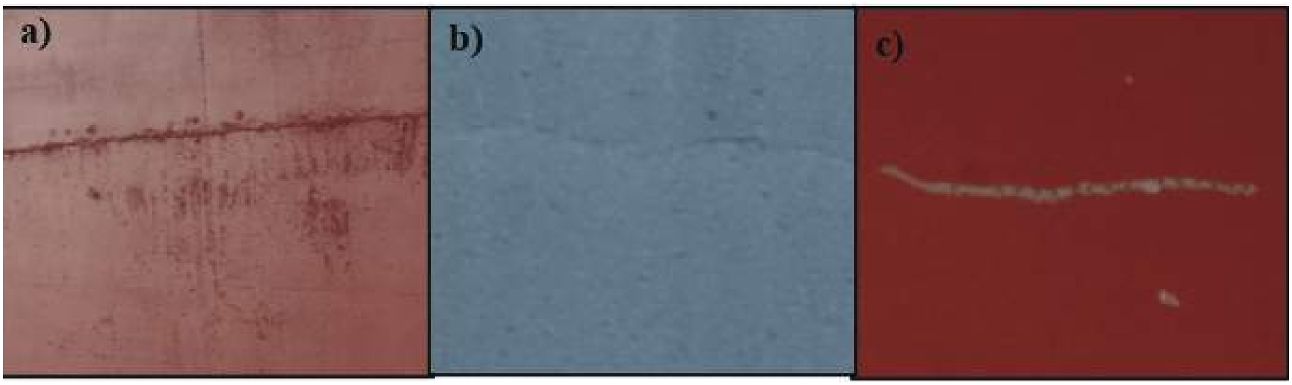


Figure 8b. Crack Types Used in Dataset: (a) Simple Crack, (b) Hairline Crack and (c) Artificial Marking Crack

A total of 2.93% significant crack pixels, 1.41% weak crack pixels and 95.93% non-crack pixels were included in the complete data set, respectively. For both sets, training and test set, total of 96.32% and 94.69% non-corrosion pixels were included, as shown in Table 2. Additionally, a total of 3.68%

and 5.31% of crack pixels were used in the current study (Table 2). Generally, a crack width in the range of 1 to 5 pixels is considered a weak crack whereas significant cracks are those that have more than 5-pixel width. It was observed that the thin cracks and surface cracks had different properties in comparison to wider cracks. Therefore, the application of traditional post-processing methods (with length constraint, curvature and geometric features) is necessary to obtain the complete and continuous thin cracks (Prasanna et al., 2016), which is a limitation of the deep convolutional networks.

Table 2. Pixel Percentages of Crack and Non-Crack Images

Pixels	Crack Pixels (%)		Background Pixels (%)
	Significant	Weak	
Total	2.93	1.41	95.93
Training	3.24	0.44	96.32
Testing	4.15	1.16	94.69

For the crack images in the current study, the height and width distributions are presented according to two levels, mainly crack and non-crack. Figure 9 illustrates the cracks in terms of spatial representation such that the width and height of crack pixels are gathered through Pytorch and WANDB (Rana et al., 2019).

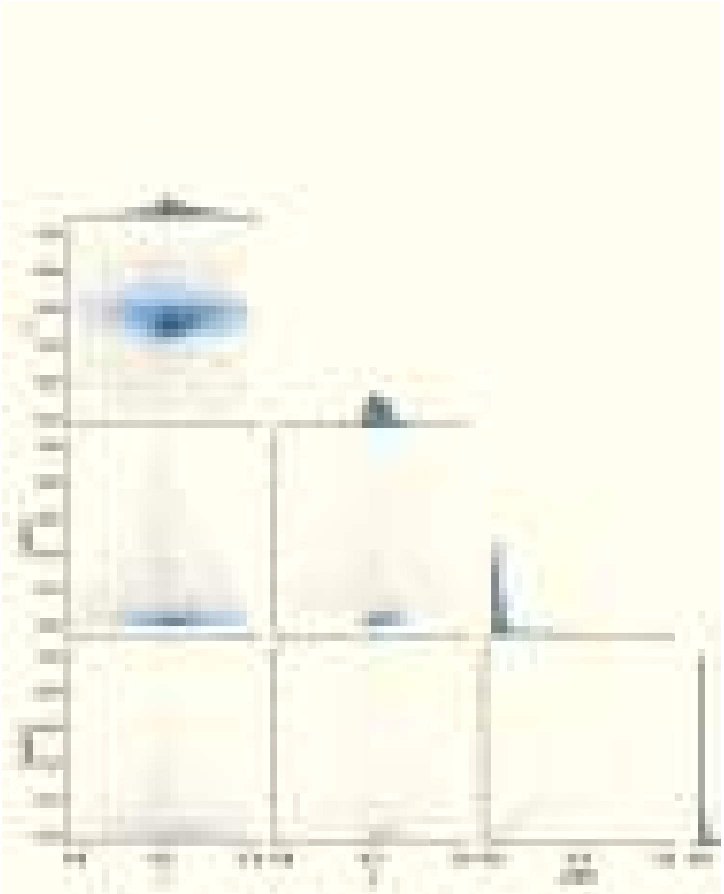


Figure 9. Height, Width and Spatial Extent of Crack Pixels in Dataset

For the current study the crack pixels frequency was predicted and the bounding boxes or labels were identified through spatial location analysis and the use of data distribution. The axis presented in Figure 10 provides the representation of size distribution, which shows that spatial or frequency distribution for our crack pixels is neither skewed nor projected at one place. Rather, crack pixels display a Gaussian or well well-distributed pixel data as shown in Figure 10 which is indicative of the fact that the pixel distribution in the selected crack dataset is devoid of biases. A large portion of the dataset consists of drive view images roughly 54% from road damage detection challenge 2020.

The total dataset for this study includes 10,000 cracks. The health of the dataset is explained through plots. The location is shown through a gaussian distribution right around the centre region where most cracks appear. Determining the size of the crack is tricky because of the transformations that can occur in cracks. By looking at a crack, the only way to analyse the size of a crack with 100% surety is to be orthogonal to the crack. Moreover, the region of a crack which is close to the camera is fully visible but the ones further away from the surface may appear like a thin edge or depict other differences due to the camera angles as well as the transformations in the crack which might make this difficult to detect. The proposed methodology can potentially enable crack analysis in terms of structure in a consistent manner. This method can generalize for the environmental setting but cannot gauge shifts in perspective. The comparison of generative and discriminative methods is shown in Table 3.

Table 3. Comparing Generative and Discriminative Methods

Characteristics & Approach	**Generative**	**Discriminative**
Learns	Latent Code	Mapping (X →Y)
Inference Speed	Slow	Fast
Generalization	Moderate	Poor

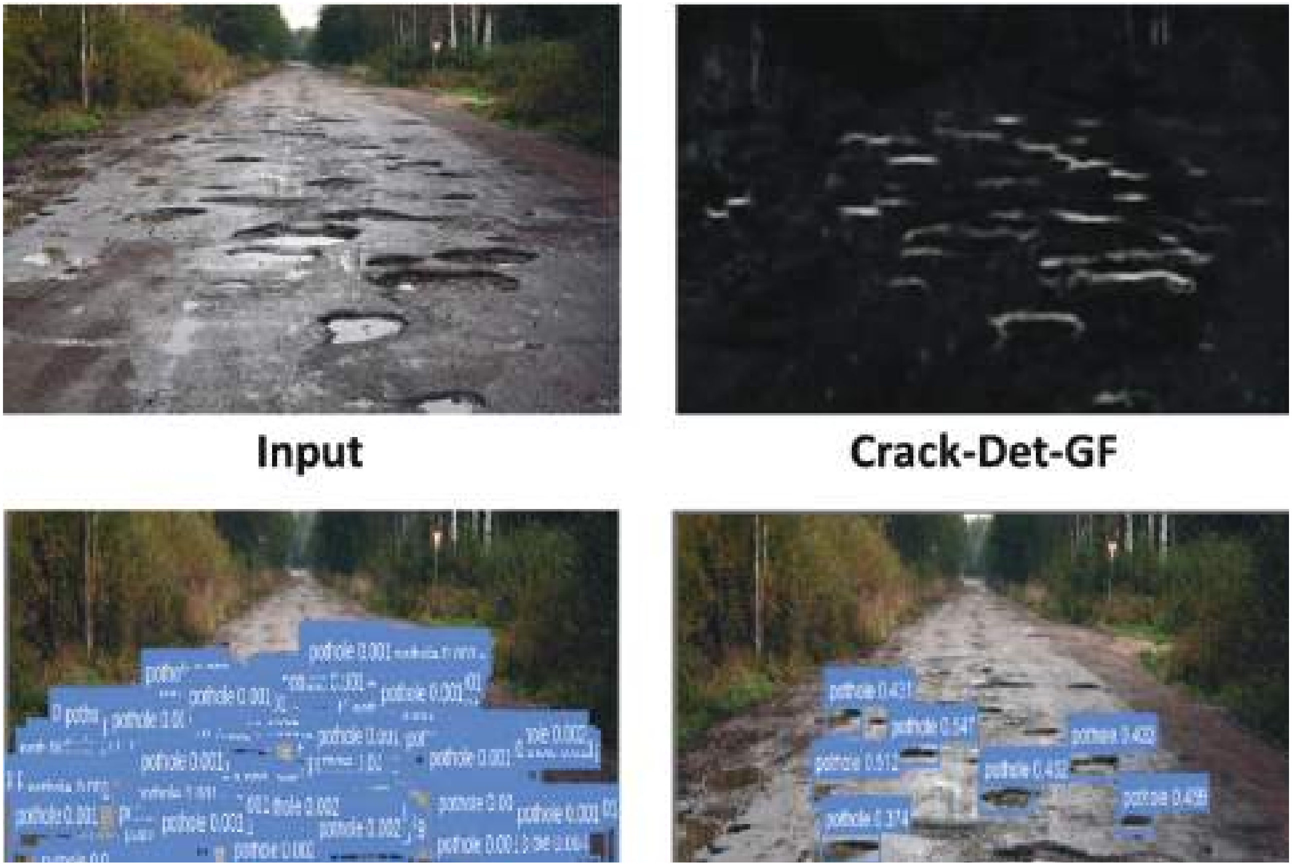


Figure 10. Comparison of Generative and Discriminative Methods

Figure 10 shows comparison of generative and discriminative results of Faster-RCNN and Yolov5-s. The highly expressive Deep CNNs entailing numerous parameters have brought considerable advancements in the classification and processing of images (Wei et al., 2017). However, the image features in the CNN's training set can be a risk as it has a tendency of over-fitting because of the non-generalized features in this network. Using an insufficient set of samples for training can lead to overfitting (Wei et al., 2017). Additionally, the collection of abundant samples is an exorbitantly costly endeavour, which has increased the utility of data augmentation methods (i.e., flipping, resizing, random cropping) to enhance image variation and to overcome the issue of over-fitting (Stentoumis, Protopapadakis, Doulamis, & Doulamis, 2016). In the overall training procedure of the proposed approach, label generation and crack detection were performed through data augmentation presented in Table 4.

Table 4: Data Augmentation Details

Augmentations	
HSV-Hue augmentation (fraction)	HSV_H: 0.015
HSV-Saturation augmentation (fraction)	HSV_S: 0.7

Augmentations	
HSV-Value augmentation (fraction)	HSV_V: 0.4
Rotation (+/- deg)	DEGREES: 0.0
Translation (+/- fraction)	TRANSLATE: 0.1
Scale (+/- gain)	SCALE: 0.5
Shear (+/- deg)	SHEAR: 0.1
Perspective (+/- fraction), range 0-0.001	PERSPECTIVE: 0.2
Flip up-down (probability)	FLIPUD: 0.0
Flip left-right (probability)	FLIPLR: 0.5
Mosaic (probability)	MOSAIC: 1.0
Mixup (probability)	MIXUP: 0.0

4.2 Per-pixel segmentation

The use of the pre-trained model for semantic segmentation does not work on general images because it is based on the association of a class label to each pixel of an image. Therefore, we used DeepCrack (a publicly available crack-detection dataset) for the training of the SegNet which aims to perform pixel-wise segmentation of the captured dataset (by UAV). The SegNet method displays limited accuracy and requires manual supervision. Therefore, per-pixel annotation was used in the current study.

4.2.1 Baseline Design (BN)

This stage consists of Max Pooling, ReLU Activation, Concatenation, and convolution operation. It consists of three sections i.e., contraction, bottleneck and expansion. For obtaining high precision results in semantic segmentation, it is vital to collect finer details while retaining semantic information. However, having a limited dataset for training a deep neural network is a limitation. This can be overcome by using a pre-trained network and applying it to the desired datasets. The extensive data augmentation carried out in U-Net is another way to overcome the raining issues. Its key contribution is the creation of shortcut connections. The performance of the U-Net can be enhanced by replacing the plain unit with the residual unit (Figure 11).

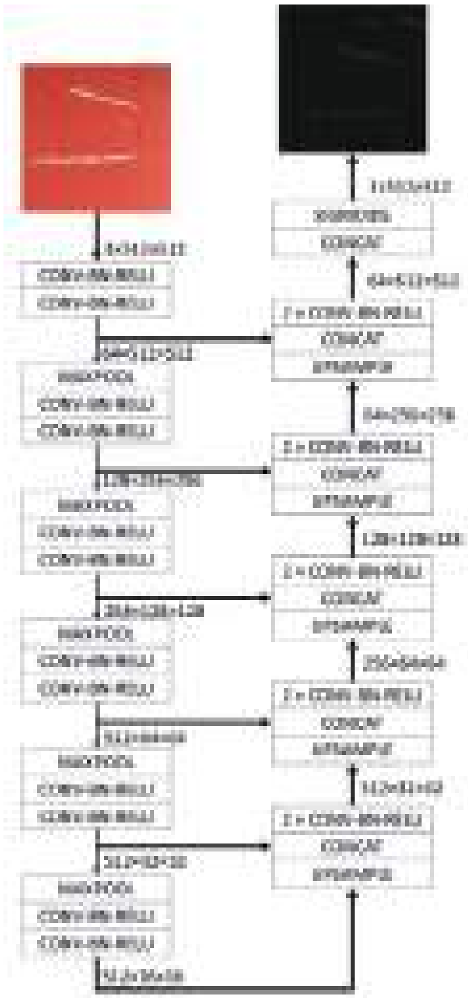
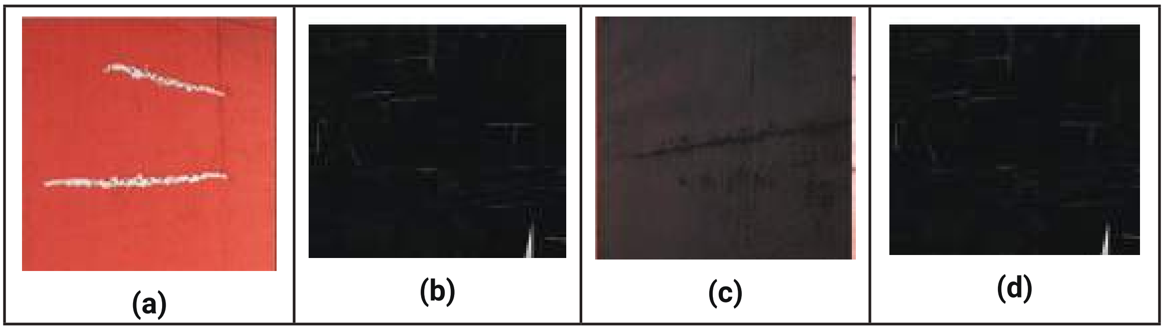


Figure 11. Proposed Deep Residual UNET Architecture

Most importantly the total crack pixels used for e-training and testing were divided into significant and weak crack pixels, respectively. This categorization was used for distinguishing crack pixels based on the pixel width. A crack having a score between 1 and 5 for pixel depth was defined as a weak crack whereas a crack exhibiting a pixel width greater than 5 was defined as the significant crack pixel as show in Figure 12.



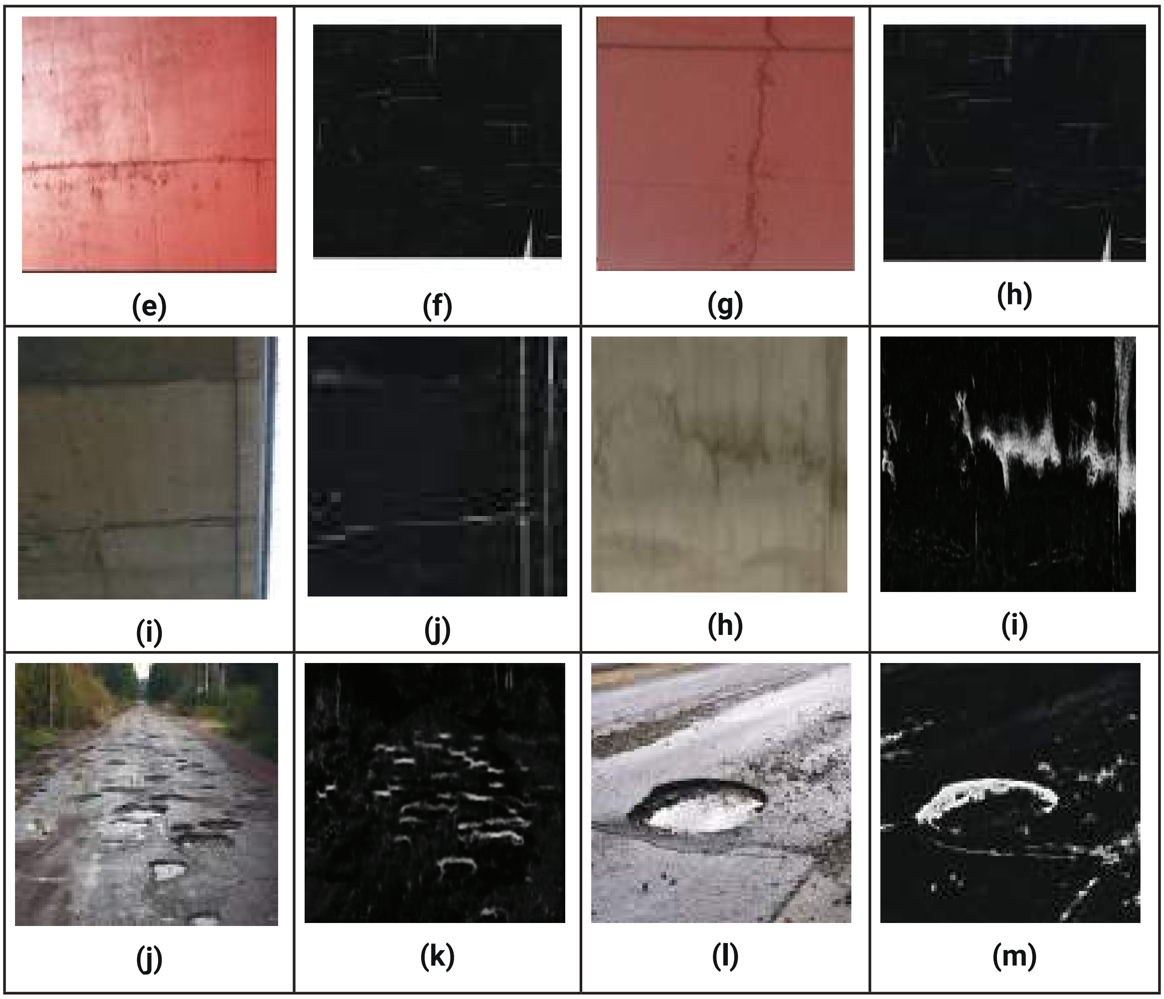

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Figure 12. Cracks Categorization Matrix Distinguish Crack Pixels Based on Pixel Width

In relation to metric values, our method generalizes better than the respective DeepCrack-BN and DeepCrack-GF as shown in Table 4. Effective data augmentation methods are essential for deep models when training data is very limited. Moreover, using refinement modules like the PS operation and convolutional layers for analyzing the overlap between the two maps shows that the proposed method can provide higher generalization and retain a greater amount of information of the low-dimensional features (Figure 12). The results of this study show that this model can perform more robustly as compared to other methods. Moreover, our method also removes the background and irrelevant noise in the dataset (Qu et al., 2020).

Our results show that when the training set is augmented 16 times, the performance improves to a greater extent. Hence, the refinement of the proposed post-processing methods is effective. In comparison to DeepCrack, HED and SegNet, our proposed architecture shows obvious improvements. It is already reported that the traditional methods involve post-processing (i.e., length constraint, curvature and geometric features). Therefore, it is indispensable for obtaining continuous and complete thin cracks. However, the convolutional neural networks (CNNs) display this weakness.

The manual investigation of damages incurred to infrastructure is a challenging endeavour that is time-consuming and lacks objectivity and reliability. Therefore, automatic crack detection through techniques such as image processing is inevitable, but the influence of noise caused by lighting, blurring and such other factors needs to be addressed. Amongst the different deep learning approaches, CNNs provide automatic learning of image features instead of image feature extraction, thus making it less influenced by noises. For this reason, we suggest a framework based on deep hierarchical CNN architecture along with Cycle GAN for predicting crack segmentation for each pixel in an approach that is end-to-end.

The proposed method utilizes the extended FCN (Fully Convolutional Networks), the DSN (Deeply Supervised Nets) and a U-net architecture. DSN delivers direct and integrated feature supervision at each convolutional stage. Moreover, the intricately designed model network learns and aggregates features as it moves from the low convolutional layers to the high-level convolutional layers during the training procedure.

Publications

Knowledge products	Title: ***An AI/ML-Based Strategy for Disaster Response and Evacuation of Victims in Aged Care Facilities in the Hawkesbury-Nepean Valley: A Perspective*** Publishing/Accepting organization: Buildings - MDPI Category: Published – Journal Paper -- Title: **Disaster Region Coverage Using Drones: Maximum Area Coverage and Minimum Resource Utilization** Publishing/Accepting organization: Drones - MDPI Category: Published – Journal Paper -- Title: **Metaheuristics for Capacitated Vehicle Routing for Flood Victims Evacuation** Publishing/Accepting organization: ICACTCE'22 Category: Accepted – Conference Paper

5. Key Takeaways from CDRI Fellowship Programme and Way Forward

Potential for implementation/ scale up of research solution	This research has a great potential of applicability in a real time disaster scenario to assess damage caused by floods and for victim's evacuation planning.
Scope for further research	This research can further be further enhanced by using on-board processing capability drones to assess damage caused by floods (Cracks – Corrosion – Potholes) and for road network detection for victim evacuation planning (safest/shortest path).

Plan for disseminating research findings	We have published two journal papers and one conference paper during this Fellowship. We will continue to contribute significantly in this domain by publishing more high quality articles.
Suggestions for expanding CDRI network - Contact details and LinkedIn profiles of DRI experts and practitioners	CDRI is an amazing body which has provided us with the platform to engage with DRI experts and practitioners. We would appreciate if all the relevant details to contact with DRI experts and practitioners are available on CDRI website and Facebook pages. Also, there should be more interactive talks and workshops by the DRI experts and practitioners. CDRI should communicate with relevant department in every university on panel countries to further expand, grow and connect professional in this domain around the globe.

References

1. Redmon, J., Divvala, S., Girshick, R., & Farhadi, A. (2016). You Only Look Once: Unified, Real-Time Object Detection. *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*: IEEE.
2. Ren, Y., Huang, J., Hong, Z., Lu, W., Yin, J., Zou, L., & Shen, X. (2020). Image-based concrete crack detection in tunnels using deep fully convolutional networks. *Construction and Building Materials, 234*, 117367. doi:10.1016/j.conbuildmat.2019.117367
3. Safiuddin, M., Kaish, A., Woon, C.-O., & Raman, S. (2018). Early-Age Cracking in Concrete: Causes, Consequences, Remedial Measures, and Recommendations. *Applied Sciences, 8*, 1730. doi:10.3390/app8101730
4. Samadani, R., & Vesecky, J. F. (1990). Finding Curvilinear Features In Speckled Images. *IEEE Transactions on Geoscience and Remote Sensing, 28*, 669-673. doi:10.1109/TGRS.1990.572977
5. Shelhamer, E., Long, J., & Darrell, T. (2017). Fully Convolutional Networks for Semantic Segmentation. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 39*, 640-651. doi:10.1109/TPAMI.2016.2572683
6. Shi, W., Caballero, J., Huszar, F., Totz, J., Aitken, A. P., Bishop, R., . . . Wang, Z. (2016). Real-Time Single Image and Video Super-Resolution Using an Efficient Sub-Pixel Convolutional Neural Network. *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*: IEEE.
7. Simonyan, K., & Zisserman, A. (2015). Very deep convolutional networks for large-scale image recognition. *3rd International Conference on Learning Representations, ICLR 2015 - Conference Track Proceedings*.
8. Sitara, S. N. (2018). Review and Analysis of Crack Detection and Classification Techniques based on Crack Types. *International Journal of Applied Engineering Research, 13*, 6056-6062.
9. Stentoumis, C., Protopapadakis, E., Doulamis, A., & Doulamis, N. (2016). A HOLISTIC APPROACH FOR INSPECTION OF CIVIL INFRASTRUCTURES BASED ON COMPUTER VISION TECHNIQUES. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLI-B5*, 131-138. doi:10.5194/isprsarchives-XLI-B5-131-2016
10. Su, T.-C. (2013). Application of Computer Vision to Crack Detection of Concrete Structure. *International Journal of Engineering and Technology, 5*, 457-461. doi:10.7763/IJET.2014.V5.596
11. Wei, Y., Wang, Z., & Xu, M. (2017). Road Structure Refined CNN for Road Extraction in Aerial Image. *IEEE Geoscience and Remote Sensing Letters, 14*, 709-713. doi:10.1109/LGRS.2017.2672734
12. Yu, Y.-H., Kwok, N. M., & Ha, Q. P. (2011). Color tracking for multiple robot control using a system-on-programmable-chip. *Automation in Construction, 20*, 669-676. doi:10.1016/j.autcon.2011.04.013
13. Yuan, M., Liu, Z., & Wang, F. (2019). Using the wide-range attention U-Net for road segmentation. *Remote Sensing Letters, 10*, 506-515. doi:10.1080/2150704X.2019.1574990

14. Zhang, K., Zhang, Y., & Cheng, H. D. (2020). Self-Supervised Structure Learning for Crack Detection Based on Cycle-Consistent Generative Adversarial Networks. *Journal of Computing in Civil Engineering, 34*, 04020004. doi:10.1061/(ASCE)CP.1943-5487.0000883

15. Zhang, W., Zhang, Z., Qi, D., & Liu, Y. (2014). Automatic Crack Detection and Classification Method for Subway Tunnel Safety Monitoring. *Sensors, 14*, 19307-19328. doi:10.3390/s141019307

16. Zheng, S., Jayasumana, S., Romera-Paredes, B., Vineet, V., Su, Z., Du, D., . . . Torr, P. H. S. (2015). Conditional Random Fields as Recurrent Neural Networks. *2015 IEEE International Conference on Computer Vision (ICCV)*: IEEE.

17. Zhu, J.-Y., Park, T., Isola, P., & Efros, A. A. (2017). Unpaired Image-to-Image Translation Using Cycle-Consistent Adversarial Networks. *2017 IEEE International Conference on Computer Vision (ICCV)*: IEEE.

Framework for Landslide-Prone Critical Infrastructure Zoning

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Abstract

Landslide cause human losses, economic losses and infrastructure disruptions. Landslide susceptibility assessment effectively predicts the likelihood of landslides in a given region. Lack of precise landslide susceptibility assessment makes it difficult to identify existing critical infrastructures that are more vulnerable to landslides, which result in poor mitigation and preparedness. A spatially consistent landslide inventory is required to develop an effective landslide susceptibility map. Terrain attributes and extreme rainfall control the landslide susceptibility. Variation of extreme rainfall in magnitude and intensity makes landslide susceptibility a dynamic phenomenon, which requires understanding landslide susceptibility at different multi-temporal scales. In this study, we manually mapped over 100,000 landslides in Nepal and then mapped landslide susceptibility from 2015 to 2020 on a multi-temporal basis. We trained a machine learning model with terrain attributes and 21 different extreme rainfall indices for this. The landslide susceptibility was then overlaid on a critical infrastructure spatial index map (representing the intensity of the presence of critical infrastructure based on open street maps). In this way, we identified the critical infrastructures prone to landslides in Nepal. Different scenarios maps are generated to help prioritize landslide-prone critical infrastructure areas and river corridors on a national scale. The final map delineates areas where climate-resilient slope infrastructure policy needs to be enforced at the granular level. The framework we developed is scalable to other countries and regions and helpful in developing national-scale infrastructure financing strategies.

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1. Introduction

The Nepal Himalayas is a dynamic and fragile mountain ecosystem that is experiencing a rapid rate of population growth, a rural economy reliant on subsistence and a more frequent summer monsoon rainfall (Chalise et al., 2019). From June to September, Nepal experiences a summer monsoon regime that is characterized by a strong north-westerly flow of moist air from the Indian Ocean that accounts for 70–93% of its annual precipitation (Chalise et al., 2019). This monsoonal rainfall makes Nepal highly susceptible to landslides (Rieger, 2021). Moreover, anthropogenic activities, such as road construction over trails undercutting slopes, allow water to infiltrate into potential landslide planes and generate debris that gets easily mobilized by heavy rainfall (McAdoo et al., 2018). Hence, a historical spatial distribution of landslides and landslide susceptibility map are fundamental prerequisites for landslide-risk management in Nepal.

To assess landslide susceptibility, a spatially consistent landslide inventory is needed. A landslide inventory shows the locations where landslides have occurred in the past with additional attribute information. The past casual conditions under which those landslides happened are analysed to predict the future landslide locations. Nepal does not have a national landslide inventory, and consequently, sustainable spatial planning is difficult to perform. The country has suffered many landslide disasters in the past that could have been avoided if proper spatial planning was in practice. This situation highlights an urgent need for a national landslides inventory and a national landslides susceptibility map. A landslide susceptibility map subdivides the terrain into zones with differing likelihoods of landslide occurrences (Ohlmacher and Davis, 2003). Evaluating the landslide susceptibility of mountain regions is generally done using machine learning (Chen and Chen, 2021; Mandal et al., 2021). The primary input in the machine learning model includes past occurrence locations of landslides as points or polygons (Dou et al., 2020) and a set of static and dynamic conditioning factor maps, e.g., slope, geology, land use, rainfall proxies (Sarkar and Kanungo, 2004). The model then learns from past landslide locations and their respective conditioning factor values and outputs a susceptibility score for every map pixel. The susceptibility score is the spatial probability of a landslide occurring in that raster pixel. Machine learning models are suitable for susceptibility assessment because of the following two reasons: they can express the highly nonlinear relationship between the landslide conditioning factors and they do not require the landslide conditioning factors to be normally distributed (Canoglu et al., 2019). These characteristics make them suitable in assessing landslide susceptibility in large/regional areas. Various machine learning approaches have been developed and tested, e.g., logistic regression, support vector machines, random forest, artificial neural networks and convolutional neural networks. Random forest is a tree-based machine learning model that provides reliable performance in landslide susceptibility assessment and has been widely applied (Merghadi et al., 2020).

Landslides impact critical infrastructure (CI) in mountain areas, thus disrupting property and economy. CI is fundamental to a functional society designed to ensure essential supplies and services to the population, such as transportation, energy, telecommunication, waste, water, health and education (Nirandjan et al., 2022). Nirandjan et al. (2022) generated a globally harmonized dataset of critical infrastructure from OpenStreetMap (OSM) comprising 39 types of CI that were clustered into a single index called Critical Infrastructure Spatial Index (CISI). CISI expresses the spatial intensity of CI. Building resilient infrastructure is an explicit part of Goal 9 of the Sustainable

Development Goals (SDG 2015). It aims to reduce the risks of natural hazards and climate change to society.

Despite disciplinary advances in characterizing extreme rainfall, mapping landslide susceptibility and scoring intensity of critical infrastructure, their inter-linking to understanding areas that need to be prioritized for climate-resilient infrastructure investment is poorly investigated. Intersection of CISI with landslide susceptibility provides a smart decision information on planning infrastructural budget allocations for design, operation and maintenance of critical infrastructure.

This study proposes a framework to map priority investment regions for climate-resilient critical infrastructure in mountain areas. The framework has three components: (1) extreme rainfall indices definition, (2) mapping extreme rainfall triggered landslide susceptibility annually using machine learning and (3) overlaying landslide susceptibility variation on critical infrastructure intensity index. The workflow yields climatically sensitive and economically important areas to mobilize limited resources to implement climate-resilient slope infrastructure investments and development policies on a national scale. The mapped hotspots are important for governments, conservation planners and insurers for decision-making.

2. Study Area

The study area is Nepal, a land-locked country containing one-third of the Himalayan mountain ranges and encompassing an area of 147,516 km^2, stretching from 26°22' to 30° 27' N and from 80°04' to 88°12' E. The elevation range varies from 60 m in the South to 8849 m in the North within a horizontal distance of less than 200 km. The country has a steep slope topography. Tectonic forces push the Indian subcontinent against STDS forming high mountains in the North and flat plains in the South. The area is tectonically active and the earthquake in 2015 caused over 20,000 landslides in central part of Nepal (Gnyawali and Adhikari, 2017).

Primarily, two weather systems influence Nepal’s climate: the summer monsoon circulation (June to September) and the westerly circulation (November to May). During the summer monsoon, Nepal receives roughly 80% of its yearly precipitation (Shrestha, 2000). Figure 1 shows the climate classification map of Nepal representing eight climatic zones based on modified Köppen–Geiger classification (Karki et al., 2016).

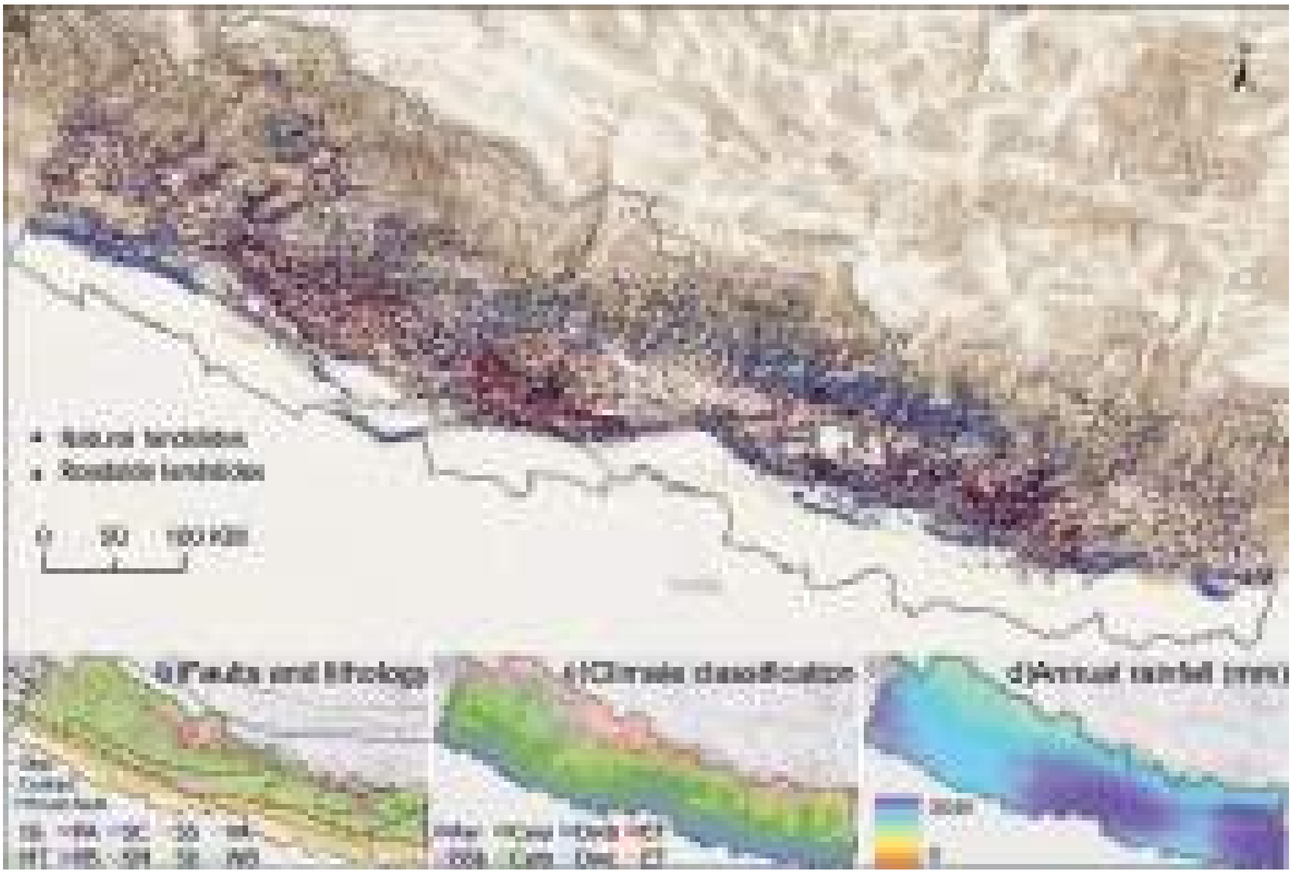

Figure 1. Regional setting of Nepal with landslides, lithology, climate and rainfall: (a) Natural landslides and landslides on roadside slopes, (b) Lithology (GLiM), (c) Climate classification by Karki et al. (2016): Aw (Tropical Savannah), BSk (Arid Cold Steppe), Cwa (Temperate climate with dry winter and hot summer), Cwb (Temperate climate with dry winter and warm summer), Dwb (Cold climate with dry winter and warm summer), Dwc (Cold climate with dry winter and cold summer), EF (Polar Frot), and ET (Polar Tundra)

3. Research Problem

To find the critical infrastructure on the landslide-prone zone, we have identified four research gaps. First, the historical data of landslides in Nepal are not available at a spatially consistent stage. Second, a national scale landslide susceptibility map is not available. Third, landslide susceptibility mapping approaches do not consider climate change impact on the trigger. And lastly, no standard exists for infrastructure financing for risk mitigation or reduction.

Although there are several landslide datasets (Gnyawali et al., 2020; Kayastha et al., 2013; McAdoo et al., 2018; Thapa and Adhikari, 2019), spatially consistent dataset is not available. The reasons are (1) no high-resolution satellite imagery is available, (2) there are too many landslides to map manually or in the field, (3) the increasing trend of the number of landslides every year and (4) no landslide reporting mechanism exists. For many purposes, some site/basin-specific landslide data is available. However, these data are not spatially consistent and not available on a year-by-year basis. Every year, the spatial distribution of landslides changes, and the spatial distribution cannot be assessed by the overall landslide data. The annual rainfall can be used to analyse yearly landslides. Rainfall increases the risk of landslides. A year-to-year comparison is not feasible and difficult.

As the nation-wide landslide inventory is not available, high-resolution landslide susceptibility assessment is not possible. Landslide susceptibility assessments are developed and applied at the basin and highway catchment levels (Meena et al., 2019; Thapa and Adhikari, 2019). However, a national scale susceptibility is not available at high resolution and cannot capture the local terrain characteristics. It creates difficulties for national infrastructure planning, landslide mitigation planning, energy, transportation, health and education that are not planned in accordance with their requirements.

Another gap in the landslide susceptibility mapping is that climate change is not considered in model development. Because the triggering and cause of landslides vary depending on rainfall, climate change can have an impact on the landslides. Climate change scenarios and models that may depict the effects of climate change should be taken into consideration to find areas where climate change has an effect. The different rainfall pattern with varying magnitude and intensity makes the landslide triggering a dynamic phenomenon, which cannot be understood in a static approach. Such variations in susceptibility cannot be understood if we disregard climate change and the future efforts to protect the climate can be unsuccessful.

Lastly, it is important to develop financing strategies for mitigation of landslide-prone zones. However, this is not possible without understanding where infrastructures are present in the landslide-prone areas. Locating all infrastructures in the landslide susceptibility map is a challenging task because all infrastructures are not mapped and details are not available publicly. The methodology that accounts for all kinds of infrastructure for landslide susceptibility classes is not yet available. Frameworks that can integrate both infrastructure and landslide susceptibility can provide both information about where a landslide can trigger and where our infrastructure is. This will allow developing infrastructure financing strategies for landslide-risk mitigation.

4. Aim, Objectives and Scope of the Research Study

This study's main objective is to create a landslide susceptibility map of Nepal by preparing a landslide inventory and applying the state-of-the-art machine learning to generate the landslide susceptibility zonation map at a national scale. This work involves the following tasks:

- Digitizing and classifying all landslide locations in Nepal detectable in satellite images provided by Google Earth. Planet labs satellite imagery may also be used to locate landslides.
- Prepare a national scale landslide susceptibility map of Nepal by applying state-of-the-art machine learning methods in the Google Earth Engine (a cloud computing platform).
- Develop integrated index based on all critical infrastructures and analysed with landslide susceptible zones to find infrastructure on the landslide-prone areas.

The resulting map classifies all areas in Nepal into zones with different likelihoods that landslides may occur, without a quantitative indication of the landslide frequency and the overlay analysis with critical infrastructure. The product will be made available for public use through an interactive web-based GIS and download portal.

5. Methodology

The proposed extreme rainfall-controlled landslide susceptibility variation framework mainly consists of five parts (Steps 1 to 4 are annual):

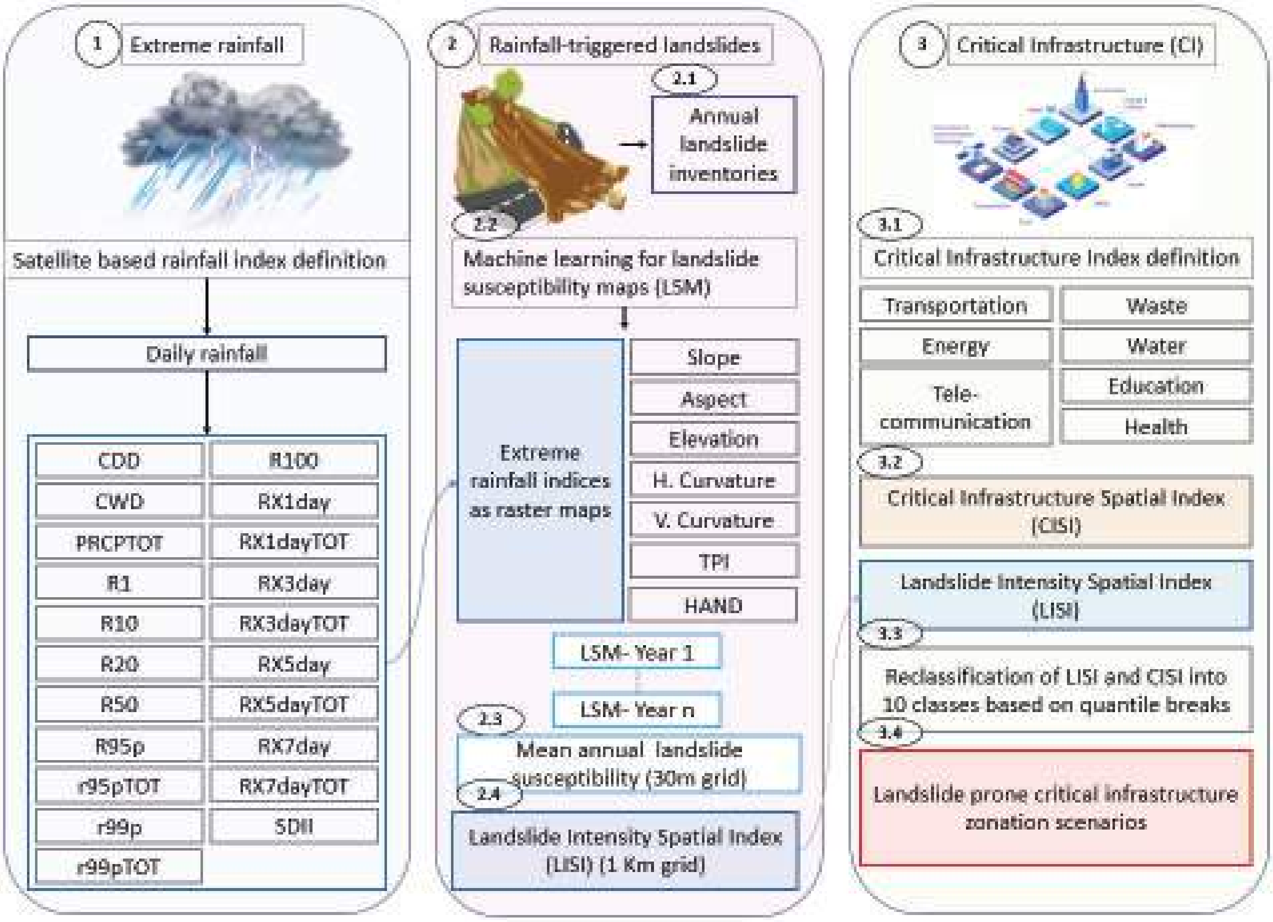

Figure 2. Framework of the proposed approach

Note: LSM 1-5 represent annual landslide susceptibility maps of the corresponding year.

Step 1: Data preparation1: landslide scarp point mapping in satellite imagery and eliminating landslides on roadside slopes from the inventory.

Step 2: Data preparation2: preparation of topographic data and annual extreme rainfall indices from satellite precipitation.

Step 3: Data preparation3: downscaling critical infrastructure spatial index from OpenSource maps.

Step 4: Analysis 1: generating landslide susceptibility maps using data from Steps 1–3 by training random forest model on annual basis.

Step 5: Analysis 2: computing coefficient of variation of annual landslide susceptibility scores on high mean susceptibility areas.

Step 6: Analysis 3: overlaying extreme rainfall modulated landslide susceptibility variation raster on critical infrastructure spatial index.

Figure 2 represents the framework of the proposed extreme rainfall-controlled landslide susceptibility variation. Each step is described in detail in the following subsections. In brief, our methodology consists of three steps: (1) Preparation of localized rainfall extreme indices: in this step, we use IMERG database to categorize the daily rainfall indexes into 21 parameters; (2) Landslide susceptibility mapping: in this step, landslide inventories were produced using PlanetScope satellite imagery basemaps and the landslide susceptibility was computed in Google Earth Engine; (3) Overlaying LSM into CISI: in this step we overlay the extreme rainfall modulated landslide susceptibility variation raster on critical infrastructure spatial index.

5.1 Landslide inventories

Annual landslide inventories were created by mapping landslide scrap points on PlanetScope satellite basemaps (~4.7 m resolution) from October to November between 2016 and 2020. The landslides mapped in the 2016 basemap contained all discernable landslides that occurred before 2016 on the basemap. But the landslides mapped in years 2017–20 contained only landslides that occurred between November and September. Since the majority of the landslides in Nepal occur during the annual monsoon season (June to September), these landslides correspond to monsoon rainfall-triggered landslides in that year. The landslides were visually segregated into natural landslides triggered by rainfall and those present on roadside slopes (anthropogenically increased susceptibility). Furthermore, earthquake-triggered landslides were not marked during digitization, by overlaying previously published earthquake-triggered landslides inventory from Gnyawali and Adhikari (2017) and Roback et al. (2018). Earthquake- triggered landslides and landslides on roadside slopes were eliminated from susceptibility modelling and only rainfall-triggered landslides used.

5.2 Terrain derivatives

The factors derived from terrain are very important because these are causative factors for landslides. Such causative factors do not trigger the landslide but set up the environment where a potential triggering factor can initiate the landslide. The triggering factor can be rainfall, earthquake, precipitation runoff, wildfires, etc. The machine learning model uses these parameters and classifies them in such a way that the areas with landslides and non-landslides can be classified. The machine learning model can understand linear and nonlinear patterns between classes and the landslide event. The class where landslides are more frequent is considered a landslide susceptible area. All the parameters are prepared at a 30 m spatial scale. All the parameters are developed within Google Earth Engine. The details about each terrain attribute is provided in Table 1 and shown in Figure 3.

Table 1. Terrain derivatives used in the model

Attribute	Description	Units
Elevation	Height of terrain above sea level	meter
Slope	Slope gradient	degree
Aspect	Compass direction	degree
Horizontal curvature	Curvature tangent to the contour line	meter
Vertical curvature	Curvature tangent to the slope line	meter
HAND	Height above nearest drainage	meter
TPI	Topographic position Index	dimensionless

5.3 Localized rainfall extreme indices

Extreme rainfall is one of the main landslide triggering factors. Landslide susceptibility assessment without rainfall does not account for the trigger scenario. It is extremely challenging to identify the intensity and magnitude of rainfall causing the landslide trigger. Therefore, it is necessary to use different indices that represent magnitude and intensity. We developed 21 different rainfall indices that can capture the intensity and magnitude. The following are the different parameters used to define rainfall indexes in the study. These data are developed from IMERG precipitation measurement. The name, definitions and units of the symbols in the figure are described in Table 2.

Table 2. Extreme and localized rainfall describing indices used in the model

S. No.	Symbol	Name	Definitions	Units
1	CDD	Consecutive dry days	Maximum number of consecutive days with PRCP <1 mm	days
2	CWD	Consecutive wet days	Maximum number of consecutive days with PRCP ≥ 1 mm	days
3	PRCPTOT	Annual total wet day precipitation	Annual total precipitation in wet days (PRCP ≥ 1 mm)	mm
4	R1	Number of wet days	Annual count of days when PRCP1 ≥ 1 mm	days
5	R10	Number of slightly heavy precipitation days	Annual count of days when PRCP1 ≥ 10 mm	days
6	R20	Number of heavy precipitation days	Annual count of days when PRCP1 ≥ 20 mm	days
7	R50	Number of very heavy precipitation days	Annual count of days when PRCP1 ≥ 50 mm	days
8	r95p	Total annual precipitation from heavy precipitation days	Annual total precipitation in wet days (PRCP ≥ 95 percentile)	mm

S. No.	Symbol	Name	Definitions	Units
9	r95pTOT	Contribution from heavy precipitation days	Ratio of r95p with PRCPTOT	%
10	r99p	Total annual precipitation from very heavy precipitation days	Annual total precipitation in wet days (PRCP ≥ 99 percentile)	mm
11	r99pTOT	Contribution from very heavy precipitation days	Ratio of r99p with PRCPTOT	%
12	R100	Number of extremely heavy precipitation days	Annual count of days when PRCP1 ≥ 100 mm	days
13	RX1day	Max 1-day precipitation	Yearly maximum 1-day precipitation	mm
14	RX1dayTOT	Contribution from max 1-day precipitation	Ratio of RX1day with PRCPTOT	%
15	RX3day	Max consecutive 3-day precipitation	Yearly maximum consecutive 3-day precipitation	mm
16	RX3dayTOT	Contribution from max 3-day precipitation	Ratio of RX3day with PRCPTOT	%
17	RX5day	Max consecutive 5-day precipitation	Yearly maximum consecutive 5-day precipitation	mm
18	RX5dayTOT	Contribution from max 5-day precipitation	Ratio of RX5day with PRCPTOT	%
19	RX7day	Max consecutive 7-day precipitation	Yearly maximum consecutive 7-day precipitation	mm
20	RX7dayTOT	Contribution from max 7-day precipitation	Ratio of RX7day with PRCPTOT	%
21	SDII	Simple daily intensity index	Average precipitation in wet days (PRCPTOT/R1)	mm/day

5.4 Infrastructure

The intensity of the presence of different types of critical infrastructure at a particular grid is defined using the critical infrastructure spatial index (CISI), as proposed by Nirandjan et al., (2022). The CISI incorporates seven major critical infrastructures: transportation, energy, water, waste, telecommunication, education and health based on vector layers from Open Street Maps (https://www.openstreetmap.org/). The CISI ranges from 0 to 1 scale, where 0 means no critical infrastructure is present and 1 means highest amount of critical infrastructure are present in the area. For this research, CISI was developed at spatial scale of 1 km and reclassified into 10 classes based on quantile breaks.

The process for obtaining CISI is summarized in the following four steps: (1) **pre-processing Open Street Map (OSM) data**: disaggregate the global unprocessed OSM database into nodes, way and polygon to create an individual file for Nepal; (2) **extraction**: extract all the infrastructure from the

OSM dataset. These infrastructures are represented by seven major CI systems that are further classified into subsystem and infrastructure types; (3) **rasterization**: develop consistent rasterized dataset containing information on the amount of CI into the grid of 1 km × 1 km. Overlay all individual CI with each grid cell. The amount of infrastructure associated with unique CI is denoted as number; (4) **composition of CISI**: these numbers are used to calculate the index from 0 to 1 to express the spatial intensity of CI. In order to obtain the value of CISI, the important scoring is conducted relatively in four levels: asset, sub-system, system and infrastructure levels. For example in the waste critical infrastructure, waste is a system, where the subsystems are solid waste and water waste; and for solid waste, the assets are landfill and waste transfer station. The asset, sub-system and system make a critical infrastructure. The presence or absence of the assets of different types are normalized at each of the four levels by yielding the value of CISI ranging between 0 and 1 in each 1×1 km grid. The detailed methodology for the preparation of CISI is explained in Nirandjan et al. (2022).

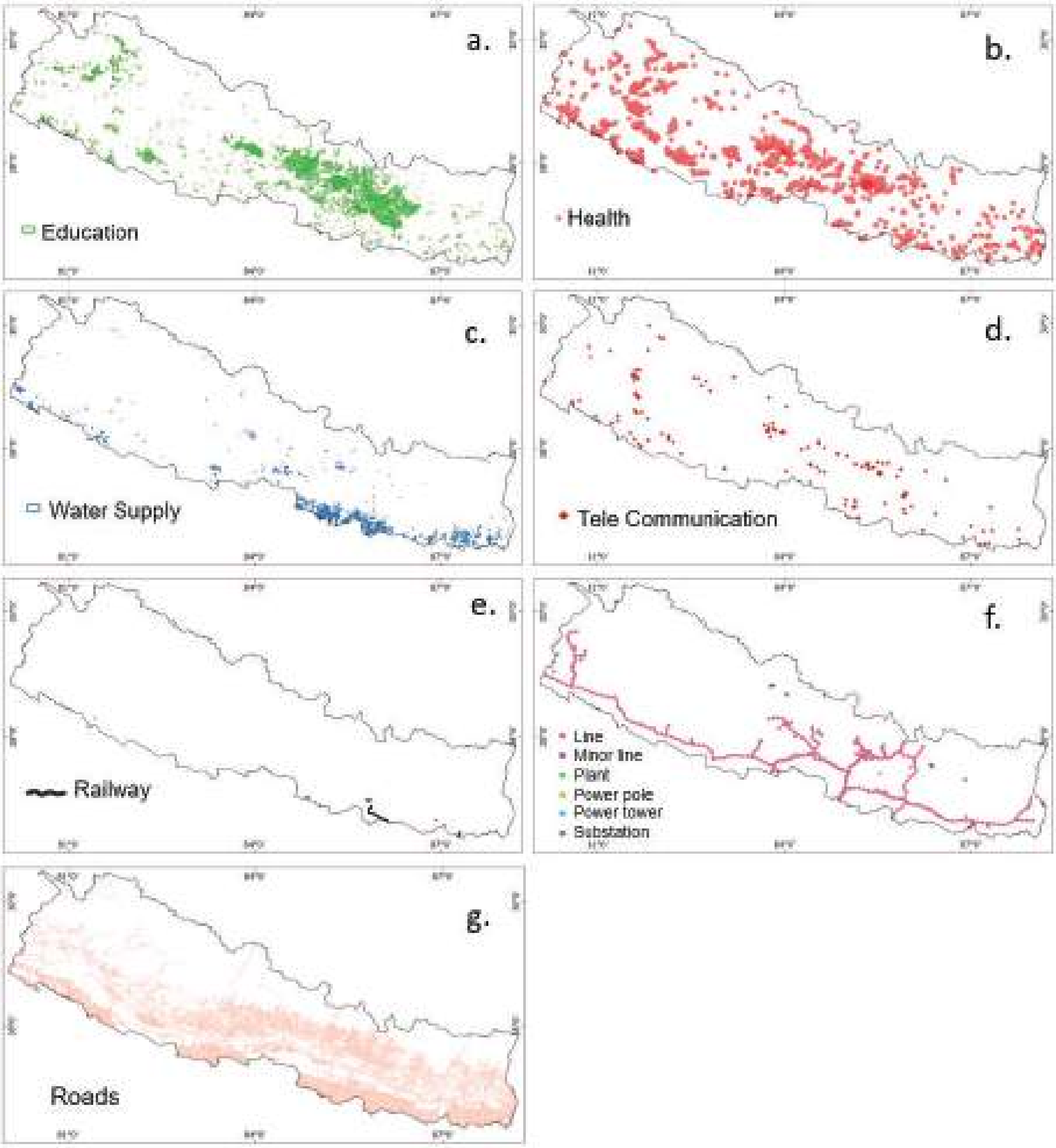

Figure 3. Seven different critical Infrastructures from Open Street Maps used to develop CISI: (a) Education, (b) Health, (c) Water Supply, (d) Telecommunication, (e) Railway, (f) Power, (g) Roads. The infrastructure locations were converted into one raster image representing all infrastructures. The CISI index ranges from 1 to 10. The CISI index will be used to overlay analysis with landslide susceptibility maps to find the critical infrastructures prone to landslides.

5.5 Landslide susceptibility modelling

Susceptibility modelling necessitates the input of two types of information: landslide locations and environment variables. Landslide location was determined at the centroid point on landslide scarps, and corresponding data from environmental variables were extracted. The data was then divided into two parts by random sampling: 70% for training and 30% for testing the machine learning model. All datasets were prepared on a 30 m × 30 m scale.

The random forest machine-learning algorithm was used in this study. The Random Forest classifiers build several de-correlated bootstrapped random decision trees and aggregate them to categorize a dataset using the mode of predictions from all decision trees (Breiman, 2001). The random forest classifiers available in GEE allows six hyperparameters (Teluguntla et al., 2018): (1) the number of decision trees, (2) the number of variables for each split in a tree, (3) the minimum leaf population, (4) bagged fraction of the input variables per decision tree, (5) out-of-bag mode and (6) random seed variable for decision tree construction. After model training, random forest implementation in GEE provides: (1) prediction model; (2) relative variable importance and (3) out-of-bag error. The random forest model is available in GEE as "*ee.Classifier.smileRandomForest (numberOfTrees, variablesPerSplit, minLeafPopulation, bagFraction, maxNodes, seed*".

After training the model, validation is done using two metrics: out of the bag error and area under the receiver characteristics curve (AUC-ROC). The out of the bag error is used as a primary testing score for training the random forest model and creating the ensembles of the trees and hyperparameter tuning. Of the available data, 30% was not used for training but for testing. This testing dataset (30%) was used for AUC-ROC validation. The AUC-ROC is a well-accepted technique for validation of the individual hazard and multi-hazard susceptibility maps (Pourghasemi et al., 2020; Thi Ngo et al., 2021). The AUC-ROC is estimated based on four parameters: true negative (TN), false positive (FP), false negative (FN) and true positive (TP), as given in Table 3.

Table 3. AUC-ROC estimated based on four parameters

Actual/Predicted	Hazard	No hazard
Hazard	TP	FN
No hazard	FP	TN

True Positive Rate (TPR) =TP/(TP + FN)

False Positive Rate (FPR) = FP/(TN + FP)

True Negative Rate (TNR) = TN/(FP + TN)

The performance indices TPR and FPR are used for generating AUC-ROC curves. The area under the curve is then calculated by the trapezoidal approximation method (Ban et al., 2011) and used as the overall model accuracy.

5.6 Annual susceptibility variation assessment

Since all the susceptibility maps are produced by the same model and have similar validation scores, we compared these different yearly maps to understand where the landslide susceptibility pattern is changing according to different years. Due to rainfall patterns, a dynamic factor, there were areas where the landslide susceptibility changed. Such areas are vulnerable to climate change and may require a different risk reduction approach. We identified these areas as rainfall modulated by landslide susceptibility. The variation assessment was done using coefficients of variation in the GIS environment. The overlay analysis of extreme rainfall modulated landslide susceptibility and CISI were done to understand critical Infrastructures prone to landslides.

6. Results and Discussion

This section presents descriptions of annual landslide inventories, annual landslide susceptibility maps, variable importance and validation of susceptibility maps, landslide susceptibility variation and overlay analysis with critical infrastructure.

6.1 Annual landslide inventories

Table 4. Total number of landslides inventories in each year from 2016 to 2020

Year	Natural Landslides	Landslides on Roadside Slopes	Total	Remarks
2016	43,009	15,166	58,175	All landslide locations seen on 2016 satellite images are marked.
2017	8,267	13,980	22,247	
2018	2,579	9,916	12,495	
2019	2,142	6,440	8,582	
2020	2,316	4,086	6,402	

Table 4 shows the total number of landslides inventories in each year from 2016 to 2020. The total natural landslide in 2016 was 58,175 with 43,009 landslides being natural landslides and 15,166 landslides being on the road sides. As all the landslides locations seen on 2016 satellite images are marked, it also contains landslides before 2016, so the total number of landslides is greater in 2016 than in other years. In 2017, the total of 22,247 landslides were seen with 8267 natural landslides and 13,980 landslides on roadside slopes. Similarly, there was a total of 12,495 landslides in 2018 with 2579 natural landslides and 9916 landslides on roadside slopes. A total of 8582 landslides were seen in 2019 with 2142 natural landslides and 6440 landslides on roadside slopes. The year 2020 witnessed the least number of total landslides (6402) with 2316 natural landslides and 4086 landslides on roadside slopes.

The trend of total landslides is seen to be decreasing each year with the highest number of landslides in 2017 to lowest in 2020 (excluding 2016). Similarly, landslides on roadside slopes are more dominant than natural landslides. From these four years, the mean of total landslide occurred in the year can be calculated as 1241 with the standard deviation of 7012.

6.2 Annual landslide susceptibility maps

Figure 4 shows the visual representation of variation in landslide susceptibility through four pockets from East to West. The value of landslide susceptibility ranges from one to hundred, where one means least susceptible and hundred means the most landslide susceptible area. Landslide susceptibility varies in different parts of the county in different years. Western pocket (P1) was most active in 2017 than in other years. The eastern pocket (P4) was active in 2017, 2018 and 2019 while in 2020 it was less susceptible. The central western pocket (P2) was active most of the year. While the central eastern pocket (P3) is less active every year. This concludes that central western is most susceptible among these four pockets and the eastmost and westmost pockets are the most varying.

We emphasize that landslide susceptibility, when combined with rainfall proxies, is dynamic and evolves year after year. The dynamic areas where susceptibility changes with rainfall may be substantially impacted by variations in rainfall magnitude and intensity in future.

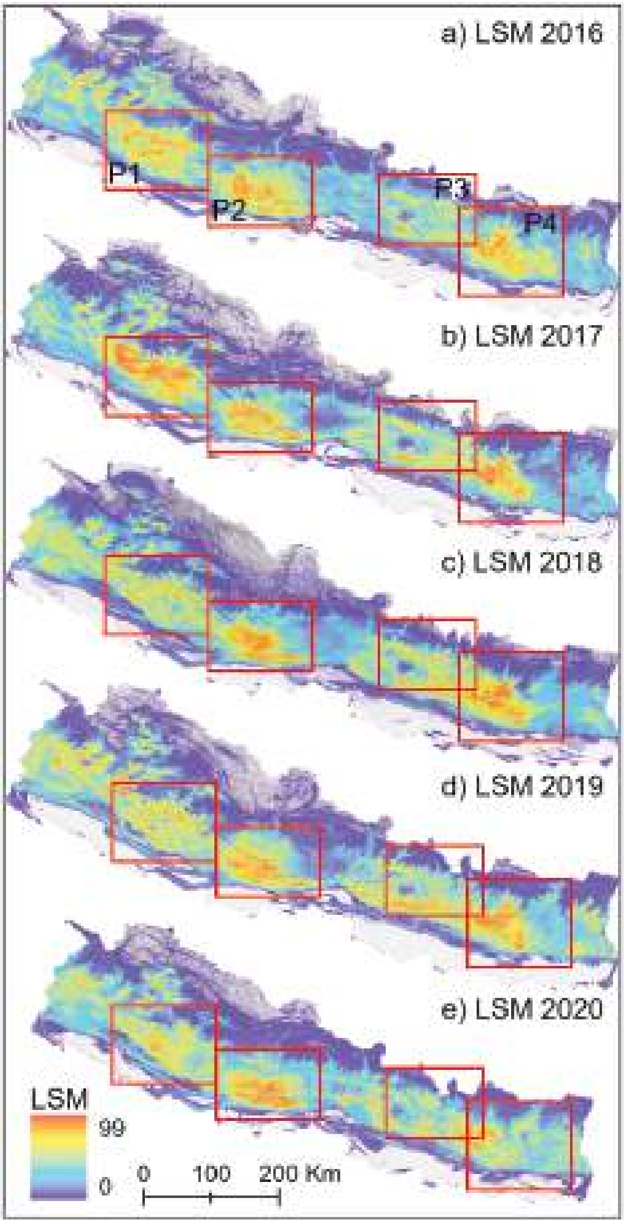

Figure 4. Landslide susceptibility variation over different years (2016–20)

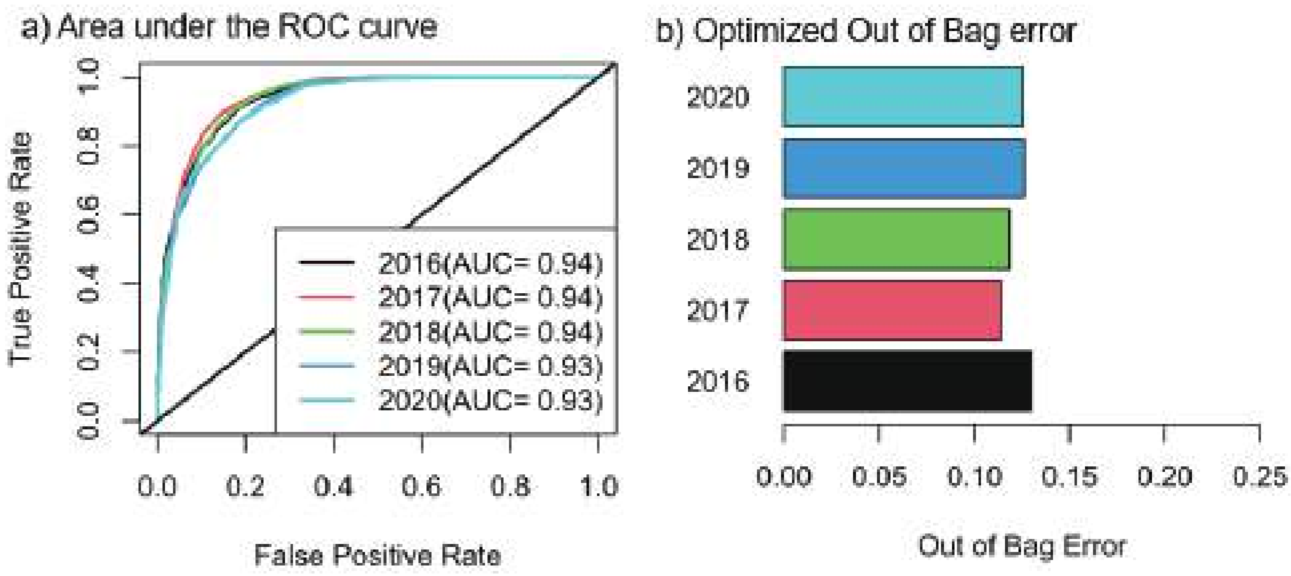

Figure 5. Validation plot for all landslide susceptibility models

The statistical validation of landslide susceptibility models were done using area under the curve and out of bag error. Both metrics achieved acceptable scores for all models. In addition to the good validation score, the values are consistent. The consistent values of validations represent that the model is robust and replicable. The out of bag error provides information about model training and the AUC provides information about model testing. The higher the value of AUC and lower out of bag error, the higher is the model accuracy. It demonstrates that the random forest model provided in Google Earth Engine is capable of modelling landslide susceptibility at regional scale.

6.3 Overlay analysis with CISI

Figure 6 shows (a) LISI is a landslide susceptibility map sampled at 1 km resolution to match the resolution of CISI with median LSM value in each 1×1 km grid. The raster is then reclassified into 10 classes (based on quantile Classification). b) CISI produced by superimposing all critical infrastructure on a scale of 1 to 10. c) Areas where both LISI and CISI are greater than 5, these are landslide-prone areas where critical infrastructure is present. Provinces 3 and 4 have a high presence of critical infrastructure and high landslide susceptibility, followed by Province 1. In Provinces 6 and 7, two major river corridors are critical. These are the locations where policymaking and infrastructure investors should focus on investing in climate-resilient infrastructure and slope land protection policies.

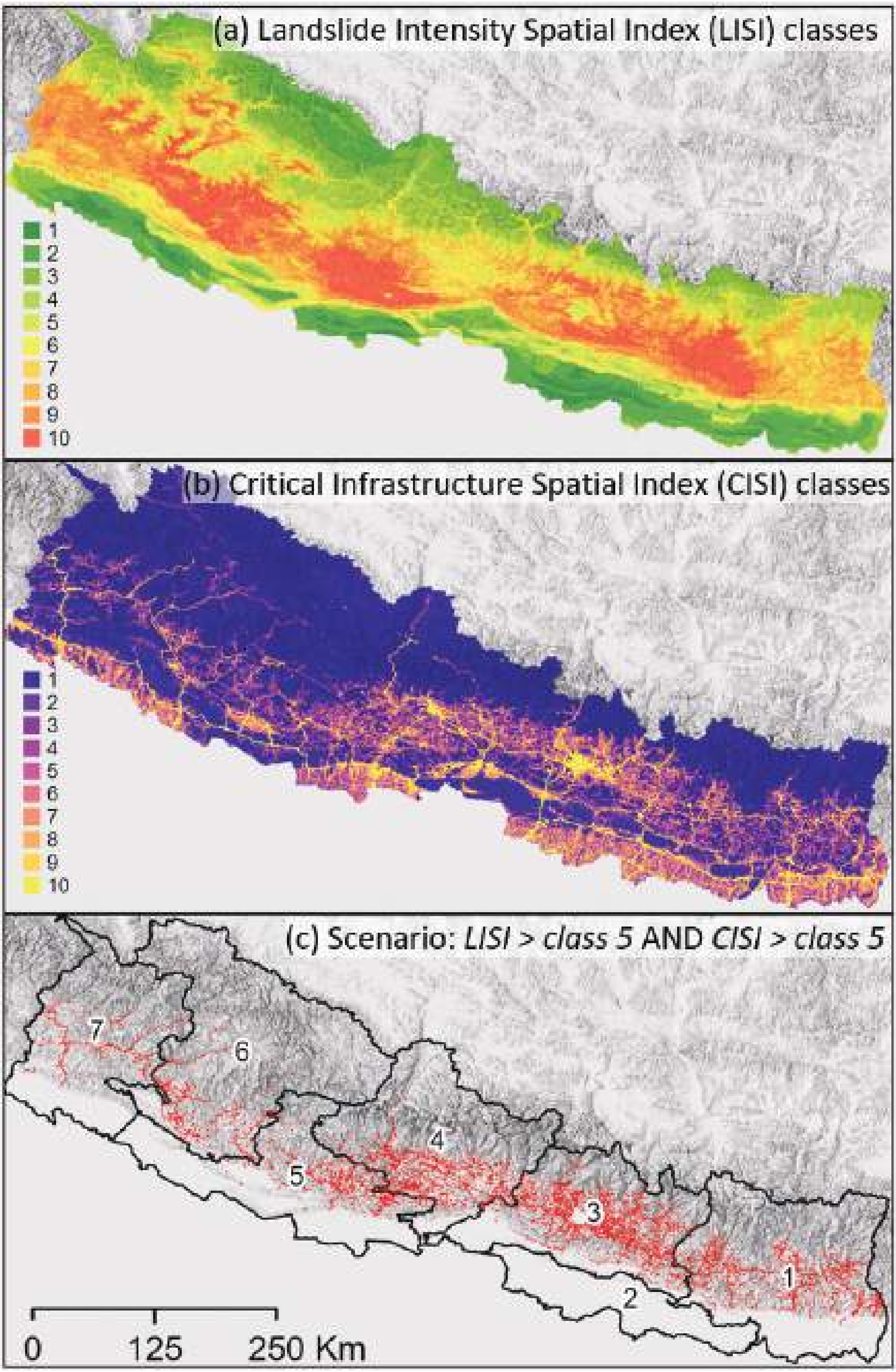

Figure 6. Landslide intensity spatial index overlaid on critical infrastructure spatial index classes

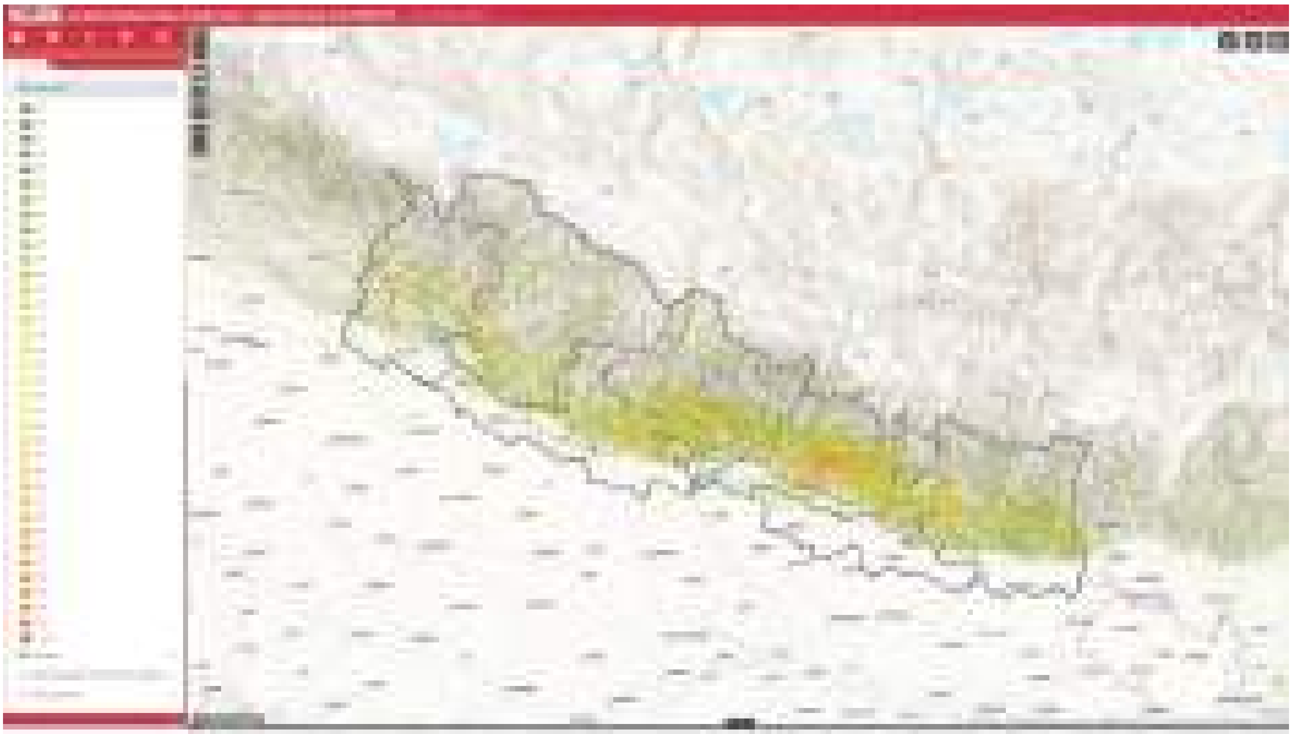

Figure 7. Screenshot of a web-application developed to disseminate the research output maps

7. Enablers and Barriers

The following are the enablers deduced from this study:

- Develop new research connections with weight: a fellowship in hand provided support to pursue challenging research with confidence
- Conference travel was accessible through supplemental funding
- Possible to hire students and young professionals during research and at peak hours
- Mentorship from the TEG member helped steer the research to more impactful outcomes

The following are the barriers deduced from this study:

- Delayed second instalment caused problems such as research assistants got financially demotivated and a planned workshop could not be conducted
- Global COVID-19 pandemic pushed the timeline by two months because some of the team members got infected or were taking care of family members

8. Key Takeaways from CDRI Fellowship Programme

The Fellowship enabled us to understand the bigger picture of disaster-resilient infrastructure. While our original research proposal was more inclined towards landslide exposure, the fellowship experience helped us steer it towards a practically implementable framework in the financing of resilience in mountain infrastructure, from landslide impact. With the CDRI Fellowship, we now have a better understanding of practical ways of researching for disaster-resilient infrastructure, better contacts to approach for future collaborations and a platform to showcase our research at a global stage.

The Community of Practice was also helpful in understanding each other's research more closely. However, we personally think that in-person meeting with the fellows could have strengthened collaborations and taken effective communication to its next level than at present.

9. Conclusion and Way Forward

The research proposes a framework to identify hotspots of critical infrastructure in landslide-prone areas at the national scale. The framework contains three modules: (i) definition of extreme rainfall indices as landslide triggers and mapping of landslides at national scale, (ii) application of machine learning to map landslide susceptibility in multiple years, (iii) classification and overlaying of landslide susceptibility map on a critical infrastructure spatial intensity map to generate multiple scenarios for investment prioritization in critical infrastructure. The final map identifies important slope areas on the national scale where relatively more critical infrastructure is located and as well as more landslides occur. The map aids in policymaking and decision-making relevant to national-scale climate resilient slope infrastructure financing and planning.

In addition to this, the research also yields two new maps of practical importance in Nepal: (1) a spatially accurate national landslide database of Nepal of landslide occurring from 2015 to 2020, (2) a database of 21 well-defined rainfall proxy maps showing extreme and localized rainfall characteristics in different areas in the same time frame and (3) a national-scale landslide susceptibility map of rainfall triggered landslides in Nepal.

The immediate way forward includes dissemination of the research framework as a journal publication, and the maps as online interactive layers freely accessible to the public and stakeholders. Then, we want to upscale/test the framework and the online system in other mountain countries for landslide management.

The research data is further being utilized in other researches including (1) estimating the resilience of mountain road networks from landslide impacts and identifying road sections needing alternative routing in disaster scenarios and (2) identifying proper land-use practices to manage landslides using nature-based solutions. The long-term vision is to make a national- level online synthesis system for disaster-risk resilience for Nepal. Once the platform is launched, it will set a baseline and further research areas will be done to keep improving it.

This project is part of a broader project theme devoted to designing and developing national-scale landslide management and decision support systems for low- and middle-income nations.

References

1. Ban, A., Coroianu, L., & Grzegorzewski, P. (2011). Trapezoidal approximation and aggregation. *Fuzzy Sets and Systems. An International Journal in Information Science and Engineering*, *177*(1), 45–59.
2. Breiman, L. (2001). Random Forests. *Machine Learning*, *45*(1), 5–32.
3. Canoglu, M. C., Aksoy, H., & Ercanoglu, M. (2019). Integrated approach for determining spatio-temporal variations in the hydrodynamic factors as a contributing parameter in landslide susceptibility assessments. *Bulletin of Engineering Geology and the Environment*, *78*(5), 3159–3174.
4. Chalise, D., Kumar, L., & Kristiansen, P. (2019). Land Degradation by Soil Erosion in Nepal: A Review. *Soil Systems*, *3*(1), 12.
5. Chen, X., & Chen, W. (2021). GIS-based landslide susceptibility assessment using optimized hybrid machine learning methods. *Catena*, *196*, 104833.
6. Dou, J., Yunus, A. P., Merghadi, A., Shirzadi, A., Nguyen, H., Hussain, Y., Avtar, R., Chen, Y., Pham, B. T., & Yamagishi, H. (2020). Different sampling strategies for predicting landslide susceptibilities are deemed less consequential with deep learning. *The Science of the Total Environment*, *720*, 137320.
7. Gnyawali, K. R., & Adhikari, B. R. (2017). Spatial relations of earthquake induced landslides triggered by 2015 gorkha earthquake MW = 7.8. In *Advancing Culture of Living with Landslides* (pp. 85–93). Springer International Publishing.
8. Gnyawali, K. R., Zhang, Y., Wang, G., Miao, L., Pradhan, A. M. S., Adhikari, B. R., & Xiao, L. (2020). Mapping the susceptibility of rainfall and earthquake triggered landslides along China–Nepal highways. *Bulletin of Engineering Geology and the Environment*, *79*(2), 587–601.
9. Karki, R., Talchabhadel, R., Aalto, J., & Baidya, S. K. (2016). New climatic classification of Nepal. *Theoretical and Applied Climatology*, *125*(3), 799–808.
10. Kayastha, P., Dhital, M. R., & De Smedt, F. (2013). Application of the analytical hierarchy process (AHP) for landslide susceptibility mapping: A case study from the Tinau watershed, west Nepal. *Computers & Geosciences*, *52*, 398–408.
11. Mandal, K., Saha, S., & Mandal, S. (2021). Applying deep learning and benchmark machine learning algorithms for landslide susceptibility modelling in Rorachu river basin of Sikkim Himalaya, India. *Geoscience Frontiers*, *12*(5), 101203.
12. McAdoo, B. G., Quak, M., Gnyawali, K. R., Adhikari, B. R., Devkota, S., Rajbhandari, P. L., & Sudmeier-Rieux, K. (2018). Roads and landslides in Nepal: how development affects environmental risk. *Natural Hazards and Earth System Sciences*, *18*(12), 3203–3210.
13. Meena, S. R., Ghorbanzadeh, O., & Blaschke, T. (2019). A Comparative Study of Statistics-Based Landslide Susceptibility Models: A Case Study of the Region Affected by the Gorkha Earthquake in Nepal. *ISPRS International Journal of Geo-Information*, *8*(2), 94.
14. Merghadi, A., Yunus, A. P., Dou, J., Whiteley, J., ThaiPham, B., Bui, D. T., Avtar, R., & Abderrahmane, B. (2020). Machine learning methods for landslide susceptibility studies: A compara-

tive overview of algorithm performance. *Earth-Science Reviews*, *207*, 103225.

15. Nirandjan, S., Koks, E. E., Ward, P. J., & Aerts, J. C. J. H. (2022). A spatially-explicit harmonized global dataset of critical infrastructure. *Scientific Data*, *9*(1), 150.
16. Ohlmacher, G. C., & Davis, J. C. (2003). Using multiple logistic regression and GIS technology to predict landslide hazard in northeast Kansas, USA. *Engineering Geology*, *69*(3), 331–343.
17. Pourghasemi, H. R., Gayen, A., Edalat, M., Zarafshar, M., & Tiefenbacher, J. P. (2020). Is multi-hazard mapping effective in assessing natural hazards and integrated watershed management? *Geoscience Frontiers*, *11*(4), 1203–1217.
18. Rieger, K. (2021). Multi-hazards, displaced people's vulnerability and resettlement: Post-earthquake experiences from Rasuwa district in Nepal and their connections to policy loopholes and reconstruction practices. *Progress in Disaster Science*, *11*, 100187.
19. Roback, K., Clark, M. K., West, A. J., Zekkos, D., Li, G., Gallen, S. F., Chamlagain, D., & Godt, J. W. (2018). The size, distribution, and mobility of landslides caused by the 2015 Mw7.8 Gorkha earthquake, Nepal. *Geomorphology* , *301*, 121–138.
20. Sarkar, S., & Kanungo, D. P. (2004). An Integrated Approach for Landslide Susceptibility Mapping Using Remote Sensing and GIS. *Photogrammetric Engineering & Remote Sensing*, *70*(5), 617–625.
21. Shrestha, M. L. (2000). Interannual variation of summer monsoon rainfall over Nepal and its relation to Southern Oscillation Index. *Meteorology and Atmospheric Physics*, *75*(1), 21–28.
22. Teluguntla, P., Thenkabail, P. S., Oliphant, A., Xiong, J., Gumma, M. K., Congalton, R. G., Yadav, K., & Huete, A. (2018). A 30-m landsat-derived cropland extent product of Australia and China using random forest machine learning algorithm on Google Earth Engine cloud computing platform. *ISPRS Journal of Photogrammetry and Remote Sensing: Official Publication of the International Society for Photogrammetry and Remote Sensing* , *144*, 325–340.
23. Thapa, P. S., & Adhikari, B. R. (2019). Development of community-based landslide early warning system in the earthquake-affected areas of Nepal Himalaya. *Journal of Mountain Science*, *16*(12), 2701–2713.
24. Thi Ngo, P. T., Panahi, M., Khosravi, K., Ghorbanzadeh, O., Kariminejad, N., Cerda, A., & Lee, S. (2021). Evaluation of deep learning algorithms for national scale landslide susceptibility mapping of Iran. *Geoscience Frontiers*, *12*(2), 505–519.

Practices on Hilly Slopes of Bhutan – A Research Compliance and Recommendation for National Adaptation

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CDRI

Coalition for Disaster Resilient Infrastructure

Disclaimer:

We hereby declare that this research titled “Disaster Resilience Building Construction Practices on Hilly Slopes of Bhutan-A Research Compliance and Recommendation for National Adaptation” is an original work and we have not committed, to our knowledge, any academic dishonesty or resorted to plagiarism in writing this research report. All the sources of information and assistance received during the course of the study are duly acknowledged.

Abstract

Located in a seminally active Himalayan region and having adverse geographical and geological conditions, Bhutan is vulnerable to various hazards. Landslide is one of the most predominating hazards in the region and intensified due to developmental activities and rainfall and claiming lives, property and loss of infrastructure. Despite high risk to landslides, major urban development and expansion are taking place in the hilly regions of Bhutan. Bhutan's total usable land available for settlement is only 1% of the total land due to its steep mountains, snow cover areas and 60% forest and environment conservation policies as per the constitutional requirements.

Regulations are in place for buildings to have adequate safety against earthquake but no such provision for safety against landslides exists. Therefore, the research aims to provide adaptation and mitigation measures before and after building construction for a landslide disaster-resilient building construction practice on the hilly slopes of Bhutan.

The findings on the mitigation and the adaptation measures for sustainable hilly slope construction practices were shared and discussed with stakeholders contributing to the awareness and landslide risk reduction practices. It will also help various organizations in framing policies and guidelines.

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1. Introduction

Located in a seminally active Himalayan region and having adverse geographical and geological conditions, Bhutan is vulnerable to various hazards. Landslides are common in the region and one of the most predominating hazards intensified due to developmental activities and rainfall. Many lives are lost while property and infrastructure are damaged as a result of the landslides. Despite the high risk of landslides, the hilly regions of Bhutan are experiencing major urban development and expansion.

Bhutan's total usable land available for settlement is only 1% of the total land due to its steep mountains, snow cover areas and 60% forest and environment conservation policies as per the constitutional requirements. Modern developmental activities and rapid urbanization that promote socio-economic development are causing pressure in the new settlement areas (NHSPB, 2019). It is projected that urban density will increase from 37.8% in 2017 to 56.8% in 2047 (BUPN, 2020).

Regulations are in place for buildings to have adequate safety against earthquakes, but no similar provisions exist against landslides. Massive construction with improper site development works and cutting of slopes for wider area have made the region susceptible to landslides. Heavy precipitation during monsoon is a major triggering factor for landslides. Rural Construction Rules-2013, Bhutan Building Regulation-2018 and National Human Settlement Policy of Bhutan-2019 do not have any provisions to make buildings constructed on hilly slopes of Bhutan resilient to landslides. Thus, better building construction practices on hilly slopes of Bhutan entail a major study to tackle the recurrent hazard that costs lives and loss of properties during monsoon. Rainfall and suction of soil induces slope instability (Yue L. J. et al, 2019). Hence, proper mitigation and adaptation measures to manage the precipitation and runoff before and after construction of buildings along the slopes, considering geological and structural factors will provide sustainable development and resilient building construction practices, which needs to be regulated through research and policies.

Research Problem

The Guidelines for Planning and Development of Human Settlements in Urban and Rural Areas of Bhutan to Minimise Environmental Impacts (MoWHS, 2013) focuses on the adverse effect of rapid urbanization on the environment and the people's way of life. The guidelines have been developed to provide a framework for human settlement in both urban and rural areas by mainstreaming environment, climate change and poverty and to promote eco-friendly technologies, conservation of natural environment, management of environmental hazards. The guidelines provide mitigation and adaptation measures to minimize hazards on settlement areas through four major categories: Site and Subdivision Design, Works and Services, Infrastructure, Buildings and Structures, and Natural Environment. The document does provide theoretical ideas on the requirement of geological data, slope steeper than 30° to be avoided, minimize the runoff control, onsite coverage and setbacks and minimum slope alteration. Construction of G+2 and above are not permitted on slopes greater than 30°. However, the guidelines lack technical recommendations and safety practices before and after construction to minimize possible hazards. It focuses more on architectural planning rather than on technical practices and actual implementation, which is a drawback between the implementer (Government Officers) and the receiver (public).

Hilly regions are the most difficult yet exciting and challenging features to carry developmental works (Kumar, 2018). Bhutan is one of the fastest developing countries with acute shortage of land for settlement and hence pressure is felt for new settlement areas (NHSPB, 2019). Urban density is projected to increase from 37.8% in 2017 to 56.8% in 2047 (BUPN, 2020). Despite high risk of landslides, there is major urban development and expansion in the hilly regions of Bhutan.

a) Dechen-zam to Langjophakha area under risk to mudslide due to continuous rainfall (Source: www.bbs.bt, August 10, 2021)

a) Changangkha Lhakhang area under risk to mudslide due to continuous rainfall (Source: www.bbs.bt August 7, 2021)

c) Landslide due to continuous and heavy rainfall at Langjophakha (Left Picture) and Olakha (Right Picture) Thimphu on August 1, 2021 (Source: www.bbs.bt)

Figure 1. Landslides recorded in Thimphu in 2021

a) Landslide at Sampheling, Phuentsholing (Source: Residence of Phuentsholing Facebook Page, June 30, 2021)

b) Landslide at Kharbandi Goenpa, Phuentsholing (Source: Residence of Phuentsholing Facebook Page, June 30, 2021)

Figure 2. Landslides recorded in Phuentsholing in 2021

The current research proposal is based on an assumption that more steep slopes will be exploited for urban expansion and growth in future. Landslide has become a major disaster in Bhutan claiming lives and properties. Fragile geological conditions, steep slopes and heavy rainfall significantly contribute to the already weakened sub-soil structure, which has lost its strength and capacity due to excessive excavation, seepage and stress associated with developmental activities. Heavy rainfall being the predominant reason for landslides along these slopes, policies need to be updated considering constructional safety against this hazard. Hence, proper mitigation and adaptation measures to manage the precipitation and runoff before and after construction of buildings along the slopes, considering geological and structural factors will provide sustainable development and resilient building construction practices, which needs to be regulated through research and policies.

2 Aim, Objectives and Scope of the Research Study

2.1 Aim

To provide adaptation and mitigation measures before and after building construction for landslide disaster-resilient building construction practices on hilly slopes of Bhutan

2.2 Objectives

The main objectives of the current research work are to:

- Determine the major factors triggering landslides on urban slopes of Bhutan
- Understand the constructional practices that favour landslides on hilly areas
- Suggest the slope angles and excavation limits for building construction along the slopes based on the safety and stability requirements
- Recommend the best constructional practices to avoid landslides on hilly slopes and recommend constructional feasibility of the slopes with or without site developmental structures or mitigations
- Provide suggestions and recommendations to update the policies and regulatory guidelines for constructional approval, implementation and monitoring on hilly urban slopes of Bhutan

2.3 Scope

The scope and limitations of the research are as follows:

- Only Phuentsholing and Thimphu cities will be considered for research.
- Research and analysis data considered are only for Bhutan.
- Theoretical research without pilot studies will be accomplished.
- Formulation of policy is out of the scope of the research project.

3. Methodology

Literature was reviewed to pave a deeper understanding on landslides in urban areas. Site visit, questionnaire survey and social reference were looked into to compile past landslides in urban areas. Questionnaire survey, field visit and geotechnical investigation were used to determine the major factors causing landslides.

Site visit to construction sites were performed to study the constructional practices on hilly areas. It was correlated with the compiled document to understand the constructional practices that trigger landslides on hilly areas.

Rainfall data and satellite images were referred to determine the catchment area, runoff quantity and to evaluate the required and existing facilities to mitigate the runoff and reduce the seepage.

Slope analysis was performed using laboratory test data, geotechnical investigation data and survey data to determine stability as well as to suggest and recommend suitable excavation and setback limits.

Recommendations from the research findings and minor and major mitigation and adaptation practices for hilly settlements were presented to the concerned agencies and stakeholders to be considered while constructing, updating policies and guidelines for future adoption and implementation for resilient building construction on slopes.

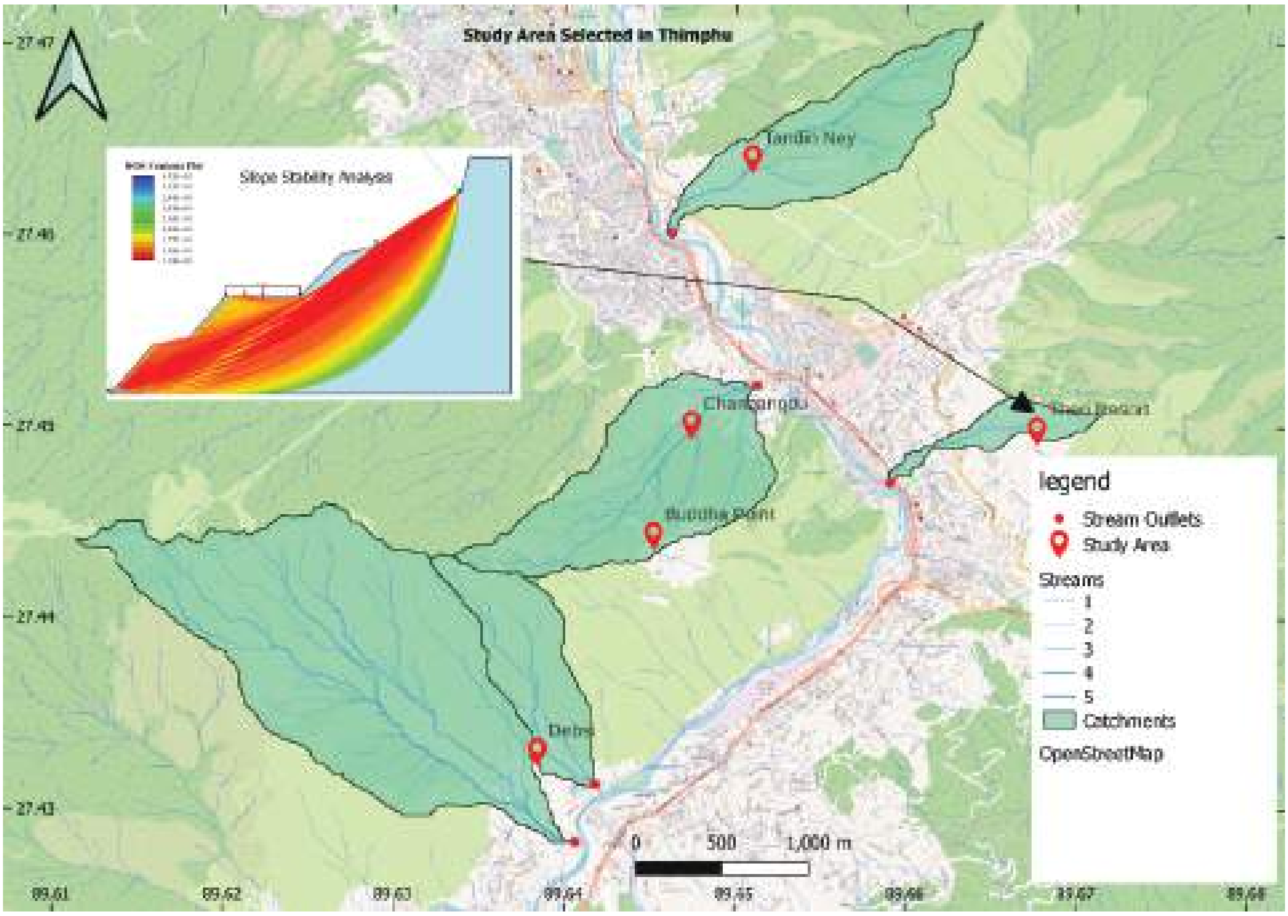

Figure 3. Research sites at Thimphu

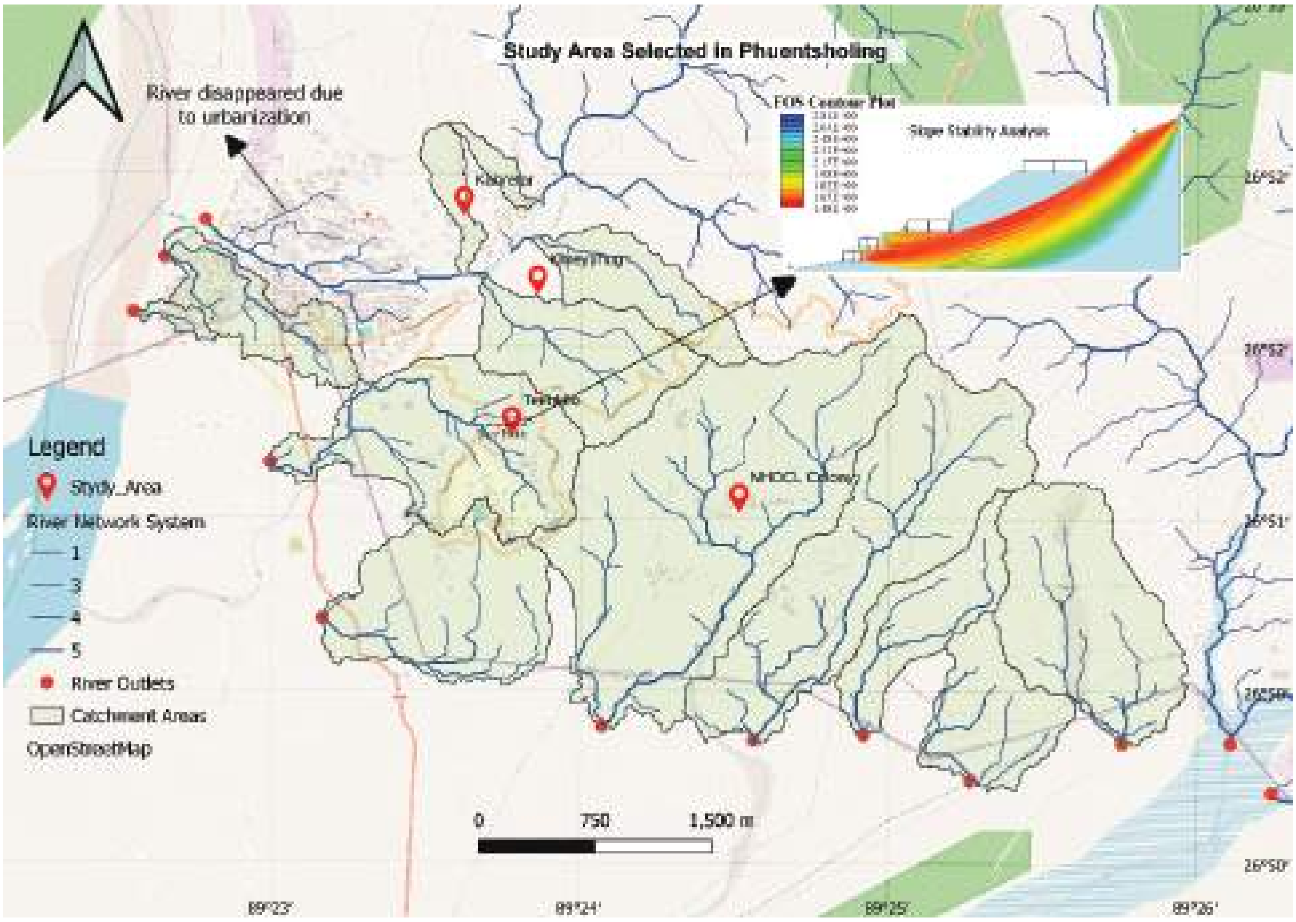

Figure 4. Research sites at Phuentsholing

4. Results and Discussion

The results and discussions are based on (1) questionnaire survey data, (2) slope stability analysis, and (3) hydraulic analysis along with past events.

4.1 Questionnaire and site survey

The questionnaire was framed based on the literature review and site observation. The questionnaire was divided into four sections: a) Details of constructed areas, b) Details of ongoing construction areas, c) Geological details, and d) Historical details. The main factors and constructional practices contributing to the landslides in urban areas were then detailed out.

The findings highlight that most of the buildings constructed on slopes are residential buildings which have implemented retaining structures to stabilize their building slopes.

The majority of the area under hilly construction in urban areas fall under 20°-30°, followed by 30°-40°which is not recommended for settlement activities. However, when the vicinity slope is compared to the constructed slope, it can be estimated that excessive excavation is adopted to avail the construction space but with minimal setback for the building. The results show that most of the construction sites do not follow slope stability measures and planned excavation approach. They also do not manage these excavated slopes to avoid erosion by providing any temporary drainage or diversion channels. Since these slopes are steep, rainfall and runoff result in visible cracks and slope instability contributing to fragile neighbourhood and mudslides. Seepage at different degrees is also visible at the constructed sites, with highest seepage occurrence from the excavated areas. This might be because of the inadequacy of the drains to cater to the runoff, which is considered as the main cause of failure in hilly urban areas as per the literature referred to.

Heavy and continuous rainfall combined with steep slopes and weak soil profile without any mitigation measures and runoff controls are some of the other factors causing landslides in Bhutan's urban areas as per the landslide occurrence study and record.

4.2 Hydraulic analysis

The peak runoff is the maximum flow that is expected due to a design storm over the catchment. For the current research and analysis, four years (2015–18) hourly data recorded by the College of Science and Technology was employed. Accordingly, a range of maximum intensity were used to compute the design storm. Figure 5 shows the runoff generated from various micro-catchment in urban region based on the selected range of rainfall intensities.

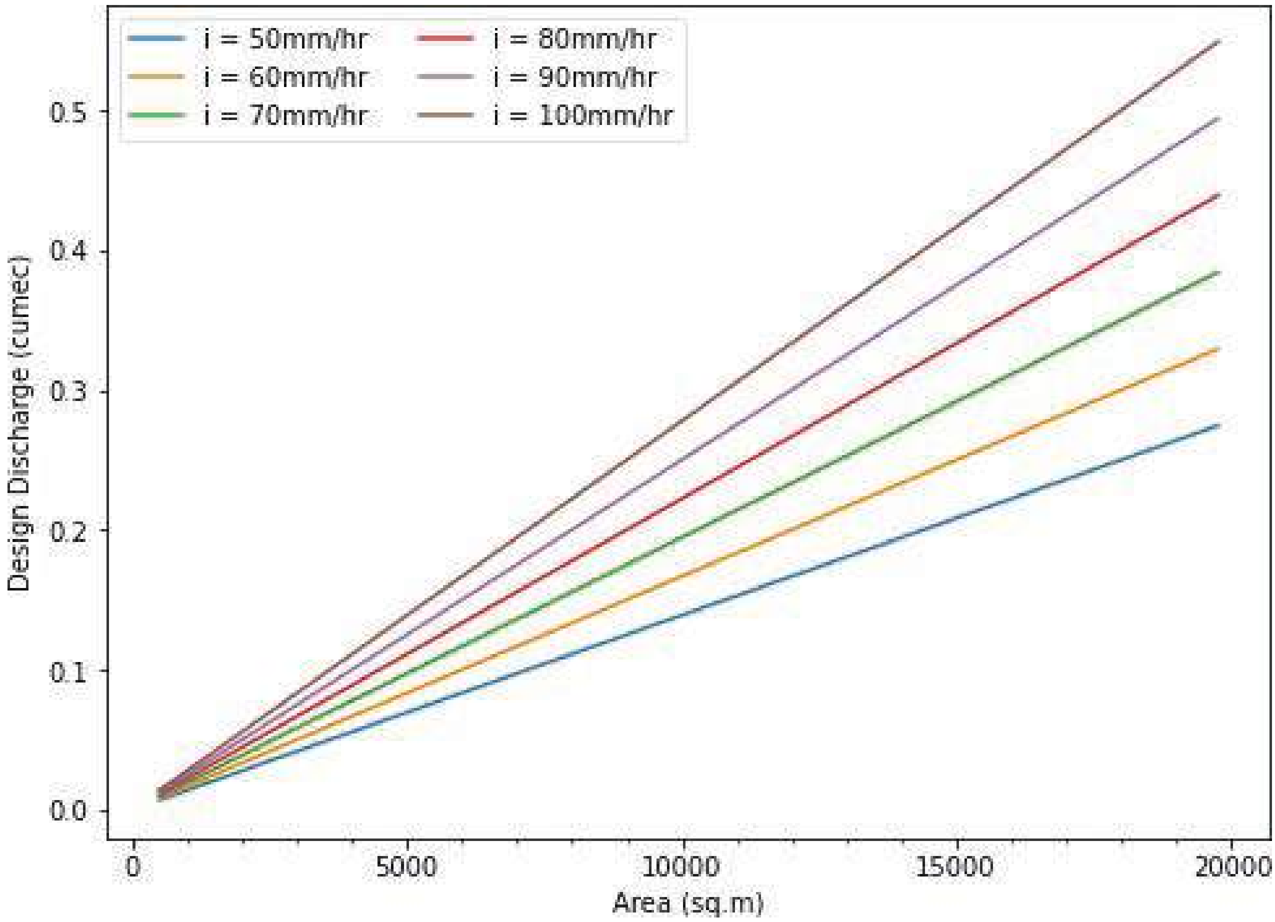

Figure 5. Design discharge graph based upon the rainfall intensity over the region and the size of catchment

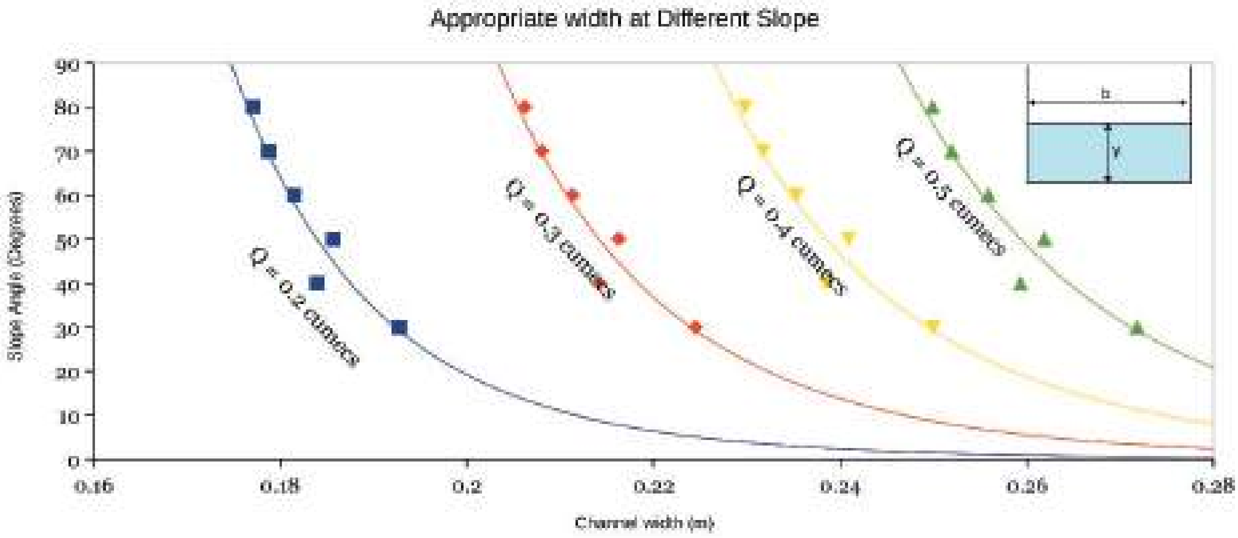

Figure 6. Slope angle vs channel width curve for various discharge (to determine the drainage width)

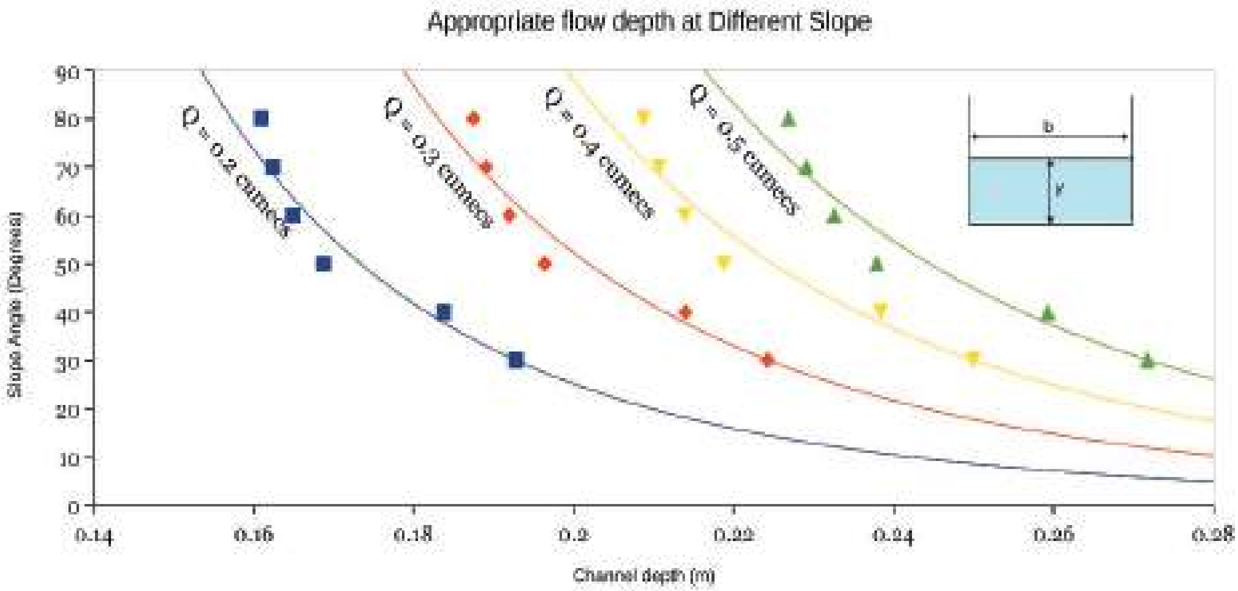

Figure 7. Slope angle vs channel depth curve for various discharge (to determine the drainage depth)

The above charts are handy outputs of the current research to determine the discharge directly based on rainfall intensity and catchment area. The depth and width of the drainage can be directly determined with reference to the slope angle and discharge (Figures 6 and 7).

It was observed that in Phuentsholing most of the drainage available at the sites are L-drains and not very suitable for steep slopes with heavy precipitation. It was also found that some channel drains were inadequate to cater to the catchment runoff. However, at Thimphu where precipitation is lower, L-drains were effective along gentle slopes.

4.3 Slope stability analysis

HYRCAN, a free slope stability software, was used to analyze the site slopes. The results were then interpreted to suggest and recommend the minimum setbacks and excavation limits for safer building construction on hilly slopes.

The slope was analyzed for undisturbed condition and constructed condition. The slopes above constructed area and below constructed area were analyzed for excavations at 45°, 60° and 90°. The stability of slopes was then checked with the determined Factor of Safety (FOS) obtained after the analysis. The failure slopes were re-analyzed using stability measures, considering soil nail and reinforced cement concrete (RCC) retaining walls only. The minimum setbacks and excavation limits were determined based on the slip surfaces obtained and FOS reflected along these surfaces. The suggestions stipulated are as provided in Figures 8 to 12 and tables below.

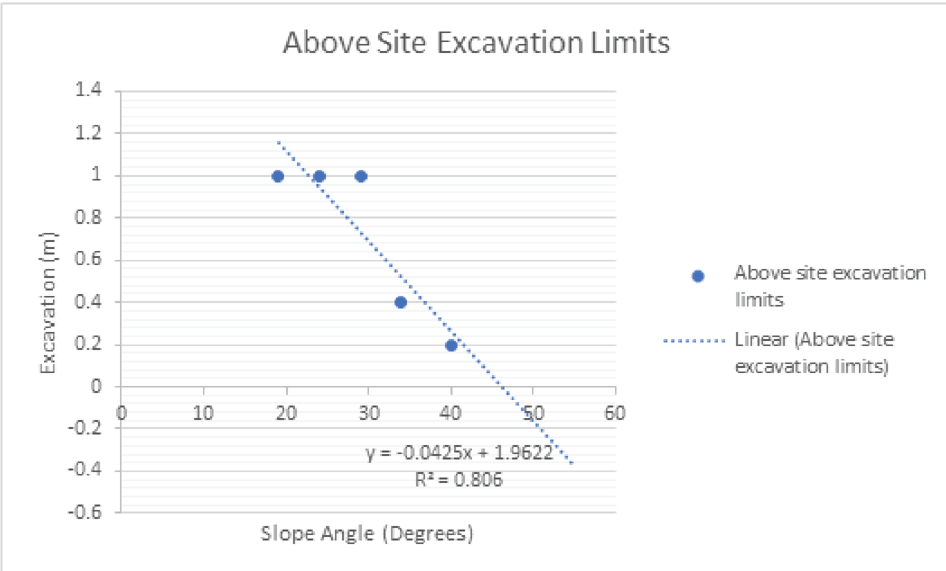

Figure 8. Maximum above site excavation limits for different slope angles (undisturbed site)

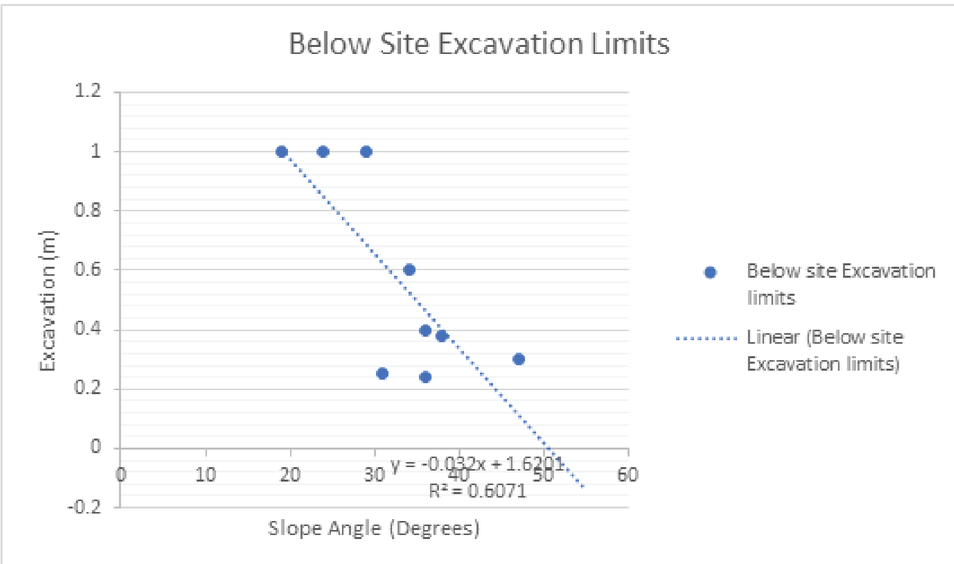

Figure 9. Maximum below site excavation limits for different slope angles (undisturbed site)

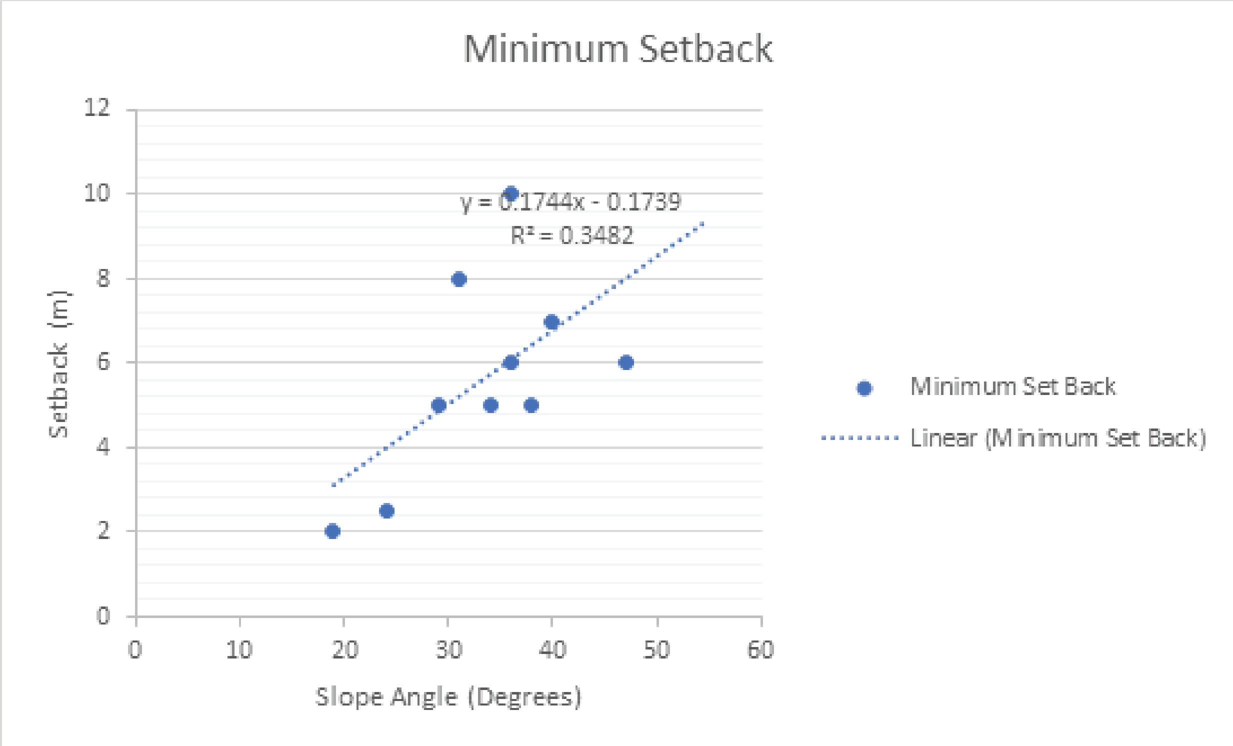

Figure 10. Minimum setback for different slope angle (undisturbed site)

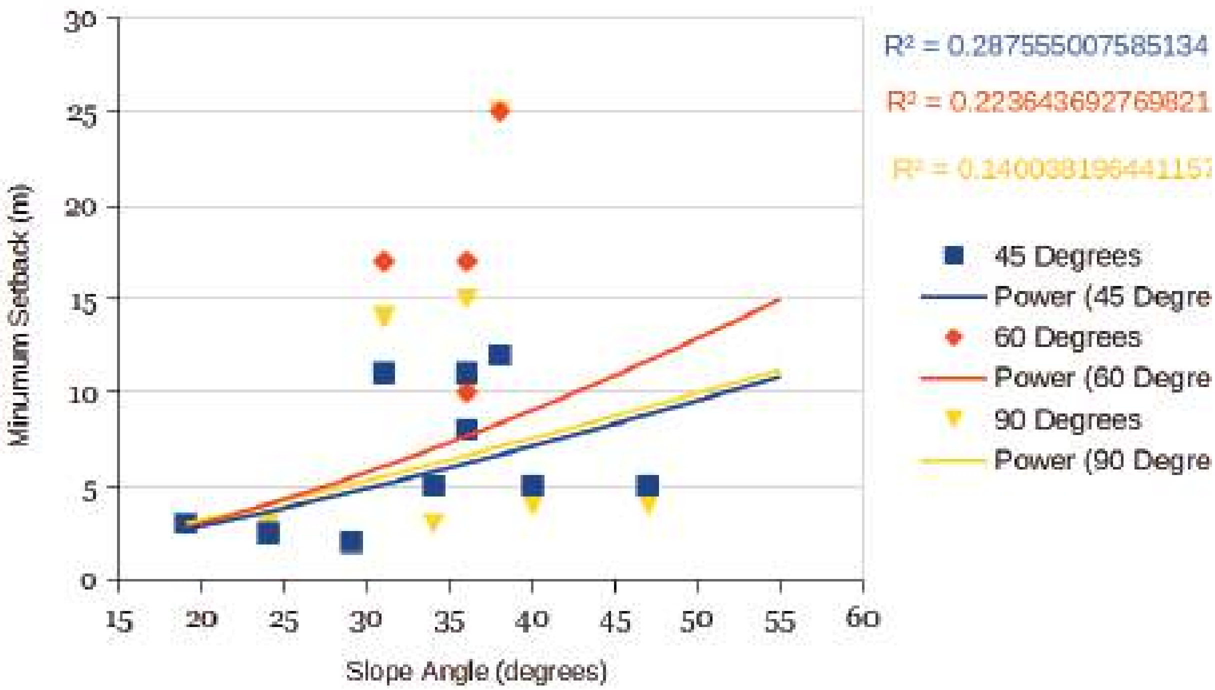

Figure 11. Minimum setback for slopes excavated at different angles (constructed site)

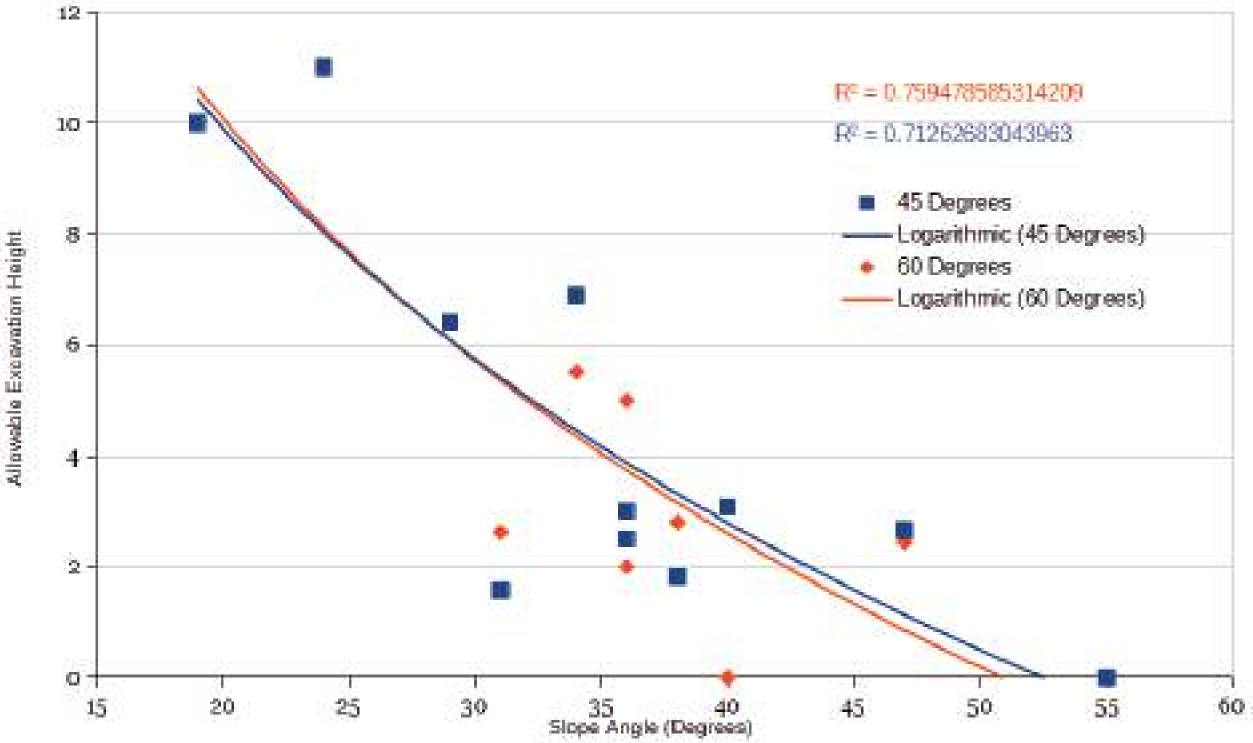

Figure 12. Maximum excavation limits for slopes excavated at different angles (constructed site)

As per the observation, 90° excavation is not recommended without consultation with a geotechnical engineer.

4.3.1 Recommendations for hilly construction

Based on the questionnaire data, slope stability analysis and hydraulic analysis recommendations are drawn as stated and tabulated below.

Before construction

- Site to be constructed should acquire topographic survey map for building planning, slope alignment and excavation with nearby amenities within 10 m.
- Geotechnical investigation and reports (i.e. soil gradation and allowable bearing capacity of the soil) are must for sites above 25°. Maps and test reports can be provided by the concerned or private agencies at a minimal charge.
- If the slope is between 15°–20°, planned excavation can be allowed with proper temporary drainage.
- If the slope is between 20°–30°, planned excavation can be allowed with proper designed drainage and erosion control measures.
- If the slope is between 30°–40°, planned excavation can be allowed with proper designed drainage and retaining walls and erosion control measures.
- Site monitoring and excavation approval should be provided with safety measures.
- Construction guidelines should be considered in planning, prior to construction approval and construction.

- Refer to Table 1 of this document.

After construction

- All constructed sites should maintain appropriate/proper runoff and erosion control measures.
- Slope stability measures should be implemented wherever required and should make sure that all the vicinity is stable within 10 m from the construction site.
- Construction guidelines and policies should be considered and implemented.
- Construction completion approval should be sought from the relevant agency within four months from the completion date.
- Construction agency should verify safe construction completion approval.
- Refer to Table 2 of this document where H = height of the slope is under consideration.

Table 1. Before construction requirements in hilly urban areas of Bhutan

Measures/Works	Slope Angle in Degrees			
	0–15	15–25	25–30	>35
Geotechnical Investigation	Required	Required	Required	Required
Survey data & slope profile	-do-	-do-	-do-	-do-
Implementation of construction guidelines & approval	-do-	-do-	-do-	-do-
Minimum Set back	-do-	-do-	-do-	-do-
Excavation approval	-do-	-do-	-do-	-do-
Excavation	Planned	Planned	Planned	Planned
Monitoring of excavation	-do-	-do-	-do-	-do-
Drainage (To control runoff)	Natural Drains (*Well-maintained Natural drains or pipes channelized appropriately*)	Temporary Drains (*Proper channelized drains with stone soling, check dams, pipes, deep excavated channels, etc*)	Permanent Drains (*Well-designed drains*)	Permanent Drains (*Well-designed drains*)

Measures/Works	Slope Angle in Degrees			
	0–15	15–25	25–30	>35
Erosion Control (Erosion control measures should be implemented immediately after excavation)	Not-required	Temporary erosion control measures (Ground cover with plastic sheet, sack-rags, hay straw, grass etc)	Designed erosion control measures (Crib walls, Silt fence, Retaining walls, etc)	Specialized erosion control measures
Above site excavation limits	H	H	0.65H-0.8H	0.1H-0.5H
Below site excavation limits	H	H	0.65H-0.8H	0.1H-0.5H
Minimum Set Backs (Front/ back and right/left)	2m	2-4m	4-5m	6m and more

Table 2. After construction requirements in hilly urban areas of Bhutan

Measures/Works		Slope Angle in Degrees			
0-15		15-25	25-30	>35	
Implementation of construction guidelines & safety measures		Required	Required	Required	Required
Drainage to cater runoff		-do-	-do-	-do-	-do-
Slope stability measures					
Slope Above Construction site	0-15	Not-required	Not-required	Not-required	Not-required
	15-25	Temporary	Temporary	Permanent	Permanent
	25-30	Permanent	Permanent	Specialized	Specialized
	>35	Permanent	Specialized	Specialized	Specialized
Slope Below Construction site	0-15	Not-required	Not-required	Not-required	Not-required
	15-25	Temporary	Temporary	Permanent	Permanent
	25-30	Permanent	Permanent	Specialized	Specialized
	>35	Permanent	Specialized	Specialized	Specialized

Erosion Control Measures					
Slope Excavation for construction (*Excavation is usually carried out at upper slope to acquire maximum built area*)	0°-20°	Temporary RRM wall	Temporary RRM wall	Temporary RRM/Gabion/ Crib wall	Temporary RRM/Gabion/ Crib wall
	30°-45°	Temporary RRM/Gabion/ Crib wall	Not Recommended without special slope stability measures	Not Recommended without special slope stability measures	Not Recommended without special slope stability measures
	50°-65°	Not Recommended without special slope stability measures	Not Recommended without special slope stability measures	Not Recommended without special slope stability measures	Not Recommended without special slope stability measures
	70°-90°	Not Recommended (Consult Geotechnical Expert)	Not Recommended (Consult Geotechnical Expert)	Not Recommended (Consult Geotechnical Expert)	Not Recommended (Consult Geotechnical Expert)
Minimum Setbacks					
Slope for excavation at construction site (*Excavation is usually carried out at upper slope to acquire maximum built area*)	0°-20°	----	----	-----	------
	30°-45°	----	2-4 m	4-6 m	>6 m
	50°-65°	----	3-4.5 m	4.5-7.5 m	>7.5 m
	70°-90°	----	3-4.5m	4.5-6.5m	>6.5 m
Minimum Set Backs (Front/back and right/ left)		-----	Adopt as per site condition	Adopt as per site condition	Adopt as per site condition

Maximum Height of Excavation					
Slope Excavation for construction (*Excavation is usually carried out at upper slope to acquire maximum built area*)	0°-20°	H	H	H	H
	30°-45°	H	0.75H-0.8H	0.55H-0.75H	0.4H
	50°-65°	H	0.75H-0.8H	0.55H-0.75H	0.4H
	70°-90°	Not recommended (Consult Geotechnical Expert)	Not recommended (Consult Geotechnical Expert)	Not recommended (Consult Geotechnical Expert)	Not recommended (Consult Geotechnical Expert)
Stabilised vicinity within 10 m		Required	Required	Required	Required
Approach Road (Mitigation measures)		Not required	Temporary	Permanent	Permanent
Construction Completion Verification by Thromde		Required	Required	Required	Required

4.4 Training and Awareness Programme

The training and awareness programme on hilly slope construction practices in Bhutan was conducted at the Training Hall, College of Science & Technology, Phuentsholing on 8 July 2022. It was also scheduled at Royal University of Bhutan Hall, Thimphu on 15 July 2022. The relevant participants from government and private agencies were invited for the training. The training was planned to create awareness on urban landslides, its causes and factors. It also focused on safer hilly slope construction practices and research findings for safer construction practices followed by an activity. The activities were framed to get an understanding on the existing protocols, policies and guidelines and practices with shortfalls and suggestions. An activity was conducted to know what each sector would look forward to and try to reframe for future sustainability of hilly slope construction and the country's development. The current research report was launched and distributed amongst the participants for their references and post survey was conducted.

The participants suggested and recommended to share the findings with higher authorities and policymakers. They expressed it as a research work of utmost relevance in the construction sector. The participants also recommended for further and long-term research to be undertaken in the research area.

Figure 13. Training participants at CST Training Hall, Phuentsholing

5. Enablers and Barriers

COVID-19 and related travel restrictions have been the key, critical barriers in carrying out the research smoothly. Team members have faced a lot of challenges to apply and request for site visit, follow travel restriction and protocols upon approval and transport of site materials and equipment. There was a tremendous pressure concerning data collection, health and workforce to complete the research. The members had to undergo 7 to 15 days quarantine to visit the research site. Crossing different district boundaries with COVID-19 protocols along with soil samples and heavy equipment was quite a draining process.

Limited site visits and workforce were also a concerning factor governing the quality sample collection. The slope profiling would be more accurate, if the soil drilling and sample collection at various depths were possible. Also, 1D resistivity test equipment has limited the output but nevertheless, the huge excavated slopes were clear reflection of the data retrieved from the equipment results which is very satisfying for the researchers.

Phase wise and online lectures during COVID-19 was another challenging factor, where availing time from the crash course works and additional responsibilities reshouldered due to various protocols were quite hectic and good lessons learnt.

However, the successful completion of the research project enables all the hardships undergone by the members in carrying out various task of the project.

6. Conclusion and Way Forward

Hilly regions are the most difficult yet exciting and challenging features to carry developmental works. Bhutan is vulnerable to various hazards and landslide is one of the most predominating hazards that has intensified due to developmental activities and poor runoff management. It claims lives, damages property and leads to loss of infrastructure. This creates havoc every year within the community and travellers all across the country. It has always been of much interest and importance to carry research in this field. CDRI Fellowship Programme has provided us with the possibility to carry out the first ever research in this area and it gives utmost satisfaction to start and provide a framework for further and future research. Despite many challenges, this journey has been quite interesting and a good lesson learnt.

Research findings are satisfactory on stating that rainfall triggered landslide are most predominant factor in Bhutan, exaggerated by the steep unstable slopes, excessive excavation and inadequate drainage facilities. Research findings provide an easy approach for designers and stakeholders to estimate and suggest the drainage dimensions concerning different slope and rainfall intensity. The slope stability analysis results also provide a better outlook on the construction approach to be followed for safer construction practices in the hilly region. The setback and excavation limits along with the drainage system and erosion control measures recommended to sufficiently cater to reducing risk in the urban slopes of Bhutan. It will also help policymakers and government agencies in developing and formulating safety guidelines and regulations.

We look forward to continuing the same research depicting larger areas and data sets for a much stronger output and results.

References

1. Abidin, M. Z., Saad, R., Ahmad, F., Wijeyesekera, D. C., & Baharuddin, M. T. (2012). Integral analysis of geoelectrical (resistivity) and geotechnical (SPT) data in slope stability assessment. *Academic Journal of Science*, 1(2), 305-316.
2. Bryson, L. S. (2005). Evaluation of geotechnical parameters using electrical resistivity measurements. In *Earthquake Engineering and Soil Dynamics* (pp. 1-12).
3. Bureau of Indian Standards (1995). I.S. 14243 Part 2, Guidelines For Selection And Development of Hill Sites. New Delhi.
4. Bureau of Indian Standards (2000). I.S. 14804, Siting, Design and Selection of Materials for Residential Buildings in Hilly Areas-Guidelines. New Delhi.
5. Bureau of Indian Standards (2005). National Building Code. New Delhi.
6. Chatwin S.C., D.E. Howes, J.W. Schwab, & Swanston D.N. (1994). *A Guide for Management of Landslide-Prone Terrain in the Pacific Northwest* (Second Edition), Published by the Research Branch, Ministry of Forests, British Columbia.
7. Chhetri, N., Sarkar R., Adhikari K., & Chettri I.B. (2019). Forecasting landslide in Chukha from index properties of soil-research to policy making. *World Scientific News*, 135, 227-248.
8. Chief Architect (J&K) (2010). Building Regulations and Bye-Laws. Kashmir Division
9. Dhamdara & Khabraytar. (2020). Development Control Regulations. Phuentsholing Thromde, Royal Government of Bhutan.
10. Dhamdara & Khabraytar. (2020). LAP Revision and Infrastructure Design, Planning and Transportation. Phuentsholing Thromde, Royal Government of Bhutan.
11. Dilushani, P. D. R., Nawodani, W. R. N., Bambaravanage, T., & Udayakumar, K. A. C. (2020). Soil resistivity analysis and earth electrode resistance determination. *IOSR Journal of Electrical and Electronics Engineering*, 15(2), 26-35.
12. Highland, L.M., & Bobrowsky, P. (2008), *The Landslide Handbook—A Guide to Understanding Landslides.* Reston, Virginia, U.S. Geological Survey Circular 1325, 129 p.
13. Hunt, Roy E. & Deschamps, Richard J. (2003). *Stability of Slopes*. CRC Press, 1-28.
14. Ho l c o m b e , L., Beesley, M., Vardanega, P., & Sorbie, R. (2016). Urbanisation and landslides: hazard drivers and better practices. *Proceedings of the ICE - Civil Engineering*, 169(3), 137-144. https://doi.org/10.1680/jcien.15.00044
15. https://www.who.int/health-topics/landslides#tab=tab_1
16. Institute of town Planners India. (2004). *Institute of town Planners India Newsletter, No. 1*, New Delhi
17. Kalinski, R. J., & Kelly, W. E. (1993). Estimating water content of soils from electrical resistivity. *Geotechnical Testing Journal*, 16(3), 323-329.
18. Karma, K. (2005). Landslides in Bhutan Himalayas. Alpha Geotech and Company. Details available at https://agcpl.wordpress.com/news/ladslides-in-bhutan-himalayas/

19. Kim, M. I., Kim, J. S., Kim, N. W., & Jeong, G. C. (2011). Surface geophysical investigations of landslide at the Wiri area in southeastern Korea. *Environmental Earth Sciences*, 63(5), 999-1009.

20. Kumar, A. (2018), Review of building regulations for safety against hazards in Indian hill towns, *Journal of Urban Management*, 7, pp 97-110.

21. McCarter, W. J., & Desmazes, P. (1997). Soil characterization using electrical measurements. *Geotechnique*, 47(1), 179-183.

22. National Disaster Management Division. (2007). Ministry of Home Affairs Additional Provisions in Building Regulations/Byelaws for Structural Safety, In Natural Hazard Zones of India. IA.

23. Popescu, M. E. (2002). Landslide causal factors and landslide remediation options. In *3rd International Conference on Landslides, Slope Stability and Safety of Infra-Structures* (pp. 61-81). CI-Premier PTE LTD Singapore.

24. Pozdnyakova, L., Pozdnyakov, A., & Zhang, R. (2001). Application of geophysical methods to evaluate hydrology and soil properties in urban areas. *Urban Water*, 3(3), 205-216.

25. Osman, S. B. S., & Siddiqui, F. I. (2015). Possible assessment of slope stability by using electrical resistivity: comparison of field and laboratory results. *International Journal of Engineering and Technology*, 7(5), 386.

26. Ministry of Housing and Urban Affairs. (2019). *Manual on Strom Water Drainage System* Government of India.

27. Saad, R., Nawawi, M. N. M., & Mohamad, E. T. (2012). Groundwater detection in alluvium using 2-D electrical resistivity tomography (ERT). *Electronic Journal of Geotechnical Engineering*, 17, 369-376.

28. Sivakumar, G.L. & Singh, V.P. (2009). Appraisal of soil nailing design. *Indian Geotechnical Journal,* 39(1), 81-95.

29. Skilodimou, H. D., Bathrellos, G. D., Koskeridou, E., Soukis, K., & Rozos, D. (2018). Physical and anthropogenic factors related to landslide activity in the Northern Peloponnese, Greece. *Land*, 7(3), 85.

30. Yue, L.J. et al. (2019). Rainfall induced residual soil slope instability: building cracked and slope failure. *IOP Conference Series: Materials Science and Engineering*, 669 012004. Retrieved from https://iopscience.iop.org/article/10.1088/1757-899X/669/1/012004/pdf

31. University of the Virgin Islands Cooperative Extension Service. (2002). Sediment & Erosion Control on Construction Sites Field Guide. University of the Virgin Islands Cooperative Extension Service, Department of Planning and Natural Resources, United Nation.

Regional Road Network Resilience using Landslide Susceptibility Model

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Abstract

The lack of a reliable landslide susceptibility map in the Western Ghats has led to poor quantification of risk associated with rainfall-induced landslides to the road networks, as these macro-level susceptibility maps fail to consider the geotechnical characteristics of the overlying soil. The study introduces a framework to improve susceptibility mapping by performing probabilistic slope stability analysis, using different simulation techniques. In addition, optimization techniques are also incorporated, to determine the location of probe points in an optimal manner, thus improving the resilience and recovery of road networks. This would eventually lead to better mitigation plans and evacuation strategies, during such incidents.

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1. Introduction

In the past three years, 13 out of 14 districts in Kerala have experienced severe landslides and such calamities still continue to occur. These calamities prove the inefficacy of the existing landslide susceptibility maps. In this study, we highlight the necessity of considering geotechnical parameters in preparing a susceptibility map, the ignorance of which could cause catastrophic failures like the one that occurred in Pettimudi, Idukki, a remote belt in the Western Ghats, killing over 60 lives. The frequent landslides in the Western Ghats in the last 3 years have proved the inefficiency of the existing zoning strategy. The study aims at incorporating soil properties in developing a first-of-its-kind, robust landslide susceptibility map. The study will also map the impact of landslides on the road infrastructure, by strategizing the road networks effectively. The model provides quantitative estimates of future slope failure and can be used by the government/policymakers in carrying out mitigation measures for such calamities, planning evacuation activities, developing road recovery strategies, restoring connectivity of roadways after blockage due to debris fall and for supplying immediate relief to needful areas.

2. Research Problem, Aim and Objectives

In recent times landslides have become a common feature all over the world. They hinder the accessibility of strategic road networks. Rainfall-induced landslides cause huge delays in travel time as the roadways become operational only once the debris is cleared. The blockage of such crucial road networks causes considerable loss to society. This study intends to prioritize those locations on the selected road network, where, if probed for geotechnical studies, would improve the resilience, keeping the overall uncertainty of the system to the minimum. The study area chosen is a stretch of NH/SH road network in Kerala, along the Western Ghats.

A significant number of studies have been conducted in the past, which focussed on preparing landslide zones, indicating areas that are susceptible to landslides. These studies aimed in the effective planning of mitigation activities and resilience improvement measures. In India, the Himalayan belts and the Western Ghats are the most landslide-prone areas. Comparatively, more studies have been conducted in the Himalayan region than in the latter. Unfortunately, the susceptibility maps that were prepared were unable to give reliable estimates of the occurrence of landslides. Also, most of the studies were carried out at a macro level with a lesser degree of precision.

Hence, it has become necessary to develop more reliable landslide susceptibility maps. At the same time, it is also important to improve the resilience/recovery rate of road networks that are prone to rainfall-induced landslides so that they can be made available to users in the shortest possible time. The proper quantification of risk associated with landslides is a necessary aspect in this regard so that the mitigation measures can be planned wisely.

2.1 Novelty

The existing landslide susceptibility mapping lack in hazard assessment and mitigation purposes as the models were developed without considering the geotechnical properties of the overlying soil. The significance of soil characteristics and slope stability analysis have proved to be crucial even in the analysis of failure mechanisms of landslides (El Jasouli, 2020). Most rainfall-induced landslides are often triggered because of the building up of pore water pressures in the overlying soil. Hence, it isn't wise to neglect the soil properties while preparing a hazard assessment system for landslides.

However, the geotechnical investigation involves tedious in-situ testing, fieldwork, laboratory experiments and computations, making it non-viable. In our study we have incorporated geotechnical parameters into the susceptibility model with minimal field and experimental works but maximum reliability by running numerous simulations to obtain the probability slope failure distribution at each pixel using geotechnical properties. Consequently, by updating the model with the slope failure probabilities, a more reliable spatial landslide susceptibility map is produced, which can be used for resilient infrastructure, hazard assessment and mitigation purposes without fail.

The study also attempts to optimize the number of probe points by minimizing the landslide uncertainties and maximizing its impact on road infrastructure using appropriate optimization techniques. Thus, the probing needs to be done only at these predefined points, which in turn could help to minimize the cost and labour-intensive testing procedures. The overall inherent uncertainty of the system would be minimized, along with the prioritization of those points, which if probed, would lead to improvement in resilience and a better estimate of the impact of landslides at various points. On optimizing probe points, the incorporation of geotechnical databases into the hazard assessment system can also be made feasible without sacrificing the reliability of the system.

2.2 Proposed solution

Initially a preliminary landslide susceptibility map is prepared, using the remotely accessible geological characteristics by applying suitable regression methods. But since geological parameters alone cannot give a clear indication of the landslide susceptible areas, the appropriate slope stability analysis using geotechnical characteristics has to be incorporated into the study.

The influential geotechnical parameters are implemented into the susceptibility map by performing numerous probabilistic slope stability analyses incorporating material properties and engineering properties of the overlying soil using various methods such as Monte Carlo simulations (MCS), FORM, etc. The result of these simulations would be a model that gives the slope failure probability distributions of different outcomes when several random variables viz., geotechnical properties, intervene in the system. By feeding these slope failure probability distributions as yet another preparatory input factor into the already developed regression model, the appropriate geotechnical aspects are taken into account and a refined spatial probabilistic map is obtained as outcome.

Afterward, the aim is to minimize the overall uncertainty of the system, by reducing the variance associated with the obtained failure probability distribution. But to make sure that the impact of landslides on the road infrastructure is mapped with utmost certainty, it the road network has to prioritized/strategized by convenient means. This is highly desirable since it is obvious that the disruption would have higher impacts at certain points of the road network, compared to that of the others. The necessary points where probing has to be carried out are optimized precisely by making use of appropriate optimization frameworks. The redefined map thus obtained would give a better picture of the landslide susceptibility. This could be used further for risk quantification and resilience improvement of road networks, which in turn will prove to be useful for effective mitigation and evacuation activities.

The objectives of the proposed solution are listed as follows:

- To prepare an updated landslide inventory of Kerala focusing on the Western Ghats region
- To develop a methodology with which geotechnical properties can be incorporated into macro-level susceptibility mapping in a reliable and feasible manner
- To prepare an improved landslide susceptibility model for the study region by taking into account the geotechnical properties of the slopes
- To suggest improvements on the regional road network resilience to landslides based on the developed landslide susceptibility model

3. Methodology

3.1 Preliminary susceptibility map

3.1.1 Landslide inventory map

Initially, a landslide inventory map is developed from a series of investigations and locating geo-coordinates of past landslide events in historical, technical and maintenance records of road networks in the study area of the Western Ghats in South India. The source and run-out areas of the landslides are mapped and digitized in a GIS environment.

As per the planned activities in quarter one, a full-fledged landslide inventory has been created incorporating more than 4700 landslide events across Kerala, focusing mainly on the Western Ghats region. All the landslide points were plotted onto the map, forming the basis of the susceptibility landslide map that has to be developed. The location of the landslide events was acquired from several landslide assessment reports of Kerala till the year 2020 from the database of the Geological Survey of India. The landslide events across the state were plotted as shown in Figure 1.

3.1.2 Preparatory factor maps

The Digital Elevation Map (DEM) tiles across the state, of the resolution 30 m × 30 m were collected from Bhuvan Geo Portal & Web Services Group (BGWSG) by National Remote Sensing Centre, Indian Space Research Organisation accessed on 15th May 2021. Apart from the already developed DEM data, a more accurate DEM of ortho resolution 2.5 m was procured from the National Remote Sensing Centre (NRSC), India for a detailed and targeted slope stability analysis accounting for geotechnical characteristics. The DEM data were merged, rastered, clipped and the digital elevation model for the state was created in ArcGIS platform. From the developed DEM data, various geological parameters were extracted, which formed the input parameters/factors for developing the susceptibility map in the upcoming quarters of the project timeline. The extracted parameters include the slope of the terrain, aspect of the slope and hill shade. All these parameters, viz., slope, aspect and hill slope were individually plotted on separate maps using ArcGIS, and factor maps of these parameters were created, as depicted in given in Figures 2, 3 and 4.

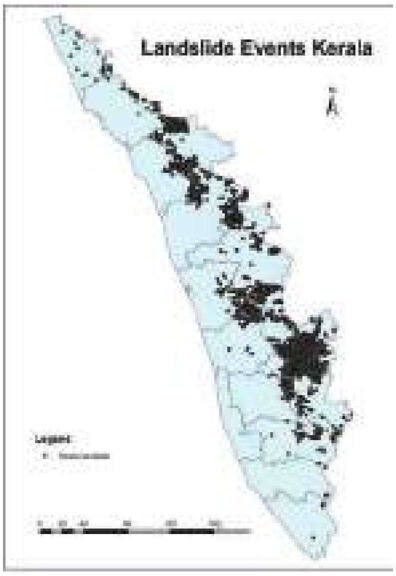

Figure 1. Landslide inventory map

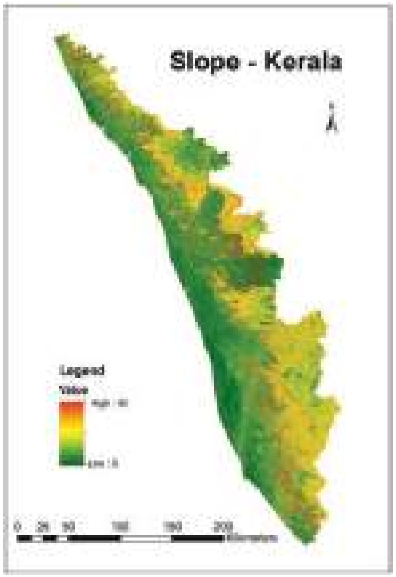

Figure 2. Slope factor map extracted from DEM data

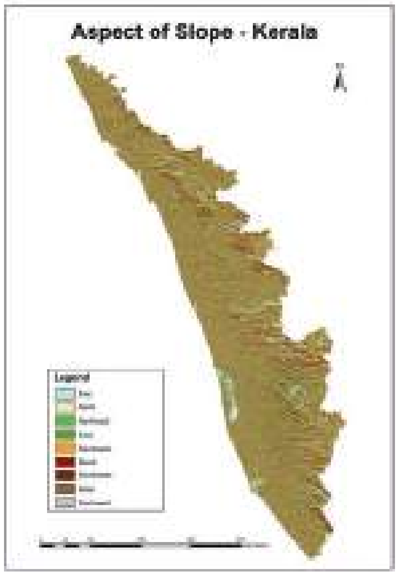

Figure 3. Aspect factor map extracted from DEM data

An additional influence parameter, namely the land cover and land use data, was procured from ESRI 2020 Land Cover data provided in the ArcGIS database. A factor map of the same was developed and data were derived for the study region. The resolution of the map is 10 m, as shown in Figure 5. The land cover and land use data were classified into 10 classes whose influence on landslide susceptibility will be studied by quarter 3 of the project timeline. The 10 classes include: water, trees, grass, flooded vegetation, shrubs, build area, clouds, barren land and snow. Also, for the resilience of the road network, shape maps including National Highway, State Highway, District roads and Village roads were collected. The data were procured from Kerala Public Works Department. The map showing NH and SH networks across the state is shown in Figure 6.

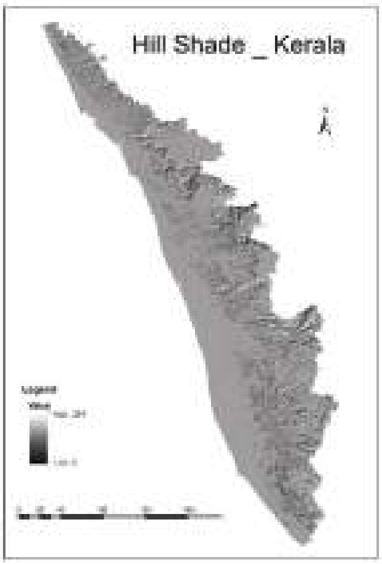

Figure 4. Hill shade

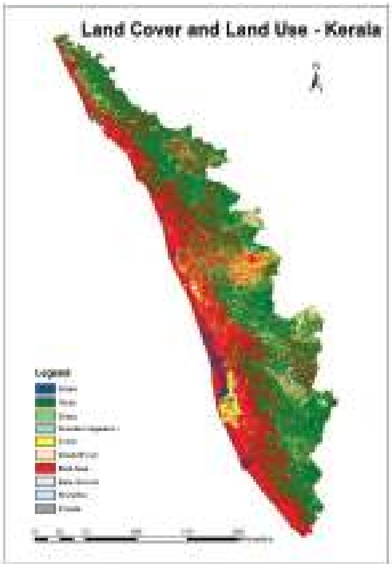

Figure 5. Developed land use and land cover data map

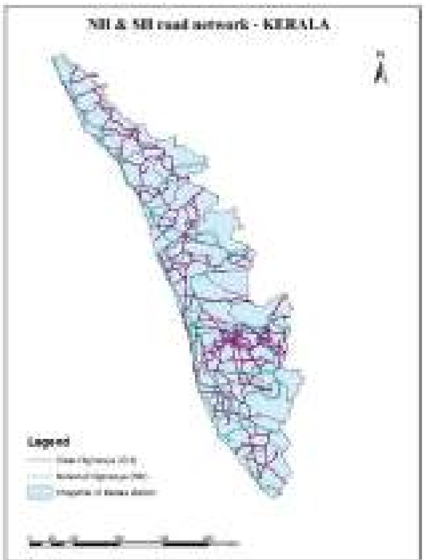

Figure 6. NH and SH road network across Kerala

Deriving influencing parameters from DEM data and rastering each parameter into a preparatory factor map for the preparation of the preliminary susceptibility map were done. The derived factor parameters include the distance to drain path, distance to national highway, distance to state highways, curvature, slope elevation, slope aspect, land use-land cover, hill-shade and elevation. A total of nine parameters were used to formulate the preliminary landslide susceptibility map. The influence of geotechnical and rainfall will be accounted for in the upcoming quarter, where geotechnical slope stability will be analysed. Incorporating the same is expected to redefine the preliminary susceptibility map. Figures 8 and 9 give the distance to roads and drains across Kerala.

Figure 7. Kerala curvature of topography map

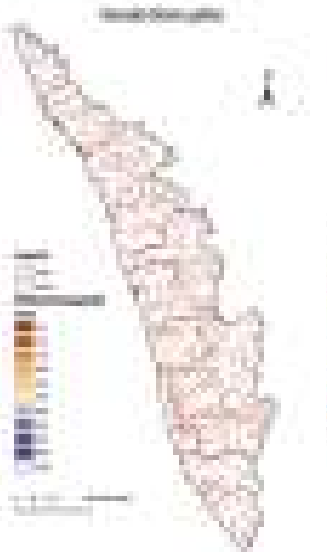

Figure 8. Kerala drain path proximity map

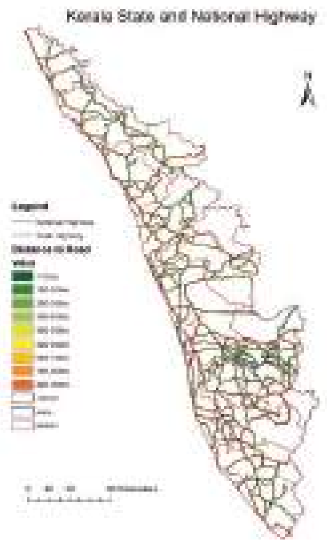

Figure 9. Kerala NH and SH proximity map

3.1.3 Frequency ratio method

The relationship between the landslide occurrence area and the landslide influencing parameters was established from the relationship between areas where landslides had occurred and not occurred and the areas of each subclass landslide influencing parameters. To identify their relationship, a simple statistical technique was applied to derive it with the frequency ratio approach. Furthermore, the FR model became valuable in ranking the preferred causative factors based on their ability to control a landslide incident (Kannan et al., 2013), because FR can describe clearly the difference of each score between landslide influence parameters in class and landslide occurrence. Thus, the number of landslide occurrence pixels on the area must be combined between influence parameters. Then the ratio for each factor is calculated by dividing the landslide occurrence ratio by the ratio of each class in causal factors (Lee and Thalib, 2005). A ratio value in each class shows the level of relationship the given factors attribute between landslide occurrences. When the ratio is more than one, it means a stronger correlation. A lower ratio than one suggests a lower correlation (Lee and Pradhan, 2006). The frequency ratio value can be calculated in the following manner:

$$FR = \frac{\frac{(ij)}{\sum PixL}}{\frac{P(ij)}{\sum Pix}} \quad (1)$$

where,

ij is the number of pixels with landslide within class *i* of *j* parameter,

P(ij) is the number of pixels in class *i* of *j* parameter,

$\sum PixL$ is the total pixel of *j* parameter with landslide

$\sum Pix$ is the total pixel of the area

The frequency ratio method was used to find the correlation between landslide locations in the past and each factor that affects landslides. In general, factor classes with a frequency ratio value of >1 will have a higher probability of landslide occurrence. The number of pixels of each class of causal factors was automatically counted by using the reclassify tool in ArcGIS software and the number of pixels of landslide occurrence in each class of causal factors was found by overlaying them. By using Eq. (1), the ratio of each class was calculated by dividing the number of pixels in each factor's class by the total number of pixels in the entire study area. Then the frequency ratio values of each factor class was computed by dividing the landslide percentage by the area of percentage as in Table 1.

A landslide susceptibility map has been constructed by calculating and classifying Landslide Susceptibility Indexes (LSI) for the whole of Kerala state. LSI indicates the degree of susceptibility of an area to landslide occurrences. To create a landslide susceptibility index, all the ratios of raster map landslide influence parameters were summed as follows:

$$LSI = FR_1 + FR_2 + \ldots + FR_n \quad (2)$$

where FR_1, FR_2, FR_3 ... FR_n are the frequency ratio raster maps of landslide influence parameters. The developed summation map with the index values was then reclassified to be expressed in percentage (0 to 100%) to get the preliminary susceptibility map. The map has been classified into five classes: Very Low, Low, Moderate High and Very High.

3.2 Redefined susceptibility map

The prepared preliminary landslide susceptibility map was redefined by making use of infinite slope stability analysis, which implicitly takes into account the soil properties of the region. Several tools and software such as ArcGIS, Probabilistic Infinite Slope Analysis Model (PISA-m) and GIS-TISSA (Geographic Information System - Tool for Infinite Slope Stability Analysis) were explored for developing a methodology by which probabilistic slope stability analysis could be carried out on such large DEM data. The methodology is schematically represented in Figure 10.

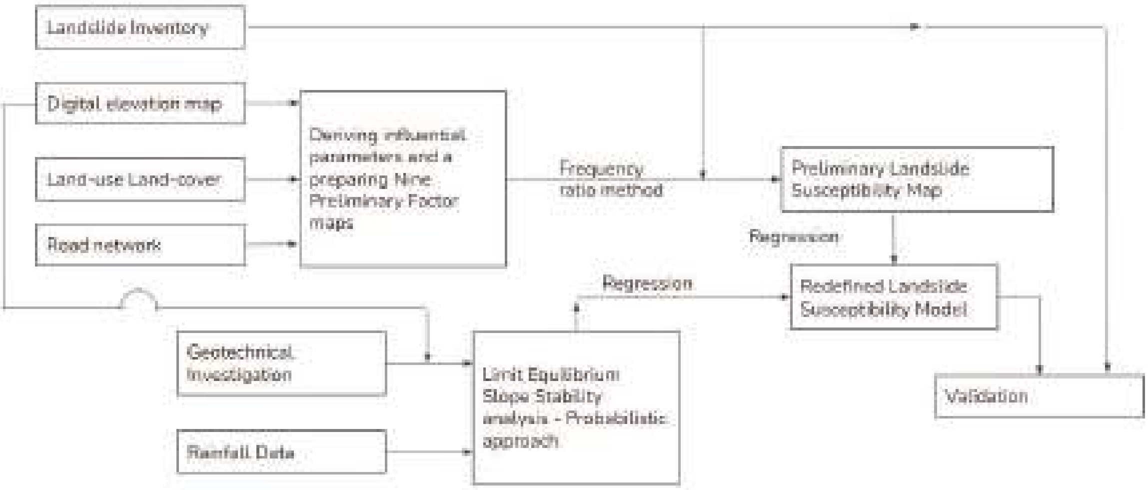

Figure 10. Methodology for developing redefined landslide susceptibility map

3.2.1 Probabilistic slope stability analysis

Initially a stand-alone map, completely based on probabilistic infinite slope stability, was developed by using Probabilistic Infinite Slope Analysis Model (PISA-m) algorithm in an ArcGIS environment using GIS-TISSA (GIS-Tool for Infinite Slope Stability Analysis). The infinite slope model characterizes the slope's stability in terms of the factor of safety (FS). The FS is the ratio of resisting to destabilizing forces acting on the slope, such that the slope is stable when FS > 1 and unstable when FS < 1, and at the limit of equilibrium when FS = 1. The infinite slope models primarily consider soil (cohesion and internal friction angle) and weight (saturated and unsaturated) characteristics, as well as the local terrain slope and soil depth. The infinite slope model can be extended to include the effects of the water table (if it is above the failure plane), and the effects of the vegetation, i.e., added weight and increased strength from root cohesion. Eq. (3) formally defines the PISA-m model (Hammond et al., 1992).

$$FS = \frac{Cr + Cs + [qt + \gamma_m D + (\gamma_{sat} - \gamma_w - \gamma_m) H_w D] \cos 2\beta \tan\varphi}{[q_t + \gamma_m D + (\gamma_{sat} - \gamma_w - \gamma_m) H_w D] \sin\beta \cos\beta} \quad (3)$$

where,

Cr is the contribution to the soil cohesive strength from the roots when vegetation is present

Cs is the soil cohesive strength

qt is the vegetation weight added to the slope (the surcharge)

γm is the unsaturated (moist, above the phreatic surface) soil unit weight

γsat is the saturated (under the phreatic surface) soil unit weight

γw is the water unit weight, a constant equal to 9810 N/m3 in SI units, or 62.4 lb./ft3 in imperial units

D is the depth of the slip surface

Hw is the height of the phreatic surface above slip surface, normalized relative to soil thickness (dimensionless varies from 0 to 1)

β is the terrain slope

ϕ is the internal friction angle of the soil

The infinite slope model in Eq. (3) evaluates under what conditions of terrain slope, soil characteristics (strength, weight, and depth), water table level and vegetation coverage, the slope may become unstable. However, it does not account for the uncertainties involved in assessing the values for these input variables. As the area of interest is relatively large, the estimation of uncertainty within the considered parameters is also significant, hence a probabilistic approach is found necessary. Haneberg (2004) introduced the use of the First Order Second Moment (FOSM) method for propagating input uncertainty (variance or standard deviation of the input variables) through the infinite slope model. The FOSM method is based on the local linearization of the model through the Taylor series expansion. Mean values for the input variables can be directly used to compute a mean value of FS, through Eq. (3), as shown in Eq. (4), and if no error correlation is assumed, the output variance (for FS) can be directly calculated from Eq. (5).

$$\underline{FS} = FS(\underline{x}) \tag{4}$$

where,

$\underline{FS}$ is the mean estimation of the factor of safety

FS is the factor of safety calculation function as defined by Eq. (3)

$\underline{x}$ is the set of mean values for the input variables in Eq. (3).

$$(\sigma_{FS})^2 = \sum_i \left(\frac{\partial(FS)}{\partial(x_i)} \right) (\sigma_{xi})^2 \tag{5}$$

where,

σ_{FS} is the standard deviation of FS

∂(FS)/∂(xi) are the partial derivative of FS, given by Eq. (3), with respect to any of the input variables x_i

σ_xi are the estimates of the standard deviation for all the input variables xi

The GIS-TISSA allows manual input of the parameters as factor maps. The raster files for all the parameters listed in Eq. (3) were generated for different probability distributions. The raster files represent the input variable information as semi-continuously varying quantities over the spatial domain. However, this level of detail is in general much higher than providing soil and vegetation characteristics in a deterministic manner. The soil properties were approximated with the help of the results from field visits, various literature and soil map data available in the Department of Soil Survey and Soil Conservation, Kerala. From the basis of various probabilistic studies, all the random parameters were assumed to follow a normal distribution. The cohesion varied from 0 kPa to 10 kPa, and the angle of internal friction varied from 27 to 33 degrees. For the cohesion contributed by vegetation roots, Huang et al. (2006) approach was used. Eq. (6) converts NDVI (Normalized Difference Vegetation Index) to root cohesion.

$$Cr = C_{min} + C_{int} * \frac{NDVI + 1}{2} \tag{6}$$

where,

Cr is the root cohesion in kPa, and

C_{min} and C_{int} are constants that are uniformly distributed within ranges of 0–20 and 0–30, respectively.

For the vegetation surcharge (qt) NDVI values less than 0.3 are not considered as they do not have enough surcharge to influence the slope stability (Norris et al., 2008; Jaafari et al., 2014). Soil and water table depth was assumed to have similar values for similar soil types. Modern interpolation and geostatistical methods like IDW were used for producing semi-continuously varying maps of these variables.

3.2.2 Redefined regression model

One of the main limitations of the PISA-m algorithm is that no explicit consideration for water pressure increase due to rainfall water infiltration is included, but the static effect of a shallow (above the failure surface) water table is explicitly included. Modelling the transient effects of increases in pore pressure due to water infiltration requires other modelling approaches like TRIGRS, which may be considered as the future scope of the study.

In this study, to account for the rainfall effects, a rainfall factor map was developed considering annual rainfall from 2000 to 2021 from available rain gauge stations across Kerala. The rainfall factor map is given in Figure 11 and has been developed from the Indian Meteorological Department (IMD) database of annual rainfall using the IDW interpolation technique. The redefined map is developed by combining the results from the probability of failure map and the preliminary susceptibility map developed in the previous quarter, along with a rainfall map, using a bivariate regression method.

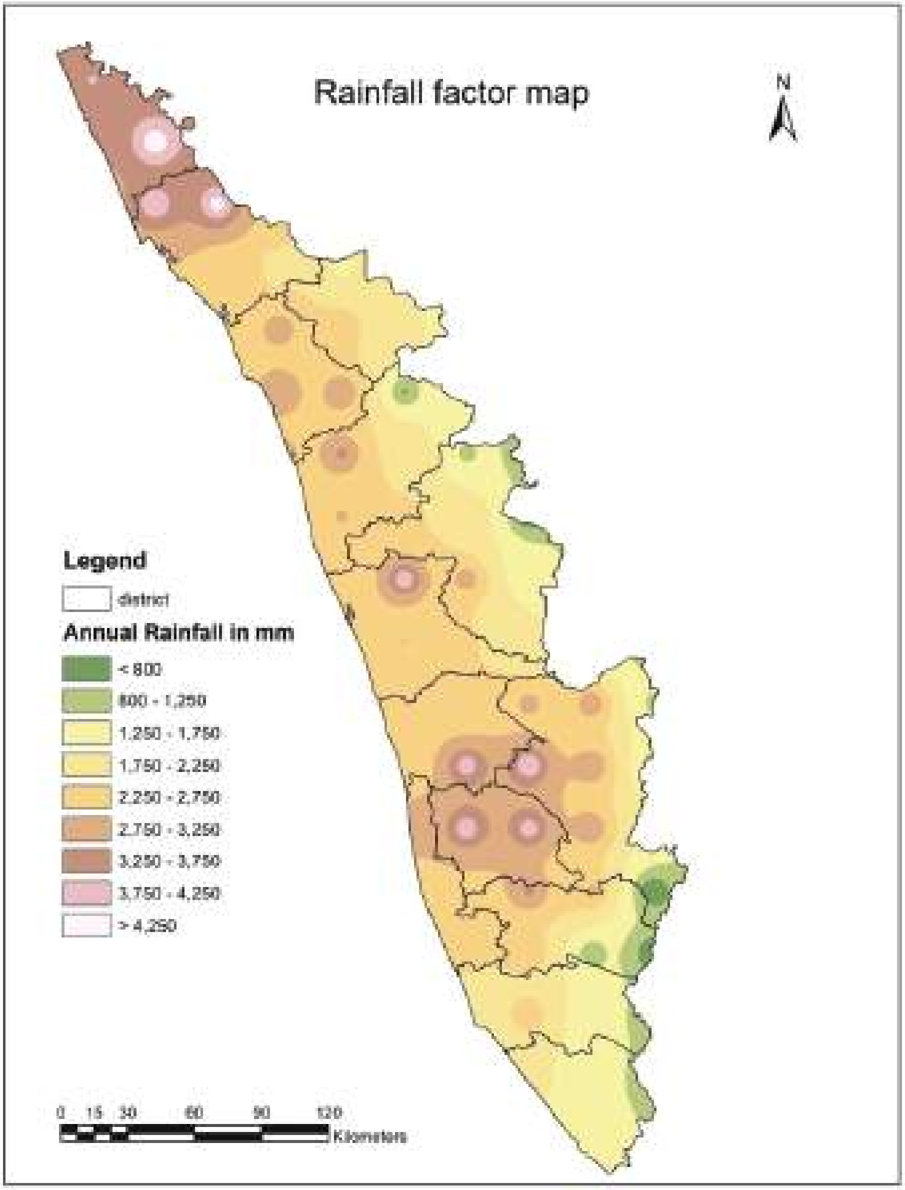

Figure 11. Rainfall factor map from 2000 to 2021

3.3 Resilience framework to identify the probing locations

Two steps were carried out to identify the probing locations:

- Delineation
- Formulation

3.3.1 Delineation

A road network that passes through a mountainous terrain like the western ghats, would consist of separate components that would fall in the category of either *strongly connected* (every node is reachable from every other node) or *weakly connected* network. Those portions of the road network that are prone to a higher landslide susceptibility (which is of interest to the present study) would usually fall in the weakly connected category. Hence, it is important to identify and demarcate such weakly connected components from the strongly connected components of the overall road network. The nodes that would help in serving this purpose are named *terminal (destination) nodes* in this context. We assume that there are '*t*' such terminal nodes.

We denote our overall road network (NH and SH) as *G*. The stretches of the road network could be either less or more susceptible to disruptions. The less susceptible network portion could be represented using G_r (resilient network), which is a single large road network. The higher susceptible network is a combination of many disconnected networks, as subgraphs, which are denoted using $G_{v1}, G_{v2},..., G_{vS}$ (*s* is the number of vulnerable networks).

$$G = G_r \cup G_{v1} \cup G_{v2} \cup ... \cup G_{vs} \tag{7}$$

Delineating, i.e., clustering of the overall road network (represented as a graph G), into subgraphs $G_{v1}, G_{v2},...,G_{vs}$ is performed with the help of a *community detection algorithm*. Community detection algorithms essentially search for dense subgraphs, the so-called communities, in a large graph.

3.3.2 Formulation

The connectivity reliability to the terminal nodes could be computed from the available susceptibility map, and we denote it by a vector *r* ($r_1, r_2,...,r_t$). After the probing process is performed, a refined susceptibility map is obtained, and some of the connectivity values might get modified, This new set of connectivity values is denoted by a vector ρ ($\rho_1, \rho_2,..., \rho_t$). Also, '*n*' denotes the number of paths from all origins to destinations. There will also be numerous links in each of these paths. Certain links would fall in common for a certain number of paths. If probing is carried out on such links that fall in common for the maximum number of paths, the accuracy of the susceptibility map would improve by a particular quantity on the basis of the proportion of *r* values getting modified to ρ values.

Consider that a particular link is common to all the terminal nodes. Such a link would be a candidate for probing. In other words, probing would be carried out at those links that would give a maximum subscription to all the destination nodes. Hence, this is considered as one of the necessary conditions for the selection of links to be probed. So, a link-to-path incidence matrix is constructed, which essentially represents the membership of links in the Origin-Destination (OD) paths. A '1' would indicate that the link would be incident to the path in consideration, and a '0', otherwise. The probing points will be decided in such a manner that the maximum value of the incidence matrix is attained.

	Path 1	Path 2	Path 3	.	.		Path p
Link 1	1	0	1				
Link 2	0	1	1				
Link 3	0	1	0				
.							
.							
.							
Link n							1

Figure 12. Model of a link-path incidence matrix

The centrality of the links in the network is another important criterion being considered while shortlisting the links that are to be probed. It is a measure of the importance of elements (nodes and links) in a network, and is a key concern in network analysis. Centrality measures could be defined for a node or a link. There are various types of centrality measures with one being the 'Betweenness Centrality'. It is a measure of centrality in a graph based on shortest paths. Betweenness centrality of links has been considered for this particular study.

Another aspect being considered is that probing at those links, which are least vulnerable to disaster, as indicated by the 'failure-probability' from the susceptibility map, would actually make the probing process very uneconomical. Hence, probing is prescribed at those links having a higher failure-probability when compared to those having lower failure-probability values.

Hence, the quantity that we maximize in the objective function of the optimization formulation is a function of the link-path incidence matrix, betweenness centrality and the failure probability of the link. The optimization formulation would look as follows:

$$\text{ıax } \mathbf{Z} = \sum_{i=1}^{n} \left(\sum_{j=1}^{m} A_{i,j} \right) P_i \, (EB)_i \, x_i \, \ldots\ldots\ldots (*$$
$$\text{such that } \sum_{i=1}^{n} C_i x_i \leq B \quad \ldots\ldots\ldots (1 \qquad (8)$$

where x_i is the decision variable that can take a value of either "1" or "0" ("1" would indicate that the probing is prescribed on the link being considered and a "0" would indicate not to do so). *n* and *m* denote the number of links and number of paths, respectively. P_i is the failure probability of link *i* as per the available susceptibility map and $(EB)_i$ indicates its betweenness centrality. $A_{i,j}$ denotes the incidence of link *i* to path *j*, whereas C_i represents the cost associated with probing for link *i*, with *B* being the total available budget.

The above-written optimization formulation would fall in the general class of *assignment problems* with the potential decision variables being either 0 or 1, constrained on the total number of probe points, based on the available budget. The assignment problem, in an operational research context, represents a special case of linear programming problem used for allocating resources (mostly workforce) in an optimal manner. The optimization code is run by developing a few scenarios, by altering the number of probe points.

4. Results and Discussion

4.1 Statistical susceptibility map

The sensitivity of each preparatory factor map towards landslide occurrence can be quantified by the value of FR that each parameter contributed. In the case of the relationship between landslide occurrence and slope angle, each slope class between the slope angles from 20° to 60° has a ratio greater than 1, which indicates a high probability of landslide occurrence. In the curvature class, the values represent the morphology of topography. A convex indicates a positive value, a concave indicates a negative and a zero value indicates a flat surface. Comparing frequency ratio values of both concave and convex, it is understood that the probability of landslide occurrence is almost similar, with a slightly higher probability of landslide occurrence in the case of concave curvature. This might be due to the accumulation of water in these classes. However, in the case of flat surfaces, the probability of landslide occurrence is very low. The frequency ratios of elevation suggests that the landslide occurrence is more likely to happen at elevations greater than 250 m. At lower values the probability is low. Likewise, at extremely high elevations, the probability tends to reduce.

In the case of aspect class, in the north, north-east, south-east, south and south-west facing slopes, the frequency ratio is >1, which indicates a high probability of landslide occurrence. In the case of distance from the national highway, state highway and drain paths, the ratio to distance/proximity is used to understand the level of influence on landslide occurrence. Distance from national highways below 400 m has a ratio of >1. This shows that as the distance from NH decreases, the probability of landslide occurrence increases. The same trend is seen in the case of SH as well, which highlights the importance of resilience road networks to be adopted. The distance from the river above 500 m has a ratio of >1. In the case of distance from rivers, the landslide densities are higher for distance classes far away. Forests and bushes in land-use classes have a frequency ratio value of >1. However, in the case of built-up area, agricultural and grasslands, the ratio is <1, suggesting a lesser probability of landslide occurrence.

The preliminary landslide susceptibility map of the state is given in Figure 13. A higher value of LSI indicates a higher susceptibility to landslide and if the LSI value is lower, it indicates lower susceptibility to landslides (Lee and Pradhan, 2007).

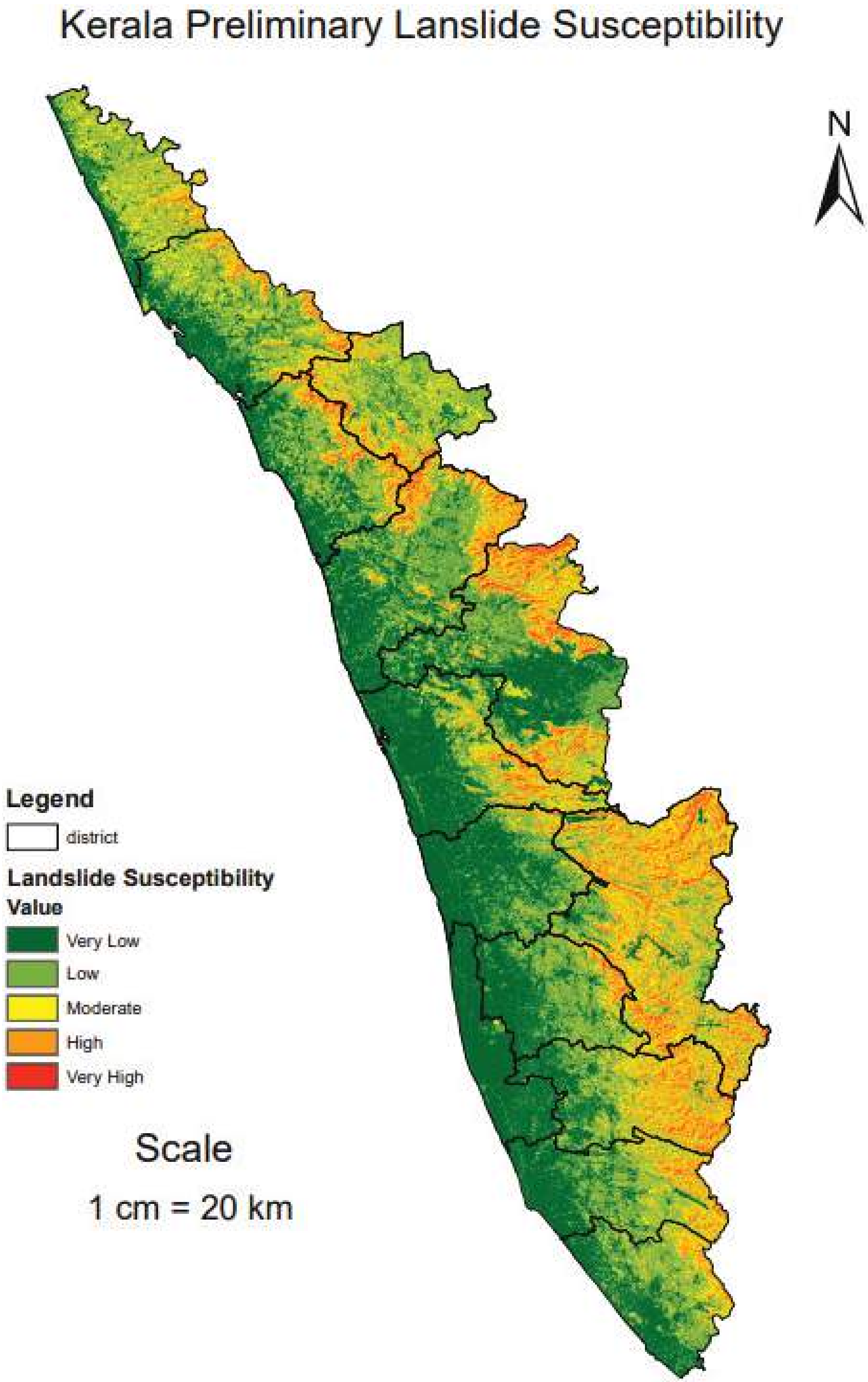

Figure 13. Preliminary landslide susceptibility map for Kerala state

4.2 Probabilistic slope stability map

The mean and variance (standard deviation) estimate for the FS, obtained from Eqs. (4) and (5) allow for the assessment of the quality and relevance of the slope stability analysis. The mean and standard deviation estimates allow the tool to calculate the RI (Reliability Index) for FS and the probability of slope failure, i.e., probability of FS < 1. Output raster files include the mean FOS map, standard deviation map of FOS, the Reliability Index and probability of failure, given in Figures 14 to 16.

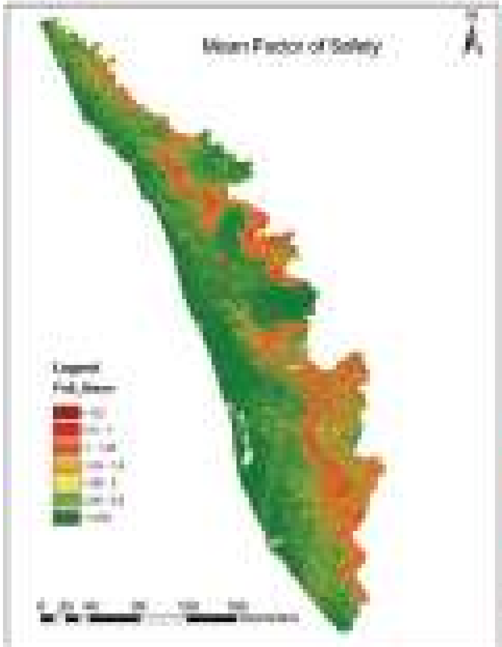

Figure 14. Mean factor of safety of slope map of Kerala

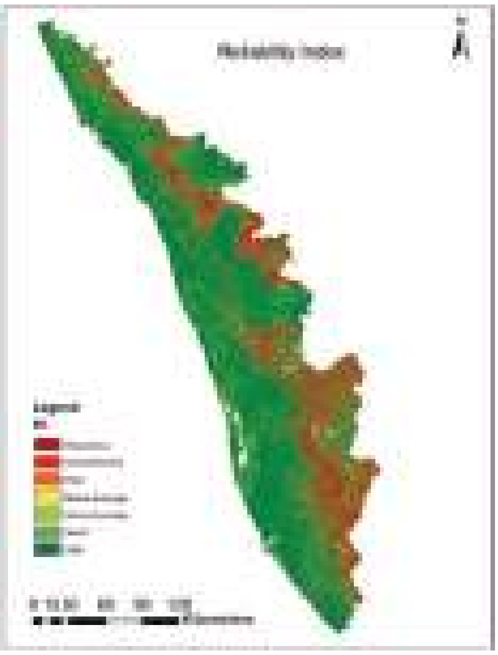

Figure 15. Reliability index of slope map of Kerala

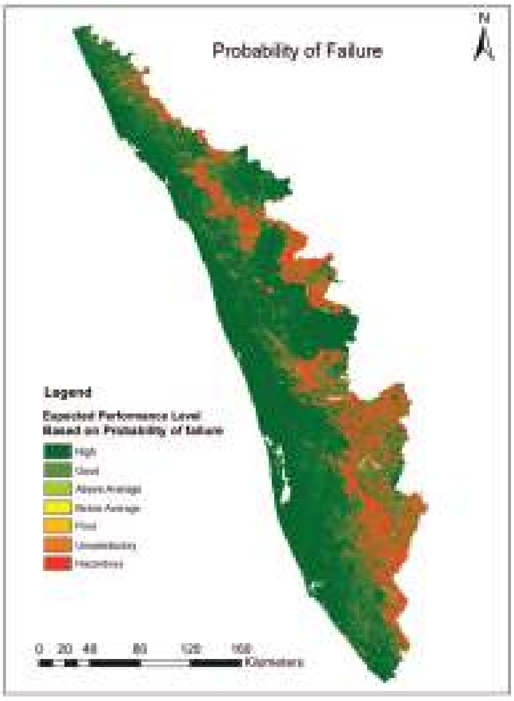

Figure 16. Probability of failure map of Kerala

4.3 Redefined susceptibility map

The redefined map accounting for geotechnical properties and rainfall is given in Figure 17.

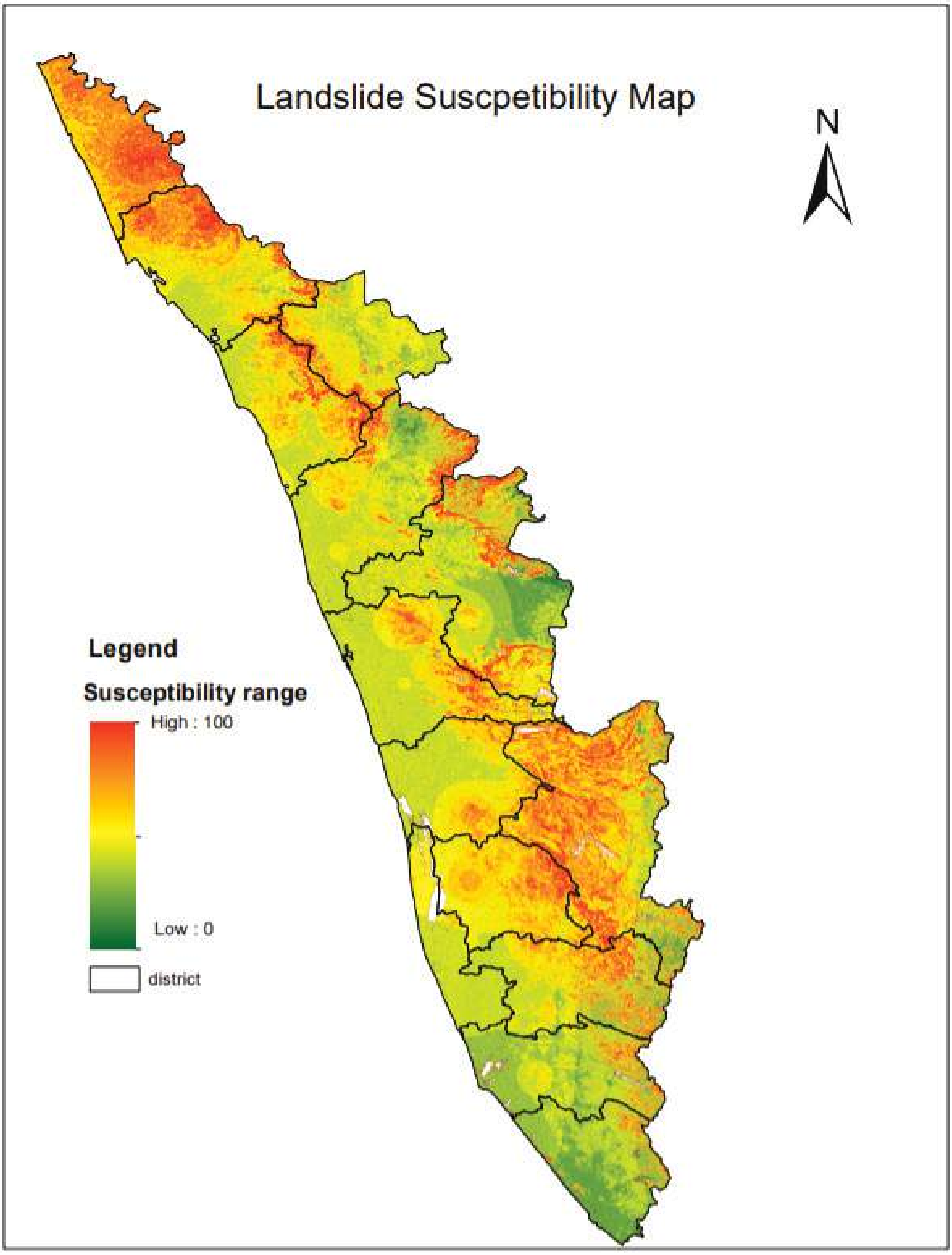

Figure 17. Redeveloped landslide susceptibility map including geotechnical properties

As a rough comparison between the preliminary susceptibility map using frequency ratio and the probabilistic infinite slope stability map, more than 35% of the existing 4700 landslides in the training dataset fall in its most susceptible region. On the other hand, only about 5% of landslides in the database fall in the most susceptible region of the preliminary susceptibility map. A detailed comparison of these maps is made in the validation stage using the Receiver Operating Characteristic curve – Area Under Curve ROC-AUC, after preparing validation test data using the recent landslide in the Kottayam district. Figure 18 shows the susceptibility map of Kerala with the Kottayam district highlighted.

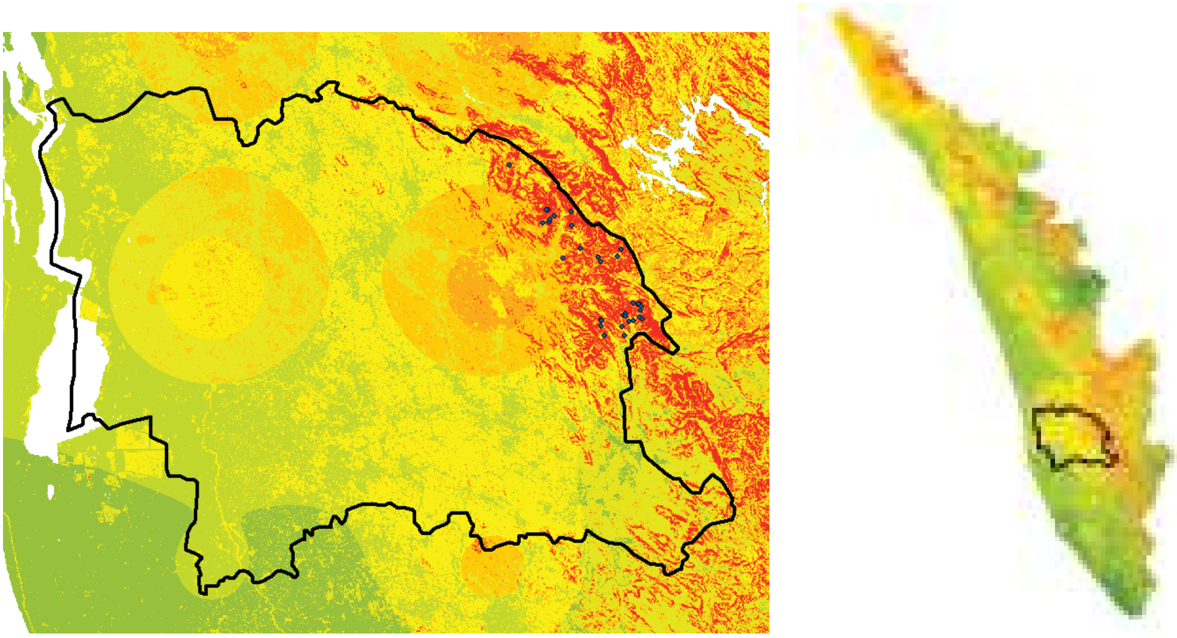

Figure 18. Susceptibility map of Kerala, border lining Kottayam district with plotted landslide locations

For the comparison of the generated models, a statistical technique used for validation of results, the Receiver Operating Characteristic curve (ROC) is used. Here, ROC is represented as a graph, which is plotted based on the true-positives of the analysis on the Y-axis and false-positive rates (sensitivity = f (specificity)) on the X-axis. When this method is applied, the generated Area Under Curve (AUC), of which the value could change in different cases, shows the reliability of the model used. Accordingly, values ranging from 0.5 to 1 indicate that the model is correct; values < 0.5 indicate a random fit (Senouci, et al., 2021). For the study, the ROC was generated and AUC was calculated using a python coded ArcGIS tool, which used 10000 Monte Carlo iterations. The result of the ROC-AUC of the redefined susceptibility map is given in Figure 19.

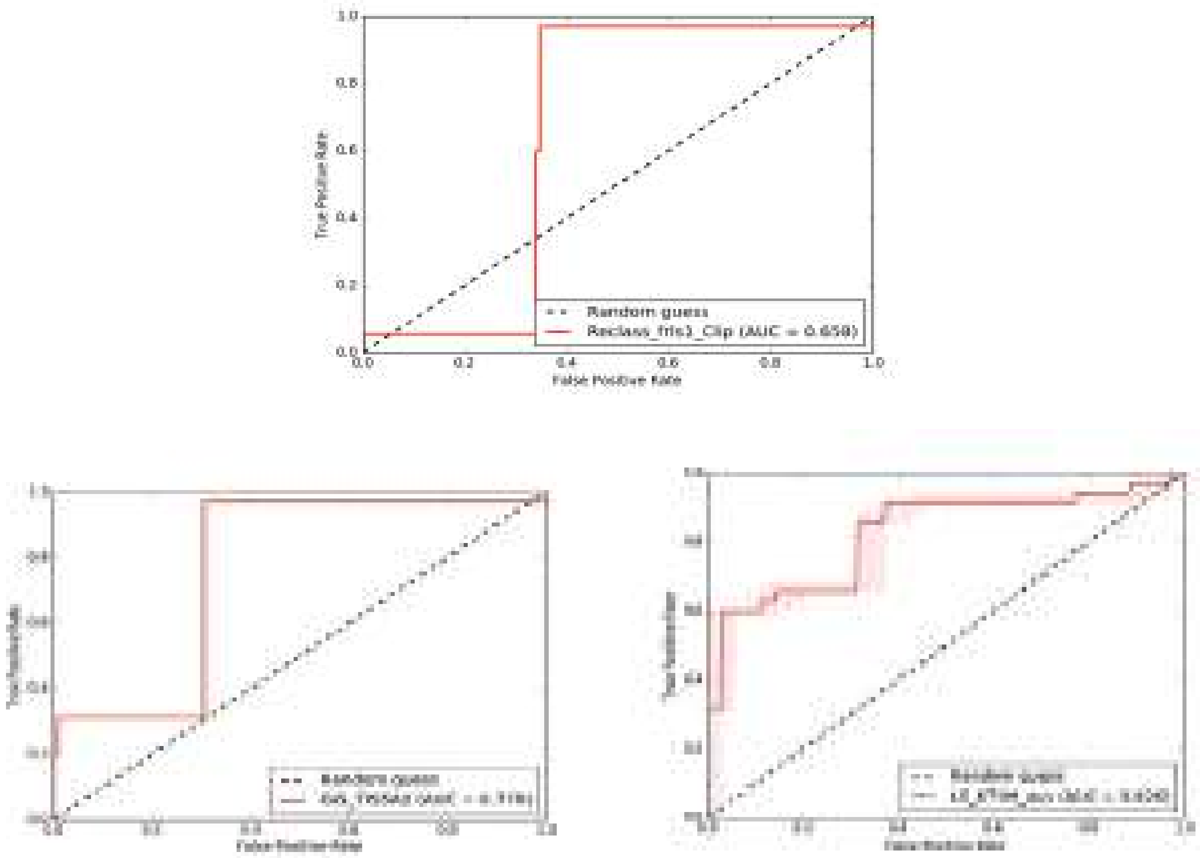

Figure 19. ROC-AUC of (a) statistical map without considering the geotechnical properties (b) probabilistic slope stability map (c) redefined map considering Kottayam district of Kerala

Field investigation was done in the Kottayam district to get the geo-locations of recent landslides, including the massive Kokkayar landslide that occurred in 2021. The true positive values were given from the landslide inventory created for Kottayam from the field survey. These had not been included in the initially created landslide inventory of the state, which was used as the training database. The created testing database of the landslide inventory is shown in Figure 20. The true negative values were generated using Monte Carlo iterations considering the area of slope<10 degrees. The ROC-AUC value was found to be 0.826, which is higher than 0.5 and closer to 1. Hence the redefined map is reliable in landslide predictions.

On comparing the redefined map with the preliminary map, which resulted in a ROC-AUC value of 0.658, the final map was observed to be an improvement of 25.53% over the statistical approach. When observed with regard to the geotechnical slope stability map of ROC-AUC value of 0.77, the redefined map was refined only by 7.27%. Hence, the importance of geotechnical properties to be considered as a primary contributor to landslide susceptibility is well established from the results. Additionally, comparing the raw statistical method of probabilistic slope stability method, it was seen that the geotechnical method was 17.02% more accurate than the statistical FR regression method. However, more data points for validation will lead to better confidence regarding the generated models. Several more validation over different locations in the state will help in framing a conclusive statement regarding the quality of improvement with the proposed framework for the entire state.

Figure 20. Site photos from field survey at Kottyam

4.5 Road network resilience

As explained in the methodology section, delineation of the road network into weaker and stronger components was performed as the initial step. This was carried out for the Kottayam district in Kerala.

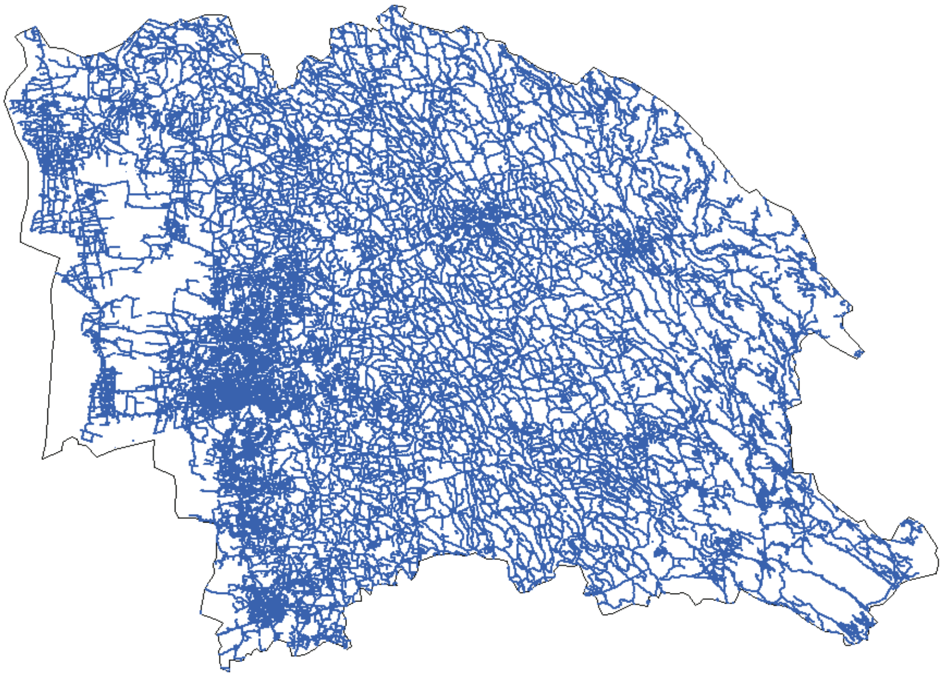

Figure 21. Regional road network map for the Kottayam district

A community detection algorithm was performed for the Kottayam district of Kerala, with the purpose being to identify the strongly and weakly connected components. A Walktrap community detection algorithm could be employed to find out the communities within the regional road network via random walks. 328 communities were identified after running the algorithm. From this, the weaker and stronger components of the overall regional road network in the district could also be easily distinguished.

```
[ ] place_name = "kottayam,india"

    # Fetch OSM street network from the location
    graph = ox.graph_from_place(place_name, network_type='drive')
```

```
[ ] len(graph.edges)

    50751
```

```
[ ] #the degree function in networkx returns a DegreeView object capable of iterating through (node, degree) pairs
    degree = graph.degree()

    degree_list = []

    for (n,d) in degree:
        degree_list.append(d)

    av_degree = sum(degree_list) / len(degree_list)

    print('The average degree is ' + str(av_degree))

    The average degree is 4.914161220843573
```

```
[ ] density = nx.density(graph)

    print('The edge density is: ' + str(density))

    The edge density is: 0.00011896391062369451
```

Figure 22. The steps being followed in community detection algorithm

```
[ ] coms = algorithms.walktrap(G)
```

```
[ ] readwrite.write_community_csv(coms, "community_kottayam_walktrap.csv", ",")
```

Figure 23. Syntax for walktrap community detection algorithm

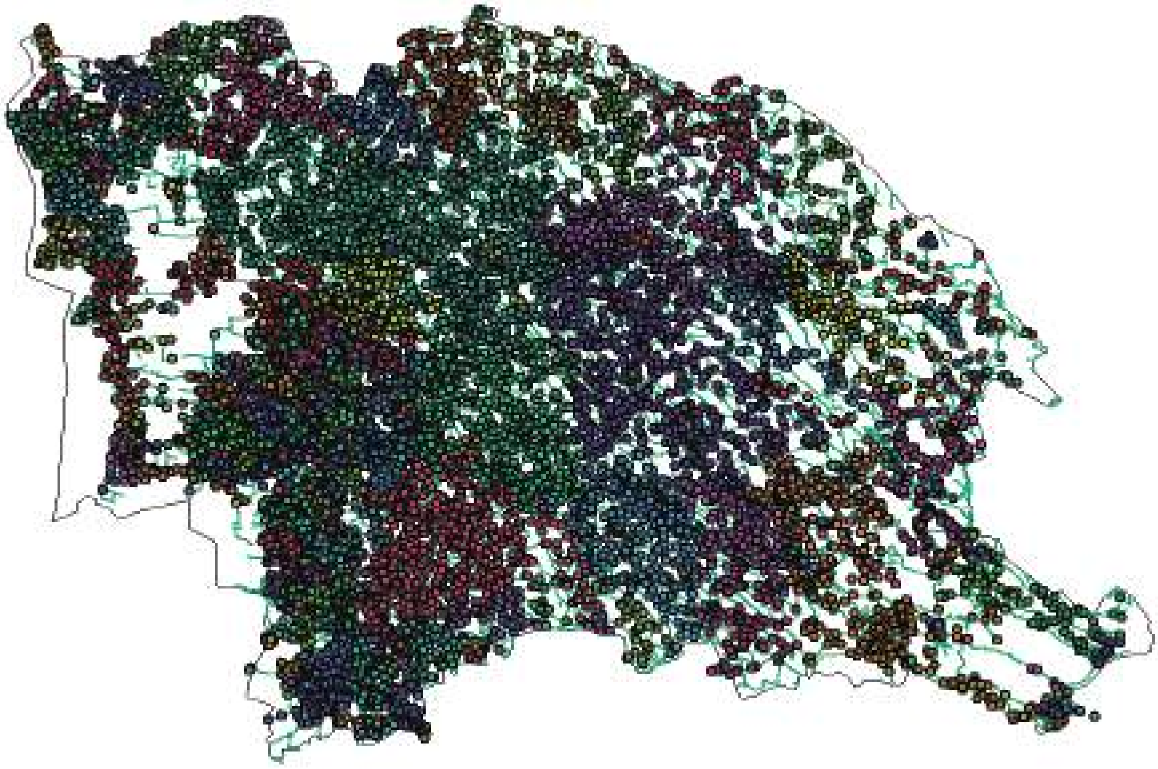

Figure 24. The communities identified after running the algorithm

Since the execution of the walktrap community detection algorithm for the 328 identified communities is computationally laborious, the already developed finer susceptibility map was utilized for identifying the weakly connected component of the overall regional road network in the district, although the former could also be applied at a much finer level.

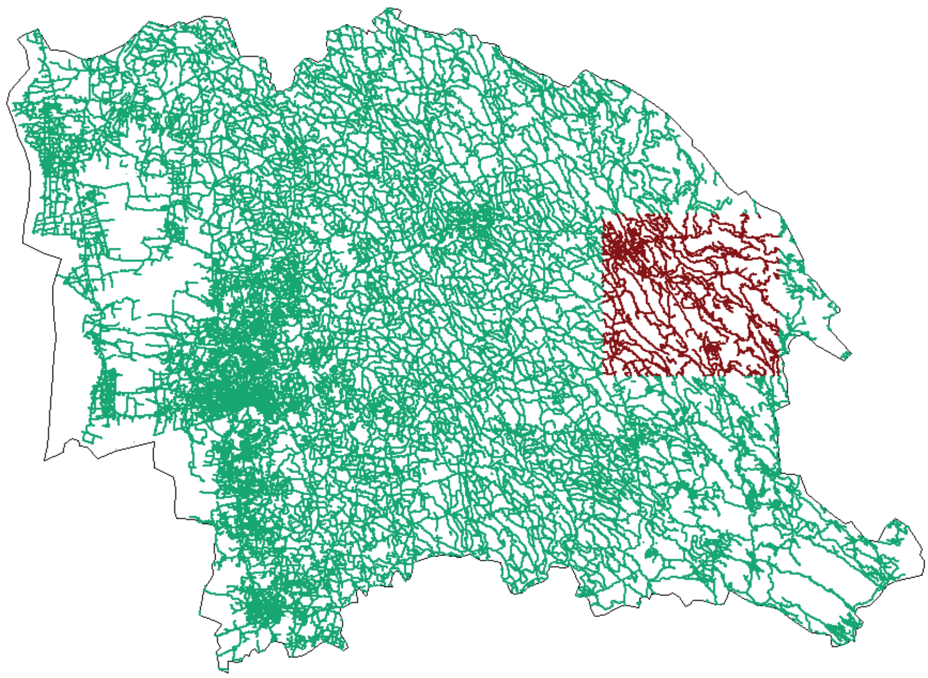

Figure 25. The identified weakly connected road network (the network shown in brown)

Figure 26 shows the syntax that was used for estimating the Betweenness Centrality of the identified weakly connected component of the district road network.

```
[ ] G

    <networkx.classes.digraph.DiGraph at 0x22cfd152af0>

[ ] nx.set_edge_attributes(G, values = 0, name = 'weight')

    D = list(G.edges.data())
    for i in range(len(D)):
        G[D[i][0]][D[i][1]]['weight'] = 1/(D[i][2]['Shape_Leng'])

[ ] len(G.edges)

    807

[ ] 1/0.00034832764524

    2870.8602767115817

[ ] edge_centrality = nx.edge_betweenness_centrality(G)
```

Figure 26. Syntax for estimating Betweenness Centrality

After running the syntax, the edge centrality values were obtained as represented in Figure 27.

```
edge_centrality

{((76.77846290038991, 9.68752130014849),
  (76.77841799978586, 9.68786630014074)): 0.0002856839682319427,
 ((76.77846290038991, 9.68752130014849),
  (76.81263419988949, 9.673848699750977)): 2.0405997730853054e-05,
 ((76.77841799978586, 9.68786630014074),
  (76.7780923002095, 9.68852609889202)): 0.00027412056951779266,
 ((76.78629810030708, 9.641469999782032),
  (76.80322920013998, 9.625155200242148)): 2.7207996974470738e-05,
 ((76.80322920013998, 9.625155200242148),
  (76.8033021003315, 9.625109000113355)): 2.4487197277023664e-05,
 ((76.77807339999327, 9.688607499602199),
  (76.77870780010312, 9.688797300364854)): 0.00020814117685470114,
 ((76.77807339999327, 9.688607499602199),
  (76.77374339967355, 9.693063099664698)): 4.625359485660025e-05,
 ((76.77870780010312, 9.688797300364854),
  (76.77901589988738, 9.688889000048164)): 0.00019045597882129517,
 ((76.77926119980032, 9.715448300427852),
  (76.77767985173443, 9.715698241757593)): 6.801999243617684e-07,
 ((76.76971435579884, 9.674638541908223),
  (76.76971435579884, 9.673115640980257)): 6.801999243617684e-07,
 ((76.76971435579884, 9.672424033002528),
  (76.77774260034431, 9.664237800420324)): 6.801999243617684e-07,
 ((76.82941580041518, 9.653440300083048),
```

Figure 27. Estimated Betweenness Centrality values of the edges with its latitude-longitude coordinates

The Betweenness Centrality values obtained were used to plot Figure 28.

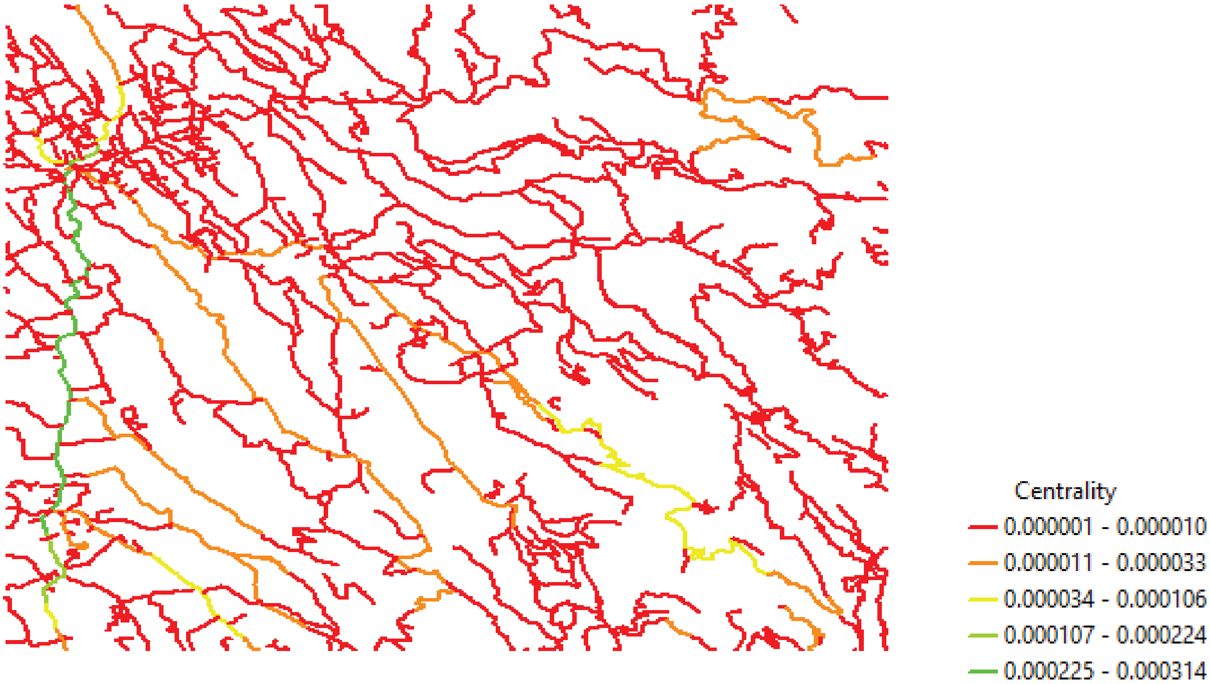

Figure 28. Betweenness Centrality of the weakly connected road network

After computing the Betweenness centrality as explained above, and after evaluating the Link-path incidence matrix, along with the failure probability values, we can estimate the links where probing is to be performed.

Figure 29 shows a sample execution of the resilience framework formulation, wherein python programming language was used to shortlist the links to be probed.

```
df['Product'] = df.apply(lambda row: (row['FP']*row['SumP']*row['BC']), axis=1)
print(df.nlargest(6, ['Product']))
```

```
     Link    FP  P1  P2  P3  P4  P5  P6  P7  P8  SumP  BC  Product
0       1  0.76   0   0   1   1   1   1   1   0     5   1     3.80
1       2  0.84   0   1   0   1   1   1   1   1     6   1     5.04
2       3  0.81   0   1   0   1   1   1   1   0     5   1     4.05
3       4  0.97   0   1   0   1   1   1   1   1     6   1     5.82
4       5  0.54   0   0   0   1   1   1   1   0     4   1     2.16
..    ...   ...  ..  ..  ..  ..  ..  ..  ..  ..   ...  ..      ...
791   792  0.80   0   0   1   1   1   1   1   1     6   1     4.80
792   793  0.51   0   0   1   1   1   1   1   1     6   1     3.06
793   794  0.38   0   0   1   1   1   1   1   1     6   1     2.28
794   795  0.16   0   0   1   1   1   1   1   1     6   1     0.96
795   796  0.28   0   0   1   1   1   1   1   1     6   1     1.68

[796 rows x 13 columns]
```

```
[ ] print("Selected links are = ", df.nlargest(6, ['Product']).iloc[0:6]['Link'].to_numpy())
    print("Mazimized value of product = ", df.nlargest(6, ['Product']).iloc[0:6]['Product'].sum())
```

```
Selected links are =  [161 198 399 701 148 241]
Mazimized value =  35.879999999999995
```

Figure 29. A snippet from the syntax for executing the formulation

5. Enablers and Barriers

The study mainly covers the risk quantification aspects and resilience improvement suggestions towards rural road networks, prone to landslides. The ArcGIS software package is used to derive the terrain parameters such as slope angle, slope length, etc. from the digitized topographic map of the study area. The accuracy of these derived parameters depends on the resolution of the available DEM.

Only those geological parameters that can be accessed remotely will be selected to prepare the preliminary map at the initial stage. The first order reliability probabilistic method was used on an infinite slope stability model so that relevant geotechnical parameters can be incorporated into the susceptibility model, considering it as random variables. More geotechnical parameters, if considered, might consume more time to yield the desired results. Consideration of more parameters need not yield a better susceptibility map, since several other factors also play a crucial part in it. Hence, the uncertainty in the values is reduced by adopting a probabilistic approach in a feasible manner

The study focused on developing a susceptibility map based on the spatial probabilistic distribution of landslides, by making use of a bi-variant regression. Though rainfall data is incorporated into the model, other landslide-triggering agents such as earthquakes, volcanic activity, etc., (which are rare events in the study area) have not been addressed here. Once they are considered, it would be possible to predict the landslides in terms of their temporal variation too. The model is being developed to provide information on the likelihood of landslides or slope failures in the study area. It is less likely to give information about areas inundated by debris. To address the latter, the magnitude/size of the landslide along with the run-out areas need to be incorporated into the hazard model.

6. Conclusion and Way Forward

The key takeaways from the project include mainly the following:

- An updated landslide inventory of Kerala focusing on the Western Ghats region
- A novel and robust methodology with which geotechnical properties can be incorporated into macro-level susceptibility mapping in a reliable and feasible manner
- An improved landslide susceptibility model for the study region taking into account the geotechnical properties of the slopes

These provide quantitative expertise on future slope failures, which could be used by the concerned authorities in land-use administration and planning. The model would improve road recovery to enhance resilience, and prioritize roads in the network based on impact, restoration time, mitigation plans and evacuation strategies

References

1. Achu, A.L., Aju, C.D., & Reghunath, R. (2020). Spatial modelling of shallow landslide susceptibility: a study from the southern Western Ghats region of Kerala, India. *Annals of GIS*, 1-19.
2. Aydin, N.Y., Duzgun, H.S., Heinimann, H.R., Wenzel, F., & Gnyawali, K.R. (2018). Framework for improving the resilience and recovery of transportation networks under geohazard risks. *International Journal of Disaster Risk Reduction* 31, 832-843.
3. Bayrak, H., & Bailey, M.D. (2008). Shortest path network interdiction with asymmetric information. *Networks: An International Journal*, 52(3), 133-140.
4. El Jazouli, A., Barakat, A. , & Khellouk, R. (2020). Geotechnical studies for Landslide susceptibility in the high basin of the Oum Er Rbia river (Morocco). *Geology, Ecology, and Landscapes*, 1-8.
5. Feby, B., Achu, A.L., Jimnisha, K., Ayisha, V.A. , & Reghunath, R. (2020). Landslide susceptibility modelling using integrated evidential belief function based logistic regression method: A study from Southern Western Ghats, India. *Remote Sensing Applications: Society and Environment*, 100411.
6. Haneberg, W.C. (2004). A rational probabilistic method for spatially distributed landslide hazard assessment. *Environ. Eng. Geosci.* 10 (1), 27–43.
7. Huang, J., Kao, S., Hsu, M., , & Lin, J. (2006). Stochastic procedure to extract and to integrate landslide susceptibility maps: an example of mountainous watershed in Taiwan. *Nat. Hazards Earth Syst. Sci*., 6, 803–805.
8. Igwe, O. (2015). The geotechnical characteristics of landslides on the sedimentary and metamorphic terrains of South-East Nigeria, West Africa. *Geoenvironmental Disasters*, 2(1), 1.
9. Jaafari, A., Najafi, A., Pourghasemi, H.R., Rezaeian, J., & Sattarian, A. (2014). GIS-based frequency ratio and index of entropy models for landslide susceptibility assessment in the Caspian forest, northern Iran. *Int. J. Environ. Sci. Technol*. 11, 909–926.
10. Jaiswal, P., van Westen, C.J., & Jetten, V. (2010). Quantitative landslide hazard assessment along a transportation corridor in southern India. *Engineering Geology*, 116(3-4), 236-250.
11. Kannan, M., Saranathan, E., & Anabalagan, R. (2013). Landslide vulnerability mapping using frequency ratio model: a geospatial approach in Bodi-Bodimettu Ghat section, Theni district, Tamil Nadu, India. *Arabian Journal of Geosciences*, 6, 2901–2913. doi:10.1007/s12517-012-0587-5.
12. Nefeslioglu, H.A., Gokceoglu, C. R. , & Sonmez, H. (2008). An assessment on the use of logistic regression and artificial neural networks with different sampling strategies for the preparation of landslide susceptibility maps. *Engineering Geology*, 97(3-4), 171-191
13. Norris, J.E., Stokes, A., Mickovski, S.B., Cammeraat, E., Beek, R., Nicoll, B.C., & Achim, A. (2008). *Slope Stability and Erosion Control: Ecotechnological Solutions*. Springer.
14. Rudiger, E., Jonathan, D. S., Vishnu, C., Oommen, T., & Sajinkumar, K. S. (2021). A GIS tool for infinite slope stability analysis (GIS-TISSA). *Geoscience Frontier*, 12(2), 756-768

15. Senouci, R., Taibi, N. E., Teodoro, A. C., Duarte, L., Mansour, H., & Yahia Meddah, R. (2021). GIS-based expert knowledge for landslide susceptibility mapping (LSM): case of mostaganem coast district, west of Algeria. *Sustainability*, 13(2), 630.
16. Schlögl, M., Richter, G., Avian, M., Thaler, T., Heiss, G., Lenz, G. , & Fuchs, S., (2019). On the nexus between landslide su sceptibility and transport infrastructure–an agent-based approach. *Natural Hazards & Earth System Sciences*, 19(1).
17. Yao, B., Hu, P., Lu, X., Gao, J. , & Zhang, M. (2014). Transit network design based on travel time reliability. *Transportation Research Part C: Emerging Technologies*, 43, 233-248.
18. Yates, J., & Sanjeevi, S. (2013). A length-based, multiple-resource formulation for shortest path network interdiction problems in the transportation sector. *International Journal of Critical Infrastructure Protection*, 6(2), 107-119.

Assessing Climate Change Risks to and Resilience of India's Seaport Infrastructure and Operations

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Coalition for Disaster Resilient Infrastructure

Abstract

In the increasingly interconnected and interdependent contemporary world, trade forms a significant component of every major economy; for India, trade accounts for over one-third of the total economy. Around 95% of India's merchandise trade, by volume, travels through the sea in cargo ships. India has 12 major ports and over 200 non-major ports that facilitate this trade and is expected to continue to grow in the future. In 2021, the Ministry of Ports, Shipping and Waterways of the Government of India unveiled the *"Maritime India Vision 2030"*. It outlines a growth model focussed on building world-class greenfield ports, creating "smart ports", modernizing existing ports, promoting port-led industrialization and public–private partnerships. While this ambitious vision and the development projects identified under it are critical in facilitating India's transition from a "*Brown Economy*" to a "*Blue Economy*", they are being and will continue to be seriously impeded by the ever-growing impacts of anthropogenic climate change. In this context, this study aims to assess the threats posed by climate change in the form of more intense and frequent extreme weather events and sea-level rise to India's port infrastructure and operations. The authors created a climate change-risk assessment framework and methodology that utilizes a combination of available climatic data, field-based research and expert interviews with port officials to generate "climate-risk profiles" of Indian ports. The framework was tested and implemented through case studies of two of India's major ports, namely the Mumbai Port Authority (on the west coast) and the Paradip Port Authority (on the east coast). Findings from the two ports were compared to bring out the differences and commonalities in the challenges facing individual ports. The study highlights the urgent need to devise comprehensive and dynamic climate-change adaptation strategies for individual ports and a concerted policy framework at the national level to ensure long-term security and sustainability of India's maritime trade sector.

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1. Introduction

At the Maritime India Summit in 2021, Shri Narendra Modi, the Prime Minister of India, declared India's ambition of becoming a major "Blue Economy" in the world. In this regard, amongst the Government of India's capstone publications documenting the country's developmental efforts, the "Maritime India Vision 2030" (MIV-2030) is arguably the most ambitious and comprehensive as it spells out a whole slew of initiatives to promote national port-led development (MoPSW, 2021a). The ports and shipping sector is a major economic sector of the country. The country has 12 major ports (under the Ministry of Ports, Shipping and Waterways) and over 200 non-major ports (under state governments or private administration) in India. Taken in aggregate, Indian ports handle around 95% of Indian trade (imports and exports) by volume and 68% by value (MoPSW, 2021b).

Formulated by the Ministry of Ports, Shipping and Waterways (MoPSW), MIV-2030 lists over 150 initiatives in the ports, shipping and inland-waterways sub-sectors, which are expected to generate over US$ 40 billion in investment, 2 million new jobs, double cargo-handling capacity and accelerate the growth of India's maritime sector over this decade (MoPSW, 2021a). In the ports sub-sector, the "creation of world-class greenfield ports, modernization of existing ports, creation of 'smart ports', enhancement of land-connectivity, promotion of port-led industrialization and public-private partnership (PPP)" are outlined as the principal themes. While the push for capacity augmentation and modernization is highly commendable, it is deeply disturbing that the MIV-2030 lays no explicit emphasis on *protecting* critical maritime-infrastructure assets against the ever-growing impacts of climate change.

Overwhelming scientific evidence clearly indicates that contemporary climate change, primarily caused by the increasing concentration of greenhouse gases in the atmosphere since the Industrial Revolution, has led to an increase in the frequency and intensity of hydrometeorological extreme events such as terrestrial and marine heatwaves, heavy rainfall events and cyclonic storms (Raghavan et al., 2020). Climate change has also led to an increase in global mean sea level since the 20th century (Oppenheimer et al., 2019). All of these trends are expected to continue at accelerating rates in the future if the global average temperature continues to rise unabated. These climate-change-induced changes pose direct and significant threats to India's holistic maritime security, as also that of every other coastal nation (Bajaj, 2020a; Bajaj 2020b; Bajaj and Honmane, 2020). Seaports are, more often than not, located in low-lying and high-risk coastal regions and are particularly susceptible and exposed to climate-related hazards.

In this regard, this study aims to highlight the current and projected impacts of climate change that continue to pose major risks to India's port infrastructure and operations. The study argues for the urgent need to develop comprehensive and dynamic climate change adaptation strategies at the individual port level as well as at the national policy level, which are informed by rigorous climate-change risk-assessments. Section 2 discusses in greater detail the research problem and objectives of the study. Section 3 outlines the research methodology, which incorporated a combination of desk-based research and field research. Sub-section 3.1 describes the climate change-risk assessment methodology that was created and implemented during the study. Section 4 presents and analyses the main findings from the case studies of three of India's major ports, namely, the Jawaharlal Nehru Port Authority, the Mumbai Port Authority and the Paradip

Port Authority. Section 5 discusses the enablers that contributed to the successful completion of the study and identifies a few of the more impactful barriers that were identified in the context of devising and implementing climate-change adaptation strategies for Indian ports. Finally, Section 6 provides a conclusion and outlines a way forward.

2. Research Problem, Aim and Objectives

As discussed in Section 1, the MIV 2030, while ambitious in its vision to expand India's maritime trade sector by the creation of world-class greenfield ports, smart ports and modernization of existing ports, puts no specific emphasis on enhancing resilience of the port ecosystem. It does not recognize the growing threats posed by the impacts of climate change, which can significantly "slow down" port operations and reduce port efficiency, causing economic losses worth crores of rupees to the country annually.

Admittedly, ports are trying to become "*green*" by reducing their emissions of greenhouse gases and other pollutants, primarily driven by the need to maintain international health and environmental standards to continue to attract international trade. MIV-2030 also encourages this through its targets of "port modernization" and creation of "smart ports", which includes, for example, increasing the level of mechanization in cargo handling procedures, which is particularly useful in reducing pollution related to the handling of dry-bulk cargo (such as coal, iron ore, fertilizer, etc.). Further, the creation of smart ports will inevitably lead to an increased usage of renewable energy sources, including solar and wind, in order to make the port's energy supply more robust.

In other words, typically, when port authorities think of "sustainability", their primary concern is on "how the port is affecting the environment" (i.e. through pollution of the air, water and/ or land degradation) and not quite so much on "how the environment might affect the port" (i.e., through the increasing frequency and intensity of extreme weather events and sea-level rise due to climate change, see Section 1.1).

This glaring gap was the primary motivation for this study. It needs to be clarified that the authors do not assert that ports are not prepared for natural and/or human-made disasters. Quite the contrary, in fact. Ports, almost invariably, have well-formulated disaster-management strategies including standard operating procedures during disasters such as tropical cyclones. However, none of the ports in India have a dedicated and comprehensive "climate-change adaptation" strategy that accounts for the changing behaviour of hydrometeorological disasters and the slow-moving yet high-impact and irreversible threat of sea-level rise.

Accordingly, the study has the following four main objectives:

1. Create awareness about the impacts of climate change on the port and the need for climate-change adaptation in addition to climate-change mitigation.
2. Determine and classify the "degree of risk" posed by individual climate change-related hazards to individual port infrastructure assets and operations, in order to inform "areas of priority" for individual ports.

3. Conduct a comparative risk analysis of India's major ports in order to inform policymakers in the Government of India of the most vulnerable ports.
4. Propose practical and implementable adaptation solutions, based on local-level capacities and limitations that could be adopted to minimize the impact of these threats.

3. Methodology

The study was divided into two major phases: (a) Desk-research phase and (b) Field work and analysis phase. The desk-research phase was primarily devoted to a comprehensive literature review to identify and assess current best practices with regard to climate-risk assessments of seaports and adaptation strategies that are being formulated or implemented by seaports internationally (Scott, et al., 2013; Nursey-Bray et al., 2013; McIntosh and Becker, 2017; Asariotis, Benamara and Mohos-Naray, 2017; Esteban et al., 2020). Conclusions were then drawn for the Indian context and the steps that could and should be taken by Indian ports to move towards a more climate-resilient future. The findings have been published elsewhere (Bajaj and Youdon, 2021). It was realized that before any climate-change adaptation strategy could be devised for Indian ports, the first step would be to sensitize the port authorities and other stakeholders, at the local level, and policymakers, at the national level, regarding the current and projected threats posed by climate change in the near- to mid-term future (05–30 years). In this regard, a climate-risk assessment framework and methodology was generated, as described in greater detail below, for the second phase of the project.

The field work and analysis phase was dedicated to implementing the climate-risk assessment methodology that had been created in the first phase with respect to Indian ports to provide a semi-quantitative understanding of the level-of-risk posed by climate change to individual infrastructure assets and operations. Three major ports were chosen for the field visits, based on a comparative "climate vulnerability" analysis of India's 12 major ports. Six indicators were utilized for the analysis to determine (a) the amount of cargo handled by the ports, which would indicate their criticality to India's overall maritime trade, (b) the performance and efficiency of the ports and (c) their potential vulnerability to the impacts of climate change such as increasingly frequent and more intense extreme-weather events and sea-level rise. The six indicators were: (i) climate vulnerability ranking of the port's district based on government data, (ii) annual cargo traffic volume, (iii) distribution of different types of cargo handled by the port, (iv) vessel turn-around time, (v) number of vessels visiting the port per year and (vi) average berth productivity. The complete analysis will be published elsewhere. Based on this preliminary analysis and considering the ease of access, the Jawaharlal Nehru Port Authority (JNPA) on the West Coast of India was chosen for the pilot study. Owing to its geographic proximity to the JNPA, the Mumbai Port Authority (MbPA) was also included in the pilot study. The Paradip Port Authority (PPA) was chosen for the second field study, as a representative port on the eastern coast of India where the local environmental conditions and climate change-related challenges are very different from those on the western coast.

3.1 Climate-risk and resilience assessment methodology for Indian ports

Following the broad definition put forward by the United Nations Intergovernmental Panel on Climate Change (IPCC), climate risk has been described as a combination of "*hazard*", "*exposure*" and "*vulnerability*" (IPCC, 2007). As alluded to earlier, in the present context, the 'hazards' correspond to extreme environmental conditions that are becoming more frequent and more intense due to contemporary climate change, such as sustained extreme temperatures (or heatwaves), extreme precipitation (that may lead to flooding) and tropical revolving storms (or cyclones). Another climate change-induced hazard that is relevant for coastal regions and, in turn, for port infrastructure and operations is the rising sea level due to increasing ocean temperatures, coupled with the melting of mountain glaciers and land-based polar ice caps.

"Exposure" (to climate-related hazards) connotes the ways in which a port or its individual infrastructure assets and operations may or may not be affected by these hazards. The port's "vulnerability" could be then described as the *degree* to which the port or its individual assets and operations may be affected. Vulnerability can, in turn, be viewed as a function of "*sensitivity*" and "*adaptive capacity*", where sensitivity is a measure of the extent of damage that could potentially be caused by an extreme event or a climatic trend, while adaptive capacity is a measure of the extent to which this potential damage can be minimized by taking some timely and commensurate action during an extreme event or in response to a climatic trend.

Consistent with existing methodologies in the available literature, the climate change-related risk to the selected port was estimated by assessing the exposure and vulnerability of individual port assets and their associated operations to climatic hazards. Five main hazards were selected that are expected to pose the most significant threats to ports: (1) extreme temperature; (2) extreme precipitation; (3) cyclonic storms (incorporating the IMD-defined-categories of "Cyclonic Storm", "Severe Cyclonic Storm" and "Very Severe Cyclonic Storm", i.e., sustained wind speeds between 62 and 167 km per hour [kmph]); (4) Extremely Severe Cyclonic Storms and higher (incorporating IMD-defined-categories of "Extremely Severe Cyclonic Storm" and "Super Cyclonic Storm", i.e., sustained wind speeds higher than 168 kmph); and (5) Sea Level Rise. Port assets were divided into three categories: *sea side*, *port side* and *hinterland side*. To determine the magnitude of climate risk posed to each asset and, in turn, to the port, a series of interviews were conducted with port officials, including the Chairman and/or Deputy Chairman and the Heads of Departments of the marine department, the traffic department, the mechanical and civil engineering department, the port planning and development department and the environment-planning department.

The interviews were conducted in a free-flowing but guided discussion format, centred upon questions designed to ascertain the exposure and vulnerability of individual assets. While determining the exposure of an asset to a particular hazard was relatively straightforward, quantifying the vulnerability of the asset was much more nuanced and relied on multiple parameters. Factors such as the age and condition of the asset, its cost, the ease and cost of maintenance of the asset, the ability of the port to function efficiently without the asset and the ability of the port to find an alternative or replacement to the asset contributed to the vulnerability. In the present context, the risk to the port arises from its dependence on proper functioning of its infrastructure assets and personnel to continue its operations at maximum efficiency. These factors were discussed during the interviews with the port authorities and the authorities were asked to assign a “risk value” to each individual asset based on the risk index described in Table 1.

To gather qualitative insights into the *resilience* of the port in the face of a high-impact extreme weather event, the port authorities were asked to share their experiences and the port’s response to an extremely severe cyclonic storm that had occurred in the recent past. In the case of the western coast ports (JNPA and MbPA), cyclone *Tauktae* (2021) was taken as the case study, while for the eastern coast (PPA), cyclone *Hudhud* (2014) was taken as the case study.

Table 1. Climate change risk scale

Risk Value	Description
1	No Risk
2	Low Risk
3	Moderate Risk (Port operation down for hours)
4	High Risk (Port operation down for days)
5	Extreme Risk (Port operation down for weeks)
N/A	Not Applicable

4. Results and Discussion

As described in Section 4, a climate-risk assessment framework and methodology was created for ports as a first step towards a climate-adaptation strategy for Indian ports. The framework was tested through a pilot study of the JNPA and the MbPA (JNPA, nd; MbPA, nd).

While the pilot field visit to JNPA was extremely insightful and allowed the authors an opportunity to sensitize the port authorities to the urgent need for climate change adaptation, the interviews and discussions with the authorities at the JNPA ended-up taking an unstructured form and were, therefore, limited to preliminary qualitative discussions regarding the potential impacts of climate change-induced hazards on the infrastructure of the port, and steps that could be taken by the port authority to minimize these impacts. Discussions also concentrated on the efforts being made by the port to minimize its environmental footprint by minimizing its interference with the surrounding natural ecosystems and by investing in renewable energy for power generation. Unfortunately, due to limited time available for interactions with the JNPA personnel, the discussions could not be unambiguously converted to a “climate-risk profile” for the port as had been envisioned in the methodology. This was an important learning-experience for the authors, and one that led to important modifications in the way the interviews needed to be structured to best utilize the limited amount of time and yet produce maximum results. A new, streamlined and focused approach was then followed during the pilot study of the MbPA, which did, indeed, led to the desired result of development of a climate-risk profile for the port, as shown in Table 2.

The second field study was conducted at the PPA, which is strategically situated between the Kolkata Port and the Visakhapatnam Port. The PPA is an artificial deep-water port located on the east coast of India in Jagatsinghpur district of Odisha (PPA, nd). The PPA handles the largest volume of dry-bulk cargo of all 12 of India's major ports, with thermal coal and coking coal being the main entities, largely due to the port's proximity to the Mahanadi coalfields. The detailed climate-risk profile of the infrastructure assets of the PPA is provided in Table 3.

The climate-risk profiles produced for the MbPA and the PPA suggest that all the three sections of the port ecosystem, viz., sea-side, port-side and hinterland side, are impacted by the different climate change-induced hazards. As was expected, both the climate-risk profiles are broadly similar in terms of the relative level of risk posed by the individual climate hazards on individual infrastructure assets. However, the absolute risk values, as prescribed by the port authorities, do vary to some extent, which could be partially attributed to the different local-level geographical, environmental and economic conditions and limitations.

The most apparent conclusion from both the risk profiles is that the highest level of risk (risk index value ranging from 3 to 5, corresponding to Moderate-to-extreme risk, see Table 1), as perceived by the port authorities, is posed by cyclonic storms, specifically from Extremely Severe Cyclonic Storms or higher, i.e., when wind speeds are higher than 168 kmph. This assessment is supported by the first-hand experiences of the port authorities of such high-intensity cyclonic storms, such as Cyclone *Tauktae* at Mumbai Port, Cyclone *Nisarga* at JNPA, and Cyclone *Hudhud* at Paradip Port. Most of the infrastructure at these ports, including the cargo-handling equipment, cargo-storage areas and administrative and residential buildings are not designed to withstand sustained wind speeds greater than 160 kmph.

Standard operating procedures dictate that during any cyclonic storm, the port is to halt all operations. All the vessels inside the port have to move outside to the anchorage area, all cargo-handling equipment have to be anchored and secured, cargo-storage facilities have to be secured appropriately (depending on the cargo type) and all staff members, except essential staff, have to vacate the port premises. This 'shut-down' period could last for a few hours to a couple of days, depending on the intensity and speed of the cyclonic storm.

Even after the emergency-preparedness protocols are followed and the infrastructure is secured, significant damage can and does accrue, particularly in the case of extremely severe cyclonic storms. For instance, Cyclones *Tauktae* and *Hudhud* recorded maximum sustained wind speeds of over 185 kmph and caused very heavy rainfall. Depending on the extent of the damage caused, the recovery period after a major cyclone could vary from a few hours to several days, during which several segments of the port, or the entire port, may be forced to halt some or all operations.

Apart from cyclonic storms, extreme precipitation events, such as heavy monsoon rains or cloud-burst events, also pose a risk to port operations (see Tables 2 and 3). In sea-side operations, the primary cause for concern is low visibility during heavy rainfall and choppy waters if there are strong winds. In extreme cases, low visibility hampers the ability of pilot boats and tugs to bring a cargo ship from the anchorage area into the port. Such conditions might stop seaside operations, albeit for a few hours at the most, if heavy rains continue to be experienced.

As far as port-side operations are concerned, barring extreme cases, heavy rainfall events typically do not affect container cargo-handling equipment or storage areas, primarily because the cargo is secured within containers. Similarly, heavy rainfall does not affect liquid-bulk cargo operations because most of it is handled through pipelines. Heavy rainfall could, however, affect handling and storage facilities for dry-bulk cargo (such as coal, iron ore, limestone, etc.). In general, low visibility and flooding during heavy rainfall events typically affect port-side operations for a few hours. Port authorities placed the risk posed by extreme-precipitation events in the range of 2 to 3, corresponding to Low-to-Moderate risk (see Table 1).

Heavy precipitation poses a greater risk to hinterland connections such as roadways, railways, power connections, communication lines, waste services and staff-access to the port, due to flooding. This is a significant concern for the MbPA during the monsoon months, when urban flooding can cause slowdown of cargo moving out of the port via road or railway (see Table 2). This slowdown in public transportation would also affect the ability of the staff to reach the port.

Extreme temperature events or heatwaves were rated as the lowest risk hazard with regard to their impact on hard infrastructure, which is negligible. The port authorities did however acknowledge that in extreme cases, heatwaves could affect work efficiency and the health of the port staff. This is particularly relevant for dry-bulk cargo-handling facilities, where already-harsh working conditions can become intolerable during heatwaves. The health impacts of heatwaves have, of course, been widely reported in medical journals. The latest and best available science unequivocally states that heatwaves will become more common and intense as the global average temperature continues to rise. Tropical countries including India are particularly vulnerable to extreme heatwaves.

While port authorities at both the MbPA and the PPA recognise the potential threat posed by climate change-induced sea-level-rise, the authors would argue that risk ratings for sea level rise may be underestimated (see Tables 2 and 3). The port authorities noted that sea level-rise might, in fact, bring some benefits for the port because an increase in sea level would increase the depth of the navigation channel of the port, which would reduce the dredging requirements for the port and allow larger vessels with greater draughts to enter the port. Dredging is a very expensive activity that is carried out frequently by ports in order to maintain the depth of their navigation channels. Clearly, any reduction in the frequency of dredging would be hugely beneficial to the port. However, there are many additional ways in which sea-level rise would adversely affect the port's infrastructure and operations. For instance, the jetties and associated cargo handling infrastructure on the jetty are designed at specific heights, which consider the vessel types that will be handled by the terminal. A change in sea level, combined with tidal variations, would change the height of the freeboard of the ship relative to the jetty, which could affect cargo handling operations. In response to this, the port authorities pointed out that height of the freeboard of the ship can be altered through ballast water management. However, they admitted that if there were large variations in sea level, around or greater than 0.5 m, in the medium- to long-term future, this could affect port operations.

Most importantly, the authors argue that sea-level rise poses a serious and irreversible threat to port infrastructure and operations due to permanent inundation of low-lying areas within the port and of low-lying areas in the city. Future projections based on the latest global climate model simulations suggest that large areas would be inundated by sea-level rise in the not-too-distant future (Climate Central, nd). This would be further exacerbated by coastal flooding, including tidal flooding and monsoonal flooding, which are experienced on an annual basis. Moreover, several scientific studies in recent years have highlighted that there are physical processes contributing to the acceleration of the melting of the Greenland and Antarctic Ice Sheets which would, in turn, accelerate global mean sea-level rise. To name a few, these processes include a reduction of ice sheet surface albedo due to algal blooms, soot-particle depositions and a consequent increase in the number of meltwater lakes, encroachment of warm ocean water from under the Antarctic ice sheet that leads to the formation and destabilization of "ice cliffs", etc. These processes are not yet included in global climate models because they have only recently been discovered (Bajaj, 2019).

Table 2. Climate change risk assessment of Mumbai Port Authority

Port Interface	Asset/ Operation	Extreme Temperature	Extreme Precipitation	Cyclonic Storms	Extremely Severe Cyclonic Storms	Sea-Level Rise
Seaside	Access Channel	1	1	3	3	1
	Anchorage/ Waiting Area	1	2	3–4	3–5	1
	Navigation Assistance (Pilot/ Tugboat)	1	2	3–4	3–4	1
	Lock Gate/ Berthing Area	1	2	3–5	3–5	3–5
Portside	Crude Oil Jetties	1	1	4	4–5	4
	Crude Oil Loading Arm	1	1	3	4	2
	Oil Pipelines/ Valve Stations	1	1	2	2	1
	Office/ Admin Buildings (*Jawahar Dweep*)	1	1	1	1	1
	Break-bulk Jetties	1	2	3	4	2
	Cargo Transit/ Storage Areas	1	3	3	4	1
	Ship-repair Facilities	1	3	3	4	1
	Commercial Fishing Facilities	1	1	3	4	2
	Admin Staff and Workers	3	3	3	4	1
Hinterland Connections	Roadways	1	3	3–4	4	1

Port Interface	Asset/ Operation	Extreme Temperature	Extreme Precipitation	Cyclonic Storms	Extremely Severe Cyclonic Storms	Sea-Level Rise
	Railways	1	3	3–4	4	1
	Power Connections	1	1	1	3	1
	Communications	1	1	1	3	1
	Waste Services	1	1	2–3	4	1

Note: Refer to Table 1 for description of risk scale. See text for detailed explanations of the factors contributing to the risk ratings

Table 3. Climate change risk assessment of Paradip Port Authority

Port Interface	Asset/ Operation	Extreme Temperature	Extreme Precipitation	Cyclonic Storms	Extremely Severe Cyclonic Storms	Sea-Level Rise
Seaside	Breakwater North	1	1	3	3-4	2-3
	Breakwater South	1	1	3	3-4	2-3
	Access Channel	1	1	3	3	1
	Anchorage/ Waiting Area	1	1	2-3	3	2
	Navigation Assistance (Pilot/ Tugboat)	2	2	3	3-4	1
	SPMs	1	1	3	3-4	1
Portside	Coal Berth	2	2	3	3-4	1-2
	Coal Handling Facility	1	2	3	3-4	1
	Iron Ore Berth	1	2	3	3-4	1-2
	Iron Ore Handling Facility	1	2	3	3-4	1-2
	General Cargo Berth	1	2	3	3-4	1-2
	North Oil Jetty	2	2	3	3-4	2-3
	South Oil Jetty	2	2	3	3-4	2-3
	Fertilizer Berth	1–2	2	3	3–4	1–2
	Multi-Purpose Cargo Terminal	1	2	3	3–4	1–2
	Ro-Ro Jetty	1	1	3	3–4	1–2
	Mobile Cranes	1–2	1–2	2–3	3–4	1–2

Port Interface	Asset/ Operation	Extreme Temperature	Extreme Precipitation	Cyclonic Storms	Extremely Severe Cyclonic Storms	Sea-Level Rise
	Clean Cargo Terminal	1	1-2	3	3–4	1–2
	Cargo Storage Facilities	1	1	2	2–3	1–2
	Ship Repair/ Dry Dock	1	1	2–3	3–4	2–3
	Office and Admin Buildings	2	2	2–3	2–3	1
	Staff and Workers	2–3	2	3	3–4	1
Hinterland Connections	Roadways	1–2	2–3	2–3	2–3	1
	Railways	1–2	1–2	2	2–3	1
	Power Connections	1	2	2	2	1
	Communications	1	2	2–3	3–4	1
	Waste Services	1	2	2	3	1
	Staff Access	1–2	1–2	2	3	1

Note: Refer to Table 1 for description of risk scale. See text for detailed explanations of the factors contributing to the risk ratings

Clearly, managing these impacts of climate change on brownfield and greenfield projects will require extensive and long-term planning and coordination between all relevant stakeholders. Some of the potential adaptation measures were discussed with the port authorities during the field visits. Typically, these measures can be divided into two categories: “hard measures” and “soft measures”. Hard measures include infrastructural upgrades or additions, such as creation of protective infrastructure (seawalls/dikes), upgrading breakwaters (construction material or dimensions), increasing the elevation of existing infrastructure, retrofitting or strengthening existing infrastructure, upgrading drainage systems, mechanizing cargo handling facilities to minimize exposure, etc. In this context, “nature-based solutions” must also be considered that focus on the protection, conservation and expansion of coastal and marine ecosystems, such as mangroves and seagrass, that act as natural protection against cyclonic storms, floods and storm surges (Cheong et al, 2013). Of course, almost all the hard infrastructural measures involve hefty financial costs and careful analysis and planning to justify those costs. Soft measures, on the other hand, mainly require changes in policies or standard operating procedures. For instance, emergency response protocols, working protocols, training exercises, building codes, etc.

All potential adaptation measures must be analysed on a case-to-case basis and evaluated for their effectiveness, technological feasibility and financial viability, in order to determine the ones most appropriate to a specific port. Arguably, a comprehensive adaptation strategy, particularly for a developing country such as India, which has limited technological and financial capacity, would necessarily constitute a combination of "hard measures" and "soft measures". As alluded to earlier, this would greatly depend on the local-level circumstances and limitations of a particular port. Much more research would be required to devise effective and practical adaptation strategies for individual ports, which was outside the scope of this study but will be addressed in subsequent ones.

5. Enablers and Barriers

It is substantially evident, even at the global scale, that efforts focussed on climate change adaptation are significantly lagging efforts focussed on climate change mitigation. While climate change mitigation through drastic cuts in greenhouse gas emissions must certainly take top priority to avoid some of the worst-case future-warming scenarios, we must also simultaneously protect and adapt our civilizations to the impacts of climate change that have already occurred or those that are projected to occur in the near future. This is even more important for a densely populated and fast-growing economy such as India and, within India, the coastal regions that are particularly vulnerable to climate change.

In this context, this study is a one-of-its-kind study in India, but the first step towards developing a comprehensive climate change adaptation strategy for the country's maritime trade and transport sector. The institutional support and patronage provided by the National Maritime Foundation (NMF) as the endorsing institute and the Coalition for Disaster Resilient Infrastructure (CDRI) Fellowship were crucial enablers of this research, particularly in facilitating the field visits to the JNPA, MbPA and PPA, which were essential elements of the study.

While most of the stakeholders that were interviewed had personal anecdotes and impressions based on those anecdotes, regarding the changes that have occurred in ocean conditions and weather patterns in recent years/decades, there was a general lack of awareness about the current and projected impacts of climate change on coastal areas, in general, and ports, in particular, based on the latest, widely-accepted scientific understanding. This sort of conviction, based solely on anecdotal evidence, invariably, leads to a biased and often incorrect understanding of the actual manner in which climate change may or may not affect a particular city or port. Arguably, the primary reason for this state of affairs is a dearth of easily accessible, local-level climate change projections for India and a lack of discussion forums where these projections and their implications for critical maritime infrastructure could be discussed between climate scientists, port authorities, policy-shapers and policymakers. In this context, the discussions that took place during the field visits within this project were a critical and much-needed first step towards sensitizing the port authorities.

For construction of greenfield infrastructure and major renovation activities of brownfield infrastructure, a port authority typically hires external consultants and construction companies to design and implement the projects based on the specifications provided by the port. Typically, the project-planning phase includes an analysis of past trends (up to 100 years) in respect of weather parameters and ocean conditions for the particular location, in order to determine the various design parameters of the marine infrastructure. However, it is no longer sufficient to consider past trends alone. Future projections of climate change impacts must be built into the design parameters during the planning stages. This would require concerted efforts between the external agencies, local climate modellers and port authorities.

6. Conclusion and Way Forward

This study reflects a critical first step towards developing a comprehensive climate-adaptation and resilience strategy for India's maritime trade sector. As climate change continues unabated, its manifestations in the form of more intense and frequent extreme weather events and accelerating sea-level rise will continue to pose direct and serious threats to India's critical maritime infrastructure, including seaport infrastructure and operations. In this context, the study aimed to highlight the urgent need for creating climate-adaptation plans at the individual port level as well as at the national level. The authors created a climate-risk assessment framework and methodology for Indian ports, based on existing international best practices. The framework included a perception-based study that relied on extensive interviews and discussions with relevant stakeholders (in this case, the port officials) to generate a semi-quantitative "climate-risk matrix" of the port's infrastructure assets and operations. Accordingly, the framework was tested and applied to generate climate-risk profiles of Mumbai Port Authority and Paradip Port Authority in consultation with the respective port officials.

As discussed in Section 4, the findings show that according to the port officials interviewed, of the various climate change-induced hazards, cyclonic storms pose the most serious threat to the port as they typically lead to operational downtimes ranging from a couple of days to over a week, depending on the strength of the cyclone. Extremely severe cyclonic storms with wind speeds greater than 168 kmph have, in the past, caused significant infrastructural damage to the port, and since such extreme cyclones are expected to become more common in the future due to climate change, they will pose a major challenge for Indian ports. Extreme rainfall events, followed by extreme heatwaves, also pose threats to port infrastructure and operations, albeit to a lower degree than cyclonic storms. While the port authorities recognized the long-term threat from climate change-induced sea-level rise, the level of risk was not perceived to be very high. The authors argue that this may be an unaffordable underestimation, but one reason for this is the lack of robust, easily comprehensible local-level climate-model projections for sea-level rise, leading to the lack of appreciation of the interconnectedness between the port and the city, wherein if large swaths of the city are inundated, it will inevitably lead to knock-on effects on the port.

While there are some generic best practices that can be followed and infrastructural upgrades that can be made to address the impacts of climate change-related hazards, more in-depth research, along with concerted effort on the part of all stakeholders, would be required if we are to devise effective and practical climate adaptation strategies for individual ports that account for local-level challenges and limitations. The authors believe that this study can and must act as a trigger for additional studies and inter-organizational collaboration on the subject. The natural extension of this study would be to expand the scope of the climate-risk assessments to a pan-India level and analyse as many major and non-major ports of India as possible. This would generate a holistic picture of the degree of risk posed by climate change to India's ports sector and maritime trade sector in general. Additionally, as discussed in this article, individual ports must invest time and resources in collaboration with external agencies, most certainly including think-tanks and city authorities, to devise dynamic and holistic adaptation-strategies that can minimize the impacts of climate change on their infrastructure and operational efficiency.

As India moves full steam ahead to achieve its goal of becoming a leading blue economy of the world, it must recognize and proactively address the ever-growing challenges from climate change, which otherwise have the potential to undo any progress that may be made by ambitious coastal-development projects. Effective climate-change adaptation would require long-term planning and the adoption of a holistic approach that accounts for the needs of all stakeholders. Therefore, we must start planning now to ensure a safe and resilient maritime economy.

References

1. Asariotis, R., Benamara, H. & Mohos-Naray, V. (2017). Port industry survey on climate change impacts and adaptation. *UNCTAD Research Paper No 18*.
2. Bajaj, P. (2019). Our best-case climate scenario could save tons of island residents. It could also be a myth. *The Print*. Details available at https://theprint.in/science/our-best-case-climate-scenario-could-save-tons-of-island-residents-it-could-also-be-a-myth/227435/.
3. Bajaj, P. (2020a). Climate Risks to India's Holistic Maritime Security Part 1: Rising Sea Level. *National Maritime Foundation Website*. Details available at https://maritimeindia.org/climate-risks-to-indias-holistic-maritime-security-part-1-rising-sea-level/.
4. Bajaj, P. (2020b). Climate Risks to India's Holistic Maritime Security Part 2: Intensifying Extreme Weather. *National Maritime Foundation Website*. Details available at https://maritimeindia.org/climate-risks-to-indias-holistic-maritime-security-part-2/.
5. Bajaj, P. and Honmane, A. (2020). Climate Risks to India's Holistic Maritime Security Part 3: Collapsing Ocean Biodiversity. *National Maritime Foundation Website*. Details available at https://maritimeindia.org/climate-risks-to-indias-holistic-maritime-security-part-3-collapsing-ocean-biodiversity/.
6. Bajaj, P., & Youdon, C. (2021). Towards a Comprehensive Climate Adaptation Framework for India's Port Infrastructure and Operations: Lessons from Global Best Practices. *International Journal on Environmental Science and Sustainable Development, 6(2)*, 48-59. Details available at https://dx.doi.org/10.21625/essd.v6i2.837.
7. Cheong, S-M., Silliman, B., Wong, P., van Wesenbeeck, B., Kim, C-H., & Guannel, G. (2013). Coastal adaptation with ecological engineering. Nature Climate Change, 3, 787-791. Details available at https://www.nature.com/articles/nclimate1854.
8. Climate Central (n.d). Climate Risk Screening Tool. *Climate Central*. Details available at https://coastal.climatecentral.org/.
9. Esteban, M., Takagi, H., Nicholls, R.J., Fatma, D., Pratama, M.B., Kurobe, S., Yi, X., Ikeda, I., Mikami, T., Valenzuela, P., & Avelino, E. (2020). Adapting ports to sea-level rise: Empirical lessons based on land subsidence in Indonesia and Japan. *Maritime Policy and Management,* 47(7), 937-952.
10. Fuchs, R.J. (2010). Cities at risk: Asia's coastal cities in an age of climate change. *AsiaPacific Issues,* 96.
11. IMDC. (2021). *Global Report on Internal Displacement 2021*. Geneva: Norwegian Refugee Council.
12. IPCC. (2007). Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linder, P.J. & Hanson, C.E. (Ed.). Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press.
13. IPCC. (2021). Summary for Policymakers. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. & Zhou, B. (Ed.). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group 1 to the*

Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press.

14. JNPA. (n.d). *Jawaharlal Nehru Port Authority Website*. Details available at https://www.jnport.gov.in/.
15. Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C-H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K. & Wu, L. (2020). Tropical Cyclones and Climate Change Assessment: Part II: Projected Response to Anthropogenic Warming. *Bulletin of the American Meteorological Society, 101(3)*, E303-E322. Details available at https://doi.org/10.1175/BAMS-D-18-0194.1.
16. Kulp, S.A., & Strauss, B.H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications, 10*, 4844.
17. McIntosh, D.R., & Becker, A. (2017). Seaport climate vulnerability assessment at the multi-port scale: A review of approaches. In: Linkov, L. & Palma-Oliveira, J.M. (Ed.). *Resilience and risk: Methods and application in environment, cyber and social domains*. Dordrecht: Springer Netherlands, 205-224.
18. Medha, Mondal, B., Doloi, G., Islam, S.M.T., & Bera, M.M. (2021). Damage Estimation using Shock Zones: A case study of Amphan tropical cyclone. *Research Square*. Details available at https://doi.org/10.21203/rs.3.rs-962664/v2.
19. Mohapatra, M., Sharma, M., Devi, S.S., Kumar, S.V.J., & Sabade, B.S. (2021). Frequency of genesis and landfall of different categories of tropical cyclones over the North Indian Ocean. *Mausam, 72(1)*, 1-26.
20. MoPSW. (2021a). *Maritime India Vision 2030*. New Delhi: Ministry of Ports Shipping and Waterways of Government of India.
21. MoPSW. (2021b). *Annual Report 2020-21*. New Delhi: Ministry of Ports Shipping and Waterways of Government of India.
22. MbPA. (n.d). *Mumbai Port Authority, India Website*. Details available at https://www.mumbaiport.gov.in/.
23. Nursey-Bray, M., Blackwell, B., Brooks, B., Campbell, M.L., Goldsworthy, L., Pateman, H., Rodrigues, I., Roome, M., Wright, J.T., Francis, J. & Hewitt, C.L. (2013). Vulnerabilities and adaptation of ports to climate change. *Journal of Environmental Planning and Management,* 56(7), 1021-1045. Details available at https://doi.org/10.1080/09640568.2012.716363.
24. Oppenheimer, M., Glavovic, B.C., Hinkel, J., van de Wal, R., Magnan, A.K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R.M., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B. & Sebesvari, Z. (2019). Sea level rise and implications for low-lying islands, coasts and communities. In: H.O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama & N.M. Weyer (Ed.). *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. In press.
25. PPA (n.d). *Paradip Port Authority Website*. Details available at https://paradipport.gov.in/.
26. Raghavan, K., Jayanarayanan, S., Gnanaseelan, C., Mujumdar, M., Kulkarni, A., & Chakraborty, S. (2020). *Assessment of Climate Change over the Indian Region*. New Delhi: Ministry of Earth Sciences, Government of India.

27. Ranasinghe, R., & Jongejan, R. (2018). Climate change, coasts, and coastal risk. *Journal of Marine Science and Engineering, 6(4)*, 141. Details available at https://doi.org/10.3390/jmse6040141.

28. Scott, H., McEvoy, D., Chettri, P., Basic, F., & Mullet, J. (2013). *Climate change adaptation guidelines for ports: Enhancing the resilience of seaports to a changing climate*. Gold Coast: National Climate Change Adaptation Research Facility.

29. Thakur, S. (2021). Ports and climate uncertainty: An economic imperative for India. *Maritime Affairs: Journal of the National Maritime Foundation of India, 17(2)*, 91-106. Details available at https://doi.org/10.1080/09733159.2022.2027115.

“InfraRivChange”: A Web-Based Application to Monitor River Migration at Sites of Critical Bridge Infrastructure in the Philippines

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Abstract

Shifting rivers represent a geomorphic hazard at sites of critical bridge infrastructure, particularly in rivers where migration rates are high. Conventional attempts to map and measure shifts in the position of rivers usually requires manual digitization of satellite imagery using Geographic Information Systems (GIS); this type of analysis is time consuming and so can only be applied to a handful of bridge sites, using a small number of satellite images. As part of the CDRI Fellowship, we leveraged the cloud computing platform Google Earth Engine (GEE) to upscale hazard monitoring assessments at large bridges in the Philippines using Earth observation (EO) data. We designed a user-friendly web-application that enables stakeholders to monitor the relative risk of river migration by analysing thousands of satellite images. The "InfraRivChange" web-application uses freely available satellite imagery from Landsat (30 m spatial resolution) and Sentinel (10 m spatial resolution). We demonstrate the workflow and show results from the Gamu Bridge on River Cagayan (Landsat imagery), Itawes Bridge on River Chico (Landsat imagery) and Don Mariano Marcos Bridge on River Lagben (Sentinel imagery). Outputs can be used by key decision-makers (e.g., the Department of Public Works and Highways) to assess the relative risk of river migration at sites of critical bridge infrastructure. We recommend using our "InfraRivChange" web-application as a low-cost remote sensing approach to monitor shifting rivers at sites of critical bridge infrastructure. We envision that the web-application can be applied to other critical infrastructure adjacent to rivers (e.g. road, rail and pipelines) and extended elsewhere to other dynamic riverine settings.

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1. Introduction

The Philippines is one of the most vulnerable countries in Southeast Asia that has been affected by climate change impacts (Yusuf et al., 2009) and consistently ranks as one of the most globally affected countries by extreme weather (Eckstein et al., 2019; 2021). Climate change is impacting the magnitude and frequency of extreme flood-generating storms (Tolentino et al., 2016; Eccles et al., 2019) and a high proportion of the population are exposed to hazards arising from fluvial flooding and erosion (Smith et al., 2019). Hydrometeorological hazards (e.g., floods and rainfall-triggered landslides) (Catane et al., 2018; Abanco et al., 2021) can be damaging to critical infrastructure, especially transport infrastructure (e.g., bridges, roads and railways).

River bridges are vulnerable nodes in transport and utility networks and are exposed to hydrometeorological hazards more than other forms of infrastructure (Pregnolato, 2019). When damaged or destroyed, a high socio-economic cost is incurred (Enke et al., 2008). River migration (i.e., general scour) represents a systemic hazard at sites of critical bridge infrastructure. In the Philippines, exposure to flooding and geomorphic risk are considerable (e.g., Dingle et al., 2019) and hence the recent expansion of infrastructural developments (World Bank, 2018) warrants quantification of river migration in the vicinity of large bridge assets. The Philippine road network handles 90% of passenger and 50% of freight transportation (Vallejo, 2015) and is a vital link for rural communities (Olsson, 2009). However, they record considerable infrastructural damages during hydrometeorological events (e.g., Typhoon Urduja in 2017 on Biliran Island) (see Figure 1). With climate change altering the frequency and magnitude of typhoons and storms in tropical regions, this may further undermine the stability of bridges, levees and other infrastructure (Eccles et al., 2019).

To address river migration in relation to transport infrastructure, Earth observation (EO) data can be used to monitor river channel change in the vicinity of bridges. This information can be used to improve the understanding of river behaviour and mitigate risks to transport infrastructure (e.g., by introducing bank protection measures). The acquisition of satellite imagery at predictable time intervals is a major advantage for mapping changes in river channels (Carbonneau and Piégay, 2012). For very large river systems, aerial or satellite remote systems can be the only way to observe and quantify planimetric morphology (Gilvear and Bryant, 2016). Satellite imagery has been used for conducting hazard monitoring around large bridges on River Padma, Bangladesh (McLean et al., 2012) and River Ayeyarwady, Myanmar (Oo et al., 2019). Although EO data supports a range of disaster risk reduction activities, it can become challenging for risk practitioners to handle and process the large volume of data available.

Technological advances in digital infrastructure, increased computing power and data storage capabilities have given rise to cloud computing platforms. These provide on-demand access to high-performance computing facilities without the need to own and maintain physical hardware (Sudmanns et al., 2019). An example is Google Earth Engine (GEE), a cloud computing platform for planetary-scale geospatial analysis (Gorelick et al., 2017). GEE holds a substantial data catalogue of EO data, enabling the users instant access and helping analyse satellite imagery spanning timescales relevant to engineering activities. As part of the CDRI Fellowship, we developed a bespoke web-based application using GEE for monitoring shifting rivers in the vicinity of critical bridge infrastructure in the Philippines.

Figure 1. Damage associated with Typhoon Urduja (2017) on Biliran Island (Visayas) at Caraycaray Bridge

Note: Satellite imagery showing the extent of flooding and shifting position of the river channel courtesy of Planet Labs, Inc.

2. Research Problem

The Department of Public Works and Highways (DPWH) is the executive department of the Philippine government. It is mandated to undertake the (a) planning of infrastructure, such as national roads and bridges, flood control, water resources projects and other public works and (b) design, construction and maintenance of national roads and bridges and major flood control systems. The DPWH provides publicly available bridge information through the Detailed Bridge Inventory Application (https://www.dpwh.gov.ph/dpwh/gis/dbi). As per the database, a bridge is a structure carrying a road over a waterway, road or other feature, with a clear span of 3 m or more between the inside faces of supports. Retrieved in April 2020, the database contained geospatial information for 8410 bridges along national roads, with attribute data including bridge deck length, year of construction and road type.

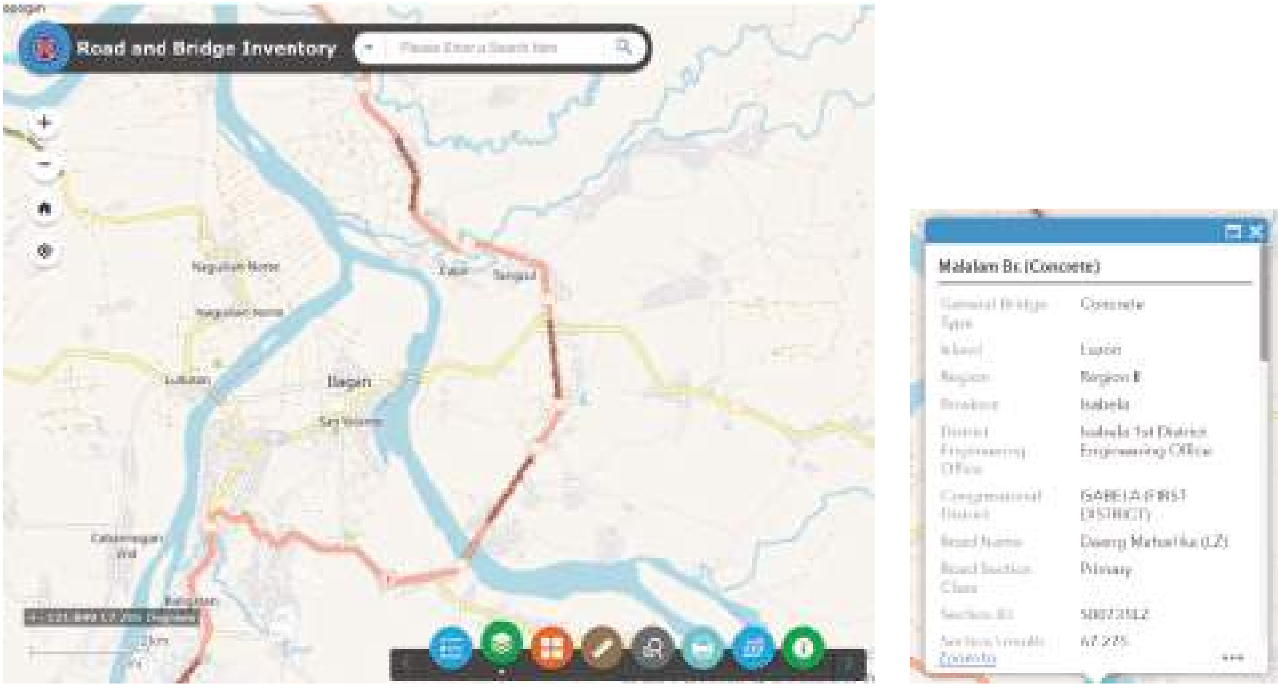

Figure 2. Information on Malalam Bridge extracted from the DPWH detailed bridge inventory.
Source: https://www.dpwh.gov.ph/dpwh/gis/dbi.

Conventional attempts to map and measure shifts in the position of rivers usually requires manual digitization of satellite imagery using Geographic Information Systems (GIS). This type of analysis is time-consuming and uses a small number of satellite images. Hence, this can usually be applied to only a handful of bridge sites. Moreover, conventional risk assessments to assess geomorphic hazards at river bridges are carried out during site visits using a mixture of qualitative and quantitative river stability indicators (Johnson et al., 1999). Both GIS and site-visit assessments are resource-intensive. Furthermore, river migration is not a local condition. It can extend upstream and downstream of a particular location and hence may not be adequately captured during local site visits (Johnson and Whittington, 2011). With the accessibility of EO data and availability of cloud computing platforms, shifting rivers can now be better monitored at higher spatial resolutions, over greater spatial extents and at finer temporal resolutions (Boothroyd et al., 2020). Innovative new remote sensing approaches can be applied to monitor river migration at sites of critical bridge infrastructure.

3. Aim, Objectives and Scope of the Research Study

3.1 Project aim

The project aims to develop a web-based application for monitoring shifting rivers in the vicinity of critical bridge infrastructure in the Philippines. It will leverage the computational power of GEE and provide a user-friendly interface to run advanced remote sensing analyses.

3.2 Objectives

The specific objectives of the project is to do the following:

- Apply a semi-automated workflow to analyse satellite imagery from Landsat and Sentinel to assess shifting rivers in the vicinity of critical bridge infrastructure.
- Design a user-friendly web-application to enable technical and non-technical users to apply the satellite imagery analyses.
- Output site-specific information that can inform decision-making activities around disaster-resilient infrastructure in the Philippines.

3.3 Scope

Our workflows and web-application will be used in combination to inform decision-making activities around disaster-resilient infrastructure in the Philippines. Insight and improved understanding of river channel change will assist long-term bridge monitoring applications. Site-specific information gathered from the web-application can be appended to existing bridge geodatabases. The outputs can be formally incorporated into bridge monitoring investigations (e.g. as a component of bridge stability assessments) and used in informing the strategic design and placement of future bridge infrastructure.

We note that the work undertaken as part of the CDRI Fellowship is specific to critical bridge infrastructure in the Philippines. The workflows have been developed and calibrated for alluvial rivers in tropical settings (that is the thresholds and parameter sets used, as noted in Section 4.1.2). Consequently, we caution against applying the web-application to other settings without site-specific validation and calibration. In all use cases (in the Philippines and beyond), we recommend sense-checking the outputs from the web-application.

We are committed to the principles of Open Access; the workflows presented in the project use freely available satellite imagery and all codes associated with the workflows/web-application are made openly available. We hope that other disaster-resilient infrastructure practitioners can modify and further develop the workflows/web-application.

4. Methodology

The research methodology involved applying the multitemporal satellite imagery analysis approach developed by Boothroyd et al. (2021) through a custom-built GEE web-application. The process is conceptualized in Figure 3. In this section, we detail each stage of the research methodology including the satellite imagery analysis workflow and design of the GEE web-application.

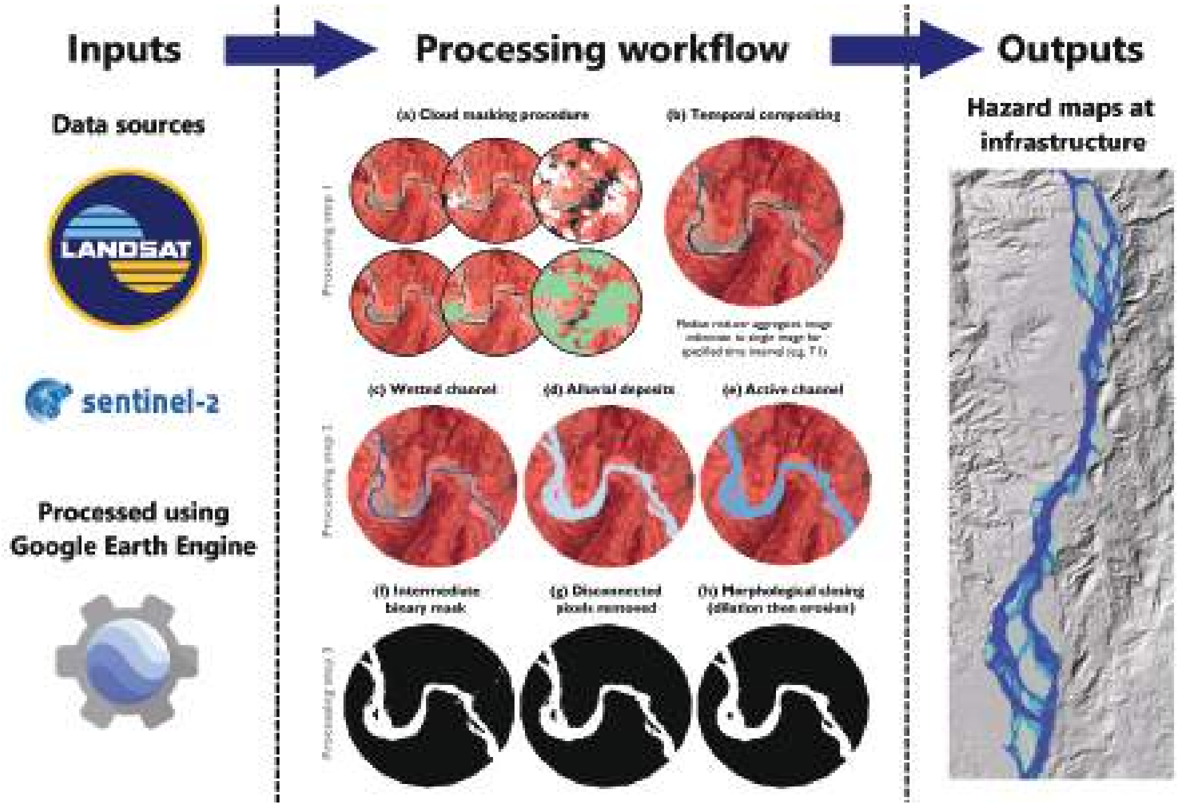

Figure 3. Conceptualization of the research methodology, including the data sources (Landsat and Sentinel imagery), processing steps within GEE and the outputs to be used by stakeholders

4.1 Satellite imagery analyses

4.1.1 Data sources

Primary data sources are shown in Table 1; they include Landsat products (30 m spatial resolution and available from 1984 to present) and Sentinel collections (10 m spatial resolution and available from 2015 to present). Multitemporal, multispectral satellite observations from the Landsat program and Sentinel constellation are particularly useful for disaster resilience applications with archives of data that span almost four decades. With multiple Landsat and Sentinel-2 satellites currently in orbit, observations can be acquired every few days for most parts of the world (Li and Roy, 2017). We used surface reflectance products from Landsat; the images have been atmospherically corrected, facilitating a more reliable comparison of spectral reflectance measurements between acquisitions. For Sentinel imagery, we used Level 1C products to maximize the record length of imagery. In future applications we recommend migrating to Sentinel SR_HARMONIZED products that were recently made available in GEE.

A key feature of both Landsat and Sentinel data is the availability of multispectral bands (e.g., near-infrared and short-wave infrared). Spectral bands can be combined to calculate multispectral indices, useful for indicating the relative abundance of features of interest (e.g., vegetation and water). Frequently used multispectral indices include the normalized difference vegetation index (NDVI) (Rouse et al. 1973), the enhanced vegetation index (EVI) (Huete et al., 2002), the normalized difference water index (NDWI)_ (McFeeters 1996) and the modified normalized difference water index (MNDWI) (Xu, 2006).

Table 1. Characteristics of the satellite imagery datasets used in the "InfraRivChange" web-application

Data Set	Spatial Resolution	Temporal Revisit	Temporal Archive	Dataset in GEE Catalog
Landsat 5 TM	30 m	16 days	1984-2012	Landsat 5
Landsat 7 ETM +	30 m	16 days	1999-now	Landsat 7
Landsat 8 OLI/TIRS	30 m	16 days	2013-now	Landsat 8
Sentinel-2 MSI	10 m	10 days	2015-now	Sentinel-2

ETM, enhanced thematic mapper; MSI, multispectral instrument; OLI, operational land imager; TIRS, thermal infrared sensor; TM, thematic mapper

4.1.2 Extracting active river channel masks

We apply the workflow developed by Boothroyd et al. (2021) to extract active channel masks from satellite imagery for different time periods. The workflow is summarized in Figure 4, with three main processing steps: (i) cloud masking and temporal compositing; (ii) active river channel classification; and (iii) binary image cleaning. In all the cases, a region of interest (ROI) is defined by the end-user (see Section 4.2.1). Validation work has previously been published to assess the accuracy of the active river channel classification (see Boothroyd et al., 2021).

Cloud cover can be persistent in the tropics (Long and Giri, 2011) and this is problematic for optical satellite imagery analyses. We applied cloud-masking and temporal compositing approaches to produce "cloud-free" satellite images. In the first processing step, a time filter was defined to select all available Landsat and Sentinel imagery within the specified analysis period. The CFmask algorithm was applied to each Landsat image in the collection to mask obstructions from cloud and cloud shadow pixels (Figure 4a) (Foga et al., 2017) and the maskS2clouds algorithm was applied to Sentinel imagery. To generate a single image from the image collection, a median reducer was applied to aggregate all non-cloud pixels. It generated a temporal composite for each spectral band (Figure 4b).

In the second processing step, multispectral indices were used to classify the wetted channel and alluvial deposits from the temporal composite images. It produced an intermediate binary active river channel mask (Figure 4c–e). The classification method of Zou et al. (2018) was used to classify water pixels. This producing a binary water mask from the normalized difference vegetation index (NDVI) (Rouse et al., 1974), the enhanced vegetation index (EVI) (Huete et al., 2002) and the modified normalized difference water index (MNDWI) (Xu, 2006). The same multispectral indices were used to classify alluvial deposits, with the active channel boundary enforced by excluding vegetated pixels. Active channel pixels were classified using relational operators. For Landsat imagery, we suggest default values where MNDWI ≥ -0.4 and NDVI ≤ 0.2. For Sentinel imagery, we suggest default values where MNDWI ≥ -0.175 and NDVI ≤ 0.2. Binary wetted channel and alluvial deposit masks were combined (i.e. geometric union) to produce the intermediate binary active river channel mask.

In the final processing step, the intermediate binary mask was cleaned using standard image processing morphological operations. Disconnected areas containing less than a user defined number of pixels were assumed to have been erroneously classified and removed (Figure 4g). We recommend areas of 100 pixels for Landsat imagery and 300 pixels for Sentinel imagery. A circular structuring element with a radius of 3 pixels performed a single iteration of morphological closing (binary image dilation followed by erosion) on the retained pixels (Figure 4h). Morphological closing eliminates small gaps, fuses narrow breaks and narrows the separation between nearby objects (Haralick et al., 1987), thereby smoothing edgelines to produce a continuous representation of the active river channel. The workflow provides a binary active channel mask in the vicinity of bridge points for each time period specified.

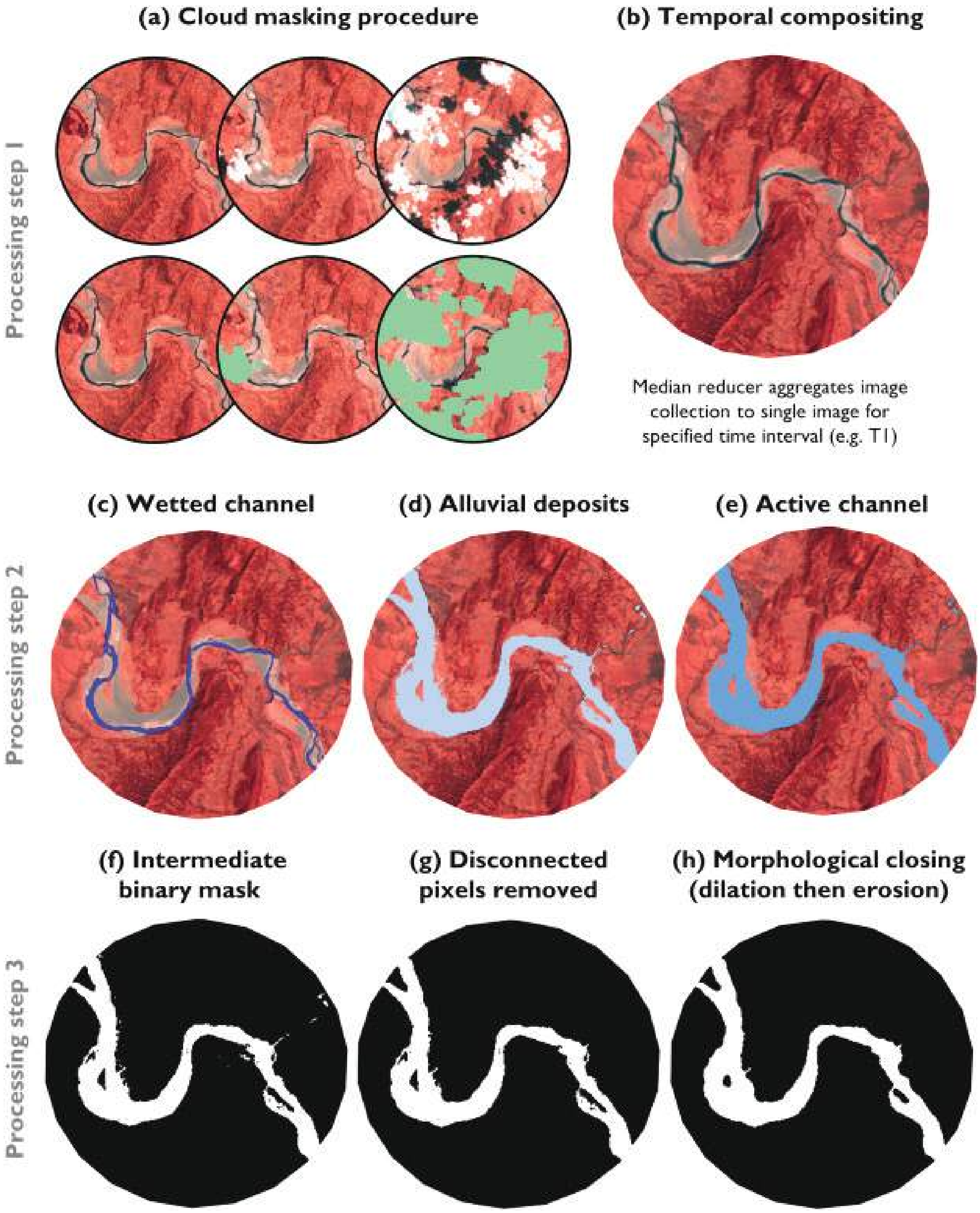

Figure 4. Visual workflow for extracting the active river channel mask from a series of Landsat satellite images in Google Earth Engine

Note: The workflow builds on previous work from Boothroyd et al., (2021)

4.1.3 Similarity coefficients to indicate shifting rivers

Similarity coefficients between binary active channel masks were calculated in GEE to indicate positional shifts in the rivers. Similarity coefficients express the proportion of area that two objects possess mutually, compared to the total area possessed by one object, or the other, or both (Hohn, 1976). We applied similarity coefficients in binary presence–absence form, summing pairwise attribute comparisons between contingency tables (confusion matrix) of successive active channel binary masks (Figure 5).

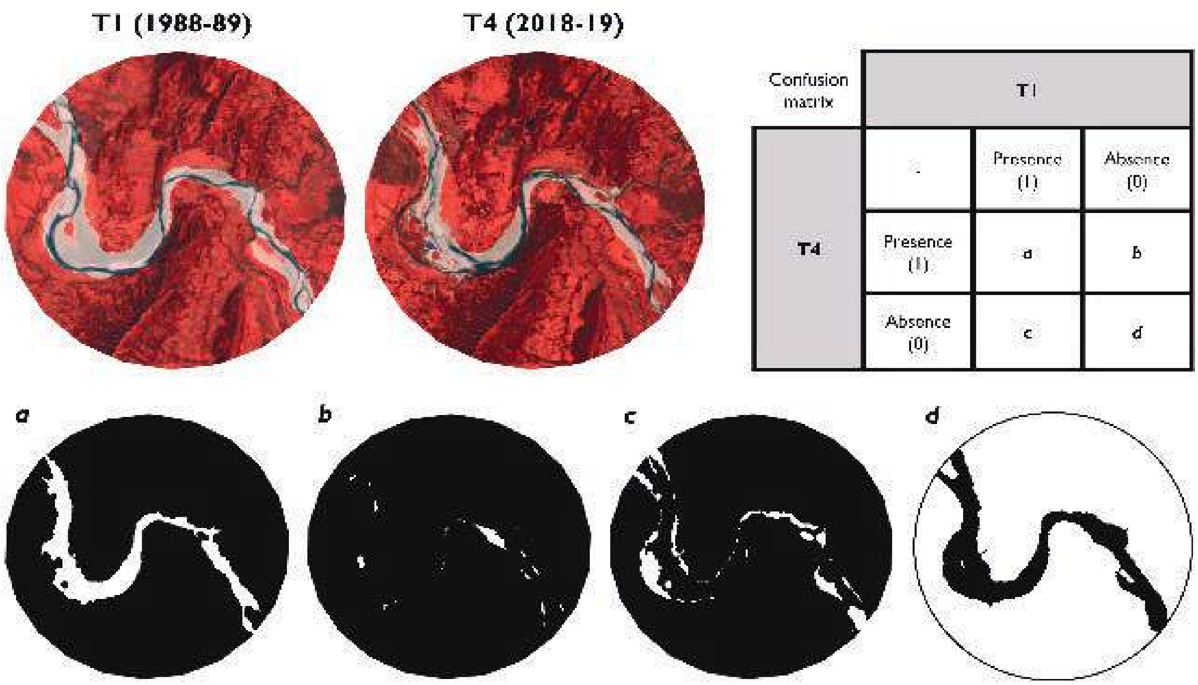

Figure 5. Schematic representation of the contingency table (confusion matrix) between two times periods (T1 and T4). Contingency table shows the definitions of (a) presence–presence instances, (b) absence–presence instances, (c) presence–absence instances and (d) absence–absence instances

The Jaccard index is given by the intersection over union. The Dice similarity coefficient is similar in form to the Jaccard index, but gives double weight to presence-presence instances (otherwise known as Sorensen-Dice). It has been favoured for assessing the similarity of datasets where there are fewer presence-presence instances (Boyce and Ellison, 2011). The Jaccard index and Dice similarity coefficients are correlated (Choi et al., 2010) and their values range between 0 and 1.

Table 2. Similarity coefficients for indicating shifting rivers at sites of critical bridge infrastructure

Similarity coefficient	Expression	Range	Reference
Jaccard index	$S_J = \frac{a}{a+b+c}$	[0,1]	Jaccard (1901)
Dice similarity coefficient	$S_D = \frac{2a}{2a+b+c}$	[0,1]	Dice (1945) Sorensen (1948)

Note: Schematic representations of (a) presence-presence instances, (b) absence-presence instances) and (c) presence-absence instances are shown in Figure 5.

Similarity coefficient values closer to 1 indicate greater similarity between active river channel masks (i.e. positional shifts in the active river channel were negligible). We use the similarity coefficients to interpret the relative risk of shifting rivers to critical bridge infrastructure, following the score ratings outlined in Table 3. In addition to similarity coefficients, we also report areal statistics for each of the binary images. We report the number of active channel pixels within the region of interest, and the area of the active channel (km^2) for each time period of analysis. Derived information on changes in the active channel area and similarity coefficients are used to infer potential threats to critical bridge infrastructure.

Table 3. Relative risk to critical bridge infrastructure based on similarity coefficients

Relative Risk to Critical Bridge Infrastructure	Jaccard Index	Dice Similarity Coefficient
Low (minor shifts in active river channel position)	0.61–1	0.76–1
Moderate (moderate shifts in active river channel position)	0.31–0.6	0.4–0.75
High (large shifts in river channel position)	0–0.3	0–0.4

4.2 Google Earth Engine web-application

We designed a GEE web-application called "InfraRivChange" that applies the satellite imagery analyses described in Section 4.1 (Figure 6). The web-application is available at https://vrindasharma.users.earthengine.app/view/infrariv. It can be accessed via any web-browser (accessible on phone, tablet or computer). GEE web-applications are dynamic and shareable. They use simple user interface (UI) elements to leverage the GEE data catalog and apply geospatial analyses. Importantly, GEE web-applications do not require coding experience and so both technical and non-technical users can use them. As a Google Account is not needed to view or interact with GEE web-application, the information is freely available and accessible to all users.

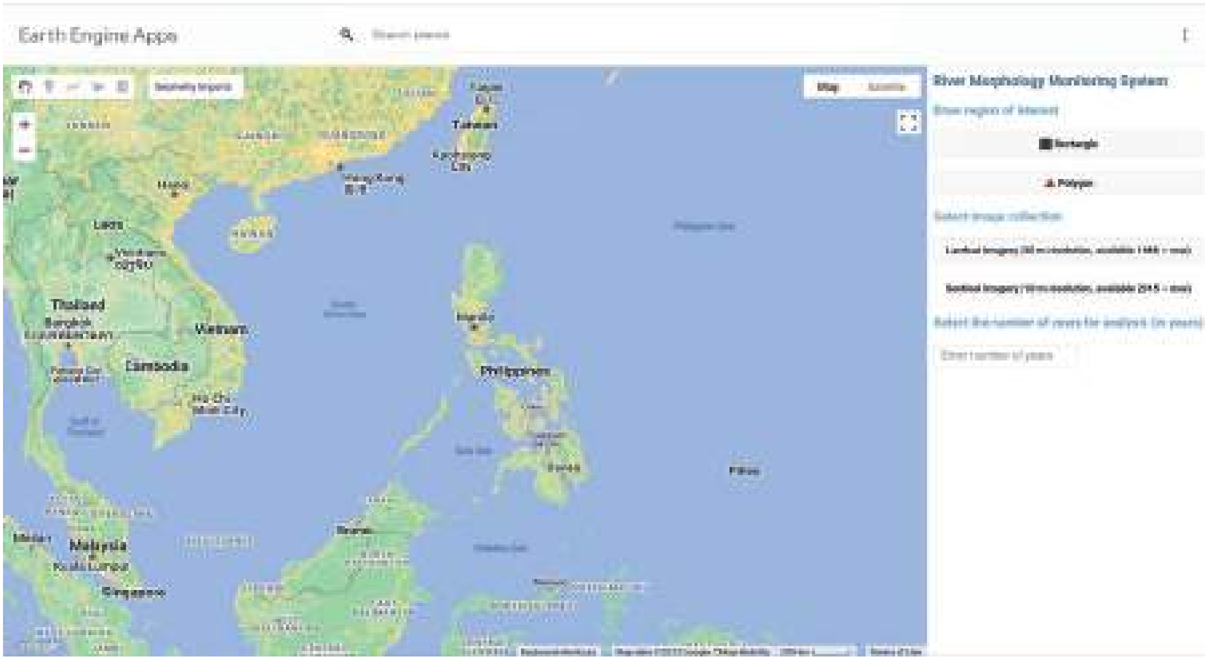

Figure 6. Landing page of the “InfraRivChange” application

4.2.1 Building the “InfraRivChange” web-application

The “InfraRivChange” web-application was built using the JavaScript API. The code is split into four scripts. A brief description of each script is provided below:

- AppUI.js (574 lines): This script defines the user interface elements (i.e., the user defined input panel in Figure 6). It allows the user to draw the region of interest, select the data source, set the time period for analysis, define the parameter sets and run the analysis. The AppUI.js script calls the other three scripts to run the satellite imagery analysis workflow. After running the analysis, the results are posted to the panel.
- DrawingRegion.js (71 lines): This script enables the user to interactively draw a region of interest (ROI) to complete the satellite imagery analysis. Depending on the use case, the user can draw a rectangle or a polygon around the critical bridge infrastructure.
- Landsat.js (457 lines): This script applies the satellite imagery workflow for Landsat imagery (as detailed in Section 4.1).
- Sentinel.js (459 lines): This script applies a similar workflow, but uses Sentinel imagery as the data source. The additional script is needed because band information of Landsat and Sentinel products differ (e.g., resolution, wavelengths and band names).

4.2.2 Using the “InfraRivChange” web-application

We designed the “InfraRivChange” web-application to offer a user-friendly solution when applying advanced satellite imagery analyses, suitable for both technical and non-technical users. Steps that the user must take in order to run the analyses are as follows:

First, the end-user must define a region of interest (ROI) for the analysis (Figure 7). The user can draw a ROI as a rectangle “■” or as a polygon “▲” around the critical bridge infrastructure of interest. We recommend drawing small regions of interest (e.g., 5 km × 5 km) in the first instance. The users should ensure the ROI is appropriately sized to the river system being analysed.

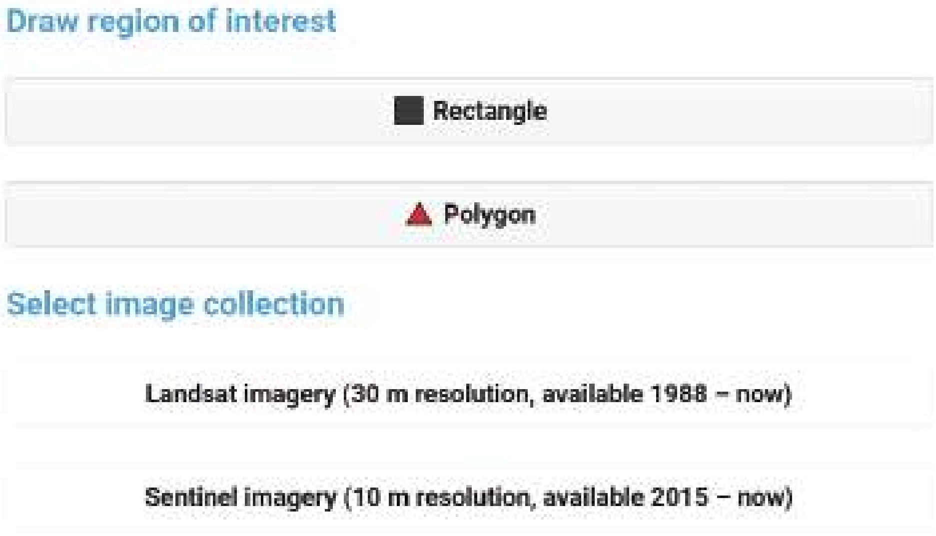

Figure 7. Defining the region of interest (ROI) for analysis

Second, the user must select the imagery collection to use for analysis (Figure 8). The options are Landsat imagery (available 1988-now) or Sentinel imagery (available 2015-now).

Figure 8. Selecting the satellite imagery to use for the analysis (Landsat or Sentinel)

Third, the user must define the date range for the multitemporal analysis; this option sets the time periods to be compared. By inputting “1” for the “number of years for analysis”, the user would use all available Landsat or Sentinel imageries within a 1 year analysis period. The user is able to select the date range over which the analysis is applied using the year slider and calendar options (e.g., 01/01/1988 to 01/01/1989). The user must define two separate periods for analysis (named T1 and T2). Temporal composite images are produced for each of the time periods specified. Figure 9 shows an example where T1 = 01/01/1988–01/01/1990 and T2 = 01/01/2018–01/01/2020. This indicates that the temporal composite image will cover two years of data.

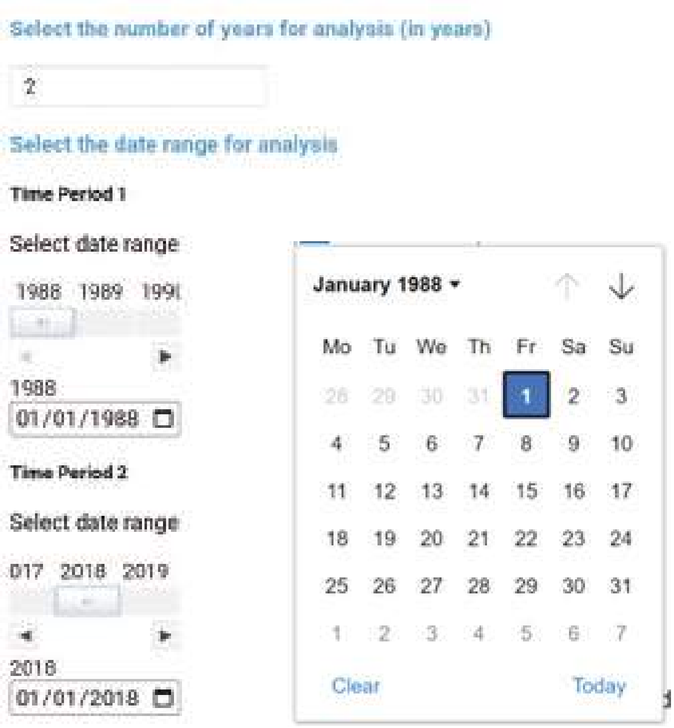

Figure 9. Defining the time period for the analysis

Note: The example has selected a 2-year analysis period, whereby T1 = 01/01/1988–01/01/1990 and T2 = 01/01/2018–01/01/2020

Fourth, the user must define the parameters and thresholds for the analysis (relational operations and binary image cleaning pixels defined in Section 4.1.2). For Landsat applications, we recommend NDVI = 0.2, MNDWI = −0.4 and binary cleaning pixels = 100. For Sentinel applications, we recommend NDVI = 0.2, MNDWI = −0.175 and binary cleaning pixels = 300. A demonstration is shown in Figure 10.

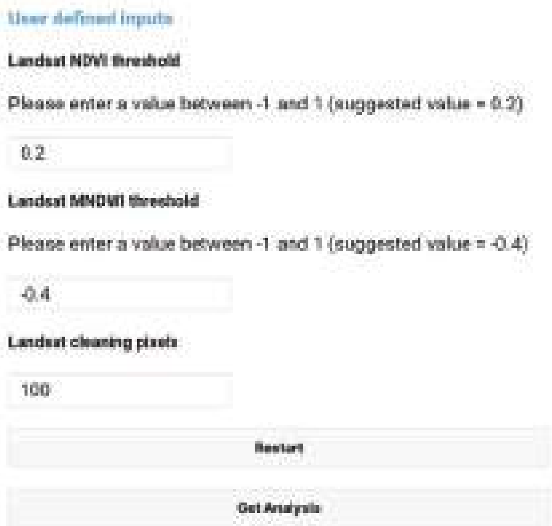

Figure 10. Defining thresholds and parameters to be used as part of the satellite imagery analysis

Note: See Section 4.1.2 for a full explanation

Finally, the user presses the "Get Analysis" button to run the analyses (Figure 11). All background processing will be carried out remotely using the Google's computational infrastructure, with results shown on the map and printed to the results console. The processing time will depend on the size of the ROI and the number of years of analysis (for small areas, e.g., 25 km^2, the processing time is approx. 1 minute). One should expect the processing times to be longer for Sentinel imagery due to higher spatial resolution of the imagery.

Figure 11. Press "Get Analysis" to run the application after specifying all input parameters

4.2.3 Viewing results in the "InfraRivChange" web-application

Results are displayed on the map console and printed to the results console (Figure 12). The user can select different layers using the "Layer" option (e.g., compare the active channel mask at T1 against T2). For each time period, the results console outputs the number of pixels in the active channel mask and the area of the active channel mask. Similarity coefficients between T1 and T2 are also printed to the results console, including the Jaccard index and the Dice similarity coefficients. Users should refer to Table 3 to interpret the relative risk to critical bridge infrastructure from shifting rivers. Users can download binary active channel images for each time period for additional analysis using external software.

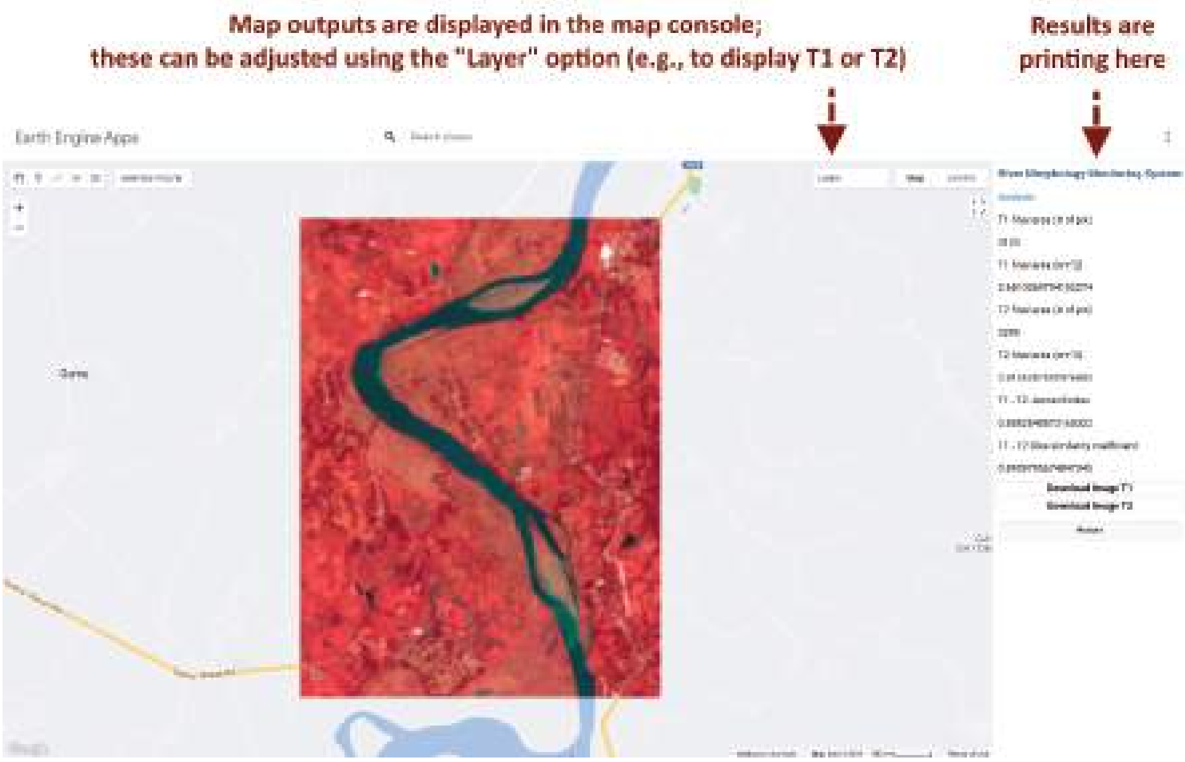

Figure 12. Viewing results in the "InfraRivChange" web-application

5. Results and Discussion

In this section we demonstrate three test cases using the "InfraRivChange" web-application. We discuss the future developments that have been planned to improve the current release.

5.1 "InfraRivChange" demonstration using Landsat imagery

In the first demonstration test case, we will show results from the Landsat imagery workflow for the Gamu Bridge on River Cagayan (Figure 13). Using default input parameters, we set the date range as T1 = 01/01/1988–01/01/1990 and T2 = 01/01/2018–01/01/2020. The results indicate that the section of River Cagayan has remained approximately stable over the 30-year analysis period. The active channel area has increased marginally (from 2.68 to 2.82 km^2), with the Jaccard index (0.81) and Dice similarity coefficient (0.89) indicating a low relative risk to critical bridge infrastructure. Results from the "InfraRivChange" application suggest only minor shifts in the active river channel position at this site.

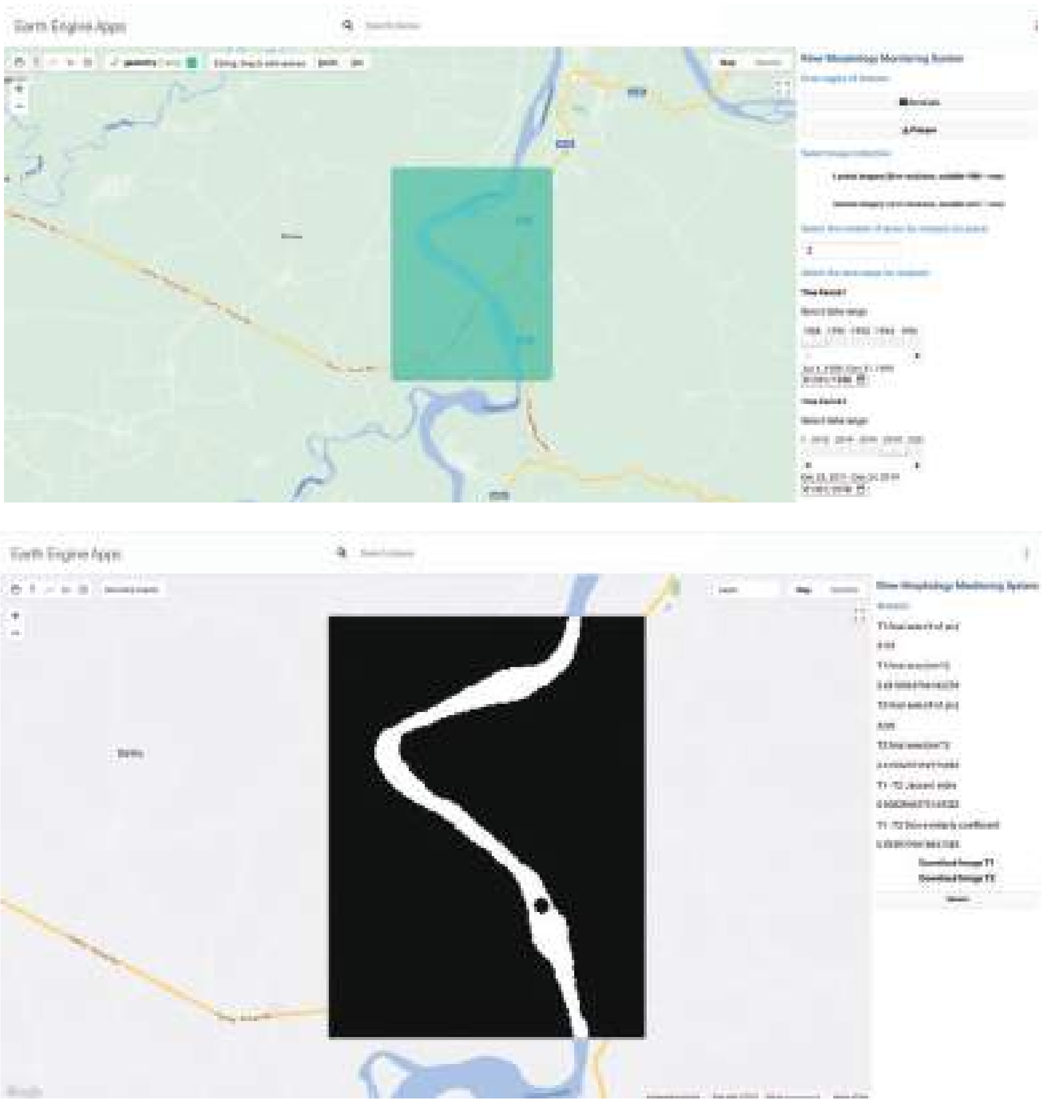

Figure 13. Input parameters and results for the Landsat test case (Gamu Bridge on River Cagayan)

In the second demonstration test case, we show results from the Landsat imagery workflow for the Itawes Bridge on River Chico. Using default input parameters, we set the date range as T1 = 01/01/1988–01/01/1990 and T2 = 01/01/2018–01/01/2020. Notable here is the mobility of River Chico in the vicinity of the bridge site over the 30-year analysis period. The active channel area has increased marginally (from 1.41 to 1.50 km^2), with the Jaccard index (0.53) and Dice similarity coefficient (0.69) indicating a moderate relative risk to critical bridge infrastructure. Results from the "InfraRivChange" application suggest moderate shifts in the active river channel position at this site. This indicates the need for further investigation and potentially applying more detailed monitoring.

Figure 14. Results for the second Landsat test case (Itawes Bridge on River Chico)

5.2 "InfraRivChange" demonstration using Sentinel imagery

In the third demonstration test case we show results from the Sentinel imagery workflow for the Don Mariano Marcos Bridge on River Lagben (Figure 15). Using default input parameters, we set the date range as T1 = 01/01/2016–01/01/2017 and T2 = 01/01/2021–01/01/2022. The results indicate that the section of River Lagben has remained approximately stable over the 5-year analysis period. The active channel area has decreased marginally (from 2.12 km^2 to 1.94 km^2), with the Jaccard index (0.83) and Dice similarity coefficient (0.91) indicating a low relative risk to critical bridge infrastructure. Results from the "InfraRivChange" application suggest only minor shifts in the active river channel position at this site. However, it is important to note that these changes have occurred over a relatively short timescale (5 years, relative to the 30 year timescale of the Landsat workflow).

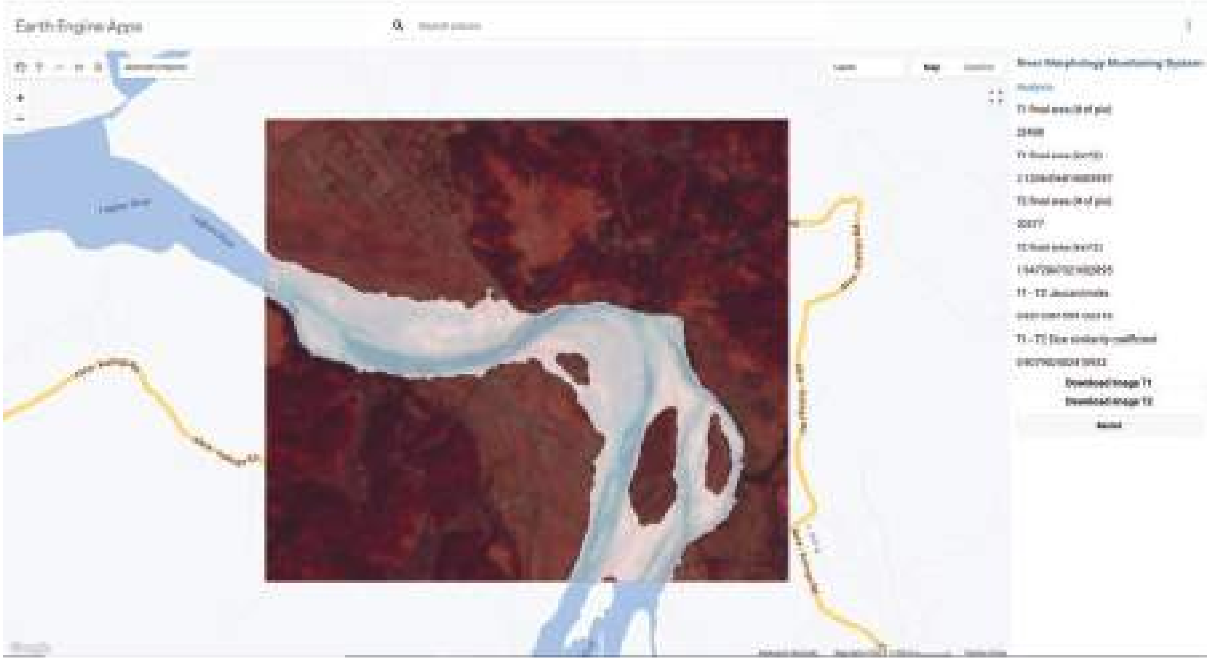

Figure 15. Results for the Sentinel test case (Don Mariano Marcos Bridge on River Lagben)

5.3 Future developments

The initial release of the "InfraRivChange" web-application represents a proof of concept demonstration. Following closure of the project, we will continue to iterate the web-application, improve the user experience and provide further insights for disaster-resilient infrastructure. Future developments that we plan to implement include the following:

- Representing bridge inventory data points within the "InfraRivChange" web-application as FeatureView objects (additional permissions required from DPWH).
- An option to analyse multiple data years. The current workflow enables end-point analysis between two specific years (e.g., 1990 compared to 2020). Improvements to the satellite imagery workflow would enable multiple data years to be included within the analysis (e.g., 1990 compared to 1991, 1992, 1993). The inclusion of multiple data years would provide a temporally rich data set, which will enable disaster resilience infrastructure practitioners to understand when positional shifts in river channels had occurred. This would be visualized using time-lapse imagery.
- Rivers in the Philippines have diverse fluvial morphological characteristics (Tolentino et al., 2022). Diversity in sedimentological and vegetation characteristics between rivers likely result in differences in observed spectral properties from satellite remote sensing. We, therefore, recommend site-specific validation and calibration of the parameter sets used (e.g., field-visits to assess sediment and vegetation properties in the vicinity of bridge sites). Field-visits could better inform the relationship between parameters used in low-cost remote sensing approach (e.g., NDVI thresholds) and in improving the river system observations.
- Output hazard maps that indicate the position of river channels throughout the analysis period in addition to the mapped position of critical bridge infrastructure.

- Improvements to the user experience, including the option to input pre-existing shapefiles as the region of interest for analyses, the inclusion of the CDRI and endorsing institute logo into the user panel of the web-application.
- Improve computation time when handling large or complex regions of interest (i.e., reduce likelihood of a "wait" message or an unresponsive page error).
- In-person training sessions due to be held in 2022/23. Provisionally these will take place with local project partners at the University of the Philippines Diliman.
- Release step-by-step training materials and YouTube video demonstrations. These are planned and their release will coincide with the publication of future journal articles.

6. Enablers and Barriers

6.1 Enablers

Web-applications relating to hazards and infrastructure are widely used in the Philippines. Detailed maps for landslide, flood and storm surge hazards are used by Local Government Units (LGUs) for disaster preparedness planning and communicated to wider audiences through a web-based disaster Geographic Information System (Web-GIS) from the Nationwide Operational Assessment of Hazards program (https://noah.up.edu.ph/). In relation to the infrastructure, the DPWH provides publicly available bridge information through the Detailed Bridge Inventory Application (https://www.dpwh.gov.ph/dpwh/gis/dbi). Similar information on the Philippine road network is also available (https://www.dpwh.gov.ph/dpwh/gis/rbi). Web-applications enable critical information to be disseminated to as wide an audience as possible (Lagmay et al., 2017). Future iterations of the "InfraRivChange" web-application should be able to feed into existing information sources that relate to hazard and infrastructure. Additional discussions with relevant government agencies will be needed to ensure the interoperability and compatibility of the resources

6.1 Barriers

A critical relationship exists between the width of the river and the spatial resolution of the satellite imagery suitable for analysis. "InfraRivChange" is designed to be applied to large rivers that can be adequately resolved in Landsat and Sentinel imagery (> 100 m wide). However, recent and future improvements in the spatial resolution of satellite imagery will likely increase the applicability of remote sensing approaches to narrower rivers (Khorram et al., 2016). Future opportunities exist to leverage higher resolution satellite imagery (e.g. Airbus Pléiades, Maxar, PlanetScope). The "InfraRivChange" application is designed to be open-ended; additional scripts could be added in future so that new datasets be used as part of the analysis workflow. The critical relationship between width of the river and spatial resolution of the satellite imagery may act as a limiting factor when attempting to apply the workflow to narrower rivers with smaller bridges. We caution against applying the workflow to rivers with an active channel width <100 m.

7. Key Takeaways from CDRI Fellowship Programme

The key takeaways from the CDRI Fellowship Programme include the following:

- Satellite imagery analyses offer a low-cost approach for monitoring the relative risk of shifting rivers (>100 m in width) to critical bridge infrastructure. We recommend that satellite imagery analyses be formally incorporated into bridge monitoring investigations (e.g., as a component of bridge stability assessments) undertaken by the primary stakeholder (DPWH) and used to inform the strategic design and placement of future bridge infrastructure.
- It is important to sense-check outputs from the "InfraRivChange" application. Although best efforts have been made to validate and calibrate parameter sets for rivers in the Philippines, we recommend that all outputs should be sense-checked and critically appraised. In terms of default values, for Landsat applications we recommend NDVI = 0.2, MNDWI = –0.4 and binary cleaning pixels = 100. For Sentinel applications, we recommend NDVI = 0.2, MNDWI = -0.175 and binary cleaning pixels = 300. Individual applications may require modifications to be made to the default values in order to improve the classification of the active river channel.
- The "InfraRivChange" application released here represents only the first iteration. Following closure of the project, we will continue to develop and improve the web-application. Specific improvements that we intend to make include adding an option to analyse multiple data years and output of hazard maps that indicate the position of river channels throughout the analysis period in addition to the mapped position of critical bridge infrastructure.
- Involvement with CoP activities are beneficial to CDRI Fellows; the CoP activities provide a space for networking, collaboration and sharing of funding opportunities. The "InfraRivChange" project benefited from involvement in the CoP on NbS for Resilient Infrastructure (Figure 16). It provided a space to share and discuss emerging research topics from the CDRI Fellowship.

Figure 16. Virtual involvement in the third CoP on NbS for Resilient Infrastructure (March 2022)

8. Conclusions and Way Forward

8.1 Conclusion

We have successfully developed a web-based application to monitor shifting rivers in the vicinity of critical bridge infrastructure in the Philippines. The "InfraRivChange" web-application has been designed to offer both non-technical and technical users the opportunity to apply advanced satellite imagery workflows to thousands of Landsat and Sentinel images. The user-friendly application enables semi-automated multitemporal satellite imagery analyses to be undertaken. Outputs can be used by key decision-makers (e.g., the Department of Public Works and Highways) to assess the relative risk of river migration at sites of critical bridge infrastructure. We recommend that the InfraRivChange web-application be used as a low-cost remote sensing approach to monitor shifting rivers at sites of critical bridge infrastructure. Satellite imagery analyses could be formally incorporated into bridge monitoring investigations (e.g., as a component of bridge stability assessments) and used to inform the strategic design and placement of future bridge infrastructure. We envision that the web-application can be applied to other critical infrastructure adjacent to rivers (e.g. road, rail and pipelines) and extended elsewhere to other dynamic riverine settings.

8.2 Way Forward

We envision that the "InfraRivChange" web-application will be used by government agencies for mandated tasks on disaster-resilient infrastructure (including DENR-MGB, DPWH-BRS, DPWH-UPMO-FCMC, PAGASA). Looking at the future, the "InfraRivCloud" web-application could make a valuable contribution to the Asset Management Information System planned for the Philippines, through Asian Development Bank (ADB) funding. Initially, the project will focus on three test catchments (Abra River Basin, Tagum-Libuganon River Basin and Agus River Basin; https://www.adb.org/sites/default/files/project-documents/51294/51294-001-iee-en.pdf). Outputs from the "InfraRivChange" web-application would support future activities as part of the Asset Management Information System.

Transferability is used as a term to describe how information or analysis from one region can be applied elsewhere (i.e., the universality of the approach). It is anticipated that the application could be transferred to other dynamic riverine settings where critical bridge infrastructure is at risk from shifting rivers (e.g., across Southeast Asia). In time, we hope that the application could be further developed, validated, calibrated and applied across a geodiverse range of settings. Figure 17 shows an example for River Ghaghara (India), with the Chahlari Ghat Bridge located at the centre of the image. The Jaccard index (0.15) and Dice similarity coefficient (0.26) are very low, indicating considerable shifts in active channel position.

We suggest that our remote sensing monitoring approach could help inform the strategic planning and placement of critical bridge infrastructure. It could also be applied more widely to other forms of critical infrastructure adjacent to rivers (e.g., road and rail). Building on road network information from the DPWH Road and Bridge Inventory, future work could monitor hazards to key transport infrastructure (e.g., the Philippine road network) (refer to Figure 18).

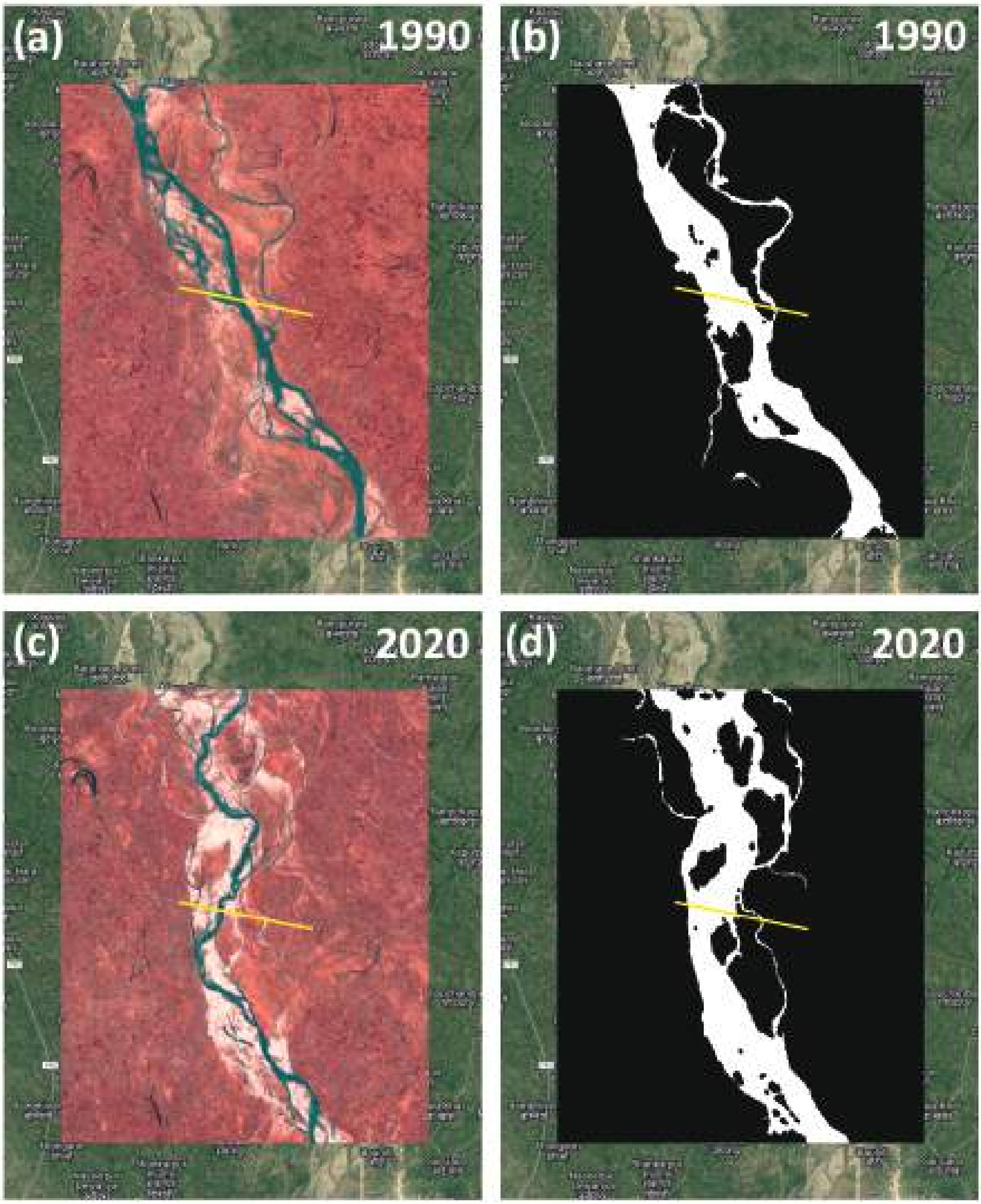

Figure 17. "InfraRivChange" web-application applied beyond the Philippines

Note: Shifts in the position of the River Ghaghara (India) are shown between 1990 and 2020 using imagery from Landsat collections. The Chahlari Ghat Bridge is located at the centre of the image (indicated by yellow line); the Jaccard index (0.15) and Dice similarity coefficient (0.26) are very low, indicating considerable shifts in the active channel position. The example demonstrates the potential of transferring the workflow from the Philippines to other dynamic riverine settings.

Figure 18. DPWH Road and Bridge Inventory Application showing the proximity of the national road network to river channels

Note: The Laoag-Sarrat-Piddig-Solsona Rd (Ilocos Norte) runs adjacent to an actively shifting river channel (River Laoag). Future work could explore the exposure of transport infrastructure (roads) to shifting rivers.

References

1. Abanco, C., Bennett, G.L., Matthews, A.J., Anthony, M., Matera, M., & Tan FJ. (2021). The role of geomorphology, rainfall and soil moisture in the occurrence of landslides triggered by 2018 Typhoon Mangkhut in the Philippines. *Natural Hazards and Earth System Sciences*, 21, 1531-1550. Details available at https://doi.org/10.5194/NHESS-21-1531-2021
2. Boothroyd, R.J., Williams, R.D., Hoey, T.B., Barrett, B., & Prasojo, O.A. (2020). Applications of Google Earth Engine in fluvial geomorphology for detecting river channel change. *WIREs Water*, 8(1), e21496. Details available at https://doi.org/10.1002/wat2.1496
3. Boothroyd, R.J., Williams, R.D., Hoey, T.B., Tolentino, P.L.M., Yang, X. (2021). National-scale assessment of decadal river migration at critical bridge infrastructure in the Philippines. *Science of the Total Environment*, 768, pp. 144460. Details available at https://doi.org/10.1016/j.scitotenv.2020.144460
4. Boyce, R.L., & Ellison, PC. (2001). Choosing the best similarity index when performing fuzzy set ordination on binary data. *J. Veg. Sci*., 12(5), pp. 711-720, Details available at https://doi.org/10.2307/3236912
5. Carbonneau, P.E., & Piégay, H. (2012). Introduction: The growing use of imagery in fundamental and applied river sciences. In PE Carbonneau & H Piégay (Eds.), *Fluvial Remote Sensing for Science and Management* (pp. 1-18). Chichester, UK: Wiley.
6. Catane, S.G., Abon, C.C., Saturay, R.M., Mendoza, E.P.P., & Futalan, K.M. (2012). Landslide-amplified flash floods-The June 2008 Panay Island flooding, Philippines. *Geomorphology*. 170, pp. 55–63. Details available at https://doi.org/10.1016/j.geomorph.2012.04.008
7. Choi, S.S., Cha, S.H., & Tappert, C.C. (2010). A survey of binary similarity and distance measures. *J. Syst. Cybern. Inform*., 8(1), pp. 43-48.
8. Dingle, E.H., Paringit, E.C., Tolentino, P.L.M., Williams, R.D., Hoey, T.B., Barrett, B., Long, H., Smiley, C., & Stott, E. (2019). Decadal-scale morphological adjustment of a lowland tropical river. *Geomorphology*, 333, 30-42. Details available at https://doi.org/10.1016/j.geomorph.2019.01.022
9. Eccles, R., Zhang, H., & Hamilton, D. (2019). A review of the effects of climate change on riverine flooding in subtropical and tropical regions. *Journal of Water and Climate Change*, 10, 687-707. Details available at https://doi.org/10.2166/wcc.2019.175
10. Eckstein, D., Künzel, V., Schäfer, L., & Winges, M. 2020. *Global Climate Risk Index*. Bonn.
11. Eckstein, D., Künzel, V., & Schäfer, L. 2021. *Global Climate Risk Index*. Bonn.
12. Foga, S., Scaramuzza, P.L., Guo, S., Zhu, Z., Dilley, R.D., Beckmann, T., Laue, B. (2017). Cloud detection algorithm comparison and validation for operational Landsat data products. *Remote Sensing of Environment*, 194, 379-390. Details available at https://doi.org/10.1016/j.rse.2017.03.026
13. Gilvear, D.J., & Bryan, R. (2016). Analysis of remotely sensed data for fluvial geomorphology and river science. In M Kondolf, H Piégay (Eds.), *Tools in Fluvial Geomorphology,* pp. 103-132. Chichester, England: John Wiley & Sons.

14. Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, 202, 18-27. Details available at https://doi.org/10.1016/j.rse.2017.06.031
15. Haralick, R.M., Sternberg, S.R., & Zhuang, X. (1987). Image analysis using mathematical morphology IEEE Trans. *Pattern Anal. Mach. Intell*., 9(4), 532-550. Details available at https://doi.org/10.1109/TPAMI.1987.4767941
16. Hohn, M.E. Binary coefficients: a theoretical and empirical study. *J. Int. Assoc. Math. Geol*., 8(2), 137-150. Details available at https://doi.org/10.1007/BF01079031
17. Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., & Ferreira, L.G. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, 83(1), 195-213. Details available at https://doi.org/10.1016/S0034-4257(02)00096-2
18. Johnson, P.A., Gleason, G.L., & Hey, R.D. (1999). Rapid assessment of channel stability in vicinity of road crossing. *Journal of Hydraulic Engineering*, 125(6), 645-651. Details available at https://doi.org/10.1061/(ASCE)0733-9429(1999)125:6(645)
19. Johnson, P.A., & Whittington, R.M. (2011). Vulnerability-based risk assessment for stream instability at bridges. *J. Hydraul. Eng*., 137 (10), 1248-1256. Details available at https://doi.org/10.1061/(ASCE)HY.1943-7900.0000443
20. Lagmay, A.M.F.A., Racoma, B.A., Aracan, K.A., Alconis-Ayco, J., & Saddi, I.L. (2017). Disseminating near-real-time hazards information and flood maps in the Philippines through Web-GIS. *Journal of Environmental Sciences*, 59, 13-23. Details available at https://doi.org/10.1016/J.JES.2017.03.014
21. Li, J., & Roy, D.P. (2017). A global analysis of Sentinel-2A, Sentinel-2B and Landsat-8 data revisit intervals and implications for terrestrial monitoring. *Remote Sensing*, 9(9), 902. Details available at https://doi.org/10.3390/rs9090902
22. Long, J.B., & Giri, C. (2011). Mapping the Philippines' mangrove forests using Landsat imagery *Sensors*., 11(3), 2972-2981. Details available at https://doi.org/10.3390/s110302972
23. McFeeters, S.K. (1996). The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, 17(7), 1425-1432. Details available at https://doi.org/10.1080/01431169608948714
24. McLean, D.G., Vasquez, J., Oberhagemann, K., & Sarker, M. (2012). Padma River morphodynamics near Padma Bridge River Flow 2012. *Proceedings of the International Conference on Fluvial Hydraulics*, 1, pp. 741-747.
25. Olsson, J. (2009). Improved road accessibility and indirect development effects: evidence from rural Philippines. *Journal of Transport Geography*, 17(6), 476-483. Details available at https://doi.org/10.1016/j.jtrangeo.2008.09.001
26. Oo, M.M., Kyi, C.C.T., & Zin, W.W. (2019). Historical morphodynamics assessment in bridge areas using remote sensing and GIS techniques. *Civ. Eng. J*., 5 (11), 2515-2524. Details available at https://doi.org/10.28991/cej-2019-03091429
27. Pregnolato, M. (2019). Bridge safety is not for granted – A novel approach to bridge manage-

ment. *Engineering Structures*, 196, 1091932. Details available at https://doi.org/10.1016/j.engstruct.2019.05.035

28. Rola, A.C., Pulhin, J.M., & Hall, R.A. (2018). Water policy in the Philippines: Issues, initiatives, and prospects. *Global Issues in Water Policy*. Springer. Details available at https://doi.org/10.1007/978-3-319-70969-7
29. Rouse, J.W., Haas, R.H., Schell, J.A., & Deering, D.W. (1973). Monitoring vegetation systems in the Great Plains with ERTS. *NASA Special Publication*. 351, pp. 309-317.
30. Smith, A., Bates, P.D., Wing, O., Sampson, C., Quinn, N., & Neal, J. (2019). New estimates of flood exposure in developing countries using high-resolution population data. *Nature Communications*, 10, 1-7. Details available at https://doi.org/doi:10.1038/s41467-019-09282-y
31. Sorensen, T. (1948). A method of establishing groups of equal amplitude in plant sociology based on similarity of species content and its application to analyses of the vegetation on Danish commons. *Biologiske Skrifter/Kongelige Danske Videnskabernes Selskab*, 5, 1-34.
32. Sudmanns, M., Tiede, D., Lang, S., Bergstedt, H., Trost, G., Augustin, H., & Blaschke, T. (2020). Big Earth data: disruptive changes in Earth observation data management and analysis? *International Journal of Digital Earth*, 13(7), 832-850. Details available at https://doi.org/10.1080/17538947.2019.1585976
33. Tolentino, P.L.M., Poortinga, A., Kanamaru, H., Keesstra, S., Maroulis, J., & David, C.P.C. 2016. Projected impact of climate change on hydrological regimes in the Philippines. *PLoS ONE*, 11, pp. e0163941. Details available at https://doi.org/10.1371/journal.pone.0163941
34. Tolentino, P.L.M, Perez, J.E.G., Guardian, E.L., Boothroyd, R.J., Hoey, T.B., Williams, R.D., Fryirs, K.A., Brierley, G.J., & David, C.P.C. (2022). River Styles and stream power analysis reveal the diversity of fluvial morphology in a Philippine tropical catchment. *Geoscience Letters*, 9(6). Details available at https://doi.org/10.1186/s40562-022-00211-4
35. Vallejo, S.C. (2015). Evaluation of major bridges in Cagayan Valley, Philippines. *Countryside Development Research Journal*, 3(1), pp. 13-18.
36. World Bank. (2018). *Philippines Economic Update, October 2018: Staying in the Course Amid Global Uncertainty*. The World Bank. *Details available at https://doi.org/10.1596/30564*
37. Xu, H. (2006). Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. *International Journal of Remote Sensing*, 27(14), 3025–3033. Details available at https://doi.org/10.1080/01431160600589179
38. Yusuf, A.A., & Francisco, H. (2009). *Climate Change Vulnerability Mapping for Southeast Asia*. Singapore.
39. Zou, Z., Xiao, X., Dong, J., Qin, Y., Doughty, R.B., Menarguez, M.A., & Wang, J. (2018). Divergent trends of open-surface water body area in the contiguous United States from 1984 to 2016. *Proceedings of the National Academy of Sciences*, 115(15), pp. 3810–3815. Details available at https://doi.org/10.1073/pnas.1719275115

Inventory of High-Altitude Wetlands for Disaster Risk Reduction in Transboundary Himalayan Region (InHAW)

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CDRI

Coalition for Disaster Resilient Infrastructure

Disclaimer:

The views expressed in this paper reflect the opinions of the author and not necessarily the official views of CDRI.

Abstract

The transboundary Himalayan region of South Asia consists of internationally recognized Ramsar wetlands valuable for maintaining ecosystem services, biodiversity and environmental flows crucial for mountain development. Nevertheless, due to wetlands' sensitivity to climate change, the Himalayan ecosystems are rapidly changing in the low-altitude (<3000 m) as well as high-altitude (>3000 m) regions. Thus, a study on the inventory of Himalayan wetlands and their dynamics is of great importance to take actions for sustaining ecosystem functions in the transboundary Himalayan region.

In this research, a maximum entropy (MaxEnt) algorithm has been used to model the existing geographic distribution of Himalayan wetlands using specific point location data, understand spatiotemporal changes in wetlands and map out the probability of new wetland formation considering climate change impact on Himalayan glacier melting. The spatial data of topographic characteristics, soil information, land use/cover and climate change were used as inputs to the model. Existing wetland locations in the territory of India were used as the training and testing data samples for the inventory modelling.

The research findings showed the formation of new wetlands in the Himalayas region due to temperature rise that caused glacier melting and formed wetlands in depressed areas. The wetland formation will continue in the future as temperature rise is likely to happen. The probability of wetland inventory is higher in the eastern and western parts of the Himalayas and high-altitude region. This study provides a valuable insight into role of wetlands in managing mountain disasters such as floods and landslides.

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1. Introduction

As global warming, that temperature is increasing, mountain glaciers are retreating almost everywhere in the world (Laghari, 2013). This increase in temperature is adversely affecting freshwater availability for mountain recreation, animals and plants. Glacier melt play an important role in irrigation and domestic use in the downstream areas and oceans levels in the long term (Berthier et al., 2007; Shea et al., 2015; Hrach et al., 2022). Climatic change has been linked to major mountain disasters such as floods and landslides. Lately, floods and landslides have become uncertain and frequently occurring, which is causing socio-economy losses and ecological biodiversity disturbances.

Among the mountains on earth, the Himalayan mountain system consists of more than 50 peaks that are over 7000 m. The Himalayas cover parts of India, Pakistan, Afghanistan, Nepal, Bhutan, Myanmar and China. Mount Everest, at 8848 m elevation, is the highest peak in the entire planet (Figure 1). Other highest peaks in the Himalayas are Karakora (K2), Kanchenjunga, Lhotse, Makalu, Cho Oyu, Dhaulagiri, Manaslu, Nanga Parbat and Annapurna (Bhamri and Bolch, 2009). After Arctic and Antarctica, the Himalayas have the third largest deposit of ice, snow and glaciers in the world. The Himalayas has Siachen glacier, which is the largest. The other notable glaciers of Himalayas include Hispur, Baltoro, Nubra and Biafo. Most of the major river systems of Asia, namely Ganga, Indus, Brahmaputra, Yarlung, Yellow, Mekong, Nuijang and Tangtze originate from the Himalayas (Negi, 1991; Phartiyal et al., 2018).

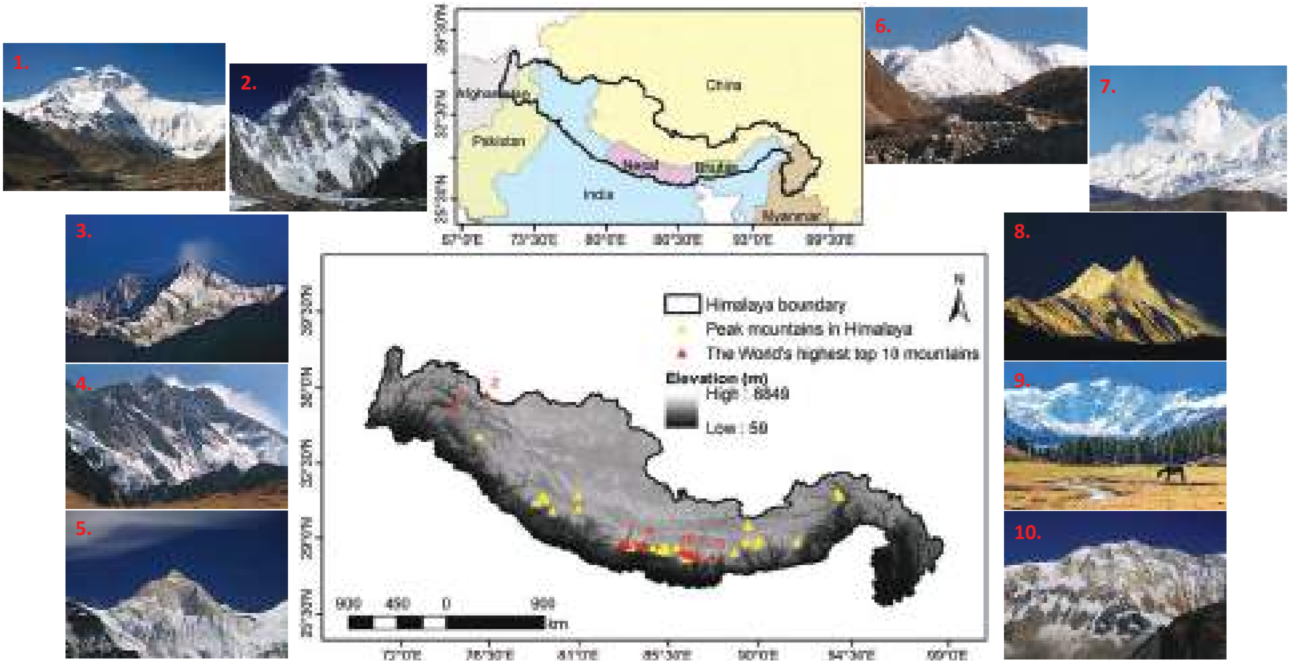

Figure 1. Transboundary Himalayan region of Asia and the top ten highest peaks (1. Mount Everest; 2. K2; 3. Kangchenjunga; 4. Lhotse; 5. Makalu; 6. Cho You; 7. Dhaulagiri; 8. Manaslu; 9. NangaParbat; 10. Annapurna
Photo Source: 1Wikipedia

1 https://en.wikipedia.org/wiki/List_of_Himalayan_peaks_and_passes

Owing to climatic events and anthropogenic activities, t*he Himalayan region is facing sudden and calamitous disaster events* such as *floods and landslides*. These directly damage *property,* cause *socioeconomic loss* and lead to *destruction and devastation of life (Laghari 2013; Romshoo et al., 2022).* Moreover, t*he* availability of Himalayan water sources also becomes *uncertain (Singh et al., 2006; Ragettli et al., 2016; Wood et al., 2020). Wetlands are important* in *reducing the flooding effect and* minimizing *landslides by depositing soil, lowering surface water flow rate, storing water and maintaining ecosystem services (Pandit and Grumbine, 2012; Shingare et al., 2019; Shirsat et al., 2021).* The *Himalayan* wetlands (in the form of lakes and ponds, meadows, marshes, swamps, bogs and fens) are generally fed by precipitation, snowmelt water, glacier meltwater or permafrost melt, and are getting affected because of rapid changes in climatic events and anthropogenic activities (Hájková et al., 2006; Sekar and Rawat, 2011; Palomo, 2017; Romshoo et al., 2011; Gupta et al., 2019). Hence, the role of wetlands in disaster risk reduction is changing over time, especially in the Himalayas.

2. Research Problem, Aim and Objectives

The Himalayas is a most influential natural system under uncertain climatic events, such as cloud bursting and heavy rainfall. This causes the occurrence of unpredicted floods and landslides in different altitude regions of the Himalayas (Akhtar et al., 2008). As climate change accelerates day-by-day, temperature rise can hasten the Himalayan glacier to melt in the most sensitive high-altitude regions which will result in less glacier coverage over time. The melted glacier water flows along with slopy mountain landscapes and forms a wetland in depressed mountain areas by accumulating water, soil and sediment flows (Bhamri et al., 2009; Pandit and Grumbine, 2012; Ghosh and Chakraborty, 2021; Sharma et al., 2022). For the inventory of such wetlands, the measured data availability is very limited for this region. Also, international boundaries of the Himalayas could be another major issue that restricts the use of classified data. Therefore, open-source remote sensing data could be an alternative solution in the present day.

Looking at the aforementioned, this research project aims to establish and implement a strategy to step up scientific excellence and innovation capacity in the area of nature-based solutions, i.e., wetlands for disaster risk reduction. It aims to do so by employing an inventory modelling approach. The project has been planned with the following objectives:

- To model the Himalayan wetlands using a maximum entropy algorithm
- To study the impact of climate change on high-altitude glacier melting and new wetland formation in the transboundary Himalayas
- To assess the potential of future Himalayan wetlands in reducing disaster risks under climate change scenarios

3. Methodology

3.1 Data collection and processing

In this study, DEM data was obtained from the USGS Earth Explorer website,[2] land cover data from the European Space Agency (ESA) website[3] and NASA Earth Data website[4], and bio-climate data from WorldClim website.[5] The available wetlands location data was obtained from Indian Government reports, such as the ISRO wetland atlas website[6] of India. The global CMIP6 climate model (BCC-CSM2-MR) dataset was used to obtain vital precipitation and temperature data-based climate indicators. The Shared Socioeconomic Pathways (SSP) of CMIP6 data, at the lowest level (ssp126) and highest level (ssp585), were selected for the study to understand the minimum and maximum levels of climate change impact in the Himalayas. Moreover, the analysis was performed for short-term (2021-2040) and long-term (2081-2100) periods to check the difference between ongoing and future climate change impacts. Hence, a total of four types of climate scenario combinations have been used for future wetland inventory modelling, as: (1) ssp126_2021-2040, (2) ssp126_2081-2100, (3) ssp585_2021-2040 and (4) ssp585_2081-2100. The required datasets of land characteristics, topographic features and bio-climatic properties were processed in the ArcGIS environment. The variables, namely landforms, Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Normalized Difference Snow Index (NDSI) and bioclimatic variables, namely isothermality, temperature seasonality, mean temperature of driest quarter, precipitation of driest month and precipitation of coldest quarter were used (Figure 3). Furthermore, wetland location (point) data, a total of 849 wetlands with an area >10 ha, were used to train and test the model prediction (Figure 4). The model training was performed with 60% and testing with 40% of the wetland location data.

2 https://earthexplorer.usgs.gov/

3 http://maps.elie.ucl.ac.be/CCI/viewer/

4 https://urs.earthdata.nasa.gov/

5 https://www.worldclim.org/data/bioclim.html

6 https://vedas.sac.gov.in/en/National_Wetland_Inventory_and_Assessment_(NWIA)_Atlas.html

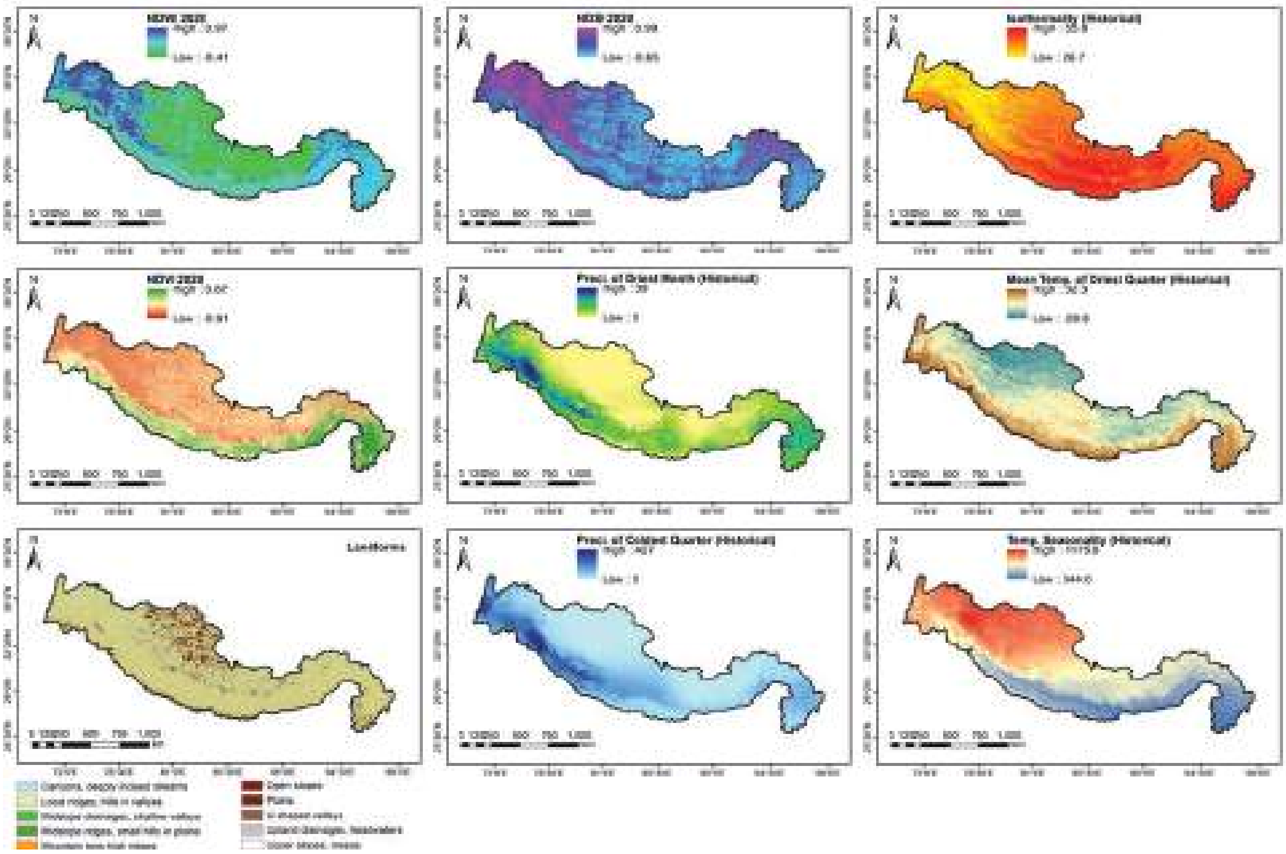

Figure 3. Spatial datasets generated for the inventory modelling

3.2 Inventory modelling using Maximum Entropy (MaxEnt)

In this project, a maximum entropy algorithm has been used to model the existing geographic distribution of Himalayan wetlands using specific point location data. The MaxEnt model helps lower the modelling uncertainties and affirm wetland inventory (Phillips, 2005; Skilling, 2013). It iteratively computes the probability of distribution of a response that maximizes entropy, that is closest to a uniform probability distribution. After data collection, the model inputs were prepared in a specific format by employing interactive time-series data processing. In this research study, the crux of the idea of wetlands inventory is the maximum entropy (MaxEnt[7]) algorithm. It provides a probability of wetland occurrence based on sensitive inputs such as topographic features, land characteristics and climate variation (Kalboussi and Achour, 2018; Raney and Leopold, 2018). It has been proposed for both historical and future wetland inventory modelling, as the impact of climate change accelerates glacier melting and forms natural lakes, reservoirs or wetlands. Such natural wetlands play a crucial role in provisioning and regulating ecosystem services. Therefore, the model inputs were used for the model setup, where two different scenarios of wetland inventory were run.

7 For more details, visit https://biodiversityinformatics.amnh.org/open_source/maxent/

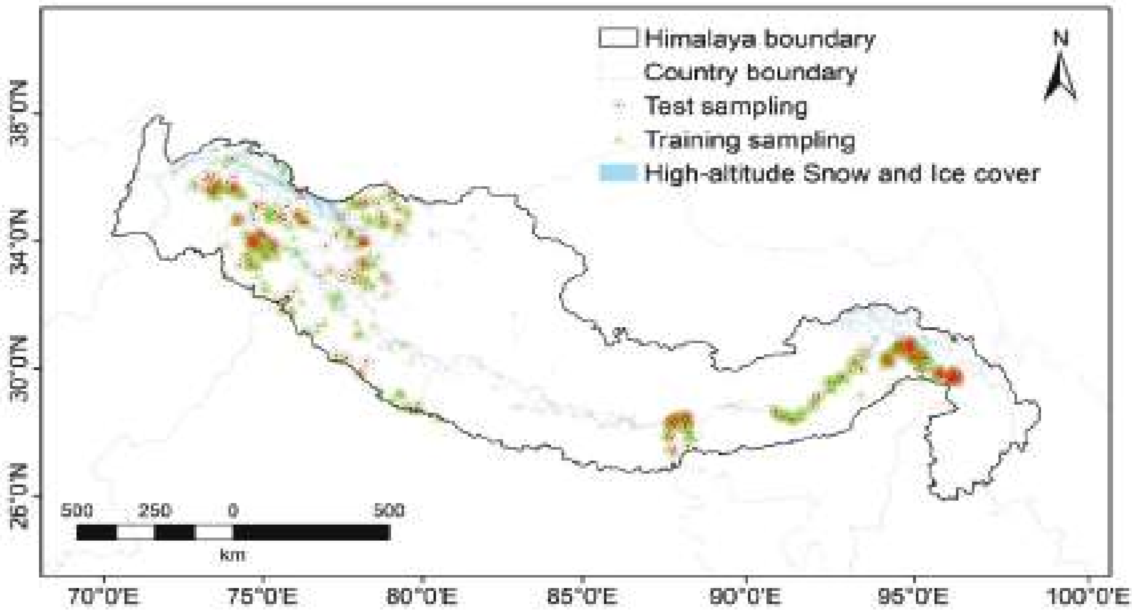

Figure 4. Wetland location sampling used for training and testing of the model

4. Results and Discussion

4.1 MaxEnt model performance evaluation

The performance of inventory modelling was evaluated using a threshold independent measure and the area under the curve (AUC). It helps quantify a model's probability of correctly simulating a random occurrence locality of wetlands. Generally, an AUC of 0.5 shows a random relationship, while an AUC of 1.0 indicates a perfect model prediction compared to observed information. In this study, an AUC of 0.950 for training and an AUC of 0.943 for testing showed an acceptable model simulation performance (Figure 5).

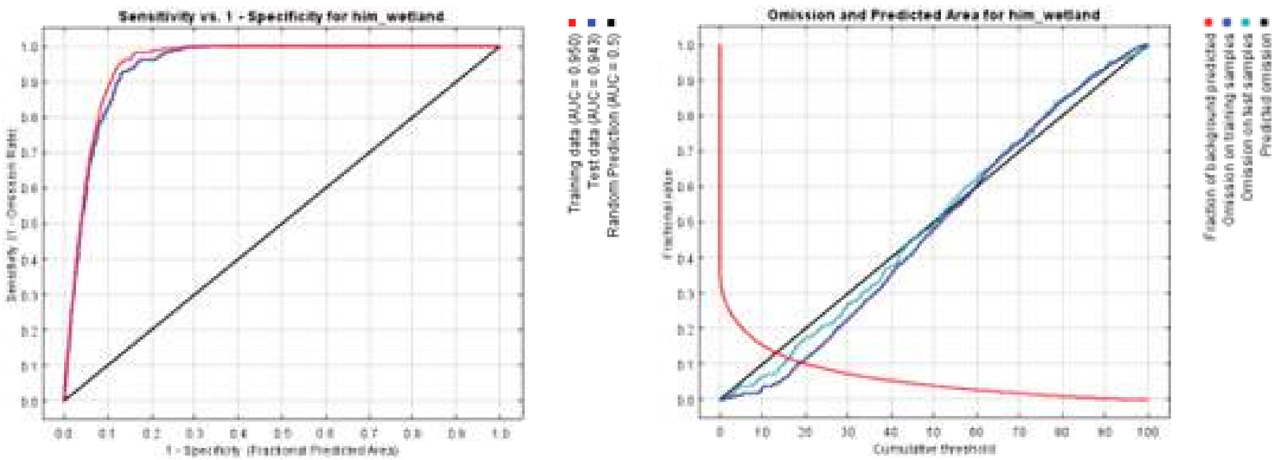

Figure 5. Performance evaluation of the model using training and testing data

4.2 Historical wetland inventory modelling

The climate data of the years 1970–2000 was used for historical inventory modelling. The probability of occurrence of wetlands in the full Himalayan region is grouped into five (Figure 6). The high to very high probability classes 0.6-0.8 and 0.8-1.0 were mainly considered to analyse the wetland areas further. The high probability class covers about 104660 km^2 (i.e., 5.5%), and the very high probability class covers about 38018 km^2 (i.e., 2%) of wetland area. Further, the glacier class from land cover data of the year 2019 was used to extract wetland probability distribution in the high-altitude Himalayan region. In the high and very high probability classes, the total historical wetland area is about 0.8% only.

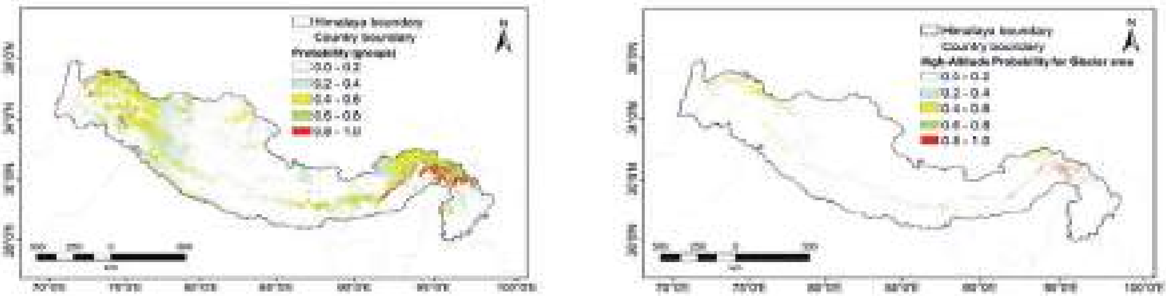

Figure 6. Himalayan wetland inventory using historical climate data

4.3 Future wetland inventory modelling

In this analysis, only precipitation and temperature data-based climate variables were changed. The remaining topographic variables were kept constant in, assuming no significant change in the topography of this region in the future. The results of the future wetland inventory modelling show that a significant variation of wetland distribution will likely happen over the years under climate change impact (Figure 7). The highest probability of wetland formation in the future is in the eastern and western Himalayan regions. Compared to historical high probability, future high wetland probability area is likely to be higher but will decrease over time. The high probability class 0.6–0.8 covers 9.2% to 17.3% area of the total wetlands in the Himalayas, and the very high probability class 0.8–1.0 covers 11.9% to 12.9% area of total wetlands in the Himalayas.

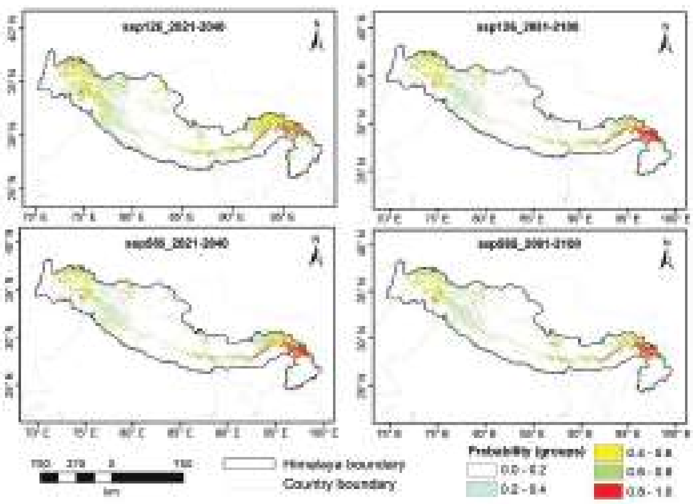

Figure 7. Himalayan wetland inventory using different future climate scenarios

4.4 Wetland dynamics and its potential in Himalayas

As shown in Figure 8, important routes (also locally called as 'pass') of the Himalayan mountains are falling under the future wetland probability distribution. The historical analysis shows that many routes are under 0.2–0.4 and 0.4–0.6 probability classes. But, under future climate change scenarios, some mountain routes (Mohan Pass, Rohtang Pass and Kunzum Pass) will fall under the 0.4–0.6 probability class, and two routes (Zoji La and Banihal Pass) of the western Himalaya will fall under 0.6–0.8 probability class. This is notable as future wetlands in these areas are likely to form and at the same time, impact the accessibility of these routes and may indirectly affect human activities in the mountain.

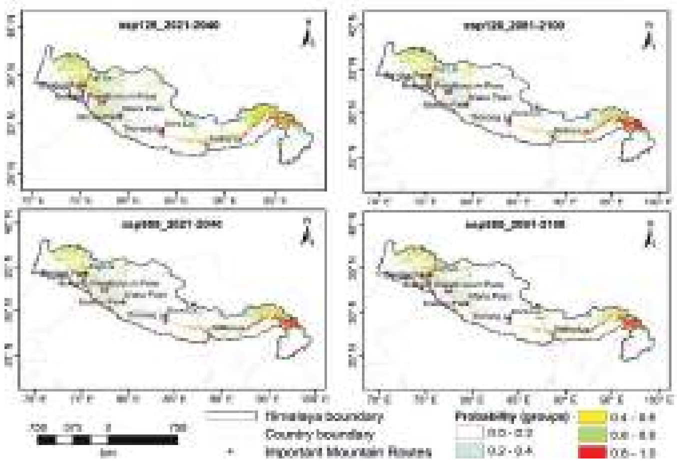

Figure 8. Important routes of the Himalayan mountains and future wetland probability distribution

5. Enablers and Barriers

This research aims to simplify a real-world problem by considering a few assumptions about input data, available wetland conditions, transboundary glacier layers and disaster-risk definition in the mountain area. In this research, major assumptions are related to datasets, i.e., spatial and temporal scales or resolutions and their availability. It is assumed that these open-source datasets are the most accurate information available in the present day. Wetland information used in this research is the most accurate and does not need any field-based cross-verification. Also, disaster risk in the high-altitude region is controlled by only climatic changes related to precipitation and temperature, which will enable climate-data-based prediction. However, in reality, anthropogenic activities somehow induce the propagation of mountain disasters and their impacts on human life. The proposed research covers only climate change impacts and excludes anthropogenic impacts. This research is limited without on-field social surveys, which could provide human insights and perceptions about Himalayan glacier dynamics and formations. Also, the data related to floods and landslides are not easily available to cross-check the locations that tend to be prone to mountain disasters. We believe this would help recognize probable wetland areas that can reduce future disaster effects. Therefore, this research discusses results based on the current modelling-based findings.

6. Conclusion and Way Forward

The study results obtained using the historical and future bioclimate variables have been compared to understand the effect of future climate change on new wetland development in the Himalayan mountains. The wetland probability range varies from 0 to 1, but this study focuses on probability ranges from 0.6 to 0.8 and 0.8 to 1.0. Changes in wetland numbers and their area/capacity in the future can have an altered impact on future disasters in the Himalayas. The end-product of the wetland inventory research is in the form of transboundary wetland datasets, probable wetland maps and an overview of the future of wetlands in the high-altitude region. This information could be used for an early-warning system in the Himalayas. Overall, this research has provided opportunities for collaboration between transboundary international stakeholders in terms of cross-institutional research and information sharing. This project has shared opportunities for capacity-building within the research timeframe in the field of wetlands. Also, this research has facilitated knowledge synthesis and contributed to creating an international research and innovation cluster. This research improves our understanding of the status of the high-altitude transboundary glacier and probable new wetland formation. Future wetlands can act as a natural system that can sustain ecosystem functions and alter mountain resilience.

The approach adopted in this study is quite new for future wetland inventory and extendable to any mountain/transboundary region, where wetland functions are primarily driven and controlled by glacier melting. However, one limitation is that this study only makes the proposed solution applicable to the high-altitude region, where the glacier layer is melting under climate change impact. Furthermore, this research study has used only one future climate model dataset. Different climate models can be used by employing an ensemble approach to minimize the model prediction uncertainty. High-resolution data for more detailed wetland inventory simulation can be used. In addition, anthropogenic effects can be considered for more insights into wetland dynamics. In this research, regional stakeholders' opinion on model development was not considered. This can be another research scope for future research on inventory modelling.

References

1. Akhtar, M., Ahmad, N., & Booij, M. J. (2008). The impact of climate change on the water resources of Hindukush–Karakorum–Himalaya region under different glacier coverage scenarios. *Journal of Hydrology*, 355(1-4), 148-163.
2. Berthier, E., Arnaud, Y., Kumar, R., Ahmad, S., Wagnon, P., & Chevallier, P. (2007). Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India). *Remote Sensing of Environment*, 108(3), 327-338.
3. Bhambri, R., & Bolch, T. (2009). Glacier mapping: a review with special reference to the Indian Himalayas. *Progress in Physical Geography*, 33(5), 672-704.
4. Chhetri, B., Badola, H. K., & Barat, S. (2021). Modelling climate change impacts on distribution of Himalayan pheasants. *Ecological Indicators*, 123, 107368.
5. Ghosh, K., & Chakraborty, P. (2021). Assessing the benefits, threats and conservation of reservoir-based wetlands in the Eastern Himalayan River Basin. Wetlands Conservation: Current Challenges and Future Strategies, 140-161.
6. Gupta, A. K., Negi, M., Nandy, S., Alatalo, J. M., Singh, V., & Pandey, R. (2019). Assessing the vulnerability of socio-environmental systems to climate change along an altitude gradient in the Indian Himalayas. *Ecological Indicators*, 106, 105512.
7. Hájková, P., Hájek, M., & Apostolova, I. (2006). Diversity of wetland vegetation in the Bulgarian high mountains, main gradients and context-dependence of the pH role. *Plant Ecology*, 184(1), 111-130.
8. Hoy, A., Katel, O., Thapa, P., Dendup, N., & Matschullat, J. (2016). Climatic changes and their impact on socio-economic sectors in the Bhutan Himalayas: an implementation strategy. *Regional Environmental Change*, 16(5), 1401-1415.
9. Hrach, D. M., Petrone, R. M., Green, A., & Khomik, M. (2022). Analysis of growing season carbon and water fluxes of a subalpine wetland in the Canadian Rocky Mountains: implications of shade on ecosystem water use efficiency. *Hydrological Processes*, 36(1), e14425.
10. Kalboussi, M., & Achour, H. (2018). Modelling the spatial distribution of snake species in northwestern Tunisia using maximum entropy (Maxent) and Geographic Information System (GIS). *Journal of Forestry Research*, 29(1), 233-245.
11. Laghari, J. (2013). Climate change: Melting glaciers bring energy uncertainty. *Nature*, 502(7473), 617-618.
12. Miserendino, M. L., Brand, C., Epele, L. B., Di Prinzio, C. Y., Omad, G. H., Archangelsky, M., ... & Kutschker, A. M. (2018). Biotic diversity of benthic macroinvertebrates at contrasting glacier-fed systems in Patagonia Mountains: the role of environmental heterogeneity facing global warming. *Science of the Total Environment*, 622, 152-163.
13. Negi, S. S. (1991). *Himalayan Rivers, Lakes, and Glaciers*. Indus Publishing.
14. Pandit, M. K., & Grumbine, R. E. (2012). Potential effects of ongoing and proposed hydropower development on terrestrial biological diversity in the Indian Himalaya. *Conservation Biology*, 26(6), 1061-1071.

15. Phartiyal, B., Singh, R., & Nag, D. (2018). Trans-and Tethyan Himalayan Rivers: In Reference to Ladakh and Lahaul-Spiti, NW Himalaya. In *The Indian Rivers* (pp. 367-382). Springer, Singapore.
16. Phillips, S. J. (2005). A brief tutorial on Maxent. *AT&T Research*, 190(4), 231-259.
17. Ragettli, S., Immerzeel, W. W., & Pellicciotti, F. (2016). Contrasting climate change impact on river flows from high-altitude catchments in the Himalayan and Andes Mountains. *Proceedings of the National Academy of Sciences*, 113(33), 9222-9227.
18. Raney, P.A. and Leopold, D.J. (2018). Fantastic wetlands and where to find them: modeling rich fen distribution in New York State with Maxent. *Wetlands*, 38(1), pp.81-93. https://doi.org/10.1007/s13157-017-0958-5
19. Romshoo, S. A., Ali, N., & Rashid, I. (2011). Geoinformatics for characterizing and understanding the spatio-temporal dynamics (1969 to 2008) of Hokersar wetland in Kashmir Himalayas. *International Journal of Physical Sciences*, 6(5), 1026-1038.
20. Sekar, K. C., & Rawat, B. (2011). Diversity, utilization and conservation of ethnomedicinal plants in Devikund-A high altitude, sacred wetland of Indian Himalaya. *Medicinal plants-International Journal of Phytomedicines and Related Industries*, 3(2), 105-112.
21. Sharma, R. K., Kumar, R., Pradhan, P., & Sharma, A. (2022). Climate-Induced Glacier Retreats and Associated Hazards: Need for Robust Glaciers and Glacial Lake Management Policy in Sikkim Himalaya, India. *Climate Change*, 161-182.
22. Shea, J. M., Immerzeel, W. W., Wagnon, P., Vincent, C., & Bajracharya, S. (2015). Modelling glacier change in the Everest region, Nepal Himalaya. *The Cryosphere*, 9(3), 1105-1128.
23. Shingare, R. P., Thawale, P. R., Raghunathan, K., Mishra, A., & Kumar, S. (2019). Constructed wetland for wastewater reuse: Role and efficiency in removing enteric pathogens. *Journal of Environmental Management*, 246, 444-461.
24. Shirsat, T. S., Kulkarni, A. V., Momblanch, A., Randhawa, S. S., & Holman, I. P. (2021). Towards climate-adaptive development of small hydropower projects in Himalaya: A multi-model assessment in upper Beas basin. *Journal of Hydrology: Regional Studies*, 34, 100797.
25. Singh, P., Arora, M., & Goel, N. K. (2006). Effect of climate change on runoff of a glacierized Himalayan basin. *Hydrological Processes: An International Journal*, 20(9), 1979-1992.
26. Skilling, J. (Ed.). (2013). *Maximum Entropy and Bayesian Methods* (Vol. 36). Cambridge, England, Springer Science & Business Media.
27. Wood, L. R., Neumann, K., Nicholson, K. N., Bird, B. W., Dowling, C. B., & Sharma, S. (2020). Melting Himalayan glaciers threaten domestic water resources in the Mount Everest Region, Nepal. *Frontiers in Earth Science*, 8, 128.

Thermal Stress Testing of Residential Building Using Reference Weather Data

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CDRI
Coalition for Disaster Resilient Infrastructure

Disclaimer:

Abstract

Weather plays a unique and significant role as it is one of the main inputs and directly affects the thermal loads and, thus, energy performance of buildings. The origin of this proposal is based on the fact that while performing building energy simulations only weather file is used as an input data to represent the outside weather conditions. Moreover, India uses only typical or average year to quantify building thermal performances developed by ISHRAE for 62 locations using data from the India Meteorological Department (IMD), the US National Center for Environmental Data (NCEI, formerly NCDC), and satellite-derived solar radiation data developed by NREL. The diversity in climate types of India suggests that there is no single strategy to eliminate thermal stresses, reduce energy demand and maximize comfort under extreme climatic conditions. In fact, there is no single standardized definition for thermal stresses in building thermal conditions. This gives rise to the need of identification and quantification of 'thermal stress' due to the extreme climate. In this study, extreme weather files inclusive of heat waves are generated. The gap between the typical and extreme thermal loads derived for a residential building type would help in defining the thermal stress for different climate types. The categorization of thermal stresses identified using cluster analysis would further help building engineers to optimize the building materials selection and its U-value. The two major outcomes from this study are extreme weather files and categorization of thermal stresses.

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1. Introduction

To understand thermal stress, it is essential that as per accepted building thermal standards one comprehends thermal comfort and discomfort. Based on climatic environment, thermal comfort is defined by four factors: Air temperature, Radiant Temperature, Air speed and Humidity (Institute of Medicine, 2011; MoSPI, 2017). These factors also help in mapping thermal discomfort. Thermal discomfort is not limited to a lack of satisfaction with the ambient temperature but reflects a situation that poses a potential threat to health. When the temperature falls below 18˚C or rises above 24˚C for a period of time, it creates thermal discomfort (Ormandy and Ezratty, 2016; Ezratty and Ormandy, 2015). As stated in ASHRAE (ASHRAE 2017), when a being is in a state of thermal discomfort, any move away from the thermal stress of the uncomfortable environment is perceived as pleasant during the transition. It can be concluded that extreme cases of thermal discomfort cause thermal stress (Amasuomo and Amasuomo, 2016; Bell et al. 2001). Thermal stress occurs due to extreme heat or cold. Over the past few decades, the increase in extreme climatic events and climate change at an unpredictable rate has led to an increase in air-conditioned spaces (Institute of Medicine, 2011). India is a developing country whose per capita energy use has been increasing by 3.3% every year (MoSPI, 2017) and its population is expected to reach 2.3 billion by 2080 (ONU, 2019). Already the outdated grid is unable to keep up with the current energy demand. And if the present trend continues, then the peak load increasing during summer due to space cooling will result in more frequent power outages. A study has revealed that space heating and cooling energy will increase by 850% from 2005 levels to 2050 if similar built and operation methods are followed (GBPN, 2014).

Among other things, a building is built to provide protection from outside environment and comfortable internal conditions to individuals so that they can perform their everyday tasks (Herrera et al., 2017). As per IEA Annex 53 (IEA, 2016) six factors impact building energy performance: climate, building envelope, building equipment, operation and maintenance, occupant behaviour, and indoor environmental conditions. In this article, we aim to understand and tackle the problem of impact of climate poses as the main input and its direct effect on thermal loads and energy performance of building during typical and extreme weather conditions. In building energy simulation, traditionally Typical Reference Year (TRY) weather data represents the climate input for building simulation. TRY is a composition of a single year historical weather data derived from at least 10 years of historical weather data, with each month representing the average or typical for that month. But various studies have found that TRY does not necessarily exemplify the average long-term performance, as buildings with different energy systems and designs respond differently to weather changes. Furthermore, a single-year weather file does not provide the range of yearly results possible due to changing weather, which is an essential component for building energy management and risk assessment during energy efficiency investments (Hong, Chang, and Lin, 2013). Existing energy building codes, e.g., ECBC (Energy Conservation Building Code), focus primarily on reductions in mean energy demand that are derived from typical weather files (Evans, Roshchanka, and Graham, 2017). Thus, extreme climate is required to be represented and evaluated against average conditions to study building resilience under changing climatic conditions.

2. Research Problem, Aim and Objectives

2.1 Research problem

The available literature on climate change and building energy indicates that buildings ventilated naturally need to use some form of air conditioning. Buildings that are already air-conditioned use it more often thus reducing the usage of natural ventilation. Lack of air conditioning will expose people to extreme heat conditions more often. To prevent and solve this problem, it is essential that building thermal performances be predicted for extreme climate.

The two key research questions then arise:

How much is peak energy loadings under extreme climatic conditions?

What design strategies would maximise peak energy demand reduction?

2.2 Aim

The aim of this research is to develop a methodology for thermal stress testing in residential building of India.

2.3 Objectives

The purpose of this research is to

i. Establish the relative significance of climate variables based on thermal response of residential buildings.
ii. Reformulate typical year weather files considering the relative significance of climate variables of bf for different climate locations.
iii. Formulate extreme year weather files to evaluate the thermal response and peak cooling demand under thermal extremes.
iv. Develop a methodology for thermal stress testing due to climate loading on buildings using typical and extreme weather files.

3. Methodology

The research methodology is divided into two parts as shown in Figure 1.

1) Construction of extreme weather files inclusive of heat waves.

2) Climate loading identification under typical and extreme conditions for thermal stress quantification.

3.1 Climate data preparation

The UK Met Office has provided 130 years (1970–2099) of hourly data at 25 km resolution over India. This was possible because of the 17-member perturbed-physics ensemble climatic model HadCM3Q0-Q16 (known as "QUMP"), downscaled with the high-resolution regional climate model, Providing Regional Climates for Impact Studies (PRECIS). From now on, we will refer to this dataset as "QUMP/PRECIS". QUMP/PRECIS offers 10 variables of interest. Future projections are obtained considering the IPCC scenario A1B (rapid economic growth, globalisation, rapid introduction of new and more efficient technologies, and a balance between the use of fossil fuel and renewable energy sources).

Based on climatological tables from Indian Meteorological Department (IMD, 1999), we calibrated the PRECIS data for the extremes and validated for 52 locations taking into account extremes from the past 110 years for each month. This work was performed in collaboration with Dr Oliver Hatfield.

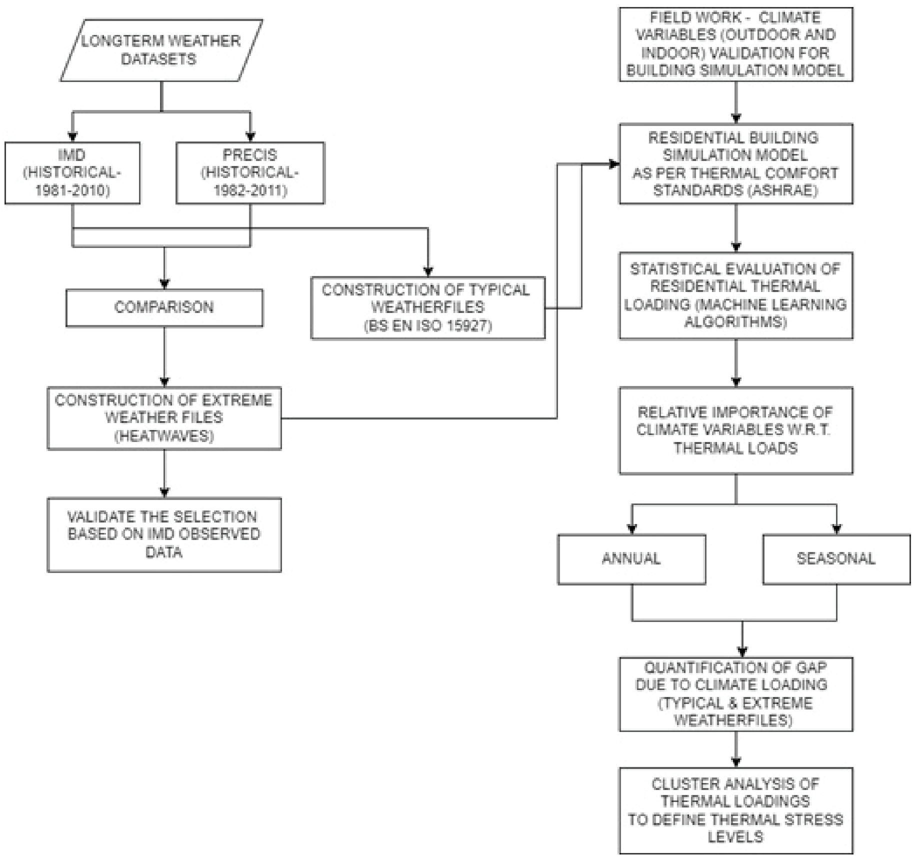


Figure 1. Flowchart for methodological approach to thermal stress testing

3.2 Generation of extreme weather files inclusive heat waves

We conducted a pilot study to generate extreme weather files for India inclusive of heat waves. This study presents an alternate approach to the existing typical weather file generation method as mentioned in BS EN ISO 15927 (BS ISO, 2005). Under the guidance of Prof. David Coley and Dr Sukumar Natarajan, the concept and execution of the study was performed. The running mean outdoor temperature has been considered in this study in the selection of extreme weather year. Adaptive thermal comfort studies have demonstrated the relevance of running mean outdoor temperature in determining indoor thermal comfort. As per BS EN ISO 15927, 7 days are considered in deriving adaptive thermal comfort temperature. In this study, return period of 1 in 30 years is considered to generate current and future extreme weather files. Further, for large-scale application, synthetic PRECIS-RCM is being calibrated and validated with IMD observed data.

3.3 Field data collection

In order to validate the approach of thermal stress testing, it is essential to validate it on original data. Thus, to record the outdoor climate variables a weather station was installed at the roof top of mid-rise apartments in Balaji Apartments, Dwarka, New Delhi. These apartments have been sanctioned by Delhi Development Authority (DDA). Further, three sensors were installed: one at the main switch board and two in air-conditioners to calculate the power as well as indoor/outdoor temperature and relative humidity of five residences. This will help in validating the building simulation models. Also, the power ratings of heavy equipment installed are taken into consideration for each residence as shown in Figure 2.

Figure 2. Sensors installed for power consumption and climate variables – indoor and outside environment

3.4 Residential building simulation model

To standardize the climate loadings obtained as weights for residential building type, a residential case study building model was validated with the actual data load for summer months with CV(RMSE) of climate variable temperature calculated 6.71. The model that fell within 30% of

CV(RMSE) values is considered calibrated as per ASHRAE Guideline 14-2002 (Hong, Chang, and Lin, 2013). To demonstrate the applicability of this approach, a base model of 4m × 4m × 3m to perform parametric analysis is modelled in compliance with the general requirements for residential buildings under National Building Code of India (NBC) for each climate type (Evans, Roshchanka, and Graham, 2017). The heating and cooling set-point of this model is 23.5°C and 25°C. It is conditioned to a fixed rate of four air-changes per hour as per recommended values under lighting and ventilation section of NBC (IMD, 1999). Dehumidification for more than 50% relative humidity to compile with the environmental thermal comfort standards for human occupancy (BS ISO, 2005). The base model does not take into account any other internal thermal loading from people, electrical and lighting equipment. To make the model robust, all eight orientations – N, NE, E, SE, S, SW, W, NW – were taken into consideration. The window wall area (WWR) ratio for residential building for base model varies between minimum 10% and 40% as the increase in ratio requires compliance with the U-value as per Indian Green Building Council standards (Amasyali and El-Gohary, 2018; White Box Technologies 2014).

3.5 Statistical analysis for climate loading

3.5.1 Machine learning algorithms

3.5.1.1 Random forest regressor (RF)

Random forest regressor (RF) is a supervised learning algorithm that uses ensemble learning method for regression. It applies multiple decision trees and bagging techniques. The final predictions are based on averaging the result of multiple decision trees (Breiman, 2001). The whole procedure of averaging the bootstrapped data is called bagging (Oza and Russell, 2001).

3.5.2 Performance evaluation

The performance of the machine learning algorithms, that is extreme gradient boost is measured on the basis of coefficient of determination (R^2) of the training dataset, that is Pearson correlation coefficient and p-value is calculated over test dataset. Pearson correlation coefficient measures the linear strength between the predicted and the actual test dataset to determine the reliability of the model. The CV-RMSE on the test dataset is as per ASHRAE Guideline 14 recommended performance evaluation metrics for evaluating energy consumption prediction models (Hong et al., 2017; Amasyali and El-Gohary, 2018).

4. Results and Discussion

4.1 Extreme weather files generation

The extreme weather files for India is a pilot step. Currently only 62 typical/average weather files are available for India for building energy simulations provided by ISHRAE. Based on this procedure, extreme weather files inclusive of heat waves can be produced.

4.1.1 Analysis of PRECIS-RCM with respect to IMD climate data

The daily maximum monthly average and daily minimum monthly average over 1981–2010 from IMD report [15] is compared with PRECIS-RCM data over 17 ensembles for period 1982–2011. In this report, we will discuss the outcomes from only one location.

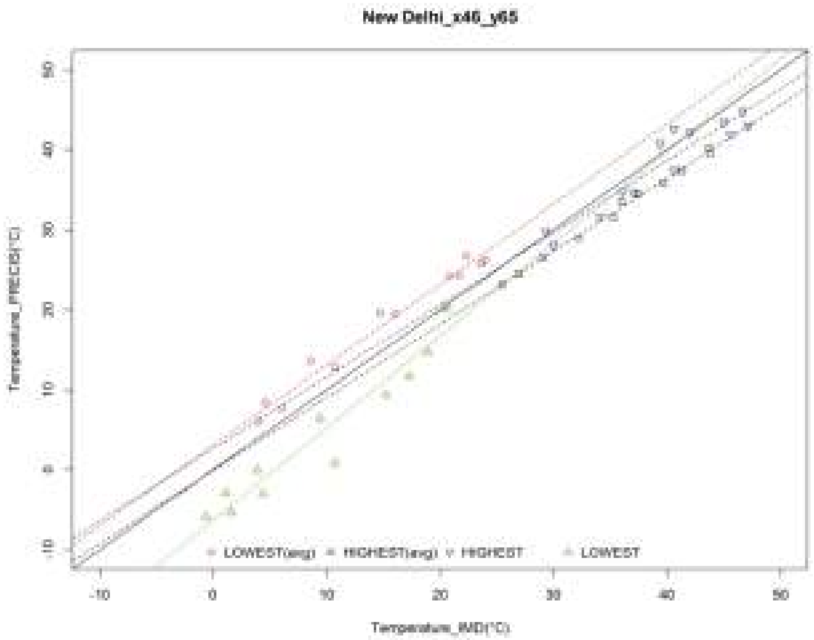


Figure 3. The calibrated PRECIS temperature extremes for each month are compared to IMD recorded extremes from past 110 years

Lowest(avg) is monthly average daily minimum, Highest(avg) is monthly average daily maximum, Highest is monthly highest daily maximum and Lowest is monthly lowest daily minimum.

In Figure 3, the data falling on solid black diagonal slope represents the similarity between the synthetic PRECIS-RCM and IMD observed data. This graphical comparison between the PRECIS-RCM extremes and IMD extremes shows that though the 'highest(avg)' and 'highest' are close to the diagonal slope, but lie below it. It means PRECIS-RCM under predicts maximum temperature values. On the other hand, 'lowest(avg)' values lies above the slope thus predicting higher temperatures than observed in IMD data. The 'lowest' values even though are closer to diagonal slope but are under predicted.

4.1.2 Extreme weather file analysis

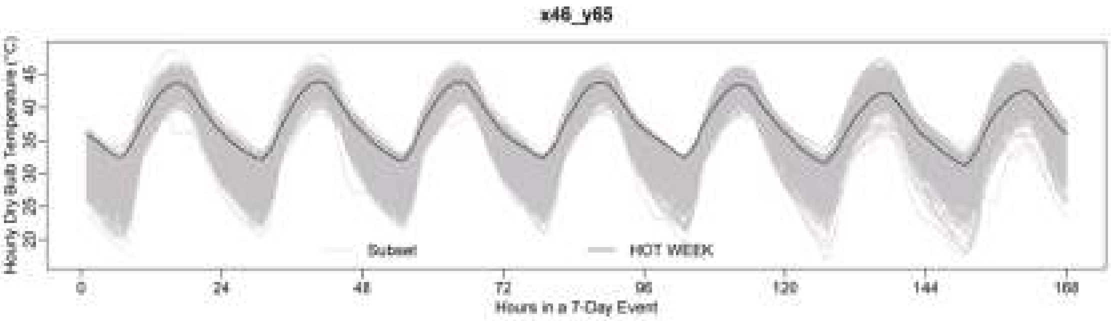
In order to validate the extreme weather files generated using PRECIS data, it is important to study if the pilot procedure opted generates weather files that are inclusive of heat waves as per standards defined by IMD and also takes into consideration WMO definition.

Three types of extreme weather files are generated:

1) Extreme hot week/event selection based on dry-bulb temperature (DBT)
2) Extreme hot week/event selection based on wet-bulb temperature (WBT)
3) Extreme cold week/event selection based on dry-bulb temperature (DBT)

4.2 Extreme Hot Week/Event Selection (based on DBT)

The extreme hot week selected for New Delhi location is shown in Figure 4. The hottest week/event from 1982 to 2011, which is 30 years and 17 ensembles, that is, 510 years, is selected. The selection is based on daily maximum dry-bulb temperature. First, daily maximum temperature from hourly data is selected and running mean based on event length (Event length: 3, 5, 7) is calculated for the dataset. Then, the temperature value at 95th percentile is selected. In order to ensure a consistent hottest event selection, a subset dataset is created having +/- 0.1 °C difference from the selected 95th percentile ‘w_{mean}’ temperature. Also, minimum variance in the diurnal temperature is considered. The subset generated is limited to +/-1 month of highest daily maximum monthly average value.



ens	year	wkno	wmean	month	day	mmean	mmax
6	23	151	43.4	5	31	41.1	45.1

Figure 4. The selected hot extreme event based on dry-bulb temperature for New Delhi location

The results show that extreme hot week/event based on dry-bulb temperature is inclusive of the heat waves. It comprises daily maximum values above 40˚C in highest monthly average temperature. The extreme weather file selected captures the extreme based on average running mean and highest monthly average value. The comparison of IMD and PRECIS 1:30 years of data is ongoing for more locations.

4.3 Extreme hot week/event selection (based on WBT)

The extreme hot week selected for New Delhi location is shown in Figure 5. The hottest week/event from the period (1982-2011), which is 30 years and 17 ensembles, that is 510 years is selected. The selection is based on daily maximum wet-bulb temperature. First, daily maximum temperature from hourly data is selected and running mean based on event length (Event length: 3, 5, 7) is calculated for the dataset. Then, the temperature value at 95th percentile is selected. In order to ensure a consistent hottest event selection, a subset dataset is created having +/- 0.1 °C difference from the selected 95th percentile “w_{mean}” temperature. The subset generated is limited to +/-1 month of highest daily maximum monthly average value.

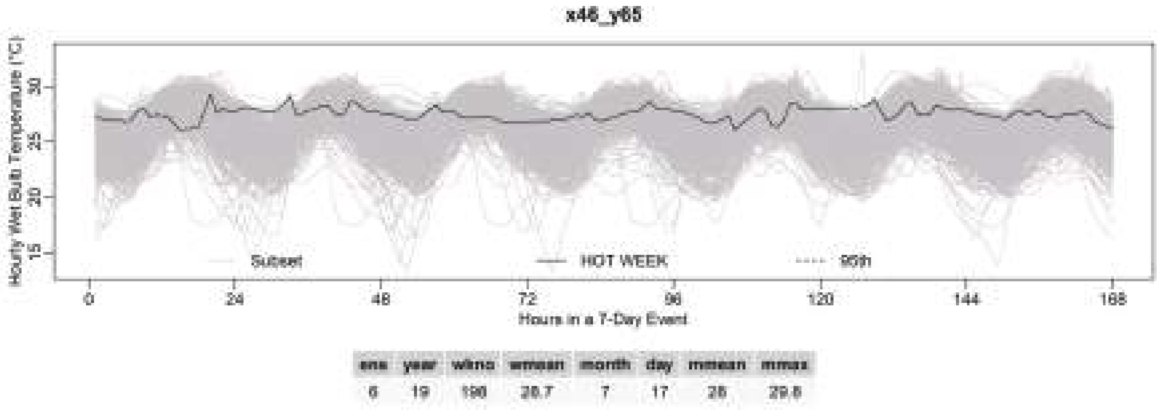


Figure 5. The selected hot extreme event based on wet-bulb temperature for New Delhi location

The results show that hot extreme event based on wet bulb temperature predicts 17 July as the start of extreme event for New Delhi. July and August are the monsoon months for the given location. The selection based on wet bulb temperature captures the highest average low temperatures for the location. Further investigation based on Heat index is required to validate the extreme file construction with respect to standards.

4.4 Extreme cold week/event selection (based on DBT)

The extreme cold week selected for New Delhi and Chennai location is shown in Figure 6. The coldest week/event from the period (1982–2011), which is 30 years and 17 ensembles, that is, 510 years, is selected. The selection is based on daily minimum dry-bulb temperature. First, daily minimum temperature from hourly data is selected and running mean based on event length (Event length: 3, 5, 7) is calculated for the dataset. Then, the temperature value (w_{mean}) at 5th percentile is selected. In order to ensure a consistent coldest event selection, a subset dataset is created having +/- 0.1 °C difference from the selected 5th percentile 'w_{mean}' temperature.

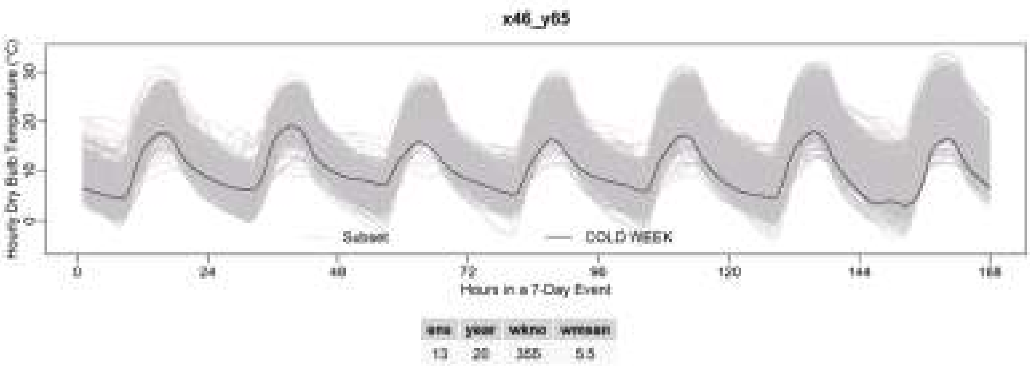


Figure 6. The selected cold extreme event based on dry-bulb temperature for New Delhi location

The results show the selection of extreme cold week for the location New Delhi for December month having lowest average daily minimum for seven-day event. To be certain that the inclusion defines the cold wave, the definition by IMD needs to be taken into consideration.

4.5 Climate loading and its validation

In this section, the relative importance of primary climate variables – temperature, relative humidity and global horizontal irradiation are calculated with respect to residential building thermal loading. These loadings are crucial in determining the thermal stress when extreme and typical weather files are compared. The concept and execution have been done under the supervision of Dr Rajasekar and Prof. D.S Arya.

4.5.1 Reweighted weather files

A mathematical approach is taken into consideration for generating re-weighted typical and extreme weather files using IMD observed dataset. It takes into consideration the smallest unit of a mid-rise apartment discussed in Section 3.4. For generating typical reweighted weather files, the daily average thermal loads are considered and for extreme reweighted weather files the daily maximum thermal loads are considered. The mathematical approach applied is supervised learning decision tree algorithm random forest. The re-weighted weather files shows closer interpretation to the actual energy simulations in comparison to standard weather file (BS ISO, 2005). The relative importance of each climate variable for construction of re-weighted typical weather files is shown in Table 1. For performance evaluation root mean square error (RMSE) is calculated in comparison to multi-year data from 1990 to 2016 for standard and re-weighted weather file in Table 2. The results show better performance in relation to predict actual energy consumption.

Table 1. Relative importance of each climate variable for construction of re-weighted typical weather files

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NEW DELHI												
T-MEAN	0.69	0.73	0.66	0.55	0.61	0.64	0.52	0.44	0.40	0.41	0.42	0.57
RH-MEAN	0.14	0.10	0.13	0.19	0.13	0.14	0.13	0.10	0.12	0.15	0.19	0.22
GHI-MEAN	0.17	0.16	0.21	0.26	0.27	0.22	0.35	0.46	0.47	0.45	0.39	0.21
R-SQUARED	99.9	99.9	99.9	99.9	99.98	99.9	99.9	99.96	99.98	99.96	99.96	99.95
Pearson Correlation	0.88	0.94	0.91	0.79	0.79	0.77	0.82	0.77	0.76	0.77	0.60	0.66

Table 2. RMSE calculation for annual average thermal load in comparison to annual average thermal loads of multi-year dataset of concerned locations for TRY

RMSE	Typical					
	Total Energy		Heating		Cooling	
	Try	Re-try	Try	Re-try	Try	Re-try
New Delhi	0.61	0.38	0.06	0.09	0.55	0.29

The results show significant improvement in prediction of typical weather file after re-weighting based on climate variable importance. New Delhi shows an improvement of approximately 38% in comparison to the standard procedure. When heating thermal loads are compared to re-weighted weather file, it shows deviation of 3% more than the standard file. The improvement in cooling load prediction is about 47% for New Delhi.

To understand which building design features impact most of the building thermal loads for 90 percentile and 10 percentile are analysed for each year (1990–2016) and the results have been discussed in Table 3.

Table 3. Building design parameters that fall into the category of top 90th and bottom 10th percentile with respect to thermal loads

Cities	90th Percentile and Above	10th Percentile and Below
NEW DELHI (Heating)	Two face exposed, 40%, U-value: 0.71, orientation: 16 deg.	Two face exposed, 10% WFA, U-value: 0.162, orientation: 91 deg.
NEW DELHI (Cooling)	Two face exposed, 40% /23.50% WFA, U-value: 1.838/1.40, orientation: 315 deg/169 deg	One face exposed, 10% WFA, U-value: 0.239 , orientation 0.

It can be concluded from Table 3 that design strategies that include lowering U-value of building envelope and minimum exposure in terms of wall and window floor area (WFA) ratio promote lower thermal loads.

Based on this study, it is valid to use machine learning algorithm 'random forest' for determining climate loading in weather files for determining thermal stress gap for each location. Further, locations with similar characteristics in the climate loadings can be grouped together based on cluster analysis and thermal stress levels can be defined based on severity in each group. This classification will further help building engineers to optimise and select design strategies such as plan-form and building materials based on thermal stress levels.

4.6 Thermal stress quantification

To study thermal stress, the extreme and typical event of 7-days is simulated for the mid–rise residential base model as detailed in Section 3.4 using extreme and typical weather files. The generation procedure of weather files is detailed in Section 3.2. In order to quantify thermal stress, the thermal loading for an average as well as extreme event for the 7-day event are compared as shown in Figures 12, 13 and 14.

The results for hot weather files of New Delhi shows a rise of 4.5% for extreme weather files based on dry bulb temperature and 12.3% rise in thermal loading for extreme weather files based on wet bulb temperature on comparison with typical weather files as shown in Table 5.

The results for cold extreme weather files show a decrease of 82% in case of New Delhi. New Delhi showed an increase in heating thermal load from 0.02 to 0.05 kWh whereas decrease in cooling thermal load from 15.49 to 2.75 kWh when typically compared to extreme weather file.

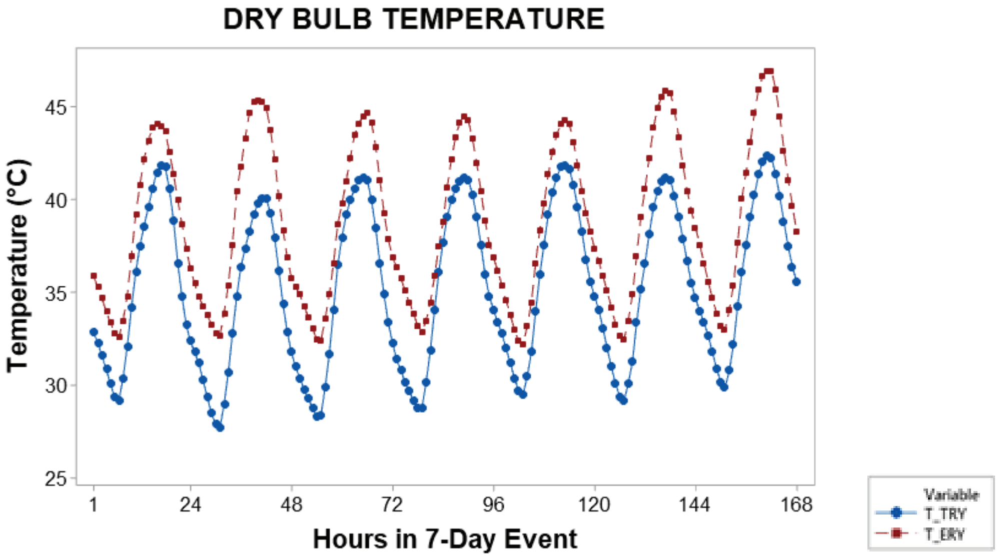


Figure 12. Comparison between the hot extreme and typical weather file air temperature for the 7-day extreme event period for New Delhi location. The extreme weather file considered is based on dry bulb temperature (DBT)

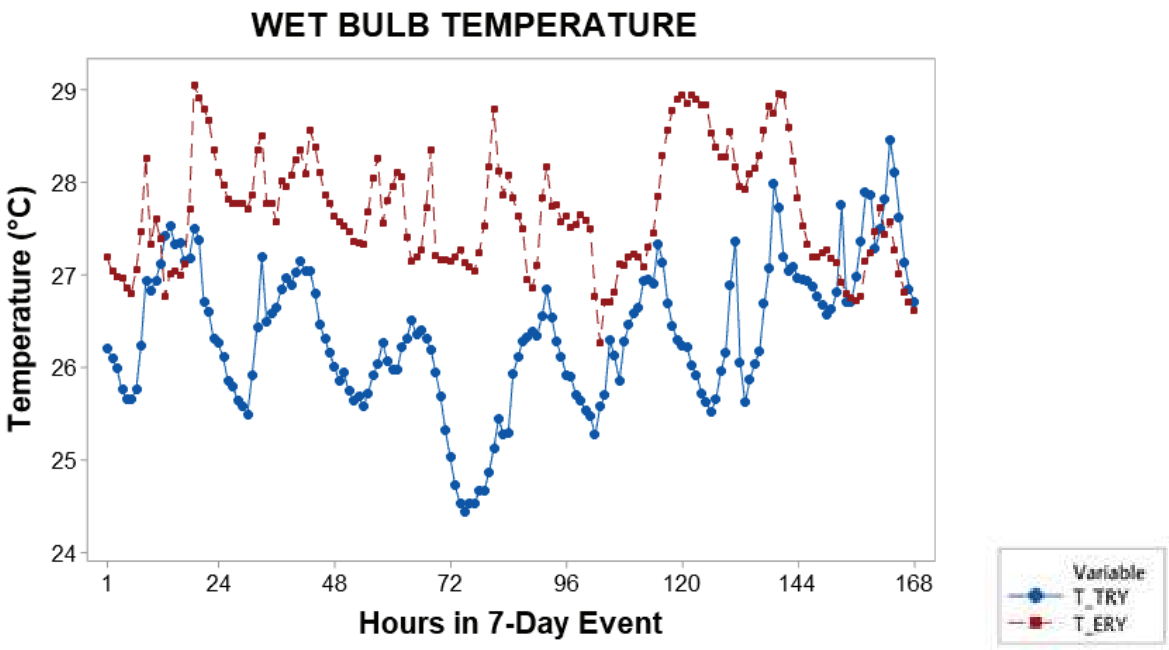


Figure 13. Comparison between the hot extreme and typical weather file-air temperature for the 7-day extreme event period for New Delhi location. The extreme weather file considered is based on wet bulb temperature (WBT)

Table 5. Comparison between the extreme and typical weather file- thermal loading(kWh) for the 7-day extreme event period for New Delhi and Chennai location

Cities	TRY - DBT (kwh)	HOT ERY-DBT (kwh)	TRY-WBT (kwh)	HOT ERY-WBT (kwh)	TRY - DBT (kwh)	COLD ERY-DBT (kwh)
NEW DELHI	59.4	62.1	38.9	43.7	15.51	2.80

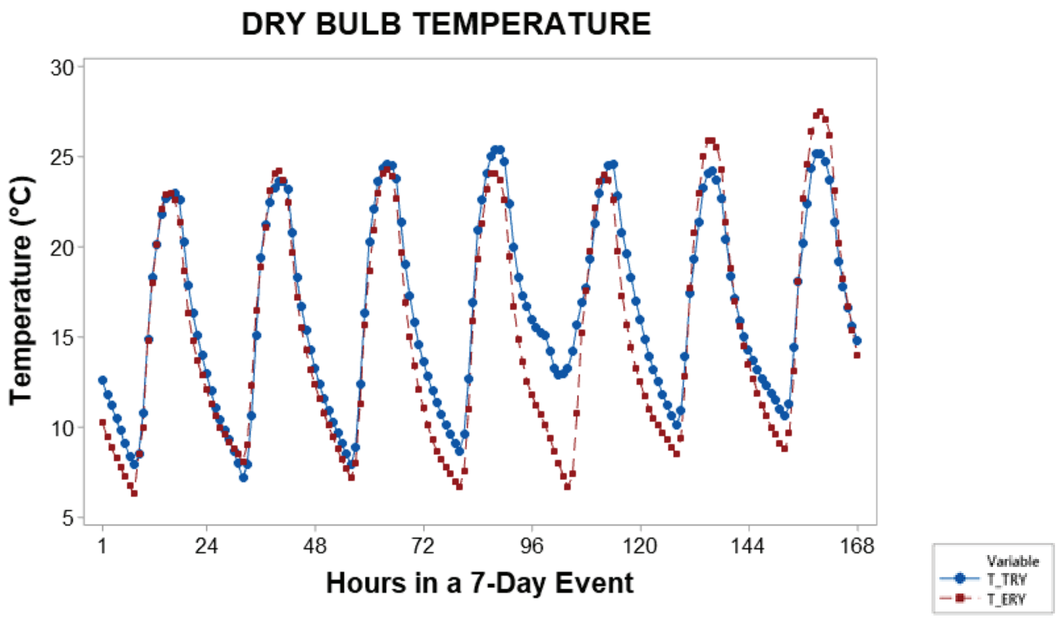


Figure 14. Comparison between the cold extreme and typical weather file-air temperature for the 7-day extreme event period for New Delhi location. The extreme weather file considered is based on dry bulb temperature (DBT)

Further classification and validation of these studies are under progress. But the results based on the current climate data from period (1982–2011) helped in establishing a procedure to identify the extremes based on heat waves and also the expected thermal stress under extreme conditions.

5. Enablers and Barriers

5.1 Weather data

The construction of weather files requires at least 10 years of hourly weather data comprising dry-bulb temperature, relative humidity, global solar radiation and wind. In case of inclusion of extreme events such as heat waves, the extremes observed data up to 100 years is taken into consideration. Extreme events are calculated in terms of 1:50 years or 1:100 years return period. But in the case of generating weather files for building energy simulation, it is essential to have the climate variables at hourly resolution.

The Indian Meteorological Department (IMD) provided the observed weather data for New Delhi, Ahmadabad, Chennai and Bangalore for period 1990 to 2016. The data is at hourly resolution with missing values. The most inconsistent data is of global solar irradiation, as it is not available at every weather station. Also, the ISHRAE weather files generated uses NREL solar radiation weather data, which is derived from satellite images (White Box Technologies, 2017). Another source from where hourly data at quarterly resolution is obtained is the World Meteorological Organisation database that contains data from the year 2000 to the present. These are surface synoptic observations and BUFR binary data (Binary Universal Form for the Representation of meteorological data), but lack information related to solar radiation data (NOAA, nd).

In order to take into account the extremes, long-term synthetic data from UK Met Office was obtained for period of 130 years (1970–2099) of hourly data at 25 km resolution over India. This was possible thanks to the 17-member perturbed-physics ensemble climatic model HadCM3Q0-Q16 (known as "QUMP"), downscaled with the high-resolution regional climate model, Providing Regional Climates for Impact Studies (PRECIS). Future projections are obtained considering the IPCC scenario A1B (rapid economic growth, globalisation, rapid introduction of new and more efficient technologies, and a balance between the use of fossil and renewable energy sources). Thus, it enabled the generation of present and future weather files for 1982–2011 and 2062–2091, respectively.

Another important document provided by Indian Meteorological Department regarding climate normals enabled the validation of the weather files generation process for extremes (IMD, 1999).

6. Key Takeaways from CDRI Fellowship Programme

As per the suggestions from TEG members, the research can be expanded further and the following attributes should be included:

1) Inclusion of Urban Heat Island effect in generation of extreme weather files.

2) Testing all the possible factors that can impact on thermal stress of a building from various dimensions and at the end put them together and see their impact together.

Due to limited time, it was not possible to include UHI and testing of possible factors that impact thermal stress in a building is under progress.

7. Conclusion and Way Forward

7.1 Extreme weather file generation

Under this research project a new methodology to generate extreme reference weather file inclusive of heat waves is generated for building energy simulations for India. These weather files are based on PRECIS –RCM weather data and are validated using IMD 1981–2010 climatological datasheet (IMD, 1999). Currently, ISHRAE typical weather files are available online for building engineers and architects for 62 locations. Based on this study and validation criteria, 52 locations across India will have extreme weather files depicting heat-wave conditions for current as well as A1B future scenario. Since PRECIS-RCM is at 25 × 25 km resolution, the solution could be extended to whole of

India. Validation of extreme week based on hot wet-bulb temperature and cold dry-bulb temperature needs to be done on the basis of IMD definitions of cold wave and heat wave based on wet-bulb temperature. After validation these weather files can also be generated at 25 × 25 km resolution.

7.2 Thermal stress categorization

Thermal stress is calculated for each location based on gap between the climate loadings of extreme and typical weather files. The climate loadings are calculated for parametric building simulation model discussed in Section 3.4. The calculation procedure performed using IMD weather data provides relative importance of each climate variable based on machine learning algorithm random forest. Further, clustering of thermal stress would be beneficial for application of early design strategies.

7.3 Design strategies

In this report, plan-form selection for a commercial building based on climate loading is studied for New Delhi location. It has been analysed that the seasonal climate loadings on a plan-form varies significantly as compared to annual climate loadings. Thus, the most consistent choice with least variation in climate loadings throughout the year is C-Shape plan-form. But it also has the highest thermal impact due to mean temperature followed by maximum temperature. Thus, the next target strategy is the selection and optimization of building material. The work on "Analysis of Phase Change Materials (PCM) performance under extreme climatic conditions – Present & Future" has also been initiated in collaboration with Ms Isha Rathore, Dr Oliver Hatfield, Dr Sukumar Natrajan and Dr David Coley.

References

1. Amasyali, K. & El-Gohary, N. M. (2018). A review of data-driven building energy consumption prediction studies. *Renew. Sustain. Energy Rev.*, 81(January), 1192–1205.
2. Amasuomo, T. T., & Amasuomo, J. O. (2016). Perceived thermal discomfort and stress behaviours affecting students' learning in lecture theatres in the humid tropics. *Buildings*, 6(2), 1–17.
3. ANSI/ASHRAE. (2017). ANSI/ASHRAE Standard 55-2017 : Thermal Environmental Conditions for Human Occupancy. *ASHRAE Inc.*, 2017, 66.
4. BEE. (2010). Energy benchmarks for Commercial Buildings 2010. Details available at https://www.beeindia.gov.in/sites/default/files/Flyer_22nd%20Jan.pdf
5. Bell, A., Greene, P.A., Fisher, T.C., & Baum J.D. (2001). *Environmental Psychology*.
6. Breiman, L. (2001). ST4_Method_Random_Forest. *Mach. Learn.*, 45(1), 5–32.
7. BS ISO. (2005). BS EN ISO 15927. Hygrothermal performance of buildings. Calculation and Presentation of Climatic Data, Vol. 3.
8. Evans, M., Roshchanka, V., & Graham, P. (2017). An international survey of building energy codes and their implementation, *J. Clean. Prod.*, 158, 382–389.
9. Ezratty, V., & Ormandy, D. (2015). Inconfort thermique dans l'habitat - Une menace pour la santé (première partie), *Environnement, Risques et Sante*, 14(3) 215–220.
10. GBPN Report. (2014). Energy-efficient multi-storey, vol. 066(September), 209.
11. Herrera, M. *et al.* (2017). A review of current and future weather data for building simulation. *Build. Serv. Eng. Res. Technol.*, 38(5), 602–627.
12. Hong, T., Chang, W. K., & Lin, H. W. (2013). A fresh look at weather impact on peak electricity demand and energy use of buildings using 30-year actual weather data. *Appl. Energy*, 111, 333–350.
13. Hong, T., Kim, J., Jeong, J., Lee, M. & C. Ji. (2017). Automatic calibration model of a building energy simulation using optimization algorithm. *Energy Procedia*, 105, 3698–3704.
14. IEA. (2016). Final Report Annex 53. Total energy use in buildings analysis and evaluation methods. *Int. Energy Agency Program. Energy Build. Communities*, June, p. 132.
15. IMD. (1999). Climatological tables of observatories in India: 1951-1980. *India Meteorol. Dep. Pune*, pp. 429–430.
16. Institute of Medicine. (2011). *Climate Change, the Indoor Environment, and Health*. Washington, DC, The National Academies Press.
17. MoSPI. (2017). MoSPI.
18. NOAA. (nd). World meteorological organisation - weather data. Details available at http://www.meteomanz.com/
19. ONU. (2019). *World Population Prospects 2019*, no. 141.
20. Ormandy, D. & Ezratty, V. (2016). Thermal discomfort and health: protecting the susceptible from excess cold and excess heat in housing. Adv. Build. Energy Res., 10 (1), 84–98.

21. Oza, Nikunj C., & Russell, S. J. (2001). Online bagging and boosting. *Proceedings of the Eighth International Workshop on Artificial Intelligence and Statistics*, PMLR R3:229-236, 2001.

22. S. I. Edition. Details available at https://boilersinfo.com.

23. White Box Technologies. (2014) "ISHRAE Weather Files," *Indian Society of Heating, Refrigeration, and Air-Conditioning Engineers*. Details available at http://weather.whiteboxtechnologies.com/ISHRAE.

The Future Ground: Urban Planning for Infrastructure Resilience (Case: Mumbai)

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Under CDRI Fellowship Programme 2021-22

CDRI
Coalition for Disaster Resilient Infrastructure

Disclaimer:

The views expressed in this paper reflect the opinions of the author and not necessarily the official views of CDRI. Part of this report have been borrowed from publications written by the author and supporting researchers. The following publications were used:

Krishnan, S., Aydin, N. Y., & Comes, T. (2021). Planning Support Systems for Long-Term Climate Resilience: A Critical Review. Urban Informatics and Future Cities, 465-498.

Krishnan, S., Aydin, N. Y., & Comes, T. (2022). Bouncing Forward: Long-Term Urban Planning Under Climate Uncertainty. Available at SSRN 4106195.

Malki M. (2022). Exploring the Impacts of Climate Change on the long-term urban growth of the Mumbai Metropolitan Region. (Student report conducted as part of the CDRI fellowship)

Abstract

The world is witnessing the most significant cumulative urban expansion in history against the backdrop of climate change and disasters. This anticipated growth requires extensive construction and renewal of reliable infrastructure systems that form the backbone of resilient urban development. These infrastructure systems will be exposed to a range of hazards, particularly hydrometeorological hazards, that are changing with a fair degree of uncertainty. Infrastructure decisions not made mindfully to adapt and respond to these uncertainties can lock in risks and face higher vulnerabilities than they were designed for. However, transitioning to resilient urbanization requires systematic changes in all major infrastructure systems, including energy, industry, land and ecosystems. Hence, risk-informed urban planning becomes pivotal in adopting a long-term view to inform infrastructure resilience.

In this research, we make the first steps toward developing a risk-informed urban planning framework using the Mumbai Metropolitan Region (MMR) case. We use the following three-step qualitative research process to arrive at:

1. The existing knowledge landscape around risk-informed urban planning and infrastructure resilience.
2. Establish the requirements and constraints planners face in translating climate and disaster variables into urban plans and infrastructure policies.
3. Make the first steps towards the development of a risk-informed urban planning framework. The framework is expected to be utilized for a more extended research project to develop future land-use scenarios for Mumbai under climate change.

The aim is to make the findings of this study applicable to a broader set of tropical cities faced with similar risks and development issues.

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1. Introduction

Against the backdrop of climate change and disasters, the world is witnessing the largest cumulative urban expansion in history. This anticipated growth will require extensive construction and renewal of reliable infrastructure systems that will form the backbone of resilient urban development. The problem is that the infrastructure systems will be exposed to a range of hazards, particularly hydro meteorological hazards that are changing with a fair degree of uncertainty. Hence, infrastructure decisions not made mindfully to adapt and respond to these uncertainties can lock in risks and make the infrastructure systems face higher vulnerabilities than they were designed for.

Transitioning to resilient urbanization requires systematic changes in all major infrastructure systems, including energy, industry, land, and ecosystems. Hence, risk-informed urban planning becomes pivotal in adopting a long-term view to infrastructure resilience (Bazaz et al, 2018). A long-term planning perspective is critical to avoid undesirable lock-ins and evidence-backed long-term trade-offs. However, the existing urban planning timeframes present neither the incentive nor the flexibility to integrate resilience goals.

Long-term infrastructure decisions require significant evidence and structural changes in the planning process. The current urban planning timeframe (ranging from 5 to 20 years) do not afford the time to account for long-term risks or the flexibility to adapt to rapidly changing disaster impacts. Especially in emerging economies, this timeframe prioritize urgent development needs. The timeframe present very little incentives to the practitioners to propose transformative resilience projects. Hence, the approach is response-oriented, even for recurring hydrometeorological hazards such as urban flooding and droughts (Khosla, 2019). Embedding long-term resilience in interconnected infrastructure systems requires scaling up several projects and aligning them with cities' development agendas (Comes, et al., 2014; Adshead, et al., 2019).

Practitioners acknowledge the significant knowledge gaps that exist and the static regulatory regime that hinder any innovation in urban planning. As a result, planners are unable to meaningfully consider changing variables and connect them to planning actions. Globally, there is a surge of frameworks, checklists, and guidelines for infrastructure resilience. However, these frameworks are neither contextual nor present a concrete method for achieving resilience within an urban plan involving multiple infrastructure system. Moreover, despite significant progress in data and scientific methods, interpreting climate/disaster variables and arriving at planning decisions are left to urban local bodies. The latter are, however, unable to keep pace with the capacities required.

Through the CDRI fellowship, our main aim is to assess the knowledge landscape in order to develop a framework for risk-informed urban planning. This will augment the urban planning process in deciding the appropriate planning actions to inform long-term infrastructure resilience.

1.1 Case study: Mumbai Metropolitan Region

The Mumbai Metropolitan Region (MMR) is an urban region in Western Maharashtra, India (Figure 1). It is the fourth largest urban agglomeration globally, consisting of three municipal corporations incorporating 16 municipal towns, 7 nonmunicipal urban centres and 995 villages with 40 planning authorities at various levels (Figure 2) (Phadke, 2014). The rapid urban growth in the region is driven by unprecedented population growth, which is expected to reach 27 million in 2025 compared to a mere 6 million in 1971 (Yu et al., 2021). MMR has a polycentric structure; Greater Mumbai is the dominating core and supported by several densely populated sub-centres. MMR's economic attractiveness has led to high inwards migration. Its urban growth has rapidly increased to crushing densities and added immense pressure to its urban infrastructure systems. Formal planning could not meet the requirements of the growing population, which is why more than half the urban population lives in informal settlements. The region is now making high-value investments in roads, high-speed rail, metro, and coastal roads.

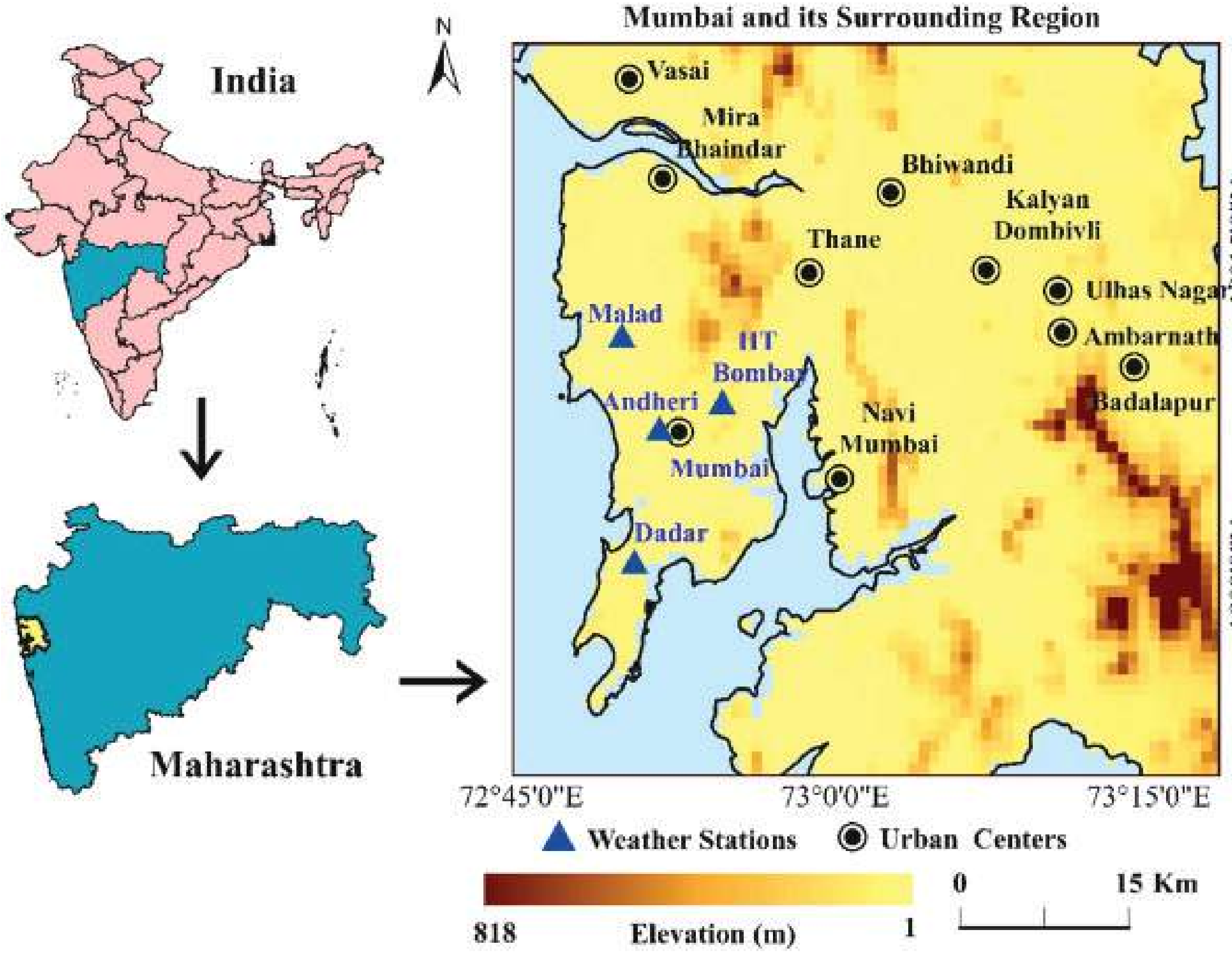

Figure 1. The Mumbai Metropolitan Region (MMR)

Source: Vinayak B. et al. (2021)

The uncoordinated and unbalanced growth in the region has led to irreversible land-use conversion. There is a decrease in arable and open lands in favour of built-up areas. By 2050, it is expected that the built-up area will account for almost 47% of the total area (Vinayak et al., 2021). The chief cause of this is a hike in the land value, proximity to nearby built-up boundaries and lack of regulatory environmental protections (Pethe et al., 2014).

1.1.1 Vulnerability

The Mumbai Metropolitan Region is a vulnerable area as the city was built on reclaimed land and a large portion of it along the coast lies below the high tide. The decrease in the open and arable land will take a toll on the urban environment as it will decrease the permeability of the impending rainwater percolation (Dar et al., 2021) and add strain to sanitation services and basic infrastructure (Rahaman et al., 2021). Mumbai is prone to flooding and witnesses severe disruptions annually. Between 2004 and 2007, Mumbai has experienced flooding each summer.

In coastal cities, such as Mumbai, flooding can get further exacerbated. The cities will be subjected to cascading risks that are associated with climate change. The most critical impacts will be increased urban heat island effect within the metropolitan region, increased flooding and rising sea levels (Schellnhuber et al., 2013). In 2005, Mumbai witnessed major flooding, which resulted in US$1.7 billion in damages and 500 deaths (Ranger et al., 2011). The most marginalized members of society were the most to be impacted. Though the current understanding of climate predictions and monsoons is riddled with deep uncertainty, one thing is clear that such flood events will become more frequent (Hallegatte et al., 2010).

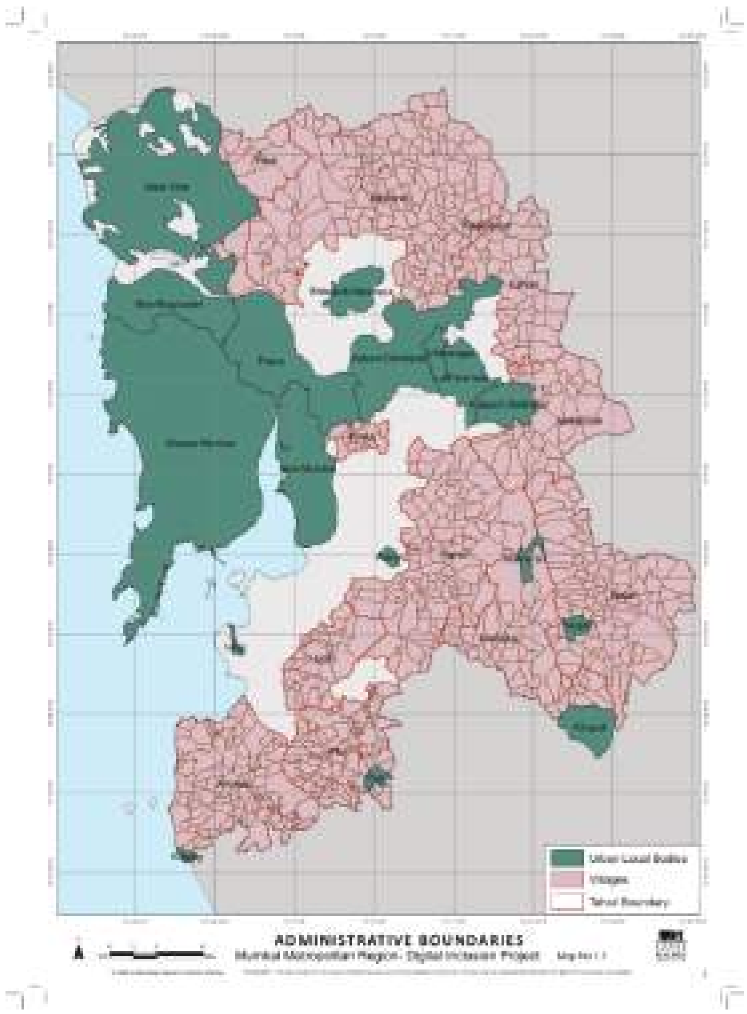

Figure 2. MMR administrative boundaries

Source: MMR mapbook: http://www.loginmumbai.org/mmrmapbook.html

Metropolitan urban regions, such as MMR, have insufficient adaptation measures in place for hazards such as extreme heat and typhoons. In cities including Jakarta, Mumbai and Tokyo, the cost of building new flood control infrastructure sea walls and other protection from flooding hazards is likely to increase as the sea levels rise. Heat waves are significantly impacting liveability and workability. Extreme heat and humidity are reducing the annual share of effective outdoor working hours by as much as 30%. Mumbai also happens to be one among several cities with more than 2% increase of extreme precipitation event (once in 50 years) (MGI, 2020).

2. Aim, Objectives, and Scope of the Research Study

In this research study, we make the first steps towards developing a risk-informed urban planning framework. Using a three-step qualitative research process, we present the existing knowledge landscape and highlight the requirements and constraints planners face in developing such a framework. In this research study, we

1. Present the existing knowledge landscape around risk-informed urban planning and infrastructure resilience.
4. Establish the requirements and constraints planners face in translating climate and disaster variables into urban plans and infrastructure policies.
5. Make the first steps towards the development of a risk-informed urban planning framework. The framework is expected to be utilized for a more extended research project to develop future land-use scenarios for Mumbai under climate change.

As evident, this exploratory research is embedded in a real MMR case study. The aim is to make it applicable to a broader set of tropical cities that face similar risks and development issues. The targeted stakeholders are urban planning authorities, infrastructure departments at the city and state levels, policymakers and researchers working on planning, climate and disaster resilience.

3. Methodology

This research uses various qualitative methods for achieving its objectives, including desk research, semi-structured interviews and qualitative coding. The methodology comprises four main steps as shown in Figure 3.

Figure 3. Research methodology

Step 1: Desk research and literature review

In this step, we first analyse the key planning documents and how they integrate different urban infrastructure systems and disaster risk management aspects in the MMR. We precisely assess the inclusion of infrastructure sectors, associated risk-management strategies and their integration with urban plans. In Appendix 1, we have given a list of documents assessed and their links.

Step 2: Interviews and data analysis

In this step, we conducted 19 semi-structured interviews. The participants were from four sub-domains that play crucial roles in planning: urban planners, strategic/policy advisors/bureaucrats, academic researchers and specialists on sustainability/environment and engineers (Table 1). The interview protocols were developed based on findings from planning documents and theoretical concepts on resilience. The final 60-minute protocol focused on thinking about processes behind disaster risks, climate-related planning responses, knowledge gaps, challenges and values considered in planning (beyond the current planning timelines) (Appendix 2). A semi-structured protocol allowed us to vary the sequence of questions and presented the scope to ask follow-up questions to enable richer discussions. A detailed account of interviewing process is discussed in Krishnan et al. (2021).

The goal of the data analysis is to: (1) analyse planning documents to map disaster and climate-related planning responses to target different infrastructure systems and (2) conduct a qualitative content analysis of interviews to understand the integration of risks and resilience in urban planning, and requirements and constraints faced by practitioners. A detailed description of the interview coding is discussed in Appendix 2.

Step 3: Development of the conceptual framework

This involves the study of relevant theoretical frameworks, including existing resilience frameworks (Jabareen, 2013; Krishnan, 2021) and the urban layers approach (Roggema, 2012). In this step, we synthesized the findings for the case study on MMR. We presented a pilot framework that can be further developed as more data becomes available.

Step 4: Real data assessment

This step involves assessing the data landscape for developing a risk-informed urban planning framework as mentioned in official planning documents. We specifically analysed data sources on disasters, climate, environmental, and socio-economic aspects. This included climate data, climate projections, hazard-vulnerability data, special infrastructure projects, and urban and state policies on infrastructure resilience, amongst others. This was not intended to be a comprehensive database but presented an overview of what is available and the critical gaps. A comprehensive list of data sources is presented in Appendix 3.

4. Results and Discussion

Findings from planning documents

MMR's planning instruments are regional plan (RP) and development plan (DP). These are updated every 20 years. The RP presents guidelines for growth across infrastructure, socio-economic and environmental sectors. The DP presents more detailed zoning and building regulations. These plans are augmented by a state-level action plan for climate change and a city-level disaster management plan that focuses on response and recovery measures to manage floods.

Despite the delayed release of the new Regional Plan for 2016-2036, little information are available about planning policies to combat the adverse events of climate change and mitigate losses of life and property. Only limited strategies are presented, including creating a network of water and green areas to relieve pressure from catchments and reduce flood risk with river corridors, regional parks and green connectors (MMRDA, 2021). Furthermore, it is unclear how these strategies will be implemented and in what timeframe they will be achieved. MMR's planning documents are critiqued for being overtly prescriptive, regulatory and prohibitory instead of being building integrated visions. They do not identify entry points for climate-related goals but stick to broad recommendations (P35) (Krishnankutty, 2018).

4.1.1 Climate hazards

Coastal cities, such as Mumbai, are subjected to cascading risks associated with climate change. These include increased land surface temperature due to the urban heat island effect, flooding, rising sea levels, and tropical cyclones.

All the key planning documents acknowledge urban flooding as a critical hazard for the MMR region. The Government of Maharashtra has set up several fact-finding committees to identify the cause of floods and to recommend measures for the future. This included the Natu Committee in 1974, Central Water Power Research Station (CWPRS) in 1978, MCGM (BRIMSTOWAD) in 1993, IIT Bombay, and the most recent, the Chitale committee. The Chitale committee listed the cause of the flooding as mainly the inadequate drainage system, rapid developments and loss of holding ponds, encroachment by the slums on and over the existing drains and a decrease in the coastal mangrove areas (Chitale, 2006). River Mithi in the north of Mumbai has been reduced to an open drain due to severe encroachments and industrial effluents being discharged into it. Nearly 54% of the original river flow has been lost to development (for example, slums and roads on the floodplains). A new sea-link is under-construction and has reclaimed the mouth of the river with about 27 ha of landfill. Other rivers that overflowed in the northern suburbs are River Dahisar and River Poisar (Gupta, 2007).

Mumbai's rapid and unplanned urbanization is quickly exacerbating the flood risk with a drainage system unable to handle heavy precipitation (Zope et al., 2016). In 2005, major flooding in Mumbai resulted in US$1.7 billion in damages and 500 deaths (Butsch et al., 2016). The consequences on marginalized populations revealed the vulnerability of the poorest members of the society. Due to climate change alone, direct and indirect economic costs are projected to increase the costs of a

1-in-100-year event to US$1.9 billion and US$2.4 billion, respectively. It is projected that by 2080, the likelihood of such a flood event will double, with a warming of 3 °C to 3.5 °C (Schellnhuber et al., 2013). Increased built-up land increases the overall impervious surface in the MMR, which increases surface runoff and river discharge rates and, consequently, higher chances of floods. Flooding can be of multiple types, namely coastal flooding, pluvial flooding and fluvial flooding (Figure 4) (Pathak et al., 2020). Despite a marginally significant decrease in long-term monsoon rainfall in Mumbai (Rana et al., 2012), heavy rainfall remains a primary catalyst for flooding in the region. To minimize the socio-economic implications of floods in Mumbai, robust climate adaptation policies are necessary (Hallegatte et al., 2016).

Floods can also occur due to sea-level rise. When conducting a survey of flood risk for 136 cities under two potential pathways (RCP8.5 and an expert-based scenario), Abadie et al. (2020) placed Mumbai in the second place under both scenarios. Even without causing floods, sea level rise can significantly impact coastal communities through a plethora of means, such as a magnified risk of extreme weather events and natural disasters, the reduction of water quality due to saltwater intrusion into surface and groundwater and associated socio-economic burdens (Nicholls 2011). Despite the reinforcement of Coastal Regulation Zones (CRZ) in 2011, the significant expansion of urban areas due to urban sprawl as stipulated by Pramanik (2017) and the growing anthropogenic trend in the MMR are exasperating climate risks and contributing to at least 50% of the observed sea-level rise. Moreover, sea-level rise is likely to increase the risk of cyclones in Mumbai (Sobel et al., 2019).

Future predictions of rainfall patterns show an increase in extreme events and the number of wet days in MMR. Hence, while planning for further infrastructure development, one should avoid flood-prone regions or proactively implement flood-risk mitigation practices to mitigate the impacts of flooding (GoM, 2014). In consultation with climate experts at World Resources Institute (WRI) and The Energy and Resources Institute (TERI), it was found that no downscaled datasets were available for western Maharashtra or the MMR region. There is reliance on state-level projections available in the SAPCC that are not granular enough for decisions on the urban scale. Similarly, future projections are also available at the state level. Available data on sea-level rise from climate change are not utilized in planning or infrastructure decisions. SLR projections are also sometimes discredited.

4.1.2 Infrastructure issues

Urban development in the MMR has been shaped by major infrastructure projects of different typologies such as suburban railway network, metro rail, highways, monorail as well as iconic infrastructure including Bandra-Worli sea link, Trans-Harbour link, Coastal Road and High-speed rail. The region's urban development has been stimulated by major urban renewal schemes such as JNNURM, Mumbai Urban Transport Projects (MUTP), Comprehensive Mobility Plan (CMP), Special Economic Zones (SEZ). Most of these schemes have opened up land for greenfield development (Figure 5).

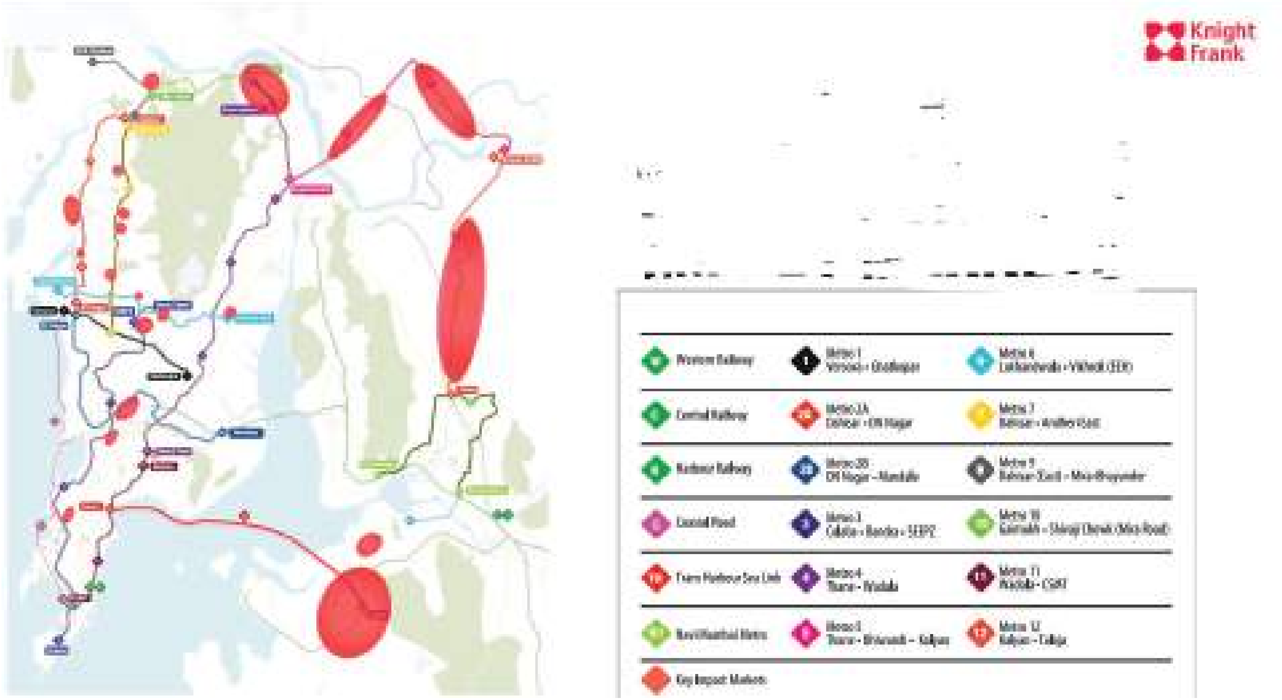

Figure 5. MMR transport infrastructure in 2030 with key impact markets

Source: Knight Frank

MMR developed from a historical core which has expanded due to the transport networks. The rapid land development has come at the cost of other infrastructure systems such as water. Large portion of the storm-water drainage (SWD) system include roadside open drains, which are in general susceptible to clogging and contamination. The network is capable of handling rainfall intensity of 25 mm/h at low tide and less during high tide (Chatterjee and Chattopadhyay, 2020). The natural drainage capacity of the city has also significantly reduced due to development on flood plains. For River Mithi in the north of the MMR, nearly 54% of the original flow has been lost due to this phenomenon (Gupta, 2007).

BRIMSTOWAD project has proposed a major overhaul and upgradation of the SWD networks by upgrading/widening the drains, reducing runoffs and monitoring them. However, the project requires significant investment of resources and has prolonged over decades. The model-based assessment carried out under the present study suggests that even after augmentation of the drainage capacity to 50 mm/h, Mumbai's low-lying areas need special attention as these areas are exposed to the risk of high flood level (Figure 6).

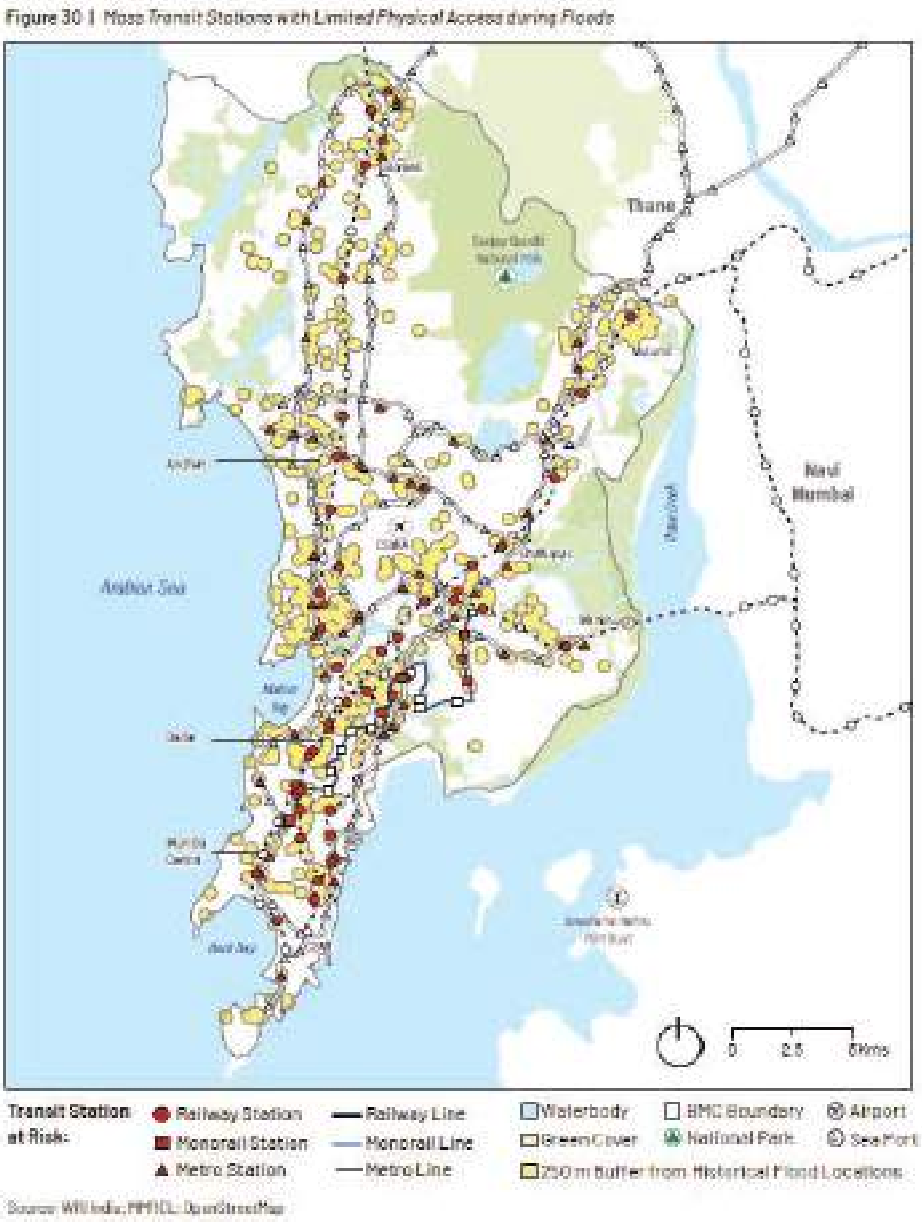

Figure 6. Mass transit stations with limited physical access during floods

Source: *Mumbai Climate Action Plan*

Heavy rainfall and flooding affects the transport infrastructure in a city by impacting its safety, operation costs, travel time and regularity of service. Based on the flood hotspot influence zone analysis, 33% of Mumbai's mass transit network – including its lifelines of the suburban rail network, Metro line and Monorail – are heavily impacted by inundation that limit physical access to transit stations (MCAP, 2022).

4.1.3 Inclusion of infrastructure in key planning documents

MMR's urban growth is closely linked to the expansion of transport infrastructure. Hence, ensuring resilient transport infrastructure development has become the key for mindful urban planning. Mumbai Climate Action Plan (MCAP), Disaster Risk Management Plan (DRMP), State Disaster

Management Plan (SDMA), State Action Plan for Climate Change (SAPCC) along with the Regional Plan (RP) and Development Plan (DP) are some of the significant documents that impact urban development and risk management for the MMR region (see Table 2).

5.0.3.1 No integration of risks

A broad assessment of these documents indicates that disasters related to climate risk have not been integrated into realizing actual planning goals. Mainstreaming of risk is discussed, but no clear guidelines or entry points are identified to integrate it into planning. For instance, Mumbai's Disaster Risk Management Plan (DRMP) presents an overview of the significant infrastructure systems in the city with structural measures to manage disasters such as floods, including construction (strengthening, standards), floodplain zoning, development of catchment areas, floodproofing (structures in floodplains) and safety audits for critical lifeline infrastructure. For every disaster, the DRMP presents SOPs for major systems before, during, and after disaster events. However, the focus remains on preparedness to be able to respond.

The SDMA also discusses mainstreaming disaster risk in development programmes and schemes. It discusses specific examples such as reconstruction and rehabilitation of housing, drought-proofing activities for the watershed, water harvesting, check dams and regulation of developmental activities in flood-prone regions. No explicit references exist to state-level or national-level standards that will ensure structural resilience. This is often problematic as the construction and upkeep of transport infrastructure falls under the purview of Urban Local Bodies (ULBs). Hence, including it in urban plans and ensuring standards is at their discretion. The DP and MCAP (both at the city scale) are the only documents that mention planning interventions such as increasing permeability, buffers, greening the grey and landslide protection. The MCAP also presents detailed vulnerability assessment for infrastructure access (Figure 7). None of the documents discuss inclusionary zoning policies or land-use regulations.

Table 2. Types of disasters and infrastructure systems discussed in official planning documents that impact MMR region

Documents	Boundary	Disasters and Hazards Mentioned	Infrastructure Systems Mentioned
Mumbai Climate Action Plan (MCAP)	Mumbai City	Urban heat, urban flooding, landslides, air pollution, coastal risks	*Energy and buildings, mobility, waste management, urban greening and biodiversity, air quality, urban flooding and water resource management*
State Action Plan for Climate Change (SAPCC)	Maharashtra	Sea level rise, precipitation, heat, flooding	*Agriculture, water, health, energy and infrastructure systems, ecosystems and livelihoods, cross-sectoral themes*
Disaster Risk Management Plan (DDMP)	Mumbai District	Floods, drought, earthquake, cyclone, tsunami, landslide, nuclear/chemical, biological, emergency, epidemics and industrial disasters	*Transport and Communication (Waterways and ports, railways, Mumbai Suburban Railway, Metro and Monorail Services, Mumbai Metro Master Plan, road transport), housing, industry, health and education*

Documents	Boundary	Disasters and Hazards Mentioned	Infrastructure Systems Mentioned
State Disaster Management Plan (SDMA)	Maharashtra	Floods, drought, earthquake, cyclone, tsunami, landslide, nuclear emergency and industrial disasters	*Transport and Communication (Waterways and ports, railways, Mumbai Suburban Railway, Metro and Monorail Services, Mumbai Metro Master Plan, road transport), housing, industry, health, education, religion*
MMR Regional Plan	MMR Region	Flooding	*Transport, housing, land use, physical Infrastructure (water supply sewerage), solid waste*
Development Plan	Mumbai City	Flooding, heat, landslides	*Transport, Housing, Land use, Physical infrastructure (water supply sewerage), solid waste*

5.1.3.2 Use of historical data

Climate change impacts show us that the past is no longer a good guide for the future. Only the MCAP and SAPCC mention future climate projections until 2050. However, neither of them is specific to the MMR boundary. The SAPCC is the only document that presents climate projections aligned with IPCC projections, but only at the state level. The IPCC A6 Atlas has stated that due to climate change the regional mean sea level will continue to rise, warning that Mumbai, along with 11 other Indian coastal cities, will witness a rise in sea level of 0.1-0.3 m over the next three decades. Thus, a lack of coastal data for the Mumbai coast makes it difficult to establish SLR as a current risk for the city (MCAP, 2022).

5.1.3.3 Variation in inclusion

A considerable variation exists in the inclusion of infrastructure across official planning documents. Impact and vulnerability assessments are often done only for housing and not for other infrastructure systems. A gap thus remains in the assessment. The more significant focus is on accessibility and provision of services, but not on the resilience of physical assets'. Possibly the city and regional authorities follow national or state guidelines for infrastructure planning, which are not included in the scope of this study.

4.2 Disaster and Climate-related Planning Responses

In Figure 8, we mapped the proposed and 'in-progress' climate and disaster-related planning responses for MMR. We connected them to Urban Infrastructure Systems that they target and highlighted resilience principles relevant for each system to assess if the responses fulfil those principles. An explanation of the resilience principles may be found in the publication Krishnan et al. (2021), which is an outcome of this research. We observed that typical responses include rainwater harvesting, upgrading and streamlining storm water drains, reinforcing landscape connections and climate-proofing vital infrastructure.

Planning in the MMR is heavily reactive and focused on managing urban flooding through community response and recovery during a disaster. Planning is incremental and prescriptive, with most actions focused on upgrading infrastructure. BRIMSTOWAD is an ongoing long-term project that aims to expand the capacities of storm water drains across the city. In the absence of a formal climate programme, MMR (see Figure 8 in blue) integrates climate into several scattered projects where it becomes a secondary objective. As open spaces become scarce, MMR emphasizes on restoring and expanding natural buffer using green corridors along rivers, regulating land conversion for more green cover and an extensive Coastal Zone Management Plan (CZMP). The MMR does not yet have a well-integrated strategy to capture rainwater at more minor spatial scales. It has enforced norms for rainwater harvesting only in new greenfield developments.

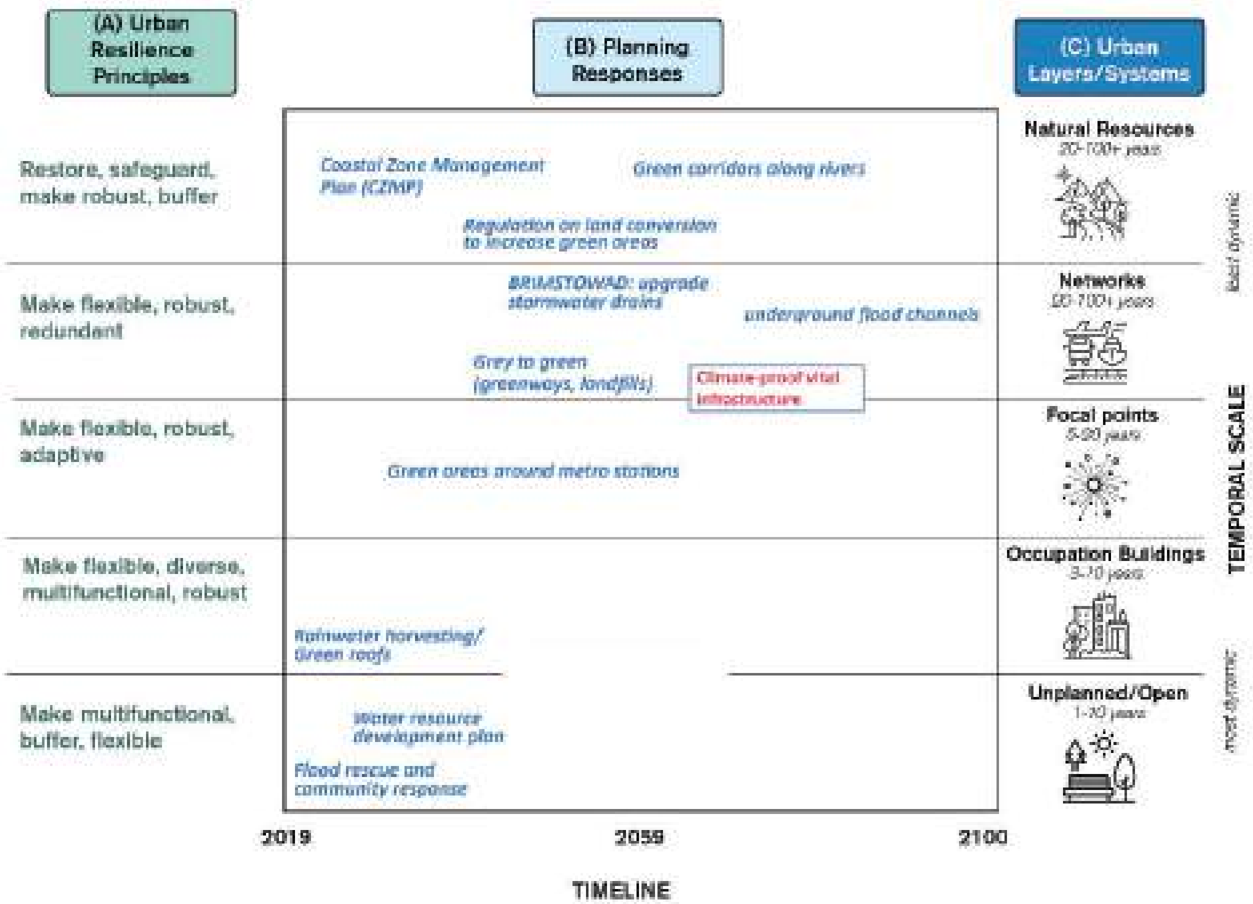

Figure 8. Mapping climate-related planning responses for MMR (in blue and italics) to the urban infrastructure systems they target

Note: Each urban layer has a recommended resilience principle to make it most effective to manage risks

Source: Roggema et al. (2012)

4.3 Findings from interviews

As MMR did not have a dedicated programme on climate action at the time of the study, resilience-related measures do not find many mentions in the interviews, but have been integrated into different planning projects and policies. The dominant principles discussed by participants were to manage urban flooding using *Adaptivity* and *Buffer* and the need to bring in more *Flexibility* and *Multiscalarity* in planning to manage unprecedented changes. Table 3 presents dominant resilience principles discussed by participants and sample quotations.

Due to Mumbai's chronic flooding, improving *robustness* of stormwater drains is a significant project (P31). The State of Maharashtra's Action Plan on Climate Change also presents system-specific strategies for transport, energy and ecosystem-based adaptation actions (P24). The transport sector is considered to be most effective to improve adaptivity given the heavy future investments and high traffic volume (P33). However, a robust, data-driven understanding of adaptation, including the implications of maladaptive planning and undesirable trade-offs, is lacking (P21). For instance, Mumbai's metro rail construction requires acquiring land preserved under natural resources. The trade-off between the mitigating properties of public transport versus the adaptive properties of damaged natural ecosystems has not been assessed, leading to conflicts. P21 criticizes that "*Adaptation is viewed as a cop-out action when the urban planning mechanism fails until recently*".

Table 3. Dominant resilience principles discussed by participants and sample quotations

Resilience Principle	Mentioned by Participants	Example Quotes
Adaptivity (+)	21, 22, 24, 25, 28, 27, 30, 31, 33, 38	*P28: "Urban adaptation schemes elite-driven. You see a major role for transnational corporations, and the projects cater to urban middle class."* *P21: "Adaptation is perceived as a cop out for governments, because they have failed to limit emissions."*
Buffer (+)	21, 22, 26, 27, 30, 31, 33, 35	*P22: "A lot of land designated for public purposes like parks eventually became a slum."* *P30: "Buffers are hard to achieve when the city is 97% built-up"*
Flexibility (-)	22, 27, 29, 30, 31, 33, 35, 36	*P27: "We have to make a master plan every year to cater to the current trends. It is the only instrument and can be very flexible and be allowed to change as we move along".* *P33: "What we should freeze is ecological areas which will remain permanently as no development zones. The other areas should be very flexible to expand and absorb intense construction."*
Multi-scalarity (-)	21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39	*P34: "You have to look at least 30-50 years and think regionally for climate resilience".* *P29: "The Metro will last for 200 years. That kind of (scale) will change the whole city's life. So projects with long-term impacts must be given a special consideration in the planning process, which is not happening".* *P36: "Follow a flexible approach for macro level planning. Use local area plans for micro level urban development by following a market driven logic to enable equitable distribution of land."*

Note: (+) and (-) indicate principles with high application and low application, respectively

Buffer is widely applied in MMR across spatial scales. New development schemes have been mandated to harvest rainwater onsite at the building level. A buffer is introduced at the neighbourhood/ward scale through land reservations and by assigning recreation areas as 'no-development zones'. Policies have been drafted to protect mangroves, wetlands and other natural ecosystems at the city scale; these ecosystems act as a sponge for coastal flooding. A city-wide blue-green network was initiated but not completed as Mumbai has hardly any large open spaces to capture rainwater within urban limits (P30, 33). In addition, Mumbai is considering developing an underground floodwater channel to store surplus water similar to Tokyo. What hinders the application of multifunctionality is that public spaces are viewed purely from a consumption standpoint to cater to a large existing population (P31). It is challenging to find synergies as the planning responses are not tied to a common climate strategy, which brings in competing priorities in a hyper-dense region.

More than half the participants criticized existing planning instruments for being overly regulatory. Rigid norms for land reservations and a moderate Floor Space Index (FSI) encourage illegal expansion in a city facing intense land scarcity. "*Instead of anticipating changes, the planning instruments are highly prescriptive and go into (unnecessary) details*", which impedes inherent Flexibility (P22, P36). Like MRA, MMR participants also recommend that the Development Plan (DP) should be updated every 5-10 years to cater to changing trends (P27, 31, 33). P33 recommends developing adaptation pathways and scenario planning for Mumbai not to be locked into blueprints.

While the urgency of climate change is recognized, it is not integrated into urban planning (P24). From a resilience theory perspective, Mumbai's annual urban flooding became an agent for resilience-building and self-organizing since each flooding event leads to small to medium-scale disruptions that allow urban systems to readjust. This has led to the emergence of a diverse set of coping strategies and high inherent adaptivity (Smit and Wandel, 2006). However, planning responses have not systematically tapped into the usefulness of *Multifunctionality* or *Robustness* to use space efficiently and absorb the recurrent impacts from flooding.

From a *methodological* perspective, MMR plans for a single future scenario, relying mainly on past trends and fixed predictions. P22 emphasizes that *"Mumbai is stuck with the impacts caused by the 2005 deluge - a 1 in 100-year flooding disaster. Most policy documents, as well as academic studies, are written considering the impacts of that single event"* (Gupta, 2007). Participants acknowledge that the formal planning framework does not recognize uncertainty or the need to consider 'what-ifs' to plan for alternative scenarios. For instance, infrastructure and building codes consider flood levels from two to three decades earlier.

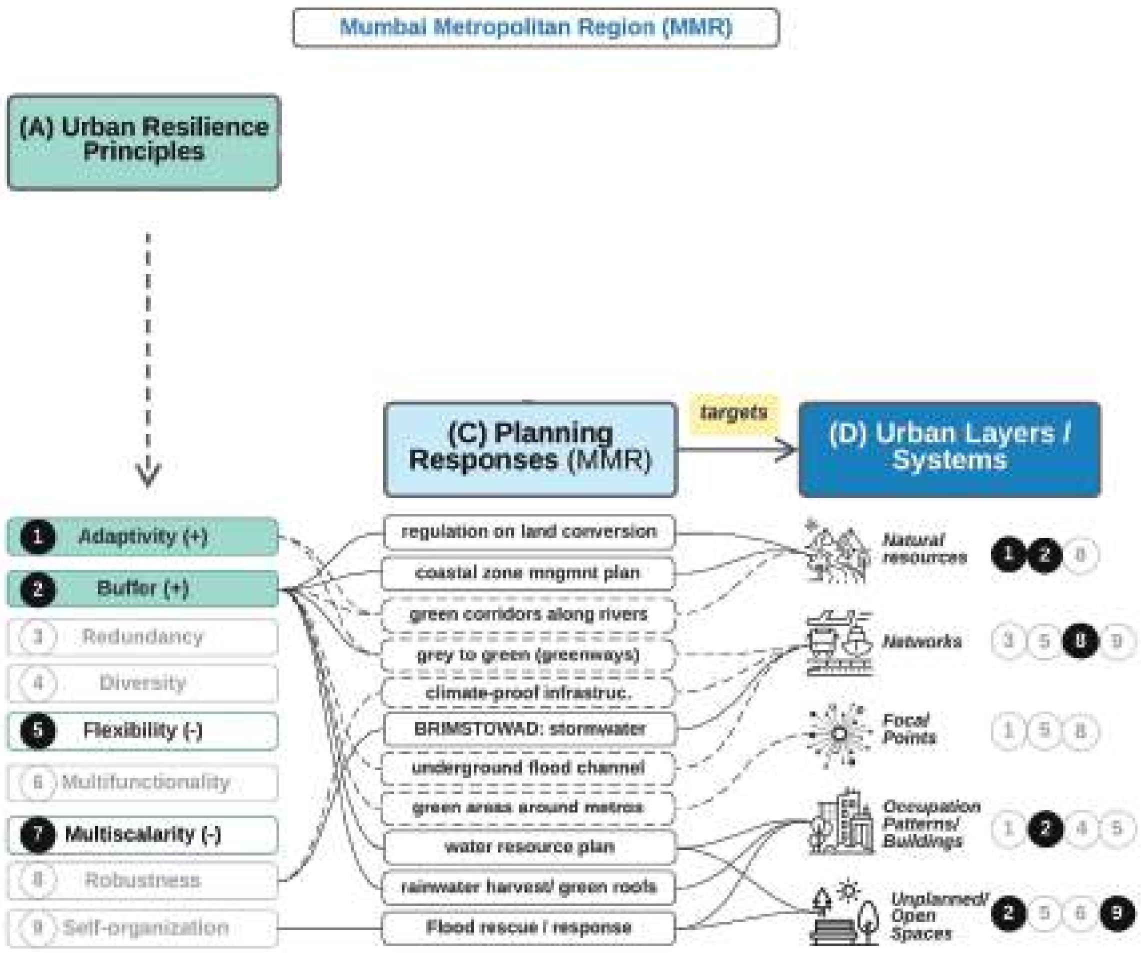

Figure 9. The conceptual urban planning framework based on desk research and findings from interviews to connect: (A) Urban Resilience Principles;.), (C) Their combined application through Planning Responses and (D) Their impact on five urban infrastructure systems

Note: (+) and (-) indicate principles with high application and low application, respectively. Grey indicates no mentions. dotted lines indicate concepts mentioned but not discussed in detail in literature or interviews.

4.4. Development of the conceptual framework

Figure 9 presents a conceptual risk-informed urban planning framework that connects (C) urban planning responses to different (D) urban infrastructure systems based on their spatial and temporal lifecycle. The planning responses to different risks are extracted from official planning documents (Appendix 1). The associated resilience principles are extracted from academic papers on urban and infrastructure resilience.

4.5 Results of data assessment

This section presents an overview of the knowledge landscape at the intersection of risk and urban planning for the MMR.

Data on regional land-use, transport networks, environmental features and socio-demographic data have been given in the MMR Regional Plan 2016-2036. Detailed infrastructure networks available in openstreetmap.org (OSM) repository include highways, railways and waterways. In addition, *'LoginMumbai' (http://www.loginmumbai.org/)*, an open-source data initiative by the Urban Design Research Institute (UDRI), is an online viewer for land-use plans, transport networks maps and additional zoning and housing reservations. Despite this, even the official regional plan acknowledges data paucity as a major issue for urban planning. Digitized data about Mumbai, and more specifically about the MMR, is scarce.

MMR's planning for climate risks is mainly reactive, open-ended and relies on feasible short-term targets. In the absence of detailed climate scenarios, planners consider only high-level assumptions and plans are designed to absorb forecasted growth. The capacity gap in MMR hinders an integrated approach to long-term planning in MMR. Climate programmes in Indian cities are outsourced to independent consultancies or international agencies due to lack of internal capacity. This leads to fragmented projects and generic responses and fostering inequality (P23). In the case of MMR, TERI and WRI agencies acted as independent consultancies.

5. Enablers and Barriers

The major barriers in this research were the unavailability of data, slow institutional responses and COVID-19-related restrictions and impacts. The research was impacted directly by not only COVID-19-related travel restrictions but also potential collaborators in the region who were impacted by COVID-19. This delayed the timeline for interviews, data collection and feedback. The challenges faced throughout the data collection process are compiled according to the framework presented by Cai and Zhu (2015). In Table 4, the different dimensions of data quality have been highlighted, with some of the main examples of challenges faced during the data collection step. This is, however, not a comprehensive classification, as many issues were repetitive and highlighted similar elements. Other challenges that were faced during the collection process included finding data that cover the whole MMR (not just Mumbai City or Greater Mumbai).

6. Key Takeaways from CDRI Fellowship Programme

In almost all the interviews that were conducted for the research, the interviewees expressed their concern about the choice of Mumbai as the case study. This concern was well-situated and most certainly a phenomenon that applies to researching disaster and climate resilience across emerging urban regions in India and generally the Global South, where data availability, capacity and timelines are often murky. The CDRI Fellowship offered an excellent opportunity to conduct this form of "high-risk playground" research, which standard funding channels do not provide. This form of an exploratory proposal for data-scarce case studies is essential to respond to urgent questions of resilient infrastructure and urbanization.

The CDRI grant offered the flexibility and a conducive platform to initiate work on this case study, which can now be developed further.

7. Conclusion

This study builds a theory for risk-informed urban planning using concepts from urban resilience and planning responses as applied to the case of MMR. This section presents four propositions developed using findings from theory and empirical insights from the interviews to reflect on the current gaps in adopting long-term planning and where theory can play a role in filling this. Each proposition is substantiated using comparative insights from our two case studies and 19 interviews. We present narrative accounts and structural findings that characterize the long-term planning process. We also discuss propositions on urban resilience, planning under uncertainty and planning in the Global North-South, towards building a theory for risk-informed urban planning

Both literature and interviews highlight the "*frequent disconnect between planning and implementation, especially in countries where governance lacks transparency and/or technical capacity*". Policies are not well understood even by practitioners who must implement them (Friend, et al, 2014).

First, MMR has yet to develop and implement actions based on a strategic understanding of the interaction between climate and development priorities (Khosla and Bhardwaj, 2019). It relies on conservative measures such as reinforcing green spaces and reactive measures including emergency response and rescue to manage disasters. It is challenging to have long-term planning trade-offs to improve resilience (Bartlett et al., 2009). MRA participants view open-ended planning systems, like the one in MMR, as advantageous for integrating unprecedented changes to build resilience. From an uncertainty perspective, not having definite outcomes is a mark of a flexible system open to change. Participants in the MMR criticize that Mumbai's open-ended approach has led to high tolerance to risk, recurrent infrastructure damage and low trust in the government to protect it.

Second, urban growth in the MMR spreads beyond formal physical and institutional boundaries. There are ways to typify informal growth to suggest appropriate climate-related responses. Since informal growth is inherently unregulated, managing unprecedented changes is challenging as planning responses may not have the expected outcome.

Third, conflict arises in decision-making for increasing density versus adopting low-impact, medium, or low density in urban morphology. Dense centres are known for their efficient urban form for better transport accessibility and lower energy consumption, which is desirable to build resilience (P27) (Jabareen, 2013). However, the same density increases the at-risk population's concentrations, leaves less space for rainwater infiltration and increases susceptibility to urban heat islands (Solecki et al., 2015; Wamsler et al., 2013). Several MMR participants endorse medium-density ecological planning to offset the impacts of a dense urban footprint around existing business districts. A few of the participants strongly argued against this as ecological planning that is not strictly regulated leads to uncontrolled urban sprawl and an imbalance of resources in the region.

Fourth, MMR planned for a single scenario without anticipating any variation, which goes against long-term thinking as an evolving process open to changes. Long-term planning under climate change will require considering changing futures and their impacts on different urban systems based on their life cycles. These can be developed using a combination of predictive (forward-looking) and normative (inverse-looking) approaches to planning. For instance, predictive approaches can be adopted to plan for changing capacities of networks such as energy and mobility. Normative approaches can be adopted to preserve natural resources in the same state for the future.

8 Way Forward

This report discusses the first outputs of a complex exercise to develop a risk-informed urban planning framework for one of the most complex urbanizing regions in the world. In order to validate this research, it would be helpful to host an expert consultation with planners working on MMR. This had initially been planned for March 2022. However, due to COVID-19-related travel constraints and the non-availability of data, the consultation is now planned for October 2022. The author has the experience of hosting a similar consultation with the Metropolitan Region of Amsterdam (MRA). During the fellowship period, the author also had the formal support of C40 Cities and Municipal Corporation of Greater Mumbai (MCGM) in facilitating this workshop.

Post the consultation, the framework will be refined and a more accessible version of the report will be made for circulation among practitioners who are pursuing actions for resilience through CDRI's networks. Eventually, a more comprehensive planning framework document will be developed, which can be disseminated to researchers and practitioners in similar cities for application.

In terms of scientific research, we will further use the planning framework to simulate land-use growth scenarios for Mumbai under climate stresses and shocks over 100 years, which will be a valuable visual resource for future planners. We will further develop this method of contributing a meaningful practice document for resilient infrastructure and urbanization.

References

1. Abadie, L. M., Jackson, L. P., de Murieta, E. S., Jevrejeva, S., & Galarraga, I. (2020). Comparing urban coastal flood risk in 136 cities under two alternative sea-level projections: Rcp 8.5 and an expert opinion-based high-end scenario. *Ocean & Coastal Management*, 193:105249.
2. Adshead, D., Thacker, S., Fuldauer, L. I., & Hall, J. W. (2019). Delivering on the sustainable development goals through long-term infrastructure planning. *Global Environmental Change*, 59, 101975.
3. Bartlett, S., Dodman, D., Hardoy, J., Satterthwaite, D., & Tacoli, C. (2009). Social aspects of climate change in urban areas in low-and middle-income nations. In *Fifth Urban Research Symposium, Cities and Climate Change: Responding to an Urgent Agenda,* Vol. 2, pp. 670-726. Marseille: World Bank.
4. Bazaz, A., Bertoldi, P., Buckeridge, M., Cartwright, A., de Coninck, H., Engelbrecht, F., ... & Waisman, H. (2018). Summary for urban policymakers: What the IPCC Special Report on global warming of 1.5° C means for cities.
5. Butsch, C., Kraas, F., Namperumal, S., & Peters, G. (2016). Risk governance in the megacity mumbai/india–a complex adaptive system perspective. *Habitat International*, 54(2):100–111.
6. Cai, L. & Zhu, Y. (2015). The challenges of data quality and data quality assessment in the big data era. *Data science Journal*, 14.
7. Chatterjee, A. and Chattopadhyay, R. (2020). Metropolitan city-satellites-fringe villages relationship: Case studies with greater Mumbai, Bengaluru and their regions. In *Satellite Towns in Neo-metropolitan Development in India*, pages 101–150. Springer.
8. Chitale, M., & Patel S. (2006). Fact Finding Committee on Mumbai Floods.
9. Comes, T., & Van de Walle, B. A. (2014). Measuring disaster resilience: The impact of hurricane sandy on critical infrastructure systems. *ISCRAM*, 11(May), 195-204.
10. Dar, M. U. D., Shah, A. I., Bhat, S. A., Kumar, R., Huisingh, D., & Kaur, R. (2021). Blue green infrastructure as a tool for sustainable urban development. *Journal of Cleaner Production*, 318:128474.
11. Department of Environment, Government of Maharashtra (2014). Assessing Climate Change Vulnerability and Adaptation Strategies for Maharashtra: Maharashtra State Adaptation Action Plan on Climate Change (MSAAPC)
12. Friend, R., Jarvie, J., Reed, S. O., Sutarto, R., Thinphanga, P., & Toan, V. C. (2014). Mainstreaming urban climate resilience into policy and planning; reflections from Asia. *Urban Climate*, 7, 6-19.
13. Gupta, K. (2007). Urban flood resilience planning and management and lessons for the future: a case study of Mumbai, India. *Urban Water Journal*, 4(3), 183-194.
14. Hallegatte, S., Ranger, N., Bhattacharya, S., Bachu, M., Priya, S., Dhore, K., Rafique, F., Mathur, P., Naville, N., Henriet, F., et al. (2010). Flood risks, climate change impacts and adaptation benefits in mumbai: an initial assessment of socioeconomic consequences of present and climate change induced flood risks and of possible adaptation options.

15. Jabareen, Y., 2013. Planning the resilient city: Concepts and strategies for coping with climate change and environmental risk. *Cities*, 31, pp.220-229.
16. Khandelwal, S. (2020). Adaptive Geographies: Towards a Flood Resilient Mumbai Metropolitan Region.
17. Khosla, R., & Bhardwaj, A. (2019). Urbanization in the time of climate change: Examining the response of Indian cities. *Climate Change*, 10(1), e560.
18. Krishnan, S., Aydin, N. Y., & Comes, T. (2021). Planning support systems for long-term climate resilience: A critical review. *Urban Informatics and Future Cities*, 465-498.
19. Krishnankutty, M. (2018). Interrogating Land Use Planning In India.
20. Mehrotra, S., Bardhan, R., and Ramamritham, K. (2018). Urban informal housing and surface urban heat island intensity: exploring spatial association in the city of mumbai. Environment and Urbanization ASIA, 9(2):158–177.
21. MMRDA Regional Plan. (2021). Mumbai Metropolitan Regional Plan 2016-2036.
22. Municipal Corporation of Greater Mumbai, Government of Maharashtra (2022). Mumbai Climate Action Plan.
23. Nicholls, R. J. (2011). Planning for the impacts of sea level rise. *Oceanography*, 24(2):144–157.
24. Pathak, S., Liu, M., Jato-Espino, D., and Zevenbergen, C. (2020). Social, economic and environmental assessment of urban sub-catchment flood risks using a multi-criteria approach: A case study in Mumbai city, India. *Journal of Hydrology*, 591:125216.
25. Phadke, A. (2014). Mumbai Metropolitan Region: impact of recent urban change on the peri-urban areas of Mumbai. *Urban Studies*, 51(11), 2466-2483.
26. Pethe, A., Nallathiga, R., Gandhi, S., & Tandel, V. (2014). Re-thinking urban planning in india: Learning from the wedge between the de jure and de facto development in mumbai. *Cities*, 39:120–132.
27. Pramanik, M. K. (2017). Impacts of predicted sea level rise on land use/land cover categories of the adjacent coastal areas of Mumbai megacity, India. *Environment, Development and Sustainability*, 19(4):1343–1366.
28. Rahaman, S., Jahangir, S., Haque, M. S., Chen, R., & Kumar, P. (2021). Spatio-temporal changes of green spaces and their impact on urban environment of Mumbai, India. *Environment, Development and Sustainability*, 23(4):6481–6501
29. Ranger, N., Hallegatte, S., Bhattacharya, S., Bachu, M., Priya, S., Dhore, K., Rafique, F., Mathur, P., Naville, N., Henriet, F., et al. (2011). An assessment of the potential impact of climate change on flood risk in mumbai. Climatic change, 104(1):139–167.
30. Roggema, R., Kabat, P. and van den Dobbelsteen, A., 2012. Towards a spatial planning framework for climate adaptation. *Smart and Sustainable Built Environment*.
31. Schellnhuber, H. J., Hare, B., Serdeczny, O., Schaeffer, M., Adams, S., Baarsch, F., Schwan, S., Coumou, D., Robinson, A., Vieweg, M., et al. (2013). Turn down the heat: climate extremes, regional impacts, and the case for resilience.

32. Smit, B., & Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, 16(3), 282-292.

33. Solecki, W., Seto, K. C., Balk, D., Bigio, A., Boone, C. G., Creutzig, F., ... & Zwickel, T. (2015). A conceptual framework for an urban areas typology to integrate climate change mitigation and adaptation. *Urban Climate*, 14, 116-137.

34. Sobel, A. H., Lee, C.-Y., Camargo, S. J., Mandli, K. T., Emanuel, K. A., Mukhopadhyay, P., and Mahakur, M. (2019). Tropical cyclone hazard to Mumbai in the recent historical climate. *Monthly Weather Review*, 147(7):2355–2366.

35. Sultana, S. & Satyanarayana, A. (2018). Urban heat island intensity during winter over metropolitan cities of india using remote-sensing techniques: Impact of urbanization. *International Journal of Remote Sensing*, 39(20):6692–6730.

36. Vinayak, B., Lee, H. S., & Gedem, S. (2021). Prediction of land use and land cover changes in mumbai city, india, using remote sensing data and a multilayer perception neural network-based markov chain model. *Sustainability*, 13(2):471.

37. Wamsler, C., Brink, E., & Rivera, C. (2013). Planning for climate change in urban areas: from theory to practice. *Journal of Cleaner Production*, 50, 68-81.

38. Yu, S., Zhang, Z., Liu, F., Wang, X., & Hu, S. (2021). Urban expansion in the megacity since 1970s: A case study in mumbai. *Geocarto International*, 36(6):603–621.

39. Zope, P., Eldho, T., and Jothiprakash, V. (2016). Impacts of land use–land cover change and urbanization on flooding: A case study of oshiwara river basin in mumbai, india. Catena, 145:142–154.

Monitoring and Evaluation in Drought-Proofing Plans: Exploring the Potential of a Social Audit Framework

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Coalition for Disaster Resilient Infrastructure

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Abstract

A people-centric approach is pivotal for building disaster-resilient infrastructure. However, it is not just sufficient to include the community in its construction but they should also partake in Monitoring and Evaluating (M&E) of the infrastructure. Using two case studies of participatory M&E models for disaster resilient infrastructure, NREGA Social Audits and Seva Mandir Gram Vikas Committee model, principles for effective monitoring and evaluation for resilience were identified. The principles include empowering the community to monitor water security infrastructure; iterative, regular, and flexible evaluation; and institutionalizing feedback loops for learnings generated in the M&E process among others. The key takeaway is that participatory approaches, combined with multi-dimensional indicator tracking, can help build a loop of learning that can identify vulnerabilities in time. This holds relevance for organizations such as the National Rainfed Area Authority or donor-led resilience infrastructure projects, which can adapt their expert-led evaluation techniques with components such as public hearings. Long-term engagement of the community can then be institutionalized as the community has a long horizon presence in the region of developed infrastructure and the greatest incentive with continued water security and disaster resilience in the region. It is this alignment of incentives with resilience that could be harnessed by well-designed participatory M&Es.

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1. Introduction

In traditional top–down programmes for water security and drought resilience, communities are often reduced to being mere end-users with a complete lack of their involvement during the planning, selection, construction and management of the systems created. This can be attributed to the rigidity of participation and monitoring processes (Basu et al., 2020). Socio-ecological resilience empowers vulnerable communities to seek accountability and mitigate the cause of vulnerabilities through participatory approaches that are institutionalized in political processes (Ferguson, 2019). In this regard, effective Monitoring and Evaluation (M&E) that focusses on systematic change and participatory learning is the key to building resilience which in turn will make the existing governance structures able to cope, adapt and transform (Stringer et al., 2006). Thus, it is important that the role and key principles of participatory monitoring models is explored in building disaster resilience.

We studied two models of multi-stakeholder partnerships in the semi-arid region of Rajasthan in India with the objective to explore people-centric monitoring, as it is critical for disaster resilience. The two models build and evaluate drought resilience and water conservation infrastructure. The first model is Social Audits, a participatory M&E method under National Rural Employment Guarantee Programme (NREGA). It is India's community-driven rural employment guarantee programme Social audits are a key component of NREGA's M&E framework. The second model is an NGO-directed and community-led approach to building and evaluating community water conservation infrastructure. This infrastructure includes community and individual assets under natural resource management pertaining to watershed development and allied agricultural activities and construction of WASH infrastructure among others.

Specifically, we study the two models to understand the following:

- How do these two models operate in the context of building water infrastructure for drought resilience?
- How do these two models operate in the context of building disaster-resilient infrastructure (in particular drought resilience)?
- What are the additional principles through which participatory resilience M&E methods can be made more effective, especially through the lens of governance?
- How can participatory M&E processes of the government and civil society (CSO) complement each other to build resilience?

The objective of this article is to identify the governance features of bottom-up M&E models that engage affected community in a comprehensive way and empower them to overcome institutional barriers to build drought-resilient infrastructure. We are especially interested to explore how community-led M&E can be used as a mechanism for facilitating learning to spur capacity building across different stakeholders.

2. Methodology

Between May 2021 and May 2022, we conducted a comparative institutional analysis through the methodology of systematic literature review, process net-mapping of two mature community-led M&E models and stakeholder interviews at various levels of governance in each model in Udaipur and Rajsamand districts of the semi-arid state of Rajasthan. We interviewed more than 40 stakeholders; these included district-, block- and village-level administrators and NREGA officials such as NREGA mates, auditors including District and Block Resource Persons (DRP), public participants of social audits and experts in social audits and resilience. The latter included officials at National Rainfed Agriculture Authority. To document the alternate model of Seva Mandir, we interviewed the Seva Mandir Natural Resource Management and Village Institutions Programme teams, paraworkers and members of village committees. We conducted the meeting with the village community members under two settings: both men and women present and then only women. In total, four Seva Mandir-led village group meetings were observed and the participants were interviewed in semi-structured group interviews. As Social Audits had to be discontinued due to COVID-19 concerns, we relied on the experience of the stakeholders to understand the process in addition to studying the literature and documentation provided. Instead of Social Audits, concurrent social audits were then conducted.

The aim of the analysis was to identify principles for participatory M&E of disaster-resilient infrastructure. We considered some of the principles proposed by World Bank (2017) for participatory M&E for resilience and analysed two such M&E models in operation against these principles. We then extended these principles based on our learnings from the two case studies. We also placed our principles and learnings in the context of M&E at different levels such as project and institution on the basis of a multi-scalar track system proposed by Faulkner et al. (2015).

The analytical framework for analysis was informed by studying the literature on participatory M&E for disaster resilience, in particular drought. The information from the interviews was coded accordingly to obtain broad, policy-relevant principles for effective participatory M&E for drought resilience.

3. Brief Results and Discussion

Case Study I: Participatory M&E under NREGA: social audits and other elements

The government of India introduced the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS and also referred to as NREGA) as a social protection scheme in India in 2005. It entitles 100 days of employment to at least one member of every rural household every financial year and enshrines the “right to work” under the National Rural Employment Guarantee Act 2005 (NREGA). While NREGA has a larger rights perspective, for our study we have focussed on the participatory approaches for building water security and drought resilience. Under Natural Resource Management, works taken up are for water conservation and water harvesting structures such as underground dykes, earthen dams, stop dams and check dams. Traditional water bodies are also restored and afforestation activities are also undertaken. In addition to this, minor irrigation infrastructure and its maintenance is done. As per the Government of India's master circular of 2019, of the 181 natural resource management works identified under NREGA, 84 are related to water. Additionally, the NREGA works are conducted in 'convergence' with other schemes and departments. For example, in Rajasthan, the NREGA was implemented in conjunction with "Mukhyamantri Jal Swavlamban Yojana", a scheme aimed at ensuring water security in water-stressed blocks in Rajasthan (Government of India, 2017).

Social Audits under NREGA involve a continuous process of public verification of the different implementation stages. An independent social audit team first conducts an audit of the implementation process and works created, and then presents its results in a public hearing. The public hearing gives the villagers an opportunity to hold implementing agencies accountable. Additionally, public hearings the villagers also get a platform to assess if their demands for particular assets have been met, thus closing the loop with the first stage of NREGA, which is community-led demand for assets that may aid in drought resilience.

In addition to social audits, which are expected to be conducted every 6 months, there is a provision for concurrent social audits (CSA). This has to be done every month. the Social Audit Unit fixes the calendar for this. The Village Monitoring Committees consisting of 5 NREGA workers are given the responsibility of monitoring this. As per the provisions, this committee should include women, workers from SC/ST households and those households who are deprived as per Socio-Economic Caste Census. For CSAs, no mandate exists for conducting public hearings. Instead, resource persons audit physical work every month and report any issues to the district unit. Villagers can attend the audits and raise their issues. COVID-19 forced dispensing public hearings and CSAs were conducted instead.

Social audit reports have to be prepared in local languages and displayed at the GP. They are also uploaded on the MIS (Management Information System). However, it was noticed that these reports are not as readily available on the website as has been mandated.

It is important to note that NREGA itself has other participatory components that social audits supplement and hence its functioning has to be viewed accordingly.

Case study 2: Seva Mandir Gram Vikas Monitoring Committee

Seva Mandir is a non-profit organization with a presence in 1300 villages in Udaipur and Rajsamand districts of Rajasthan. It has been working in the region since the early 1980s. The Seva Mandir model uses an elected village-level committee as the nodal forum for bottom-up decision-making process for natural resource management and participatory M&E. Building upon existing village committees that existed in the region, Seva Mandir makes interventions to create inclusive committees to be used as the central forum for implementation of interventions to better educational, health and natural resource management outcomes.

Village groups or **Gram Samuhs** are formed with a voluntary membership of resident households in the village. The aim is that every resident household in the village group should participate. The Gram Samuh, facilitated by Seva Mandir, elects a Gram Vikas Committee (GVC) to coordinate and supervise projects and lead their monitoring and evaluation. The GVC typically comprises 11 members, of which 50% are mandated to be women and include two young persons (aged 15–16 years), in addition to the inclusion of representatives from all castes. The GVC is an elected body responsible for the supervision and management of assets developed by the village group. It facilitates village meetings, elicits demand for works, coordination action on funding and approvals and monitoring and evaluation of built infrastructure by the nodal agency.

S. No.	Key Features	Public Hearing (used by NGOs also)	Concurrent Social Audit	Regular Social Audit	Seva Mandir Model
1.	When	At the start	During implementation	During implementation and at the end	At the start and end, with monthly Monitoring
2.	Frequency	Gram Sabha	Every month	Every Six months	Evaluation of outcomes at the end of project, monitoring of process is monthly
3.	Process	Village development plans are discussed at public hearings	Calendar sent by state unit, BRPs conduct audits with village officials at worksite where quality of work is checked and grievances of workers is heard	Calendar sent by state unit, BRPs conduct audits with village officials at a public hearing where quality of work is checked and grievances of workers is heard	Calendar decided with the help of NGO for monthly monitoring meetings. External Evaluation done for outcomes
4.	Follow-up	Plans are submitted to district/ state/centre	Grievances sent to state unit	Grievances sent to state unit	Grievances either solved with help of committee or with Seva Mandir as facilitator

S. No.	Key Features	Public Hearing (used by NGOs also)	Concurrent Social Audit	Regular Social Audit	Seva Mandir Model
5.	Type of information captured	Demand for works and type of works	Grievances	Grievances, demand for works and types of works	Grievances, demand for works and types of works

Source: Field observations/discussions, interviews conducted with Government officials

Format based on Dhungana, H., Clement, F., Otto, B., & Das, B. (2021). *Examining social accountability tools in the water sector: a case study from Nepal* (Vol. 179). International Water Management Institute (IWMI)

5.4 Resilience M&E Analysis

5.4.1 Background

To understand how the two models perform in the context of participatory M&E of community-led drought-resilient infrastructure, we proposed a conceptual framework for the analysis. The framework was applied in the context of Social Audits and Seva Mandir Model, which helped us further identify how the two models perform on the principles of resilience and where they can be improved.

The Framework was structured primarily on principles of resilience M&E, including those in the World Bank (2017). These principles were then studied with respect to the multiple scalar framework of M&E (Faulker et al., 2015). The principles identified are also based on the definition of resilience as proposed in (OECD, 2014), which is the ability of a system to absorb, adapt, and transform.

Therefore, the broad definition of resilience used for our study based on OECD (2014) includes the ability of a system to:

Absorb: The ability to prepare for drought events by building requisite water conservation and augmentation infrastructure. This would enable understanding the prevailing risks to water security and enable answering questions such as what mechanisms exist to ensure regular monitoring and maintenance of structures?

Adapt: The ability to change or accommodate drought events by making modifications to build infrastructure and governance processes. This would enable seeking answers to questions such as what mechanisms are there for community-led decision-making to ensure the longevity of water source via changes in consumptive behaviour.

Transform: The ability to create new processes for drought events. This would enable getting answers to questions such as what mechanisms exist for building infrastructure that mitigates drought risk via learning from past experiences, traditional knowledge systems and expert inputs.

5.4.2 Principles of resilience M&E

Principle 1: Flexibility with a focus on accountability, transparency and learning

In the context of drought resilience, which is in most cases slow-onset disasters, it is important that the approach for Monitoring, Evaluation and Learning (MEL) incorporates learning and captures processes instead of just outcomes. The indicators should not only be flexible to measure multiple outcomes, but the process itself should be flexible to incorporate different voices. For example, an open-ended public hearing gives an opportunity to the beneficiaries to voice their concerns about the process of the intervention and acts as a platform for cross-learning in case another set of beneficiaries is yet to encounter that problem.

Principle 2: Participatory in nature with emphasis on inclusion

As building resilience to droughts also means the ability of the local constituents to adapt and transform their existing systems, it is necessary for them to have a stake in M&E. For instance, we find that the inclusion of women's voices in the SM GVC process leads to discussion of more nuanced issues in water security. To further distil this argument, the young women views may differ from the older women based on responsibilities carried out. This makes the decision-making process more informed. In our case, we emphasize that for true participation, communities should not be treated as homogenous entities, and sharing of power is pivotal for representation (Faulkner et al., 2015; Agarwal et al., 2001).

Principle 3: Leveraging existing reporting systems in an inclusive manner

Resource constraints dictate that it is prudent for M&E systems to build on existing reporting channels. Additionally, familiarity with existing systems help engender greater participation.

Principle 4: Existence of feedback loops across scales and dimensions

Drought resilience projects are usually implemented by multiple agencies across different levels (local to central) and time scales (immediate and long term). Thus, it is necessary for the learning from the M&E process to flow to other agencies and actors. Additionally, multi-dimensionality (beyond the intended outcome of intervention) helps capture the effect of processes across different dimensions to understand positive and negative spillovers.

Principle 5: Regular and pre-planned schedules

Since resilience is measured using indicators that capture the process, particularly shocks and stressors, monitoring and evaluation have to be conducted at a higher frequency (Bene et al., 2013). Moreover, drought resilience of infrastructure is a long-term phenomenon and should be evaluated over a longer horizon rather than the project duration. In practice, the desired frequency of M&E is limited by cost and resource constraints, thus necessitating the optimization of each participatory M&E meeting. We argue that a pre-announced, preferably fixed schedule of public meetings can be useful in easing the participation of the stakeholders, especially the community.

Principle 6: Continuous long-term capacity building of stakeholders and facilitators

A common thread across our conversations with government functionaries, NGO workers, academics, and the local community workers was the need for regular capacity building as per their role defined in the monitoring process. Additionally, a prerequisite for effective capacity building is the need for a long engagement with the community.

These principles are highly interconnected and often feed into each other; for instance, diversity in actors as well as institutions is a step towards inclusivity and can lead to the resilience of the institution itself. Cross-sectoral knowledge-sharing between participants in a public M&E meeting leads to co-learning and enhances feedback loops. An important aspect of the information exchange between community participants, domain experts and administrators is mainstreaming of information.

Table 1: Assessment of social audits and Seva Mandir monitoring committee method viz. principles

	Social Audit under NREGA	Seva Mandir Monitoring Committee
Flexibility with a focus on accountability, transparency and learning	Public hearings offer an avenue for open-ended evaluation and grievance redressal at the level of workers/ villagers. The focus is on both the process and the outcome. However, higher government departments have fixed formats	Flexible process in membership, meeting schedule, works undertaken and evaluated. However, end-term impact evaluation is not flexible
Participatory in nature with emphasis on inclusion	Though mandated by law, it needs active capacity building for implementation	Active push by NGOs to ensure representation in committees
Leveraging existing reporting systems in an inclusive manner	Leverages NREGA MIS and auditors for monitoring, gram sabha for participatory evaluation	Complementarity of social audits and GVC-led gram samuh meetings for evaluation
Existence of feedback loops across scales and dimensions	Monitoring at community and agency levels; social learning in the public hearing	Monitoring at community, project site and agency levels; social learning in a public meeting
Regular and pre-planned evaluation	Social audit calendar by state unit every six months (regular) or monthly (concurrent)	GVC-led fortnightly meetings
Continuous long-term capacity building of stakeholders and facilitators	Provision for capacity building, led by civil society organizations, however needs to be strengthened	Regular capacity-building workshops of the community by the NGO

Source: Authors' analysis from Singh, Srishti, Goyal, Ananya & Yadav, Meghna (forthcoming), Participatory monitoring and evaluation for water security: case studies from India, *i-WSSM UNESCO Global Water Security Issues (GWSI) Paper Series 2022*, UNESCO and International Water Resources Association

4. Enablers and Barriers

For our study, we identified the following enablers and barriers as encountered during the course of our study:

- A key enabler was the response of the stakeholders we contacted who was willing to share their vast knowledge and experience with us. The officials were willing to share both the achievements and the weaknesses of their systems.
- A key stakeholder in conversations on water security is a woman. While the women were initially hesitant in speaking to us, which proved to be a barrier , we were fortunate that we were able to have multiple meetings with them, at the village level and the officials who were women shared their insights with us, which are key to resilience M&E.
- A key barrier was COVID-19-induced stop in public hearings. Therefore, we had to rely on the literature available and the experience of the stakeholders interviewed. The number of field visits and the type of interviews that could be conducted, with disruptions in the research plan also slowed the project and reduced its scope.

5. Conclusion and Way Forward

A people-centric approach is pivotal for building disaster-resilient infrastructure. However, apart from including the community (individuals, households, levels of administration) in its construction, they should also partake in monitoring and evaluating the infrastructure. In this context, the project helps identify the key principles of participatory M&E models for building drought-resilient infrastructure.

The principles include empowering the community to monitor water security infrastructure; iterative, regular, and flexible evaluation; institutionalizing feedback loops for learnings generated in the M&E process; and capacity building of the community in participatory methods among others. We take an institutional perspective to study these M&E models, which highlight a systems approach to building multi-stakeholder partnerships.

The study of social audits under NREGA helped us understand that the key to a successful participatory approach also lies in the wider dissemination of information across stakeholders and being consistent with that information. Capacity building of all the stakeholders is an important key, yet often neglected when taking sustained engagement with the community to achieve. People do find strength in numbers, not just in terms of the ability to hold implementing bodies accountable but also as a means to exchange information and learnings on how to better maintain the existing infrastructure.

The study of a comparative model by Seva Mandir helped us understand the importance of feedback loops across time scales. Additionally, it highlighted the fact that there is a need for a balance between community-led decision-making on the type of infrastructure and the advice of experts, with the latter being equally important.

Moreover, as identified from conversations with stakeholders and process net-mapping of the case study models, the presence of multiple and distinct participatory M&E models in a region can lead to checks and balances and a complementary model of managing water security infrastructure and community forests.

The key takeaway is that participatory approaches, combined with multi-dimensional indicator tracking, can help build a loop of learning that can identify vulnerabilities in time. This holds relevance for organizations such as the National Rainfed Area Authority, which can adapt their expert-led evaluation techniques with components such as public hearings. Long-term engagement of the community can then be institutionalized as the community has a long horizon presence in the region of developed infrastructure and the greatest incentive with continued water security and disaster resilience in the region. It is this alignment of incentives with resilience that could be harnessed by well-designed participatory M&Es.

References

1. Agarwal, B. (2001). Participatory exclusions, community forestry, and gender: an analysis for South Asia and a conceptual framework. *World Development*, 29, 1623–48
2. Ahluwalia, M. (1997). Representing communities: The case of a community-based watershed management project in Rajasthan, India. *IDS Bulletin*, *28*(4), 23-35.
3. Basu, M., DasGupta, R., Hashimoto, S., & Hoshino, S. (2021). A multi-actor and bottom-up perspective on attaining rural water security: qualitative evidence from India. *Environment, Development and Sustainability*, *23*(2), 1461-1484.
4. Béné, C. (2013). Towards a quantifiable measure of resilience. *IDS Working Papers*, *2013*(434), 1-27.
5. Biggs, R. Schuter, M., Biggs, D., Bohensky, E.L., BurnSiver, S., Cundill, G., & West, P.C.(2012). Towards principles for enhancing the resilience of ecosystem services. *Annual review of Environment and Resources*, 37, 42-448.
6. Bours, D., McGinn, C., & Pringle, P. (2014). Guidance note 1: twelve reasons why climate change adaptation M and E is challenging. Details availabe at https://www.ukcip.org.uk/wp-content/PDFs/MandE-Guidance-Note1.pdf.
7. Census (2011). Basic population figures of India, states, districts, sub-district and village, Registrar General of India, Ministry of Home Affairs, Government of India, Available at: https://censusindia.gov.in/census.website/data/population-finder
8. Colfer, C. J. P. (2005). The complex forest: communities, uncertainty and adaptive collaborative management. RFF Press and CIFOR, Washington, D.C., USA and Bogor, Indonesia.
9. Dhungana, H., Clement, F., Otto, B., & Das, B. (2021). Examining social accountability tools in the water sector: a case study from Nepal. *International Water Management Institute* (IWMI), Vol. 179.
10. Faulkner, L., Ayers, J., & Huq, S. (2015). Meaningful measurement for community-based adaptation. *New Directions for Evaluation*, 147, 89-104.
11. Ferguson, P. (2019). Discourses of resilience in the climate security debate. *Global Environmental Politics*, *19*(2), 104-126.
12. Fischer, H.W. (2020) Policy innovations for pro-poor climate support: social protection, small-scale infrastructure, and active citizenship under India's MGNREGA. *Climate and Development*, 12(8), 689-702, DOI: 10.1080/17565529.2019.1676690
13. Greenwood, D. J., Whyte, W. F., & Harkavy, I. (1993). Participatory action research as a process and as a goal. *Human Relations*, *46*(2), 175-192.
14. Government of India. (2013). *Mahatama Gandhi National Rural Employment Guarantee Act (2005): Operational Guidelines*. New Delhi: Ministry of Rural Development.
15. Government of India. (2017). *Mission Water Conservation under MNREGS: An Introduction*. New Delhi: Ministry of Rural Development.
16. Government of Rajasthan. (2014). *Crisis Management Plan*. Jaipur: Government of Rajasthan.

17. Holling, C. S., & Gunderson, L. H. (2002). Resilience and adaptive cycles. *In Panarchy: Understanding Transformations in Human and Natural Systems, 25-62*.
18. Hooda, S. M. (2017). *Rajasthan Water Assessment : Potential for Private Sector Interventions*. New Delhi: International Finance Corporation.
19. Mehta, L. (1997). Social difference and water resource management: Insights from Kutch, India 1. *IDS Bulletin*, *28*(4), 79-89.
20. Joy, K. J., & Srinivasan, V. (2021). Climate change and rural water security. In *The Crisis of Climate Change* (pp. 149-163). Routledge India.
21. Rao, Nitya, et al. (2019). A qualitative comparative analysis of women's agency and adaptive capacity in climate change hotspots in Asia and Africa. *Nature Climate Change,* 9(12), 964-971.
22. Ravindranath, N.H. & Murthy, I.K. (2021) Mitigation co-benefits of carbon sequestration from MGNREGS in India. *PLoS ONE* 16(5): e0251825.
23. Reed, M. S. (2008). Stakeholder participation for environmental management: a literature review. *Biological Conservation*, *141*(10), 2417-2431.
24. Richards, C., Carter, C., & Sherlock, K. (2004). *Practical approaches to participation*. Aberdeen: Macaulay Institute.
25. Rowe, G. & Frewer, L., 2000. Public participation methods: a framework for evaluation in science. *Technology and Human Values,* 25, 3–29.
26. Steinbach, D., Soanes, M., Barrett, S., Venkataramani, V. and Cheranda, T.M. (2020). *Deepening Knowledge of MGNREGS' Contribution to Climate Resilience. A Study of Rajasthan and Uttar Pradesh*. IIED, London.
27. Stringer, L. C., Dougill, A. J., Fraser, E., Hubacek, K., Prell, C., & Reed, M. S. (2006). Unpacking "participation" in the adaptive management of social–ecological systems: a critical review. *Ecology and Society*, *11*(2).
28. Sultana, F. (2009). Community and participation in water resources management: gendering and naturing development debates from Bangladesh. *Transactions of the Institute of British Geographers*, *34*(3), 346-363.
29. Tiwari, R., Somashekhar, H. I., Parama, V. R., Murthy, I. K., Kumar, M. M., Kumar, B. M., & Ravindranath, N. H. (2011). MGNREGA for environmental service enhancement and vulnerability reduction: Rapid appraisal in Chitradurga district, Karnataka. *Economic and Political Weekly*, 39-47.
30. UNESCO, UN-Water (2020). *United Nations World Water Development Report 2020: Water and Climate Change*. Paris, UNESCO.
31. World Bank Group, & Global Facility for Disaster Reduction and Recovery. (2017). *World Bank Resilience M&E: Good Practice Case Studies*. World Bank.

Disaster Resilience of Bridges Exposed to Climate Change and Growing Traffic Load during Design Life

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Abstract

The concept of resilience-based performance evaluation, which integrates vulnerability, loss and recovery measures, is rapidly gaining global importance in bridge engineering research and practice. In this context, the current research, supported by CDRI, has developed an analytical framework to assess disaster reliance of reinforced concrete (RC) bridges located in chlorine-laden and dense traffic environments. Floods and earthquakes are identified as the two primary natural disasters that triggered a majority of bridge failure in the past. Within the research scope, bridges on surface and over waterways have been assessed. Gradual degradation of these bridges is modelled by taking the combined effect of corrosion degradation and traffic-induced fatigue, commonly known as corrosion-fatigue degradation, over life cycles of these bridges. Modelling material deterioration due to corrosion-fatigue involved the simulation of truck traffic on bridge girders using stochastic samples of trucks obtained from weigh-in-motion (WIM) measurements and the estimation of fatigue stresses at critical locations of bridge girders. For performance simulation of these bridges under natural disasters, finite element (FE) models of these bridges have been developed. These FE models are updated according to the time-variant deterioration of composing materials owing to corrosion-fatigue degradation of bridge girders and corrosion of piers. Nonlinear time history analyses (NLTHA) are performed to assess bridge performance under the stated natural disasters. From the obtained results, time-variant disaster risk and resilience are estimated for different life-cycle years of the bridges. Results showed a declining trend in disaster resilience of the bridges as time progressed. Overall, the research demonstrates the confronting role of bridge degradation for developing disaster- resilient bridge infrastructures.

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1. Introduction

Worldwide, there is a growing recognition and interest among engineers and decision-makers in building disaster-resilient bridges that are important components of civil infrastructure systems. An approach towards meeting this goal is to analyse and design bridges after considering possible single and multiple hazard scenarios and gradual performance deterioration during bridge service life. The concept of resilience-based performance evaluation, which integrates vulnerability, loss and recovery measures, is gaining importance in the current state-of-the-art research and practice of bridge engineering. However, a major challenge associated with the development of disaster-resilient bridge infrastructure (DRBI) is accounting the gradual health degradation of bridges and transient nature of disasters expected at different stages of bridge service life. The current research, supported by the CDRI Fellowship Programme, addresses this issue through life-cycle resilience assessment of degrading bridge infrastructure under earthquakes and floods. At the same time we have taken into account the evolving natures of traffic load demand over bridge lifespan.

2. Research Problem

Bridge failure statistics indicate that the average age of a bridge failure in India is 35 years, whereas the same is 52 years in the United States (Garg et al., 2022). This literature also emphasized that flood and earthquake are the two primary natural disasters that trigger a majority of bridge failures globally; gradual degradation (aging) and overstressing are identified as the other major causes of bridge failures (ibid). These facts show a pressing need for selecting appropriate bridge maintenance strategies that would help increase the survival probability of bridges during natural disasters and enhance bridge service span. For this purpose, a comprehensive knowledgebase on various bridge degradation mechanisms is needed. Existing literature showed that repeated load-cycles from traffic load can enhance the degree of corrosion degradation of bridge girders, which is referred to as corrosion-fatigue degradation. If expected future growth in traffic volume is added to this, then corrosion-fatigue will have even higher potential to accelerate degradation of bridge girders. Moreover, aggregation of corrosion-fatigue with flood-induced scour at foundations of river-crossing bridges may produce significantly large impact on time-variant seismic vulnerability and resilience of these bridges. This stated problem is indeed critical for developing DRBI and such impacts have not been studied yet.

Although the American Association of State Highway and Transportation Officials (AASHTO, 2010) mandates stability check of bridge foundations against flood-induced scour for design-level flood events, the current design codes do not provide specific guidelines for ensuring seismic safety of bridges, with and without scoured foundations, subjected to capacity degradation during bridge service life. A compound effect of overstressing and ageing elevates the chances of bridge collapse during extreme natural events, resulting in enormous socio-economic losses. Climate change over bridge design lives can further accelerate seismic vulnerability of river-crossing bridges subjected to a multi-hazard scenario involving earthquake and flood (Devendiran et al., 2021).

3. Aim, Objectives, and Scope of the Research Study

3.1 Objective of the research

The key objective of this research was to develop an analysis-based framework to estimate life-cycle disaster resilience (LCDR) of bridges undergoing gradual degradation due to corrosion and/or corrosion-fatigue (a combined effect of corrosion and traffic load cycles). LCDR analyses accounted for (i) individual and multi-hazard impacts of earthquakes and floods and (ii) time-evolving nature of traffic load demand. The concept of estimating LCDR for bridges was particularly important because (a) gradual degradation makes bridges more vulnerable to natural hazards and consequently, post-disaster repair cost (i.e., direct loss) increases and (b) due to the elevated level of damage expected for ageing bridges, post-disaster recovery will take longer time in future than that would be required under present conditions. Our research experience on life-cycle seismic resilience of bridges (Vishwanath and Banerjee, 2019) helped in formulating this research idea. The concept of integrating fatigue-corrosion in LCDR assessment framework was particularly innovative that such an analysis quantified the impact of repeated load cycles, in conjunction with the future traffic growth, on bridge performance degradation.

3.2 Aim and scope of the research

Based on the stated objective and available knowledgebase on corrosion-fatigue degradation, the scope of the current research lies in developing a quantitative framework to assess the influence of corrosion-fatigue degradation on life-cycle seismic performance and resilience of RC bridges, which are located on surface and over waterways. These bridges represent the major population of bridges in the selected study regions. For the bridge on surface, corrosion-fatigue of bridge girder and corrosion alone of substructure (with the time progression) are considered to formulate time-variant gradual degradation of the bridge. For the river-crossing bridge, several past studies (Devendiran et al., 2021) including those of ours showed that flood-induced scour can enhance seismic vulnerability, risk and resilience of bridges. For the riverine bridge, therefore, corrosion-fatigue for bridge girder and scour at foundations are considered. The flowchart shown in Figure 1 is from the originally submitted proposal to CDRI. It shows the stated research scope and expected outcomes. The ensuing sections of this report discusses the methodology for modelling corrosion-fatigue degradation for RC T-girders, followed by its application to multi-span case study bridges to calculate LCDR.

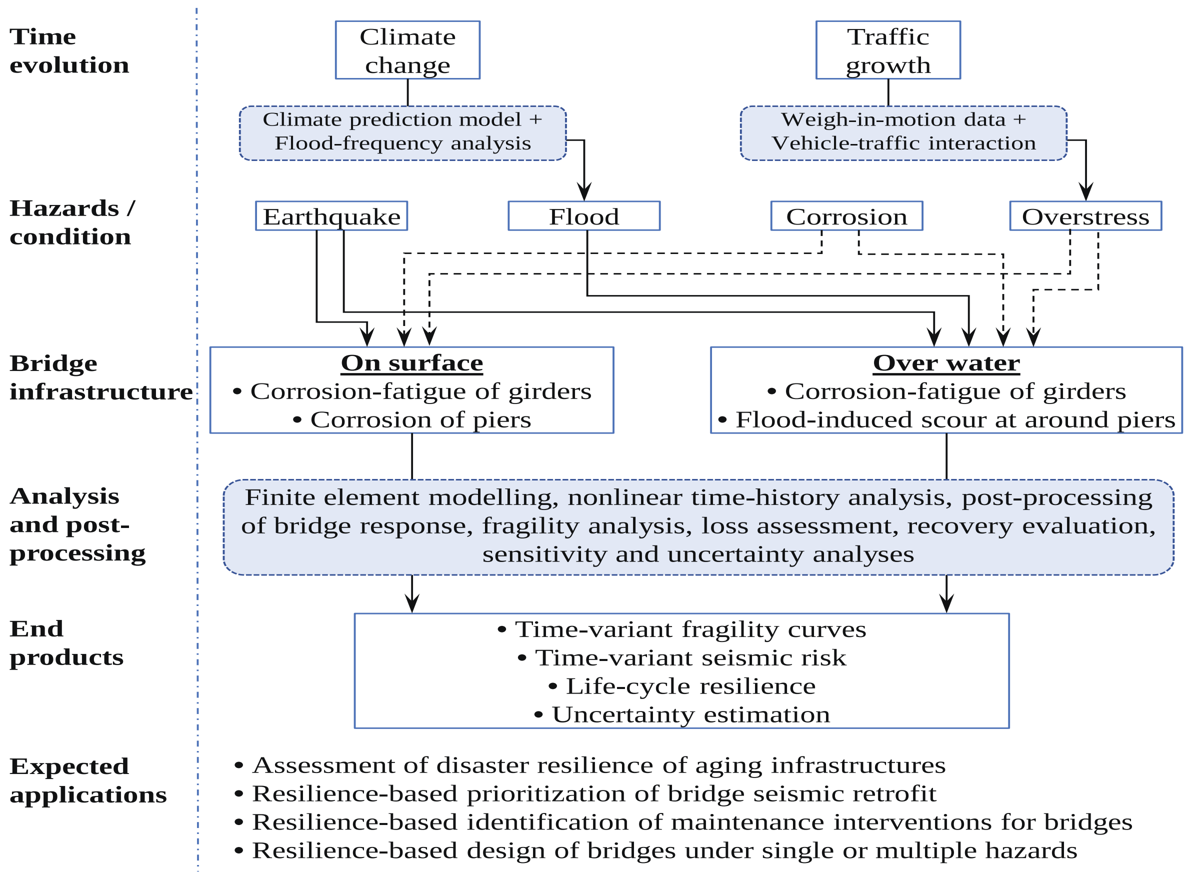


Figure 1. Flowchart showing the scope of the research and expected outcomes

Source: From the original proposal submitted to CDRI

4. Methodology

4.1 Sample bridges

Two highway RC T-girder bridges were selected as case study bridges to study the impact of traffic-induced fatigue on bridge disaster resilience. The bridge on surface, henceforth referred to as Bridge I, is located in California, USA. This type of bridge consumes around 43% of multi-span simply supported (MSSS) T-girder bridges in California (NBI, 2022). Moreover, similar MSSS bridges are very common in other seismic regions as well (Nielson, 2005). The design of this bridge follows the AASHTO (2010) bridge design specifications. The bridge on river, henceforth referred to as Bridge II, is located on River Shetrunji in Gujarat, India as the state has several river-crossing T-girder bridges. According to the statistics given in Dey and Sil (2021), 82 out of 100 bridges in Gujrat are on rivers, and these river-crossing bridges are typically multi-span simply supported or continuous RC T-girder bridges. Accordingly, a three-span simply supported RC T-girders bridge is taken as Bridge II. The basic design criteria as per IRC-SP 114 (2018) is followed here for designing the bridge. This bridge experiences a scour condition that would result from 100-year flood in River Shetrunji.

Both bridges have three spans with total length of 60 m; each span is 20 m in length and simply supported at their ends. They are supported at the ends by seat abutments, and elastomeric bearings are used to support the superstructure on the substructure. The substructure of Bridge I is composed of three piers bent (double curvature column) while Bridge II is composed of two piers bent. Both bridges are supported on pile foundations. Figure 2 presents the illustration of two bridges. Finite element modelling of these bridge is discussed later in this report. As these bridges are located in chloride-laden environments and experience high traffic volumes, they are susceptible to corrosion-fatigue degradation.

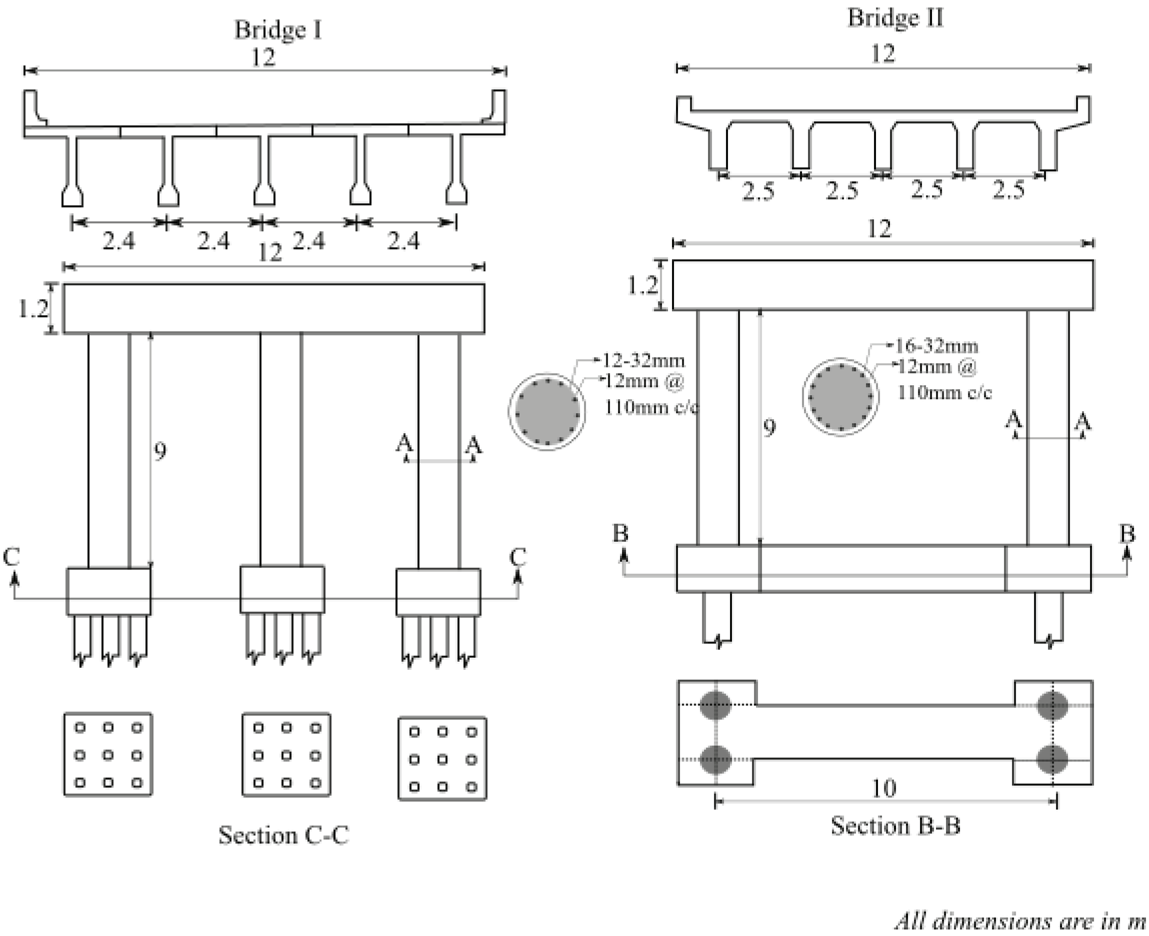


Figure 2. Sectional view of case study bridges

4.2 Regional traffic data on bridges

These representative bridges are expected to carry design traffic loads, and hence, the current study does not intend to judge the safety of these bridges from flowing traffic. Rather, the study here investigates how and up to what extent traffic load cycles (and induced fatigue stresses) accelerate the chloride-induced corrosion process of bridge girders. Thus, region-specific information on actual load cycles from truck traffic (observed from the real-life traffic survey) is considered here. Such required traffic data is obtained from observed weigh-in-motion (WIM) measurements from the two regions. For Bridge I, WIM data observed in the Interstate LA-710 is obtained from Lu et al. (2002), while the same for Bridge II in the highway corridor of Gujarat is obtained from MES (2022). Further details on these observed data are given in the detailed report. These observed data for both bridges are used to calculate fatigue stresses in bridge girders.

4.3 Vehicle-bridge interaction (VBI) analysis

As observed, the traffic data for both bridges are composed of various types of trucks and other vehicles. Based on the observed proportion, gross vehicle weights (GVWs) of multi-axel trucks are generated. Each generated sample of GVW is used to calculate the dynamic stress of bridge girders at critical locations. Then the vehicle-bridge interaction (VBI) analysis is performed. In the analysis, the vehicle is modelled as a three-axel fatigue load model that can accurately represent the vehicle dynamics (Chotickai and Bowman, 2006). This VBI analysis resulted in mid-span deflection of bridge girders from which stress-time histories are calculated at this region for each GVW.

To demonstrate obtained response of VBI analysis, Figure 3a shows the variation of stresses with time for fatigue-critical rebars of Bridge I under three different GVWs. As these plots indicate, stress increases with increasing GVW for obvious reasons and the maximum stress at the mid span occurs when the steering axle comes at that location. From thus obtained stress-time histories for each GVW, equivalent stresses are estimated. The adopted procedure of VBI is validated using the observations reported in Deng and Cai (2009) from a real-time in-field experiment. To maintain consistency while performing the validation study, structural- and traffic-related parameters are kept the same. Results from this validation study is shown in Figure 3(b) that reveals a fair agreement between the observed response from the literature and that analytically predicted through the VBI model.

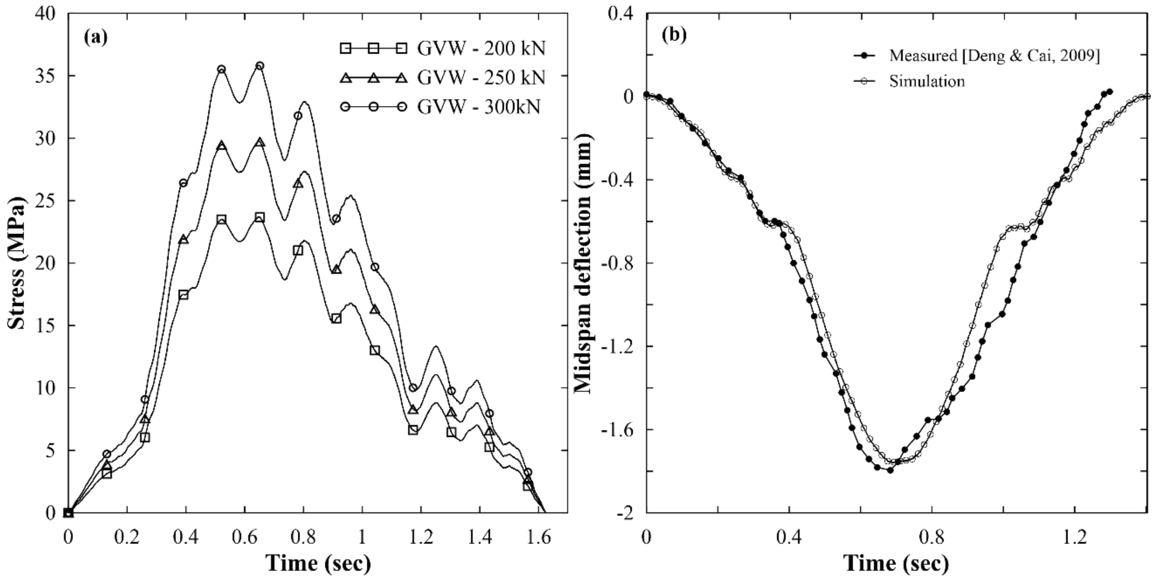


Figure 3. (a) Stress-time history for three samples of trucks for Bridge I and (b) Comparison of obtained response in VBI analysis with measured response

4.4 Estimation of equivalent fatigue stress

The stress time-history obtained for each sample of GVW is composed of stresses with low-amplitude and high cycle. Based on the established procures from literatures, stress histories are converted to equivalent stress for each GVW. To do that, rainflow cycle counting algorithm (Yan et al., 2017) and linear damage accumulation hypothesis (through S-N curves) are applied. Here, the underlying assumption ensures that calculated equivalent stress for a GVW will result in fatigue damage of steel rebars similar to that from corresponding stress ranges (Yan et al., 2017). In accordance with this method, equivalent stresses are calculated for every truck sample for Bridge I and Bridge II.

For each bridge, the information on Annual Average Daily Truck Traffic (AADTT) is used to estimate the total number of daily trucks that pass the bridges. It helps counting the total number of equivalent stress cycles per year that the bridge girders are exposed to. Further, the information is integrated with yearly expected growth in traffic cycles in both the bridge sites. This is because the current study aimed to capture the life-cycle performance of bridges for which projected growth in observed traffic volume was necessary in order to account for the expected traffic load scenario on bridges in future years. Past studies for the California region suggested that a yearly growth of 4% can be taken to project future truck traffic in that region (Lu et al., 2009). Consequently, cumulative projected truck traffic from 1995 (first recorded time) to 2094 (after 100 years) is estimated for Bridge I. These cumulative traffic cycles are used to estimate accumulated fatigue stresses on the girders of Bridge I. Similarly, truck traffic is expected to grow at a rate of 3.5% per year in Gujarat (DPR, 2013). Hence, 3.5% yearly growth of traffic is used for Bridge II to project truck traffic in future years on the bridge.

4.5 Corrosion and corrosion-fatigue degradation models for both bridges

4.5.1 Corrosion of rebars in girders and piers of Bridges I and II

This report first discusses the impact of corrosion degradation on bridge components. Following that, the impact of corrosion-fatigue on properties of steel rebars is discussed. The current study assumes diffusion as the dominant mechanism of chloride ingress into the concrete media. Consequently, the study estimates the time for corrosion initiation (*Tini*) using the Fick's second law of diffusion as expressed in Eq. (1), in which *Xcov*, *Ccr*, *Dc* and *Cs*, respectively, represent the cover depth of bridge members, critical chloride concentration for corrosion initiation, diffusion coefficient and chloride concentration at the exposed surface of concrete.

$$T_{ini} = \frac{X_{\mathrm{cov}}^2}{4D_c}\left[erf^{-1}\left(\frac{C_s - C_{cr}}{C_{cr}}\right)\right]^{-2} \qquad [1]$$

For Bridge I, *Xcov* is taken as 50.8 mm [according to the structural drawings given in Yan et al. (2017)]. Corrosion guidelines given by the California Department of Transportation (Caltrans, 2021) suggest that *Ccr* may have a uniform variation between 0.71 kg/m^3 and 1.77 kg/m^3. A specific value of *Ccr* is difficult to obtain even for a given region due to the spatial variability of environmental condition. Thus, the current study considered a *Ccr* of 1.62 kg/m^3, a randomly generated value based on the stated uniform distribution. The diffusion coefficient *Dc* is set at 161.15 mm^2/year, which is the mean diffusion coefficient of the 252 concrete samples collected from 49 bridges in California (Weyers et al., 1994). Spellman and Stratfull (1969) conducted a field survey on 19 RC bridge decks (that were built 9 years prior to the inspection) and reported mean chloride concentrations at 1 inch (or 25.4 mm), 2 inch (or 50.8 mm) and 3 inch (or 76.2 mm) depths of the girders. These reported concentrations are used to calculate chloride concentration at the exposed surface using Equation [1]. Based on the estimated value of *Cs*, *Tini* is calculated to be 8 years for Bridge I components.

For Bridge II, *Xcov* is taken as 38 mm following Dey et al. (2019). This literature showed that the spatial distribution of chloride concentration for this region exceeds the maximum permissible limit of chloride concentration on concrete surface. As per the marine atmosphere in Gujarat, the surface chloride concentration and the threshold concentration of chloride to initiate corrosion are reported to be 2.57% and 1.6% respectively, by the weight of binder (Dey and Sil, 2021). The remaining parameters required to quantify the initiation time of corrosion are obtained from Duracrete (2000). Using Equation [1], the study estimated the initiation of corrosion in girders are piers of Bridge II is 7 years.

To avoid complex formulation of non-uniform corrosion, the study here assumes uniform corrosion of rebars. After a time *z* years from corrosion initiation, the available cross-sectional area of rebar *A*(*tz*) can be calculated based on the relation given below. In this *dini* represents the initial diameter of rebars and the corrosion rate is expressed with *rcorr*.

$$A(t_z) = \frac{\pi}{4}[d_{ini} - r_{corr}(t_z - T_{ini})]^2 \quad for\ t_z > T_{ini} \tag{2}$$

For Bridge I, *rcorr* is taken as 0.05 mm/year, which is an average estimate for the California region according to the Caltrans Corrosion Guidelines (Caltrans, 2021). As Bridge II is subjected to marine exposure scenario, time-dependent corrosion rate is considered for the study following recommendations of Vu and Stewart (2000). It should be noted here that other secondary effects of corrosion (e.g., strength reduction of steel and concrete, loss of bond) are not considered within the analysis framework. This is to keep a control on the computational complexity and time for projecting the impact of corrosion-fatigue degradation to the LCDR of the bridges.

4.5.2 Corrosion-fatigue of bridge girders

Kim and Heffernan (2008) mentioned that the stress range and maximum stress limit primarily govern the fatigue behaviour of rebars. As the number of fatigue load cycle increases with time, stresses accumulate in rebars that eventually lead to the formation of fatigue cracks. As a result, the cross-sectional area of rebars reduces with time (Zhang et al., 2017). The limiting area A_N^f at which a rebar may get fatigue fracture can be written as

$$A_N^f = \sigma_{s,\max} \frac{A_o}{f_y} \tag{3}$$

Here *N* is called as fatigue life of rebar. It expresses the number of load cycles at which rebar fractures at limiting area . and are, respectively, the maximum nominal stress and yield strength of rebar. *A0* expresses initial cross-sectional area of rebar before fatigue degradation initiates. In the study here, time-dependent degradation involves the simultaneous effect of corrosion and fatigue degradations after corrosion initiates in rebars. Thus, the expression for coupled corrosion-fatigue degradation is given as

$$A_z = \frac{\pi}{4}\left(d_{ini} - (t_z - T_{ini})r_{corr}\right)^2 - \left[\sum_{k=1}^{z} \frac{n_z - n_{z-1}}{N_{z-1} - n_{z-1}}\left(A_{z-1} - A_N^f\right)\right] \tag{4}$$

In this, *Az, nz* and *Nz* are, respectively, the residual area of rebars, number of traffic cycles and fatigue life of rebar after time *tz* where z = 1, 2, 3,…. Based on equivalent stresses and degree of rebar corrosion at time *tz*, analytical expression of *Nz* is obtained from Hahin (1994) and Zhang et al. (2012).

4.5.3 Effect of fatigue on properties of concrete

The literature shows that the fatigue-induced degradation of concrete properties is lower than that for steel; however, the combined degradation of concrete and steel due to corrosion-fatigue may become significant for overall performance evaluation of degrading bridge girders. Thus, the study here considered the change in elastic modulus of concrete due to corrosion-fatigue following Han et al. (2015) and Balaguru (1981).

5. Results and Discussion

5.1 Representative bridges and FE models

The representative bridges, shown in Figure 2, have three spans, each 20-meter long. These spans are composed of five parallel T-girders having intermediate diaphragms. All bridge piers are circular. Three-dimensional (3D) finite element (FE) models of these bridges have been developed in OpenSees. Figure 4 shows the schematic FE model and the non-linear characteristics of key bridge elements.

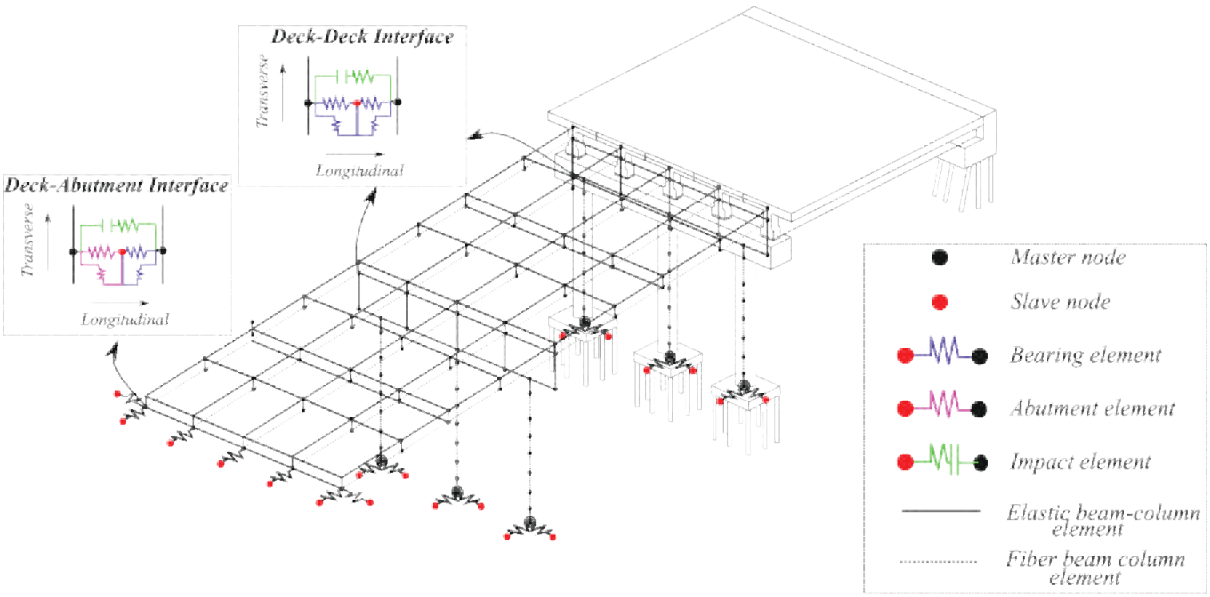


Figure 4. Schematics FE model of various bridge components

To account for the damage owing to corrosion-fatigue, nonlinear beam column element with fibre section is assigned for the web portion of the T-girder. Flanges of T-girder are represented as a grillage of elastic beam-column element with the sectional properties obtained from the discretized cross-section. To ensure a rigid action between web and flanges of T-girder, rigid elements are used to restrain them. Intermediate diaphragm within the bridge span is represented as rigid elastic elements in the transverse direction. To ensure rigid action between bridge girders and decks, the girder and deck elements are constrained together by rigid elements. Therefore, developed 3D models of bridge girders are assemblages of nonlinear and linear elements that are constrained together with rigid elements at respective joints. This modelling technique is adopted from available literatures in which similar bridges were analysed under seismic ground motions (Tapia-Hernández et al., 2017; Wan et al., 2021). The applicability of this modelling technique is validated by using experimental data from a full-scale field test conducted on a T-girder bridge by Song et al. (2002). For comparison purpose, the examined bridge superstructure is modelled in OpenSees using the above-described modelling approach and analysed for the load used in the field study. It is observed that the obtained response values are well in agreement with that from the literature; hence, the developed grillage model of bridge girders can adequately capture the longitudinal and transverse stiffness of bridge deck.

Bridge piers at each bent is idealized using nonlinear beam column element with necessary fibre section that accounts for cover concrete, core concrete and longitudinal reinforcement. Seat-type abutments at both ends of the bridge are individually modelled in both longitudinal and transverse directions. The backwall-backfill interaction in the longitudinal direction is idealized using uniaxial material object *ElasticPPGap* in OpenSees. The strength and stiffness property of *ElasticPPGap* are assigned by following the guidelines specified in Caltrans (2019). The abutment strength and stiffness in the transverse direction is idealized by using *ElasticPP* material. *ElasticPP* is also used to model the response of elastomeric bearings on abutments and piers in both the longitudinal and the transverse directions. Bearing response in the vertical direction is modelled using linear elastic spring and its stiffness value is calculated by following the formulation given in Warn et al. (2007).

Foundation piles beneath the pile cap are idealized using elastic beam-column elements. *PySimple1* and *TzSimple1* from OpenSees material library are used and assigned along the length of pile and at some portion of pier to represent the nonlinear interaction of pile or pier with surrounding soil. *P-y* springs provide soil resistance in two horizontal seismic shaking direction while *t-z* springs provide shaft resistance along the pile/pier length. Parameters required as an input for *PySimple1* and *TzSimple1* are calculated using the specifications given by the American Petroleum Institute (2003). Since Bridge II experiences scour due to possible flood event in the river, *p-y* and *t-z* springs up to the depth of expected scour are removed in the scoured model. After removing these springs, the properties of remaining springs in FE model are recalculated with respect to new river-bed elevation.

Time-dependent reduction of rebar area of girders due to corrosion-fatigue at each life-cycle year is implemented in the FE models by uniformly reducing the cross-sectional area of rebars along their lengths. For corresponding life-cycle years, the observed reduction in elastic modulus of concrete due to corrosion-fatigue is incorporated by revising material models assigned to the fibre section of girders. Moreover, area reduction of longitudinal rebars of bridge piers due to corrosion is accounted for while updating FE models developed for different life-cycle years of these bridges. Thus, these updated FE models properly capture deteriorating states of investigated bridges along their service lives. The analysis of these bridges under regional hazards shows degrading trends of bridge performance along their service lives.

5.2 Regional hazard conditions

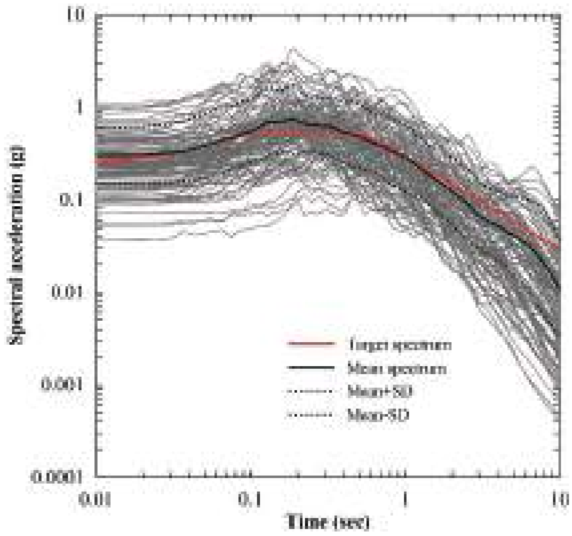
5.2.1 Seismic hazard for Bridge I

The seismic performance of the investigated bridges in pristine and degraded states is analysed using a nonlinear time history analysis (NTHA) method under regional ground motions. This is the most advanced and well accepted method for seismic performance assessment of structures. It provides time-histories of bridge response (i.e., displacement, rotation) from which the maximum response of the bridges under a ground motion can be obtained and used for fragility analysis. Note that no traffic load is considered while performing NTHAs; otherwise, bridge performance only under seismic excitations cannot be estimated. For Bridge I, 30 pairs (i.e., 60 motions) of orthogonal ground motions (GMs) having 2%, 10% and 50% exceedance probabilities in 50 years were obtained from Somerville et al. (1997). The peak ground acceleration (PGA) of selected ground motions varies between 0.14 g and 1.30 g. These ground motions, originally generated for the California region, are used here as information related to bridge corrosion and traffic load is also acquired for the same state.

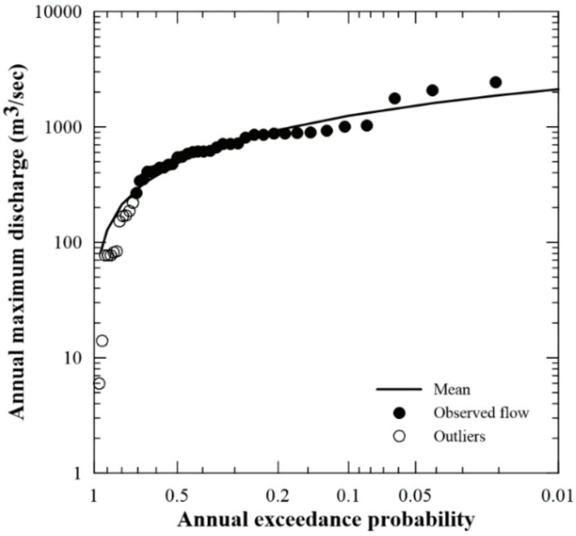
5.2.2 Seismic and flood hazards for Bridge II and expected scour depth

Seismic hazard in Gujarat has been historically characterized with frequent large earthquakes and less probable moderate earthquakes (Shukla and Choudary, 2012). Since the number of ground motions recorded in the study region is insufficient for seismic hazard analysis of the case study bridge, earthquake records from other parts of the world were obtained in such a way that the seismicity and tectonics of the selected ground motions match with that of the study region. The criteria set to select the ground motions were (i) maximum earthquake moment magnitude ranges between 5 and 7.7 Mw, (ii) the nearest fault distance is within 10 and 30 km, (iii) the fault mechanism is strike-slip and (iv) the shear wave velocity is within 300 m/s and 800 m/s. These conditions are representative seismic parameters of the study region (Kamra et al., 2020; Vijaya et al., 2020). Based on these selection criteria, a total of 77 sets of ground motions from the PEER NGA ground motion database (PEER, 2022) were selected. The average response spectrum of these 77 ground motions matches well with the design spectrum of the study region (shown in Figure 5a). The peak ground acceleration (PGA) of selected ground motions varies between 0.04 g and 1.3 g.

Flood frequency analysis is carried out using the observed annual maximum discharge data obtained from the Central Water Commission (CWC 2019) for River Shetrunji. Generally, the flood discharge associated with varying annual exceedance probabilities is represented by the flood hazard curve. For the observed data, flood hazard curve is generated to represent the regional flood hazard scenario at the bridge site (shown in Figure 5b). The flood discharge corresponding to the 100-year flood (i.e., the design flood) is calculated to be 2118 m^3/s. Since the geometric configuration of the river cross-section is not available, the flood flow velocity is assumed to be within 1 m/s to 2 m/s. Based on the assumed stream velocity and using the formulation given in Arneson et al. (2012), the scour depth around the bridge pier is calculated to be 5 m. Note that the current study is based on the basic consideration that the bridge is safe from the evaluated scour depth. Hence, the probability of bridge failure due to expected scour depths is not studied here.



(a)



(b)

Figure 5. (a) Seismic hazard and (b) Flood hazard at Bridge II site in Gujarat

5.3 Impact of corrosion-fatigue on bridge seismic vulnerability

For each set of seismic ground motions from respective suites, nonlinear time-history analyses (NLTHAs) are performed for both the bridges. Response values of various bridge components are recorded. These are called engineering demand parameters (or EDP) which include nonlinear flexural response (or curvature ductility) of bridge piers, abutment displacements in the active and passive directions and displacement of bearings in the longitudinal and transverse directions. For every degraded state of the bridges, the same analyses are repeated and EDP values are recorded. These values are then used in a probabilistic framework to evaluate seismic vulnerability of Bridge I and Bridge II. This procedure of seismic response analysis of bridges is very common and has been extensively used by us in our research and by other researchers worldwide. As all models relevant to this study are thoroughly validated, it is believed that the numerical analyses of the bridges under earthquakes will appropriately yield bridge response that is expected in real-life when the same bridges are subjected to the same earthquakes.

The obtained seismic response of abutments, bearings and piers are compared with respective threshold limits reported in Yilmaz et al. (2016) and Nielson (2005). This comparison facilitates in categorizing recorded bridge response in four damage states, namely minor, moderate, major damage and collapse states. The physical description of the bridge seismic damage at these damage states is given in HAZUS (HAZUS-MH-MR4 2003) and widely used to analyse the seismic fragility of bridges. The process is repeated for different degraded conditions of the bridges till they reach 100 years of lifespan.

Figures 6 and 7 illustrate the seismic fragility curves of Bridge I and Bridge II, respectively, at four damage states and for five life-cycle years. Here peak ground acceleration (PGA) is used as the seismic intensity measure. The fragility curves provide probabilities of exceeding various seismic damage states of the bridges for any given ground motion with a PGA value. Parameters of these fragility curves at various damage states (referred to as median values, c) are mentioned within the figures. For Bridge I, Figure 6 shows almost no observed variation in fragility curves at the minor damage state of the bridge. Besides, the fragility curves of the bridge in all damaged states show degradation that indicates increasing seismic vulnerability of the bridge as it deteriorates due to corrosion-fatigue during its service life. For example, if the bridge is subjected to an earthquake of PGA 0.6g, it has a probability of exceeding major damage state of 0.435 at its 25th year and 0.645 at its 100th year. Similar degrading trends are visible for Bridge II in Figure 7.

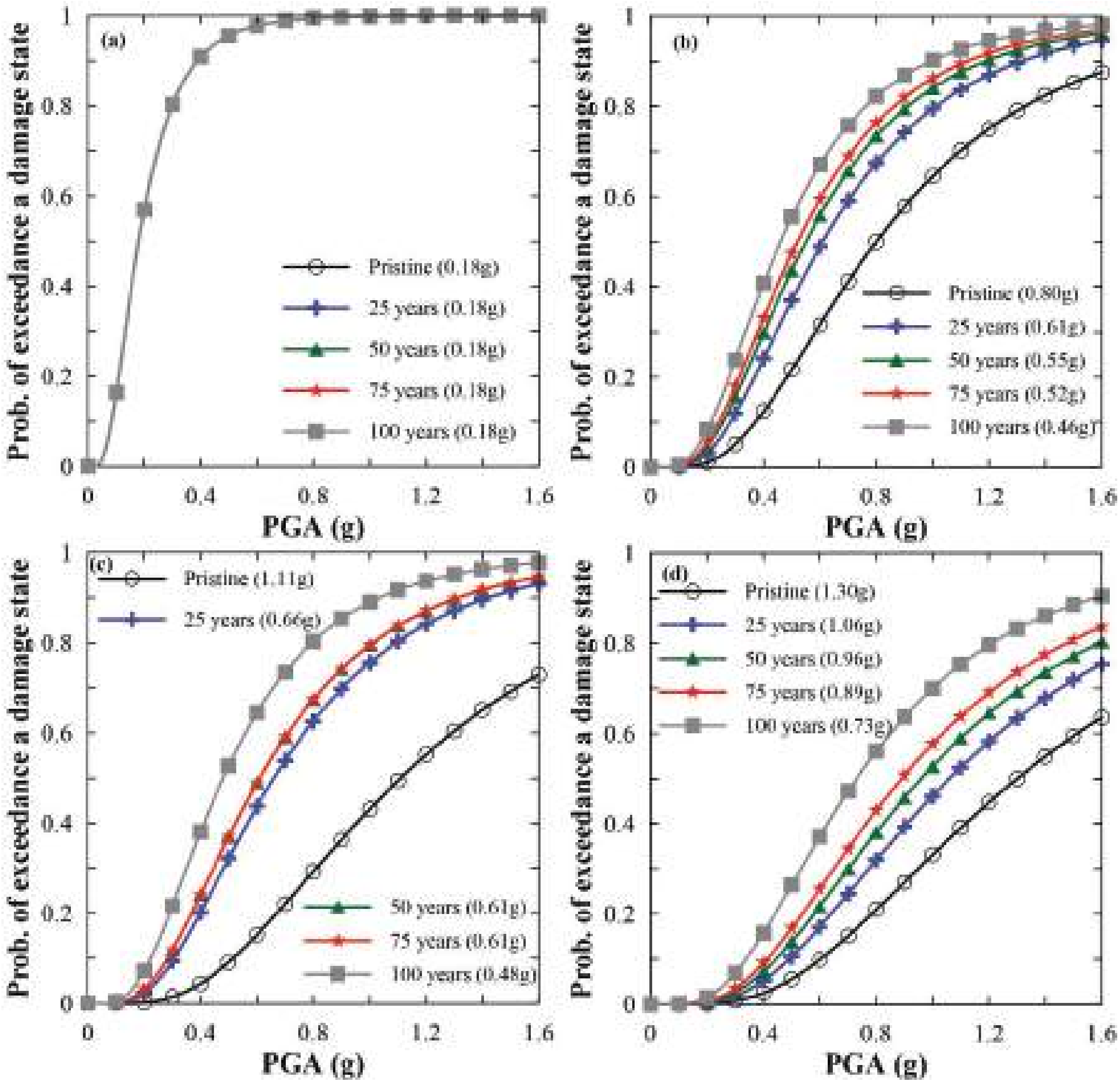


Figure 6. Time-dependent seismic fragility curves of Bridge I: (a) at minor damage, (b) at moderate damage, (c) at major damage, and (d) at collapse state

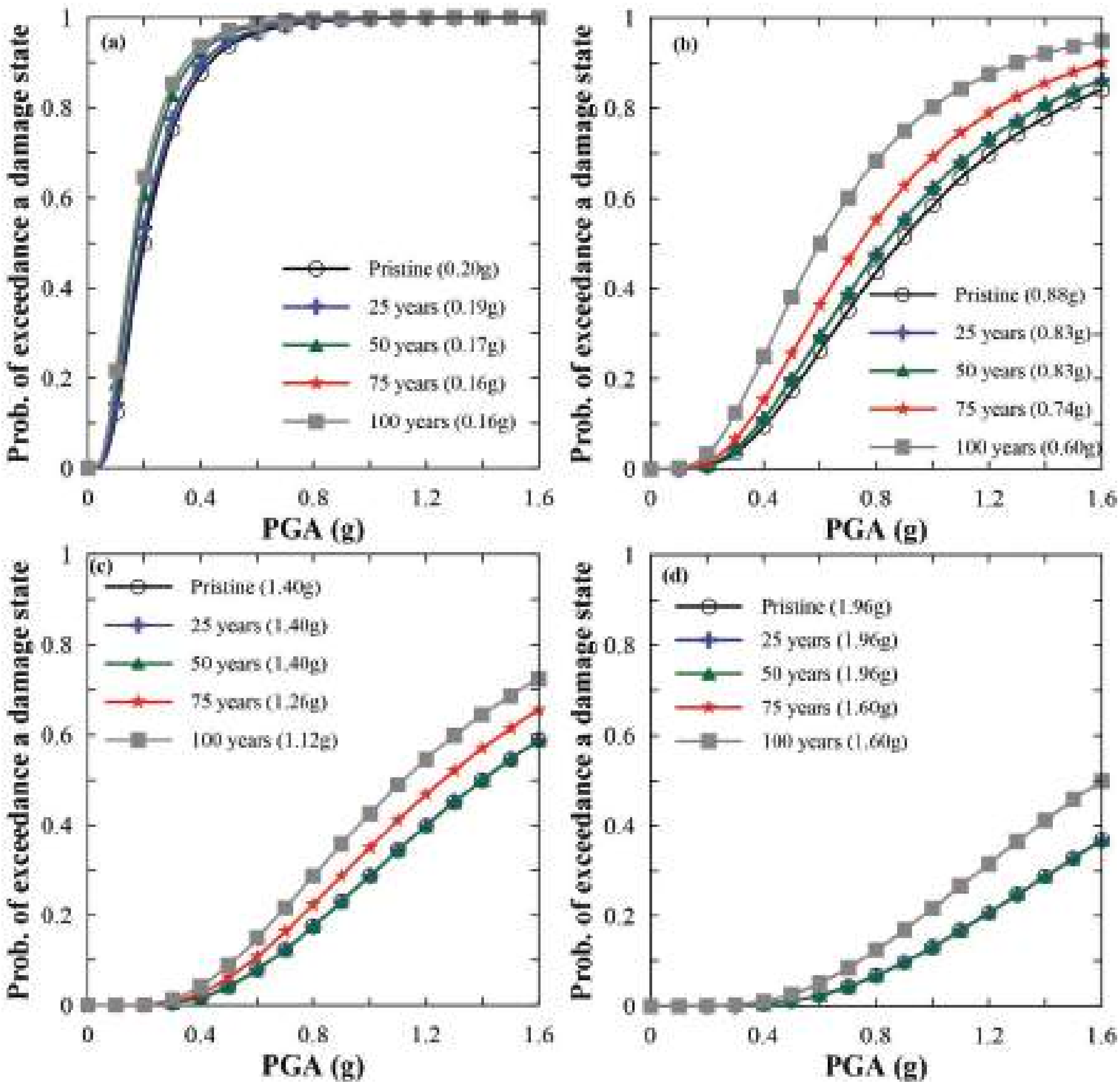


Figure 7. Time-dependent seismic fragility curves of Bridge II: (a) at minor damage, (b) at moderate damage, (c) at major damage and (d) at collapse state

5.4 Impact of corrosion-fatigue on seismic risk and resilience of bridges

Time-evolution of seismic bridges risk and resilience of bridges are estimated for each life-cycle year. By definition, risk provides the measure of expected post-disaster losses owing to bridge damage. Here bridge restoration cost due to damaged bridge components are taken to express post-disaster losses in risk evaluation. For Bridge I, Figure 8(a) shows the seismic hazard for the study region [obtained from USGS (2022)], while Figure 8(b) expresses seismic risk of the bridge. For Bridge II, Figure 9(a) shows the seismic hazard for the study region [from Bashir and Basu (2018)], while Figure 9(b) expresses seismic risk of the bridge. As these risk curves demonstrate, the seismic risk of the bridges increases with increasing level of bridge degradation.

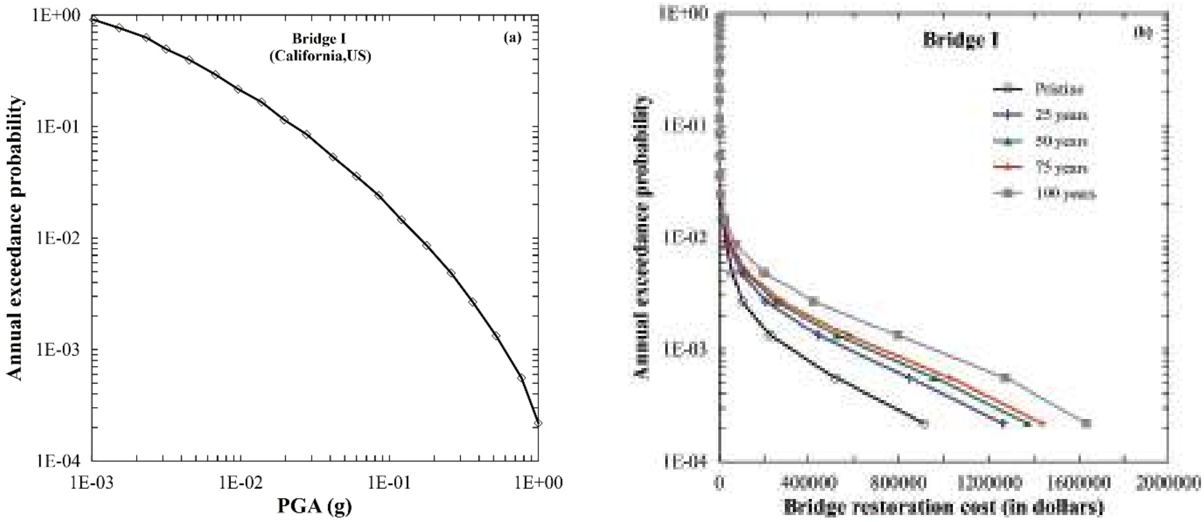


Figure 8. (a) Seismic hazard curve for the California region and (b) seismic risk curve of Bridge I

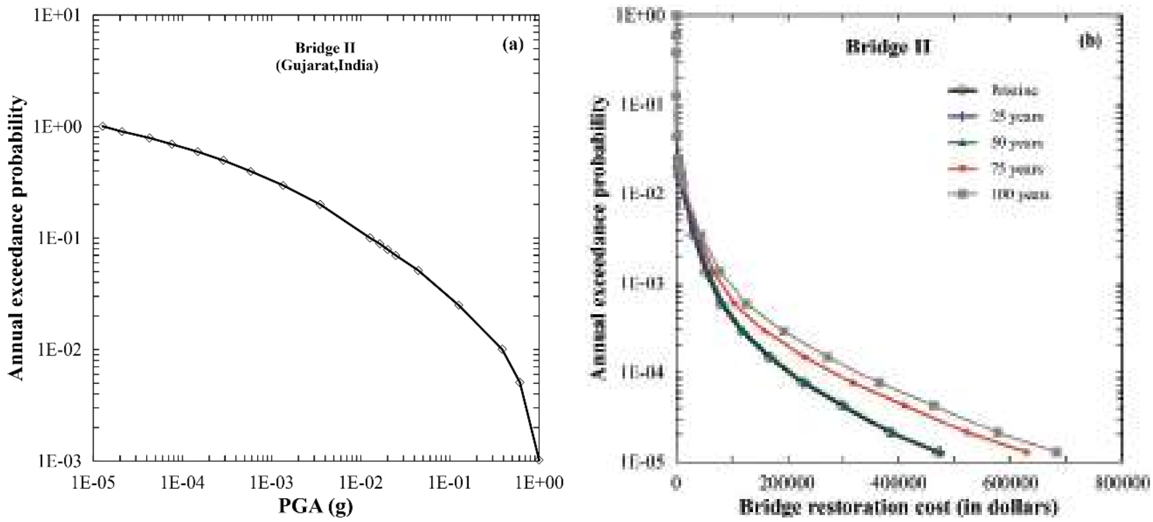


Figure 9. (a) Seismic hazard curve for the Gujarat region and (b) seismic risk curve of Bridge II

Disaster resilience of bridges is an integrated measure of bridge damage, post-disaster losses and recovery. Due to the inclusion of recovery measures, estimated resilience values express how quickly a damaged infrastructure can revert to its pre-event functionality level. The study here estimates LCDR of Bridge I and II based on the pervious theoretical framework adopted by us in our previous publications (Banerjee et al., 2019; Vishwanath and Banerjee, 2019; Devendiran et al., 2021). Fragility curves are used to estimate post-event seismic losses of the bridges. Damage-state specific recovery functions, as developed in Vishwanath and Banerjee (2019), are used to estimate bridge resilience. The resilience value is computed as a dimensionless quantity between 0 and 100%. Higher value indicates better resilience. Figures 10(a) and (b) show seismic resilience of Bridge I and Bridge II, respectively, at pristine and various degraded conditions for the considered traffic growth. With increasing intensity of ground motions (i.e., PGA), resilience of the bridge reduces. For every life-cycle year, seismic resilience of the bridges reduces as deterioration proceeds, which certainly implies the significant adverse impact of combined corrosion-fatigue degradation on life-cycle seismic resilience of investigated bridges. These degrading trends are almost linear for lower

PGA values; however, they take nonlinear forms for PGA values. This observation is in accordance with our previous work on life-cycle seismic resilience of bridges (Vishwanath and Banerjee, 2019).

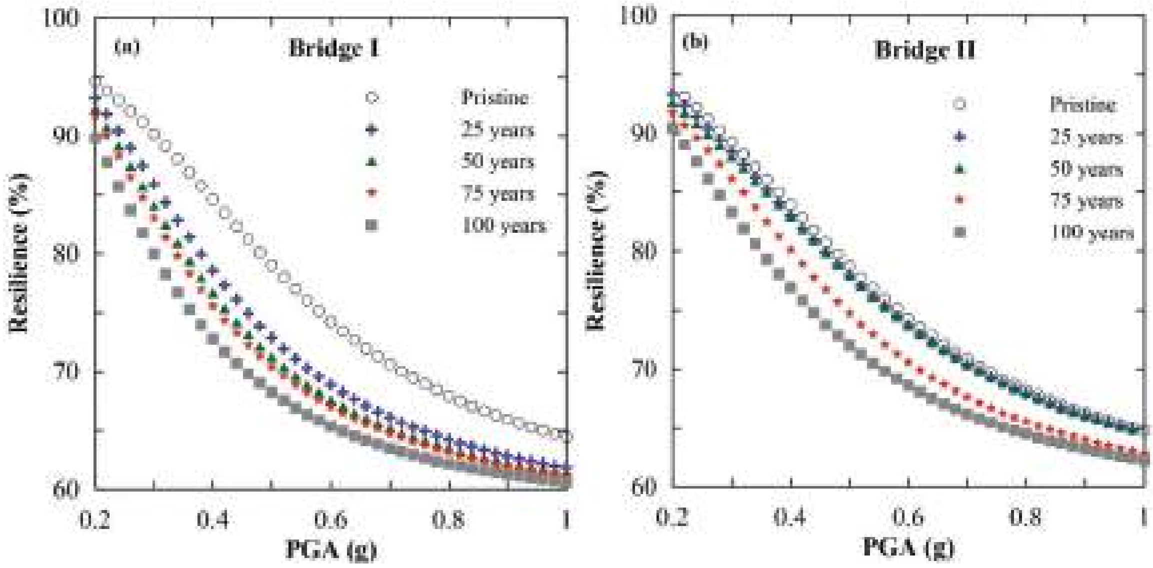


Figure 10. Life-cycle disaster resilience of (a) Bridge I and (b) Bridge II

Estimated vulnerability, risk and resilience of the investigated bridges provide information on expected outcome when these bridges are subjected to earthquakes having certain PGA values. However, the prediction of residual service life of these bridges cannot be done directly based on the observed outcome. It requires further research that will aim at estimating residual service life of bridges in which bridge maintenance innervations should be studied. Moreover, a thorough uncertainty analysis is also required to judge the probable uncertainty band of the expected outcome. The following section discusses the uncertainty that is performed within the scope of the current research.

5.5 Impact of parameter uncertainty on seismic vulnerability of bridges

The previous section discussed the influence of chloride diffusion and action of repetitive loads on the mean residual area of rebar over time. It should be noted that the derived mean residual area of rebar affected by corrosion-fatigue deterioration is contributed by several truck samples that imposed different magnitudes of equivalent stresses (or fatigue stress) on bridges. As a result, the reduction of rebar diameter is inherently uncertain with the imposed equivalent stress.

Taking this uncertainty into consideration, the study investigated the impact of girder deterioration on seismic response of critical bridge components (i.e., EDP values). The observed variations in EDP values are expected to produce variability in the disaster resilience of the bridges.

6. Enablers and Barriers

Assumptions are inseparable part of any numerical simulation. Likewise, some realistic assumptions were made that enabled us to conduct the current study. These assumptions are related to various design and analysis modules including hazard models, bridge models, corrosion degradation model, traffic load model, loss and recovery models. The major ones are described here.

(i) Analysed bridges are assumed to have no maintenance during their lifespans. This assumption enabled to compute expected impact of corrosion-fatigue alone on bridge disaster resilience at various life-cycle years. While developing their FE models, appropriate assumptions were taken for bridge idealization.

(ii) For the bridge on water, multi-hazard scenario was formulated based on the assumption that an earthquake strikes to a bridge site before flood-induced scour depth gets replenished automatically. This is a realistic assumption as automatic replenishment of scour depth in active riverbeds usually takes longer time.

(iii) It is considered that the bridge on river is safe from the evaluated scour depth. Hence, the probability of bridge failure due to expected scour depths is not studied here. It is also assumed that flood discharge will not overflow or cause collapse to the bridge.

(iv) Bridge sites are not liquifiable. This assumption enabled to isolate the multi-hazard effect of earthquake and flood-induced scour on bridge performance from that caused by any other seismic-induced hazard, such as liquefaction and lateral spread.

(v) The trend of traffic growth in future years is assumed to follow the trend observed over the past years at the same location.

(vi) Utilized suites of seismic ground motions are either taken from past literature or generated based on regional seismicity. Hence, all ground motions within these datasets are not recoded specifically for the study regions.

(vii) It is assumed that diffusion is the major mechanism in the corrosion process. Accordingly, the Fick's second law of diffusion is considered here for predicting corrosion initiation time. The required model parameters are obtained from available past studies done for the regions of interest.

(viii) Assumptions related to post-disaster loss assessment and bridge recovery are considered as described in Vishwanath and Banerjee (2019).

While the above assumptions enabled conducting the study, there exists some barriers in applying the research outcome directly to other cases. These are as follows:

(i) Observed results cannot be used directly in predicting LCDR of RC bridges that belong to other types/classes. However, the same framework can be used for any other type of bridges/infrastructure components.

(ii) Obtained results do not imply the outcome of any multi-hazard scenario involving earthquakes and floods. Results strictly adhere to the hazard scenario discussed here.

(iii) Results should not be used to predict probable impacts of other modes of bridge performance degradation (such as carbonation and thermal cycles) on life-cycle resilience of bridges.

(iv) The obtained results are region-specific, and hence, should be used only for similar regional hazard, traffic and atmospheric conditions.

7. Key Takeaways from CDRI Fellowship Programme

The major takeaways from the project include the following:

(a) New knowledge that the project generated in the area of LCDR of RC bridges. Major conclusions of this study are discussed next in the Conclusion section.

(b) The developed analysis-based framework is the major outcome of this research. The developed framework is generic in nature and can be utilized further for various other purposes. These include (i) resilience-based identification of optimal maintenance interventions for bridges: the degrading trend of bridge life-cycle resilience, one of the end-products of the research, will facilitate identifying such maintenance interventions that should be applied to bridges as and when bridge resilience reaches a pre-defined minimum threshold. (ii) Risk- and resilience-informed budget allocation for bridge retrofit under constrained budget scenario: the estimated risk and resilience of bridges through the developed framework will facilitate in performing this task. (iii) Assessing disaster resilience of ageing infrastructures in a life-cycle context: though aging RC bridges are discussed in this research, developed framework is generic and can be adopted for other bridge types and civil infrastructure components or systems.

8. Conclusion and Way Forward

The major conclusions arrived from the study are as follows:

(i) Traffic-induced fatigue in addition to corrosion degradation causes corrosion-fatigue scenario for bridges and it results in higher rate of bridge degradation than that due to either corrosion or fatigue.

(ii) The overall performance of bridges degrades with increasing level of corrosion-fatigue deterioration as bridges continue to age.

(iii) The life-cycle disaster resilience of bridges reduces with increasing intensity of hazard. Reducing trends at various degraded states may take linear or nonlinear patterns depending on the value of hazard intensity.

(iv) Overall, the research outcome demonstrated the critical impact of corrosion-fatigue degradation on bridge performance along its service life. It suggests that the stated degradation phenomenon should not be overlooked for ensuring bridge safety and serviceability during natural disasters.

In the years ahead, further research is needed for the following:

(a) Developing resilience-based design guidelines for bridges under single and multiple hazards: With the advancement of technology and knowledge base, this new paradigm of bridge design will embrace the key socio-economic factors (related to losses and recovery) that are ignored otherwise in the current practice of bridge design. The basic requirement in developing such a new design approach involves a thorough understanding on the impact of several key design parameters on LCDR of bridges. The knowledge generated through the current research will be useful for this purpose.

(b) Incorporating the secondary effects of corrosion-fatigue degradation: Other possible impacts of steel corrosion, such as reduction in yield strength of rebar, need to be incorporated within the analysis framework.

(c) Studying the effect of corrosion-fatigue on LCDR of other types of bridges: This is helpful in generating a comprehensive knowledgebase on this topic, which will be anyway necessary for proposing resilience-based design guidelines for bridges.

References

1. AASHTO. (2010). *AASHTO LRFD Bridge Design Specification* (Fifth edition). American Association of State Highway and Transportation Officials.
2. American Petroleum Institute (2003). *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platform-Working Stress Design,* Washington, DC.
3. Arneson, L. A., Zevenbergen, L. W., Lagasse, P. F., & Clopper, P. E. (2012). *Evaluating Scour at Bridges* (No. FHWA-HIF-12-003). National Highway Institute (US).
4. Bashir, A., & Basu, D. (2018). Revisiting probabilistic seismic hazard analysis of Gujarat: an assessment of Indian design spectra. *Natural Hazards*, *91*(3), 1127-1164.
5. Balaguru, P. N. (1981). Analysis of prestressed concrete beams for fatigue loading. *Prestressed Concrete Institute*, *26*(3), 70-94.
6. Banerjee, S., Vishwanath, B. S., & Devendiran, D. K. (2019). Multihazard resilience of highway bridges and bridge networks: A review. *Structure and Infrastructure Engineering*, *15*(12), 1694-1714.
7. Caltrans (2021). *Corrosion Guidelines* (Version 3.2). California Department of Transportation Division of Engineering Services Materials Engineering and Testing Services Corrosion Branch.
8. Caltrans. (2019). Caltrans *Seismic Design Criteria* (Version 2.0). State of California Department of Transportation.
9. Chotickai, P., & Bowman, M. D. (2006). Truck models for improved fatigue life predictions of steel bridges. *Journal of Bridge Engineering*, *11*(1), 71-80.
10. CWC. (2019). *Water Year Book – Mahi, Sabarmati & Other West Flowing River* (2018-2019). Central Water Commission.
11. Deng, L., & Cai, C. S. (2009). Identification of parameters of vehicles moving on bridges. *Engineering Structures*, *31*(10), 2474-2485.
12. Devendiran, D. K., Banerjee, S., & Mondal, A. (2021). Impact of climate change on multihazard performance of river-crossing bridges: Risk, resilience, and adaptation. *Journal of Performance of Constructed Facilities*, *35*(1), 04020127.
13. Dey, A., & Sil, A. (2021). Advanced corrosion-rate model for comprehensive seismic fragility assessment of chloride affected RC bridges located in the coastal region of India. In *Structures* (Vol. 34, pp. 947-963). Elsevier.
14. Dey, A., Miyani, G., & Sil, A. (2019). Reliability assessment of reinforced concrete (RC) bridges due to service loading. *Innovative Infrastructure Solutions*, *4*(1), 1-17.
15. DPR (2013). *Revalidation Study and Overal Appraisal of the Project for Four-Lanning of Selected Road Corridors in the state of Gujarat: E-Ahmedabad-Viramgam Corridor*. Dorsch Consult (India) Private Limited.
16. DuraCrete. (2000). Statistical quantification of the variables in the limit state functions. *The European Union-Brite EuRam III-Contract BRPR-CT95-0132-Project BE95-1347/R9*.

17. Garg, R. K., Chandra, S., & Kumar, A. (2022). Analysis of bridge failures in India from 1977 to 2017. *Structure and Infrastructure Engineering*, *18*(3), 295-312.
18. Hahin, C. (1994). *Effects of Corrosion and Fatigue on the Load-carrying Capacity of Structural and Reinforcing Steel* (No. FHWA/IL/PR-108). Illinois. Dept. of Transportation. Bureau of Materials and Physical Research.
19. Han, J., Song, Y., Wang, L., & Song, S. (2015). Residual strain analysis of non-prestressed reinforcement in PPC beams under fatigue loading. *Materials and Structures*, *48*(6), 1785-1802.
20. Hazus, MH-MR4. (2003*). Hazus MR4 Technical manual,* FEMA Mitigation Division, Washington, D.C.
21. IRC - SP 114 (2018). Guidelines for seismic design of road bridges, Indian Roads Congress, New Delhi.
22. Kamra, C., Chopra, S., Yadav, R. B. S., & Joshi, V. (2020). Characterization of major fault systems in the Kachchh Intraplate Region, Gujarat, India, by focal mechanism and source parameters. *Seismological Research Letters*, *91*(6), 3496-3517.
23. Kim, Y. J., & Heffernan, P. J. (2008). Fatigue behavior of externally strengthened concrete beams with fiber-reinforced polymers: State of the art. *Journal of Composites for Construction*, *12*(3), 246-256.
24. Lu, Q., Harvey, J., Le, T., Lea, J., Quinley, R., Redo, D., & Avis, J. (2002). Truck traffic analysis using weigh-in-motion (WIM) data in California. *University of California, Berkeley, Institute of Transportation Studies, Pavement Research Center, Berkeley, California, USA*.
25. Lu, Q., Zhang, Y., & Harvey, J. T. (2009). Estimation of truck traffic inputs for mechanistic–empirical pavement design in California. *Transportation Research Record*, *2095*(1), 62-72.
26. MES (2022). *A Design of Axel Load Survey Report For, Bagodra- Dhandhuka- Ranpur- Umrala road on both LHS and RHS side of the section in Dhandhuka city in state of Gujarat.* Mattest Engineering Service, Gujarat.
27. NBI. (2022). *Bridges & Structures*. https://www.fhwa.dot.gov/bridge/nbi/ascii2021.cfm
28. Nielson, B. G. (2005). *Analytical Fragility Curves for Highway Bridges in Moderate Seismic Zones*. Georgia Institute of Technology.
29. PEER. (2022). *PEER Ground Motion Database*. https://ngawest2.berkeley.edu/site
30. Shukla, J., & Choudhury, D. (2012). Estimation of seismic ground motions using deterministic approach for major cities of Gujarat. *Natural Hazards and Earth System Sciences*, *12*(6), 2019-2037.
31. Somerville, P. G. (1997). *Development of ground motion time histories for phase 2 of the FEMA/SAC steel project*. SAC Joint Venture.
32. Song, H. W., You, D. W., Byun, K. J., & Maekawa, K. (2002). Finite element failure analysis of reinforced concrete T-girder bridges. *Engineering Structures*, *24*(2), 151-162.
33. Spellman, D. L., & Stratfull, R. F. (1969). *Chlorides and bridge deck deterioration* (No. D-3-11). Division of Highways, Materials and Research Department.
34. Tapia-Hernández, E., Perea, T., & Islas-Mendoza, M. A. (2017). Design assessment of short-span steel bridges. *International Journal of Civil Engineering*, *15*(2), 319-332.

35. USGS (2022). *Unified Hazard Tool. https://earthquake.usgs.gov/hazards/interactive/*
36. Vijaya, R., Boominathan, A., & Mazzieri, I. (2020). 3D ground response analysis of simplified kutch basin by spectral element method. *Journal of Earthquake and Tsunami*, *14*(01), 2050003.
37. Vishwanath, B. S., & Banerjee, S. (2019). Life-cycle resilience of aging bridges under earthquakes. *Journal of Bridge Engineering*, *24*(11), 04019106.
38. Vu, K. A. T., & Stewart, M. G. (2000). Structural reliability of concrete bridges including improved chloride-induced corrosion models. *Structural Safety*, *22*(4), 313-333.
39. Wan, H. P., Su, L., Frangopol, D. M., Chang, Z., Ren, W. X., & Ling, X. (2021). Seismic response of a bridge crossing a canyon to near-fault acceleration-pulse ground motions. *Journal of Bridge Engineering*, *26*(6), 05021006.
40. Warn, G. P., Whittaker, A. S., & Constantinou, M. C. (2007). Vertical stiffness of elastomeric and lead–rubber seismic isolation bearings. *Journal of Structural Engineering*, *133*(9), 1227-1236.
41. Weyers, R. E., Fitch, M. G., Larsen, E. P., Al-Qadi, I. L., Chamberlin, W. P., & Hoffman, P. C. (1994). *Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques. Service Life Estimates* (No. SHRP-S-668).
42. Yan, D., Luo, Y., Lu, N., Yuan, M., & Beer, M. (2017). Fatigue stress spectra and reliability evaluation of short-to medium-span bridges under stochastic and dynamic traffic loads. *Journal of Bridge Engineering*, *22*(12), 04017102.
43. Yilmaz, T., Banerjee, S., & Johnson, P. A. (2016). Performance of two real-life California bridges under regional natural hazards. *Journal of Bridge Engineering*, *21*(3), 04015063.
44. Zhang, W., Song, X., Gu, X., & Li, S. (2012). Tensile and fatigue behavior of corroded rebars. *Construction and Building Materials*, *34*, 409-417.
45. Zhang, W., Ye, Z., Gu, X., Liu, X., & Li, S. (2017). Assessment of fatigue life for corroded reinforced concrete beams under uniaxial bending. *Journal of Structural Engineering*, *143*(7), 04017048.

Risk-Informed School Evaluation Tool (RISE Tool)

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The views expressed in this paper reflect the opinions of the authors and not necessarily the official views of CDRI.

Abstract

Schools are the centres accommodating a highly vulnerable group, the children. These institutions must be in safer regions, as they are the second home to the users and part of the critical infrastructures. The Asia Pacific Report of 2019 suggests that investments in the educational sector can empower students and is a crucial entry point for breaking the link between poverty and disasters in the long term. Asia has experienced multiple hazards and cascading risk patterns associated with climate change in the last decades, with statistics suggesting around 200 million affected children every year. Conventional school selection in Asian countries such as India is driven by the factors including academic programmes, curriculum and staff quality with less thrust on safety and disaster risk management issues. Lessons from past calamities such as the Gujarat Earthquake of 2001, the 2011 East Japan Earthquake and the Tsunami point out the need to give equal weightage to risk-informed school selection along with school curricula to safeguard the life of school students and prevent disruption in school education.

Indian cities have grown inherently, and the growth has resulted in poor choice-making. India has witnessed many school-related accidents that have taken the lives of hundreds of innocent children. The National School Safety Policy (2016) points out a disconnect between education programmes and disaster response and preparedness, which raises concern. These issues must be addressed, and the incidents be regulated for liveability. Presently, there are no available indices to understand the school infrastructure's vulnerability and address the innate academic quality, which affects the decision-making and policy planning. The study aims to address the present gap, whereby significant studies are encouraged to understand the composite risk patterns surrounding them and promote sustainable models. The study's methodology involves a theoretical literature review of significant case studies on the themes: parental school selection and school disaster resilience. The indicators derived on both themes were then systematically finalized using the Delphi survey method and fed into the matrix to devise the Risk Informed School Evaluation (RISE) tool. The goal of the study is to promote interventions in the conventional school selection process and check the level of awareness and preparedness towards disaster risk management in one of the key critical infrastructure, i.e. school, and adding to the promotion of sustainability and resiliency through the application of the derived tool.

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1. Introduction

In compliance with the CDRI Fellowship Programme's mission to bring innovations for the resilience of the existing infrastructure or new infrastructure, the current study considers school as an essential unit of a resilient society. Thus, providing due consideration to the importance of schools in nation building, the study understands the need to realize the school's resilience factors and its role in promoting disaster education.

Schools are a significant critical infrastructure and the second home to students of age groups from 3 to 18 years (NIDM, 2018). Thereby it becomes utmost important to promote its safety. Cities, especially in India, have grown organically, resulting in mixed land-use patterns. The geographic location of the schools has been promoted generally without giving due consideration to natural hazard risks (National School Safety policy of India, 2016). Further, this is complicated by the lack of significant comprehension of the evolving hazards risks such as land-use changes, which puts many lives at risk. Both India and Japan have witnessed many school-related accidents/disaster events. Past incidence of disasters directly affected schools and children (2011 East Japan Earthquake and Tsunami, 2004 Kumbakonam Fire Tragedy in Tamil Nadu, 2001 Gujarat Earthquake, 1995 Dabwali Fire Accident in Haryana) and recent similar incidents such as a fire at a coaching centre in Surat, Gujarat and Pune Floods in 2019 point out to the need to focuses on school safety along with school curricula. A critical review on the impacts of hydrogeological hazards on schools by Pazzi et al. (2015) suggest that more than 31 most damaging geo-hydrologic occurrences, between 2004 and 2015, worldwide had a direct impact on schools and school children in terms of *"victims, injuries and psychological consequences"* (Pazzi et al., 2015)). The national school safety programme in India and similar efforts on school safety in Japan have focused on overall school safety, but there is a dearth of decision-making tool concerning school infrastructure and associated risk patterns (Nakum et al., 2022).

For a country like India, the problem is even more complicated owing to a lot of factors. India is highly challenged by various hazard-risk patterns because of its geographic positioning and anthropogenic reasons. The National Disaster Management Authority of India states that around 59% of the landmass is at the risk of moderate to extreme earthquakes, and 12% of the total land area is prone to flooding and soil erosion. Similarly, the region is challenged by various other natural and human-made disasters (NDMA, 2019). This is significant as the country has one of the highest student populations in the world and has a history of student casualties during disasters such as the Gujarat Earthquake in 2001, Kashmir Earthquake in 2005 (UN-ESCAP, 2019). While significant policymaking have been undertaken to address the existing and emerging disaster risks, such as the National Disaster Management Act of 2005, National Policy of Disaster Management 2009, National School Safety policy of India, 2016 recent events such as Cyclone Fani of 2019 reported damages in more than 6500 schools in Odisha (Times of India, 2019), reiterating the importance of improved research and learning for empowering the school resilience and for addressing the goals of Sendai Framework. Further, the dearth in a comprehensive platform for capacity building combining school academics and school resilience adds to the issue (Nakum et al., 2022).

2. Research Problem

Considering the incumbent gap in the school selection and resilience, as discussed above, this study aims to dwell into the following two critical factors to bridge the current gap:

1. Parental aspects make while choosing the school as they are pivotal in decision-making for their children, and
2. Critical factors significant for school safety and resilience.

The study generates a database for a composite risk index based on the evaluation of parental school selection and school disaster resilience parameters. Thus, the study gives users a decision-making tool that is based on not only the excellence of education but also the safety and wellbeing of children. India's school disaster resilience planning has a dearth of tools for effective decision-making. The project will promote a prototype that has the potential to address the problem. The tool aims to comprehend various aspects of school-based risks. The tool would allow the user to identify the risk regions and their problems. The information on the table could direct the institutions in re-framing the existing management models because of user demand. Now, this could also influence future land-use planning.

3. Aim, Objectives and Scope of the Research Study

The study aims to create a composite risk index of schools, a 'risk-informed school evaluation' tool (RISE Tool) for Gandhinagar, Gujarat, India, which was affected by 2001 Gujarat Earthquake. The study focuses on promoting parents and other users a decision-making tool that is based on not only excellence of education but also the effective disaster-risk reduction measures.

The objectives of the study are as follows:

- To generate relevant information concerning the key themes and indicators for parental school selection and school disaster resilience
- To carry out filtration by undertaking consensus through Delphi survey to generate the relevant set of themes and indicators with reference to Gandhinagar, India
- To further formulate a rating application for parents to deliver significant considerations for risk-informed school selection

Scope and Limitations: The study covers major issues about the school infrastructures and related risk patterns that are relevant to disaster risk management and academics such as teaching staff quality, natural hazards, etc., and are listed as indicators and sub-indicators. The major limitation is that the indicators chosen are based on the study region and relevant indicators could be added to the index concerning a different study.

4. Methodology

The current study followed a mixed method research process. It utilizes integrated literature review assessment method for generating significant insights into the concepts and derive incumbency.

The authors focused on two aspects of the study, parental school selection and school disaster resilience. The authors focused on identifying significant literature from Google Scholar and Science Direct databases by utilizing advanced key searches to generate the significant literature. Besides, the authors undertook literature collection using references from reports, and other important frameworks to generate a detailed summary of significant literature for the study.

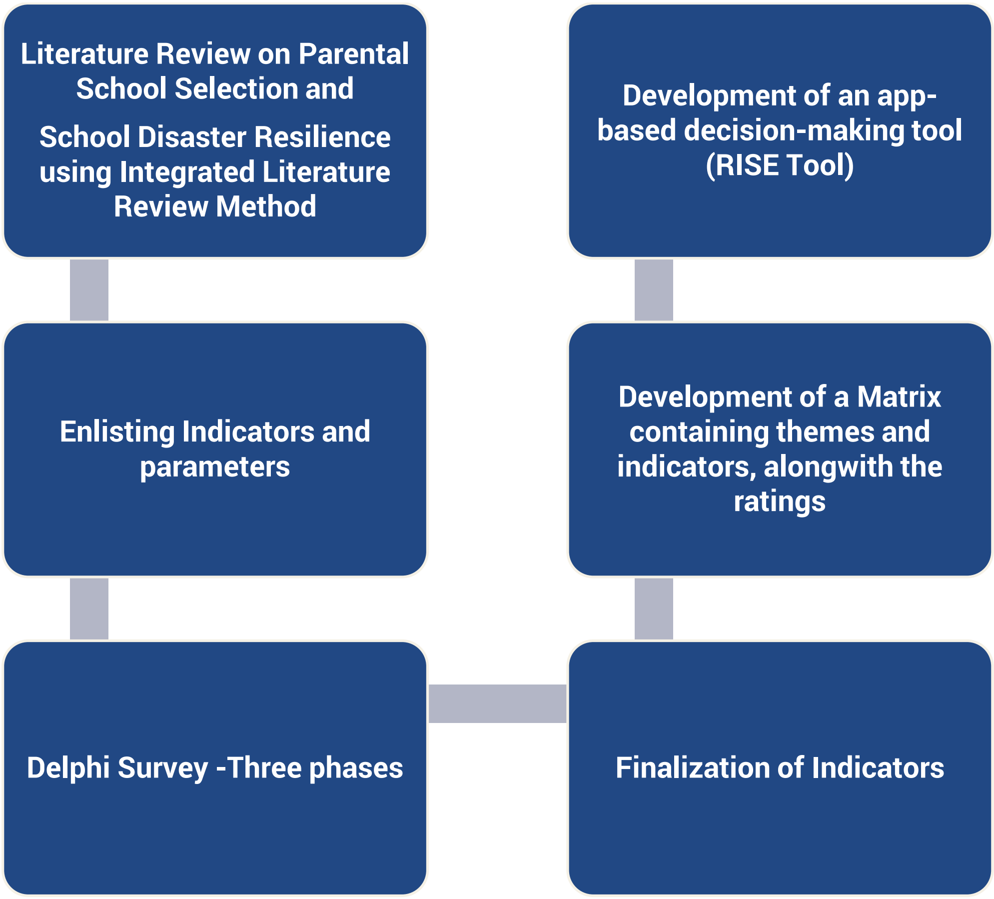


Figure 1. Work flow for the project

Initially efforts were made to gain in-depth knowledge around the topic and conceptualize the overall framework of the study. A detailed review of literature has been conducted around the topics of parental school selection choices and school disaster resilience to get conceptual clarity. A series of discussions and brainstorming sessions were held with the mentors and between team members to break through the concept and bringing it to a framework. Overall, a total of 883 pieces of literature were identified including scholarly articles, reports, policies and frameworks. Finally 59 literature studies were selected and reviewed based on content analysis to generate a preliminary list of indicators affecting parental school choices and school disaster resilience. Eight dimensions emerged for parental school choices whereas 10 dimensions emerged for school disaster resilience with over 70 indicators. The study further used the Delphi survey technique to gain consensus over indicators through three rounds of questionnaire surveys. The Delphi technique is a research approach used to gain consensus through a series of questionnaire surveys, usually two or three, where information and results are fed back to panel members between each round (Yao, 2016). The survey questionnaire and results were shared with experts/respondents between each round. The first round of Delphi involved consolidated 69 indicators that were achieved from the literature review. After the first phase of the Delphi Survey, the second and third phases of the survey were conducted to refine the indicators and get a final consensus. The identified indicators were rated on Likert' scale (0-5) and finalized after the analysis. The identified stakeholders were dispatched with the initial list of tentative indicators for round 1. The samples were asked the opinion concerning the indicators identified as a part of the literature study and asked to add or delete themes and indicators identified under the two sections of Parental School Selection and Disaster Resilience, which they deemed important. The survey was attended by 22 experts, ranging from disaster management experts, academicians, parents-teachers association members. The results achieved were analysed, which led to a total of 48 indicators distributed in two sections: Parental School Selection and Disaster Resilience. The researchers for further consensus shared the survey form for the second round of the Delphi process, whereby the researchers asked the samples to rate the identified indicators based on Likert' scale (0-5). A matrix was developed using the final indicators where each indicator was scaled, and associated weights were provided as per the expert opinion survey to attain the composite risk index. The tool was linked with artificial intelligence (AI) and the user interface allowed the parents to select options and receive result based on the inputs provided.

5. Results and Discussion

The survey process reveals critical insights into the process and the overall outcomes of the study. At the outset, the researchers reflect on the Delphi process and associated mobilization of participants for multiple rounds, and suggest the process as a time-consuming effort, however being fruitful in the due course of time, as it is based on consensus. The analysis sheds key insights concerning the school safety amongst multiple stakeholders. A key revelation is that academic aspects received more consensus in percentages, with 90% of them gaining consensus in round 2, while 60% of the disaster resilience aspects received consensus in the second round. Several indicators concerning the presence of hazards did not receive consensus. This indicates the skewed perspective of stakeholders, as they are more attached to the school academic progress report than disaster resilience aspects, which was a major theorem by the researchers. A key indicator would be the general consensus of 100% for indicators such as passing percentages, number of teachers and so on. The third round resulted in more disaster resilience indicators receiving consensus, such as presence and frequency of hazards, emergency funding, interactions with local agencies and so on. However, certain aspects that are critical to disaster resilience such as the age of the building, intensity of hazards, mock drill did not receive consensus, which may indicate lack of awareness amongst the stakeholders concerning school safety. However, certain indicators such as intensity of hazards may indicate disconnect from the public life as Gandhinagar has not been challenged by intense hazards lately. However, overall output suggests that there is a strong consensus with the indicators developed as part of the study, and the researchers expect that this could promote more entry points for enhancing school safety.

After the finalization of the indicators, the matrix has been developed providing evaluation criteria to each of the indicator. The matrix has been divided into three parts, starting with school profile, and then the themes parental school selection and school disaster resilience indicators and their evaluation criteria. Indicators were further reshaped into question forms and checked for evaluative and non-evaluative categories. Based on the expert opinion and relevance, each indicator was assigned with the weightage derived from the Delphi survey analysis. The process was designed to derive the weighted mean from the expected input from the user and pre-assigned indicator weightage. The final scores were then designed to indicate the overall performance of the school as well as of individual themes.

Table 1. Final indicator matrix for the RISE tool

	School Profile	
1	Name of the school for which you are using the RISE Tool?	
2	What is the category of the school?	1. Higher Secondary (with grades 9 to 12) 2. Secondary/Senior Secondary (only with grades 9 and 10) 3. Upper Primary (with grades 1 to 8) 4. Primary (with grades 1 to 5)
3	What is the type of school management?	1. Government/Local Body 2. Government Aided 3. Private Unaided
4	Which type of the board school offer?	1. CBSE 2. ICSE 3. State Board 4. Other
5	Where is the school located?	State
		City
		Area/Locality
		Postal/Zip/Pin code? (optional)
6	What is the medium of instruction in the school?	1. English 2. Hindi 3. Gujarati 4. Other
A	**Parental School Selection Indicators**	**Evaluation Criteria**
1	Up to what levels does the school have achievements in academic and cocurricular competitions?	1. School has represented at the international level 2. School has represented at the national level 3. School has represented at the state level 4. School has not represented in any competitions yet

	School Profile	
2	What is the Pupil–Teacher Ratio (PTR) (number of students per teacher) in the school?	1. Below 15:1 2. 15:1–30:1 3. 30:1–45:1 4. 45:1–60:1 5. Above 60:1
3	What percentage of teachers in the school have more than five (5) years of experience?	1. Above 80% 2. 60%–80% 3. 40%–60% 4. 20%–40% 5. Below 20%
4	What is the percentage of subject-specialised teachers in the school?	1. Above 80% 2. 60%–80% 3. 40%–60% 4. 20%–40% 5. Below 20%
5	What is the teacher retention rate in the school? (Serving for more than five (5) years in the same school)?	1. Above 80% 2. 60%–80% 3. 40%–60% 4. 20%–40% 5. Below 20%
6	Is the transport facility available in the school?	0. Yes 1. No
7	Does the school have subject-specific laboratory facilities?	0. Yes 1. No
8	Does the school have smart classrooms?	0. Yes 1. No
9	Does the school have extracurricular and recreational facilities such as a playground for sports?	0. Yes 1. No
10	Does the school have basic amenities such as safe drinking water, sanitation and hygiene (WASH) facilities and cleanliness?	0. Yes 1. No
11	Does the school have a dedicated disciplinary policy?	0. Yes 1. No
12	Is there a student cell/counsellor for student-related issues in the school?	0. Yes 1. No

	School Profile	
13	Is the school campus disability-friendly, i.e. does it have inclusive designs to accommodate the differently abled persons?	0. Yes 1. No
14	Does the school have a crime-free neighbourhood?	0. Yes 1. No
15	What is the average student attendance rate in the school?	1. Above 80% 2. 60%–80% 3. 40%–60% 4. 20%–40% 5. Below 20%
16	How frequently does the school organizes Parents Teachers Meeting (PTM)?	1. PTM conducted monthly 2. PTM conducted quarterly 3. PTM conducted half-yearly 4. PTM conducted annually 5. PTM not conducted
17	Does the school have a regular check on parents' feedback and take action as per recommendations?	0. Yes 1. No
18	Does the school maintain regular updates on students' progress and school programmes?	0. Yes 1. No
19	What is the average passing percentage of students in the board examinations in the school?	1. Above 80% 2. 60%–80% 3. 40%–60% 4. 20%–40% 5. Below 20%
20	What percentage of students score above distinction (75% and above) in board examinations in the school?	1. Above 80% 2. 60%–80% 3. 40%–60% 4. 20%–40% 5. Below 20%
21	What is the average annual fee of the school (in INR)?	1. Below 20,000 2. 20,000–40,000 3. 40,000–60,000 4. 60,000–80,000 5. Above 80,000

	School Profile	
22	Does the school provide merit-based scholarships to the students?	0. Yes 1. No
	Sub-total A	
B	**School Disaster Resilience Indicators**	
1	Has the school building been built per the prevailing guidelines, codes and standards for construction, such as National Building Code (NBC), Indian Standard (IS) Code, municipal bylaws, fire safety regulations, and school safety guidelines?	1. School building is fully built/retrofitted as per the prevailing guidelines, codes and standards for construction 2. School building is partially built as per the prevailing guidelines, codes and standards for construction 3. School building is not built as per the prevailing guidelines, codes and standards for construction
2	Does the school building undergo regular structural safety checks/audits and maintenance?	0. Structural safety checks of the school building are conducted every year 1. Structural safety checks of the school building conducted once in five years 2. Structural safety checks of the school building not conducted
3	Is there a structural safety certificate issued by the competent authority?	0. Yes 1. No
4	Have the emergency evacuation routes and exits been designed and marked in the school building?	0. Yes 1. No
5	Are the exit routes, staircases and corridors in the school free from any obstacles?	0. Yes 1. No
6	The non-structural elements such as false ceiling, bookshelves, storage cabinets, display cupboards, laboratory equipment, ceiling fans, light fixtures, and other hanging and wall-mounted items in the school are checked, anchored, and secured?	1. Fully done 2. Partially done 3. Not done
7	Does the school have received NOC from the Fire and Emergency Services?	0. Yes 1. No

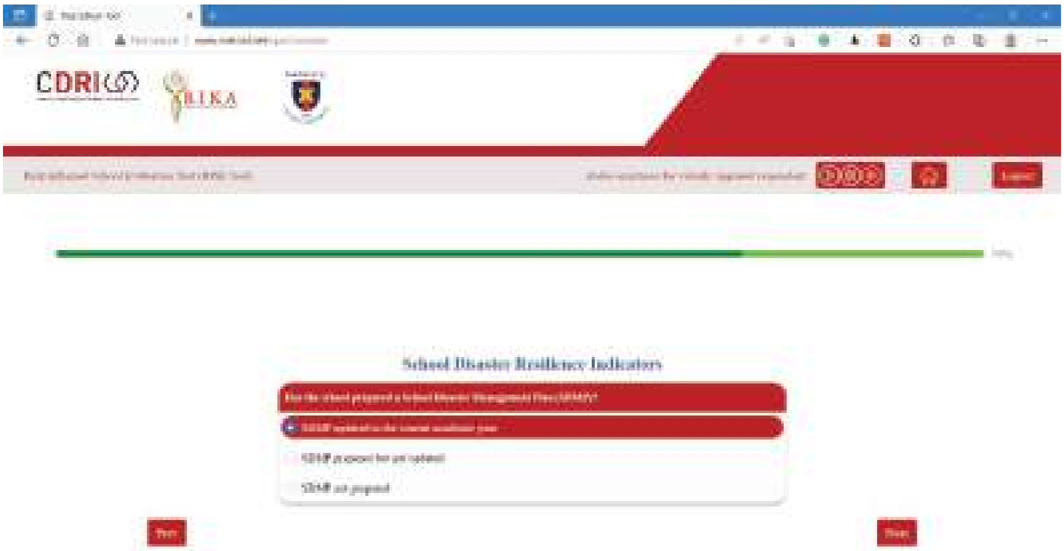
	School Profile	
8	Does the school have dedicated emergency resources such as emergency siren/fire alarm, fire extinguishers, fire hydrant points, first aid kits, rope, emergency torch, ladder, etc. for early warning and response?	0. Yes 1. No
9	Do the school have demarcated emergency assembly points on the campus?	1. Emergency assembly points are demarcated and communicated to students and staff 2. Emergency assembly points are demarcated but not communicated to students and staff 3. Emergency assembly points are not demarcated
10	Has the school prepared a School Disaster Management Plan (SDMP)?	1. SDMP updated in the current academic year 2. SDMP prepared but not updated 3. SDMP not prepared
11	Does the school have designated Nodal Officer to carry out disaster management activities?	0. Yes 1. No
12	Does the school carry out mock drills on disaster risk management?	1. Mock drill conducted every year 2. Mock drill conducted but not every year 3. Mock drill not conducted
13	What percentage of teachers and staff of the school have received training on disaster risk management?	1. Above 80% 2. 60%–80% 3. 40%–60% 4. 20%–40% 5. Below 20%
14	Are the teachers and staff regularly trained in disaster risk management?	1. Trained every year 2. Trained once in five year 3. Not trained
15	Does the school participate and celebrate "School Safety Week" every year?	0. Yes 1. No
16	Does the school management actively interact with local authorities, emergency response agencies and nearby communities for disaster responses?	0. Yes 1. No
17	Does the school integrate disaster-risk management (DRM) into the school curriculum and teach DRM to students?	0. Yes 1. No

	School Profile	
18	Does the school have emergency funds to carry out disaster-risk management activities?	0. Yes 1. No
19	Which are the most prominent hazards in and around the school?	1. Fire 2. Earthquake 3. Floods 4. Cyclones 5. Drought 6. Landslides 7. Heat Wave 8. Cold Wave 9. Road Accidents 10. Epidemic 11. Gas Leakage 12. Other
20	How frequent are these hazards to which school is prone?	1. Very low (Once in more than 30 years) 2. Low (Once in 30 years) 3. Medium (Once in 10 years) 4. High (Once in 5 years) 5. Very high (Every year)
21	What is the severity of these hazards to which school is prone?	0. No damage to school infrastructure and education 1. Damage to school infrastructure but could not disrupt education 1. No damage to infrastructure but disrupt education 2. Damage to both school infrastructure and disruption of education
22	Is the school located within a one (1) km radius of the following?	1. Near Highway 2. Near Coast 3. Near Industry 4. Near Hill Slope 5. Near Forest 6. Near River 7. None of the above

	School Profile	
23	Does the school have transportation safety guidelines, and are parents, students and drivers aware of the same?	1. Parents, students and drivers are well aware of the transportation safety guideline of the school 2. The school have documented the transportation safety guidelines but has not discussed them with parents, students and drivers 3. The school does not have transportation safety guidelines
24	Does the school have Internet security and ensures safe use of services in the school network?	0. Yes 1. No
25	Does the school have student and staff awareness classes on the safe use of social networking sites to check cyber-crimes?	0. Yes 1. No

The RISE tool has been calibrated as per the indicator matrix. It provides a rating-based score system for the school based on user inputs. The initial test run showcased the fair functioning of the model. The tool generates results in two forms. One, it shows the school's overall performance as a RISE indicator score ranging from very poor to excellent. Second, it shows the performance of both parental school selection and school disaster resilience indicators in a graphical representation. A few screenshots of the tool are given below. It is anticipated that the tool would generate more fair results based on the larger sample set once it goes public.


CDRI
RIKA
Risk-Informed School Evaluation Tool (RISE Tool)


CDRI
RIKA
School Disaster Resilience Indicators


CDRI
RIKA

6. Conclusion and Way Forward

School infrastructures are a major part of nation-building, as countries such as India have seen tremendous growth in school infrastructures and student population over the years (FICCI, 2014). In India and Japan, schools are considered safe shelters or evacuation points also. Hence it is of importance to see that they are physically safe. While in Japan, cities are divided as school districts and in the case of any disaster, schools remain prepared and act as the evacuation centres, this is not a case for every school in India. The National School Safety Policy (2016) of India points out that there is a huge disconnect between the education programme and disaster response and preparedness, which underlines these concerns.

Under the National School safety programme in India, schools are encouraged to prepare disaster management plans and conduct rapid visual surveys but the implementation remains a challenge. So, this tool will have the two-pronged benefit of being a decision-making tool to aid parents to invest long term in school selection and at the same time ensure school administration school preparedness for any eventuality. Studies suggest that decision for choosing a school currently is based on the school curricula but such decisions should be integrated with hazard risk and also prevention, mitigation, preparedness and capacity development measures taken up by the schools. The underlying aspect of the study is that while schools are considered to be the second home for students, as parents are unaware or disregard the significance of disaster resilience in favour of academics. This leads to poor school choices that are pivoted on school academics rather than school safety. To address the gap, the study recognizes the significant themes that are pivotal on parental school selection and school disaster resilience. The tool could also aid in capacity building and preparedness for disaster risk management.

Additionally, the study and the derived tool can be used and up scaled for further research and application. Indicators can be up scaled and adapted based on the need and relevance to different geography and study. Apart from the parents considered as an identical user group for this study, the RISE tool can also be profoundly adapted and used by the other diverse stakeholders, including local authorities, school management, international non-governmental organizations, social sector organizations, research organizations, researchers and practitioners working in the area of education, disaster risk management, child safety, WASH, architecture and engineering.

References

1. Azim Premji University. (2018), School choice in low- information environments: Details available at https://azimpremjiuniversity.edu.in/sitepages/pdf/SchoolChoices_Web.pdf.
2. Bastidas, P. (2011). 2011 School Safety Baseline Study. Details available at https://www.preventionweb.net/files/23587_doc18766contenido.pdf.
3. Benard, B. (1991). Fostering Resiliency in Kids: Protective Factors in the Family, School, and Community. *School and Community*, August, 1–27.
4. Coughlan, S. (2016). Pisa tests: Singapore top in global education rankings. BBC News. Details available at https://www.bbc.com/news/education-38212070.
5. CRED. (2018). Natural Disasters 2018, Emergency Events Database, Center for Research on the Epidemiology of Disasters. Brussels. Details available at https://www.emdat.be/.
6. Duman, J., Aydin, H., & Ozfidan, B. (2018). Parents' involvement in their children's education: The value of parental perceptions in public education, *Qualitative Report*, 23(8), 1836–1859. doi: 10.46743/2160-3715/2018.3216.
7. Hill, E., Samson, M., & Dasgupta, S. (2011). 'Expanding the School Market in India: Parental Choice and the Reproduction of Social Inequality'. Details available at https://www.jstor.org/stable/23017914.
8. Hussain, S. N., Zulfqar, A., & Hameed, A. (2018). School-parents communication as determinant of school selection in context of declining enrollments in government elementary schools. *Journal of Elementary Education.* 28(1), 13–23.
9. Ibrahim, N. M., Osman, M. M., & Bachok, S. (2014). Public school development and planning: parents' criteria of selecting public school in Gombak district. *Procedia - Social and Behavioral Sciences*. 153(February), 274–285. doi: 10.1016/j.sbspro.2014.10.061.
10. Kelleher, L., Smyth, A., & McEldowney, M. (2016). Cultural attitudes, parental aspirations, and socioeconomic influence on post-primary school selection in Northern Ireland. *Journal of School Choice*, 10(2), 200–226. doi: 10.1080/15582159.2016.1153378.
11. Mathews, M., Lim, L., & See, T. S. (2017). Parents' Perceptions of the Singapore Primary School System', (27). Details available at https://lkyspp.nus.edu.sg/docs/default-source/ips/wp-27_parents'-perceptions-of-the-singapore-primary-school-system.pdf.
12. McMillan, J. H., & Reed, D. F. (1994). At-Risk students and resiliency: factors contributing to academic success. *The Clearing House: A Journal of Educational Strategies, Issues and Ideas*, 67(3), 137–140. doi: 10.1080/00098655.1994.9956043.
13. Mirzaei, S. et al. (2019) School resilience components in disasters and emergencies: A systematic review. *Trauma Monthly*, 24(5). doi: 10.5812/traumamon.89481.
14. Muñoz, V. A., Carby, B., Abella, E. C., Cardona, O. D., López-Marrero, T., Marchezini, V., & Wisner, B. (2019). Success, innovation and challenge: School safety and disaster education in South America and the Caribbean. *International Journal of Disaster Risk Reduction*, 101395. doi:10.1016/j.ijdrr.2019.101395
15. National Disaster Management Authority. (2016). *National Disaster Management Guidelines – School Safety Policy – 2016*. National Disaster Management Authority, Government of India.

16. NDMA. (2016). *National Disaster Management Guidelines, School Safety Policy*. New Delhi. Details available at https://www.ksndmc.org/NDMA Guidelines/School Safety Policy.pdf.
17. NUEPA. (2015). Evaluation for Improvement School Standards and Evaluation Framework.
18. O'Connell, J. M. (1993). An examination of parent perceptions of the quality of school practices and their relationship to parent support for the school. ProQuest Dissertations and Theses, p. 197. Details available at https://search.proquest.com/docview/304047417?accountid=13042%0Ahttp://oxfordsfx.hosted.exlibrisgroup.com/oxford?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:dissertation&genre=dissertations+%26+theses&sid=ProQ:ProQuest+Dissertations+%26+Theses+Gl.
19. Nakum, V. et al. (2022). Developing a framework on school resilience for risk-informed decision-making. *Progress in Disaster Science*, 15, 100237. Details available at https://doi.org/10.1016/j.pdisas.2022.100237.
20. Shiwaku, K. et al. (2016) School disaster resilience assessment in the affected areas of 2011 East Japan earthquake and tsunami. *Natural Hazards*. doi: 10.1007/s11069-016-2204-5.
21. Shiwaku, K., Ueda, Y., Oikawa, Y., & Shaw, R. (2016). School disaster resilience assessment in the affected areas of 2011 East Japan earthquake and tsunami. *Natural Hazards,* 82, 1. Details available at https://doi.org/10.1007/s11069-016-2204-5
22. Tong, T. M. T. & Shaw, R. (2016). School-based disaster risk reduction education in primary schools in Da Nang City, Central Vietnam. *Environmental Hazards*. DOI: 10.1080/17477891.2016.1213492
23. Tong, T. M. T., Shaw, R., & Takeuchi, Y. (2012). Climate disaster resilience of the education sector in Thua Thien Hue Province, Central Vietnam. *Natural Hazards*, 63(2), 685–709. Details available at https://doi.org/10.1007/s11069-012-0178-5
24. UNDRR. (2015). Sendai Framework for Disaster Risk Reduction 2015-2030. Details available at https://www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf.
25. UNDRR. (2017). Comprehensive school safety. Details available at https://www.undrr.org/publication/comprehensive-school-safety.
26. UN-ESCAP. (2019). *The Disaster Riskscape Across Asia-Pacific: Pathways for Resilience, Inclusion and Empowerment*. Bangkok: United Nations. Details available at https://www.unescap.org/publications/asia-pacific-disaster-report-2019.
27. Widowati, E., Istiono, W., & Husodo, A. H. (2021). The development of disaster preparedness and safety school model: A confirmatory factor analysis. *International Journal of Disaster Risk Reduction*, 53, 102004.

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Managing Landslides and Road Construction in Chure Hill Region (CHR), Nepal

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Coalition for Disaster Resilient Infrastructure

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The views expressed in this paper reflect the opinions of the authors and not necessarily the official views of CDRI.

Abstract

Landslides in hilly areas of Nepal is a natural process; however these days it is more rampant due to anthropogenic activities. This study attempts to investigate the problem, causes and consequences of frequent landslides in Nepal's rural areas, where dozer-built motorable roads are being constructed rampantly without sufficient planning and heeding to fundamental rural road requirements. Though infrastructure development is a necessary requirement in rural areas where motorable roads are prioritized, the targeted populace is not reaping the expected advantages. These roads are not only causing landslides and threatening agricultural fields, but are also hurting ecological services. In such a context, building more roads without considering their resilience is exceedingly questionable. Managing landslides in the delicate Chure hill region, where landslides are common, requires a distinct approach. Understanding resilience (in the local context), Chure Hills' vulnerability and local population's development priorities are critical at this point. This study investigated all these factors and attempted to provide practical solutions to the country's pressing problems. One of the adaption methods could be resilient planning by local stakeholders to prevent landslides, in which local indigenous knowledge is combined with current scientific understanding. Furthermore, national, provincial and municipal governments must collaborate on ground-level solutions, which may include suitable policies for landslide management. Another issue that must be thoroughly carried out as stipulated in IEE/EIA and DPR is effective monitoring of ongoing construction operations. Though finance appears to be a primary limitation for managing landslides at the local level, it is also a management issue and as a result the quality of operations suffers.

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1. Introduction

Nepal, the country with young mountains, tectonically active and fragile geology, is prone to landslides. Every year landslides affect several people and damage millions worth property. MoHA (2019) has listed landslides as the second most frequently occurring disaster in the country. In 2021 alone, there were 337 landslide incidences that took lives of 178 people and damaged property worth NPR 34,635,000 (MoHA, 2022).

Various natural and anthropogenic factors are responsible for triggering landslides. In Nepal, the natural factors that contribute to landslides are the rugged mountain topography and fragile geology of young Himalayan mountains that experience frequent soil erosion, high intensity monsoon rainfall and earthquakes. Likewise, unpredicted cloudbursts, which could be due to climate change, have further intensified landslide incidents (Amatya, 2016). The Himalayan rivers and streams, having steep gradients and high velocity flow, are also responsible for mass wasting. On the other hand, unplanned urbanization and rapid construction of infrastructures such as roads and irrigational canals without fully analysing the hazards are increasing landslides (Upreti and Dhital, 1996). Additionally, deforestation, blast quarrying, tunnelling, mining and vehicle vibrations contribute to landslides (Lamsal, 2014).

Currently, haphazard road constructions have become an issue of concern as they are triggering landslides in the vulnerable landscapes of Nepal. With the establishment of multi-party democracy in Nepal in 1990, road constructions became the priority of the government and it intensified more rapidly when Maoist conflict ended in 2006 and paved the way for the establishment of the federal government (DoLIDAR, 2016; Upreti and Shrestha, 2017). The road density has almost tripled in the country from 3.22 km/100 km^2 in 1998 to 9.14 km/100 km^2 in 2018 (DoR-GoN, 2018). Even investment in road infrastructure has increased substantially (owing to promulgation of the 2015 Constitution and the Gorkha earthquake). The budget allocated for road construction in 2018/19 was 7.5 times the budget allocated in 2007/08 (Dixit et al., 2021). This shows the increasing prioritization of road from the development point of view.

Local road constructions in the mountains and Chure Hill Region (CHR) are mostly non-engineered, which have altered the physical landscape. These types of road constructions heavily undercut and destabilize the slope and its insufficiently disposed spoils can increase weight and change the natural drainage system (Sidle et al., 2006). Heavy machineries such as dozers and excavators are frequently used to speed up the construction work. However, the movement and vibrations created by these machines can also trigger landslides (McAdoo et al., 2018). The use of these machines in the fragile Chure region is increasing the susceptibility of the landslides and threatening the communities. Local politicians upon request of communities often collaborate with dozer operators/owners and construct roads that lack basic grading or drainage (ITAD, 2017; Singh, 2018). Consequently, these types of non-engineered roads get washed out during monsoon (WB-GON,2013) and have to be cleared up at a costly rate post-monsoon. This process of road collapse and clearing will continue until the loose soils no longer create nuisances (Leibundgut et al., 2016).

Despite the risks in the vulnerable terrains, roads are extensively prioritized by the local and federal government bodies of Nepal. The local communities themselves demand road constructions as roads are perceived as an infrastructure that will improve people's livelihood and well-being opportunities. The roads are expected to improve mobility and reduce drudgery of walking along long distances especially for women, children and elderly. Furthermore, roads will open avenues for economic opportunities and increase land prices too (Dixit et al., 2021). Settlements increases at faster rate in the area where a road is nearby. If landslides occur in such dense settlements, there will be more number of casualties and economic loss (Nepal et al., 2019). Landslides not only affect newly urbanizing dense settlements but also the settlement having impoverished and marginalized population.

Though the linkage between landslides and road construction is well recognized, it is an understudied phenomenon (McAdoo et al. 2018). Road construction companies do not follow the guidelines proposed by EIA or IEE. In many cases, the EIA itself is questionable. The government agencies fall prey to business or political influence and do not adequately monitor the construction. With limited studies and evidence, construction companies lack an understanding of the relationship between road and landslides. This research intends to explore the road–landslide relationship in Chure region, gain an in-depth understanding of factors that influence decision-making on road construction, identify the policy gaps and empower road stakeholders on safer road construction through resilience planning.

1.1 Understanding the resilience

While defining resilience in the context of infrastructure, the following concepts were found to be effective in a local scenario involving poorly constructed rural roads in Chure hill areas.

- Wan et al. (2018) define resilience "as the ability of a transportation system to absorb disturbances, maintain its basic structure and function and recover to a required level of service within an acceptable time and costs after being affected by disruptions".
- Resilience is the ability of the system to withstand a major disruption within acceptable degradation parameters and recover within an acceptable time and composite costs and risks (Haimes, 2009).
- Resilience is the ability to prepare and plan for, absorb, recover from and, more successfully, adapt to adverse events (Cutter et al., 2013).
- OECD (2021) defines resilience as "the capacity of systems to absorb a disturbance, recover from disruptions and adapt to changing conditions while retaining essentially the same function as prior to the disruptive shock".

All these definitions of "resilience" focus on the ability or aptitude to absorb stress when a setback happens and disrupts the system in which people live.

Bruneau and Reinhorn (2007) describe resilience of physical and social systems using four components, also called the four Rs of resilience (4Rs):

- **Robustness**: The ability of elements, systems and other analytical measurements to resist a specific level of stress or pressure without degrading or losing function.

- **Redundancy**: The amount to which elements, systems or other analytical measures are interchangeable, i.e. capable of satisfying functional requirements in the event of disruption, degradation or loss of functionality; the extent to which elements, systems or other measures of analysis exist that are substitutable.
- **Resourcefulness**: The potential to become aware of problems, set up priorities and mobilize sources while situations exist that threaten to disrupt some element, system or other measure of analysis. Resourcefulness can also be defined as the ability to employ material (monetary, physical, technological, information and human) resources in the recovery process to satisfy stated priorities and achieve goals.
- **Rapidity**: The ability to satisfy priorities and goals on schedule in order to limit losses, restore functionality and minimize future interruption.

2. Research Problem

Nepal is highly vulnerable to landslides owing to both natural and anthropogenic factors. Because of their geological status, the Chure Hills (between Mahabharat and Terai Plain) are extremely fragile. Natural factors such as earthquake and torrential/erratic rainfall and socio-economic factors such as informal and non-engineered roads trigger landslides during monsoon (Petley et al., 2007; Froude and Petley, 2018). At present, haphazard road constructions are increasing at faster pace as roads are perceived as a major indicator of development in Nepal and for local community road is the utmost important infrastructure. The aspiration of communities and local leaders in a way are an invitation for landslides to occur in Chure Hills because of the unsafe road construction practices. Like other parts of Nepal, the use of heavy machineries such as dozer for road constructions is rampant and roads are constructed without adequate planning. Such actions could trigger landslides and threaten the lives and economy of rural communities. Also, unusable and poorly maintained roads not only contribute to landslides but also harm the ecosystem services.

Several studies have acknowledged the relationship between road and landslides. However, those types of studies focussing on Nepal are limited and especially for Chure even less. Due to limited studies on non-engineered roads and landslides relationship, stakeholders are not adequately informed on repercussion of such constructions. These types of studies are essential for evidence-based decision-making and to raise awareness among stakeholders and further contribute in the conservation of Chure. The Government of Nepal has recognized the fragility of Chure landscape and even launched Chure Conservation Programme. Therefore, the research on managing Chure landslides and road could supplement the agenda of Chure conservation and promote the concept of safer road constructions.

3. Aims and Objectives

The aim of this study is to find the way out of safe rural road construction with minimum impact on landslide, soil erosion and ecosystem degradation while exploring the possible measures. The objective is

- To analyse the connection between rural road constructions (non-engineered roads without proper planning) and triggering landslides and gain an in-depth understanding of socio-economic-political factors that influence decision making on road construction.
- To support and facilitate the stakeholders (road builders, local government and community) to develop resilience plan focusing on landslides and rural roads
- To identify the policy gaps and provide recommendations on safer road construction to the stakeholders (policymakers, province and local government and builders)

4. Framework

The study uses infrastructure-resilience planning framework developed by CISA (2021) as a guideline to conduct resilience planning exercise in our study locations. The framework is slightly modified to suit the local context. This framework provides tools and methods for addressing critical infrastructure resilience and security and support local government and community. This resilience planning framework has five important steps:

1. Lay the foundation: Communities define and scope the planning effort, form a planning team to execute the effort and review existing data, plans, studies, maps and other resources.
2. Understand infrastructure needs: Assess and evaluate if road infrastructure is actually necessary in the region and prioritize the regions where it needs to be constructed. This step also involves understanding the influence of road on community and livelihood, and seeking alternative options if feasible.
3. Risk assessment: Support communities through the process of conducting a risk assessment of critical infrastructure to include evaluating vulnerabilities to threats and hazards, and consequences that may result.
4. Develop actions: Provide guidance on the development of a strategic action plan for addressing risk and enhancing infrastructure resilience by identifying and prioritizing potential solutions.

The study team closely worked with the local government and local stakeholders of the road alignment areas to develop the resilience planning. Through consultations with national level experts, Bakaiya Municipality of Makwanpur district was identified as the ideal location for piloting infrastructure-resilience planning.

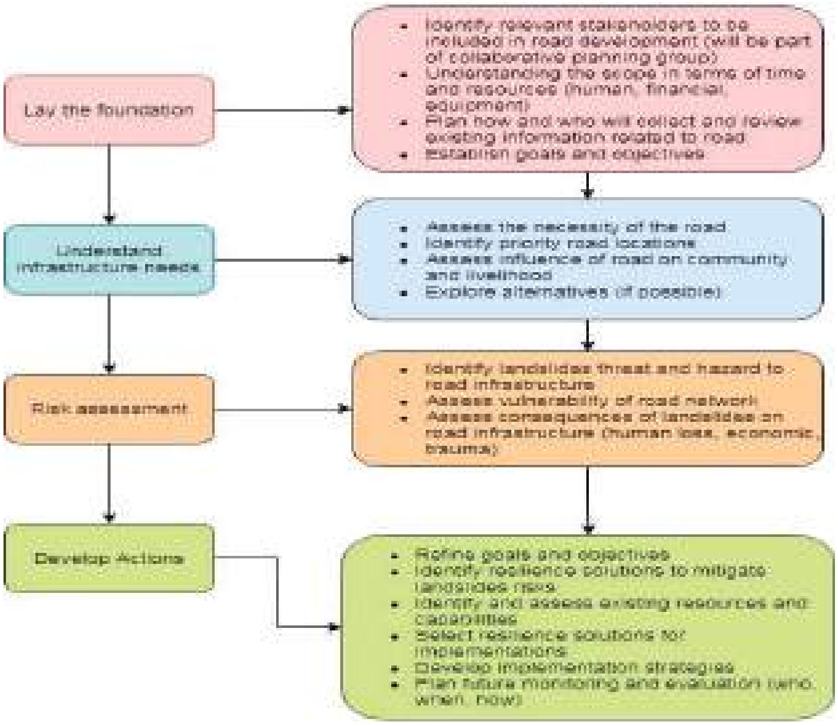

Figure 1. Conceptual framework for resilience planning

Source: CISA (2021)

5. Methodology

5.1 Data collection methods

Literature review: The review included information, data and the practices related to landslide and rural road construction in Nepal. This helped in collecting the baseline information with key actors. The study examined the linkages of rural road construction and occurring landslides in CHR in the context of Nepal. The present national and local policies/acts/regulations and guidelines of the country were reviewed along with the government's EIA/IEE provisions for construction feeder and rural road projects. The journal articles were explored in google scholar and science direct.

We identified the widely cited journal articles that are relevant to our objective and used the references of those articles to explore other research. We prioritized the articles that gave major emphasis on landslides and road construction.

Likewise, landslides data of different years (2011–2021) and places were downloaded from Nepal Government Disaster Risk Reduction portal for analysis. The municipal profile was also studied to gather field-related information. Chure road information was gathered from PCTMCBD (2018).

Sites observation and picturization in case study sites: The study team observed the case study sites through transact walk and documented landslide-affected location using photos and videos between 23 October and 28 October 2021.

Before interacting with locals, the study team thoroughly observed the total road length, landslide areas, type of the soil and topography and the landscape. The team observed vulnerable settlements due to landslides. It also took into account the distance between road and the landslide areas.

Focus group discussions (FGD): FGD was conducted at the community level at each site (Kamlamai, Municipality, Sindhuli and Bakaiya Rural Municipality, Makwanpur). The participants included were local people such as farmers, traders, ward officials, villagers, women, youths/students of maximum 8 to 10 people. Checklist was prepared to guide discussions on the past and current landslides status, impacts of roads on landslides, impacts on property and livelihoods, priority development initiatives and role of community. The FGDs took place on 24–27 October 2021 and lasted between 1 hour and 1.5 hours.

Key informant interviews (KIIs): Potential interviewees who have sound knowledge on the issues and local conditions were identified for KII and contacted for interviews. They were road user committee members, experts, engineers, local government officials and representatives, local political leaders and landslide victims. A well-worked out checklist was developed, interviews were scheduled with interviewee and proper consents were undertaken prior to interviews. The field-level KIIs took place between 24–27 October 2021 and KII with national expert took place on 3 May 2022. The KIIs lasted 2–2.5 hours.

Shared learning dialogue (SLD): Shared learning is an approach to participatory planning and problem-solving for complex issues. This approach assumes that by fostering iterative deliberation between local practitioners and external analysts and by sharing their sector- and/or group-specific knowledge, the quality and effectiveness of decision-making improves. The SLD process is a semi-structured, dynamic and strategically facilitated succession of interactions. Therefore, prior to resilience planning, detailed orientation on the landslide status, causes, impacts (natural/ anthropogenic), Chure vulnerability and resilience was conducted with participants to enhance their understanding on the issue and post-orientation participants prepared their resilience plans. Resilience planning took place on 9 June 2021 in Bakaiya Rural Municipality meeting hall. About 20 participants from government sector, engineers, micro finance, farmers group and local enterprise took part in the planning. The programme was conducted between 10 a.m. and 5 p.m.

5.2 Analysis of the field data and information

Analysis of the field-level information was carried out through various statistical tools such as graphs, charts and flow diagram in infographics. Both qualitative and quantitative data were used. Within quantitative information, frequencies of landslides, temporal and spatial details of road construction and landslides and economic losses was presented using bar diagram. First, we analysed the landslides data for all over Nepal. For that we analysed the landslide trend and deaths between 2011 and 2021. Then we also segregated data province- wise and month to observe the most affected province and season in the past 10 years. For analysing landslide status in Chure districts, we downloaded the data between 2011 and 2021 for all the 36 Chure districts and segregated them into seven provinces to observe the landslide frequencies, deaths, affected families and financial loss. We also identified the districts in Chure that had most numbers of landslides, deaths and financial loss. The Chure rural road information gathered from PCTMCBT

(2018) were analysed province-wise and the roads with longest length were identified. However, we were not able to establish statistical correlation between Chure roads and landslides due to data gaps. The pictorial evidences of Google map taken at different locations at different time period showed this relation.

For qualitative information, we reviewed the notes and documented them. Then we organized the information into various themes and developed a narrative.

5.3 M & E, communication and coordination

The study team was regularly monitored by the mentor (professor) of the endorsement institute to track the progress against the set objectives. Further the study team members received feedback and comments from the TEG (Technical Expert Team) assigned by the CDRI. This feedback was received during the quarterly review meetings, and in other occasions through email and other communication channels.

5.4 Reporting and report preparation

The progress of each quarter was shared and presented with CDRI in review meeting. The final study report was prepared after receiving feedback from CDRI and other experts.

5.5 Dissemination of key messages

The team members chose various media to disseminate key messages related to landslides and unplanned road construction. The article titled, "Landslide vulnerability and rural roads were published in reputed news portal named Khabarhub"[1] and blog titled "Landslide status in Nepal: what does it signify to planners?" were published in ISET-Nepal's website.[2] Likewise, the team also discussed the issue in the radio programme (Candid FM). These messages reached wider audience and the write-up were shared by the readers.

5.6 Site description

This section highlights the Chure Hills fragility, which explains why Chure was chosen and why landslides occur in Chure Hills. Chure Mountain (also known as Siwalik Hills) is a young mountain range lying between the Mahabharat Range in the North and the Terai plains in the South. About 40 million years ago, sediments deposited during the development of the Himalayas produced this range. It is composed of geologically young and soft sedimentary rocks such as mudstones, shale, sandstones, siltstones and conglomerates that are structurally weak, highly erodible and fragile (FRA/DFRS, 2014; Shrestha, 2015). It extends East–West as a continuous landscape through 36 districts in Nepal. It accounts for approximately 12.78% of the country's land area and is home to more than half of the inhabitants (Rayamajhi et al., 2019). Chure is a source of freshwater as several streams originate here. It has a diverse flora and fauna that contribute to a healthy ecological balance between the Tarai and

1 https://english.khabarhub.com/2022/03/239705/

2 http://isetnepal.org.np/11858-2/

Mahabharata ranges. Chure's climate ranges from subtropical to moderate temperate, with hot and humid summers, heavy monsoon rain and cold, dry winters. The average annual minimum temperature is between 12°C and 19°C, while the average annual maximum temperature is between 22°C and 30°C. Throughout the year, Chure receives rainfall ranging from a minimum of 1138 mm to a maximum of 2671 mm. The elevation of Chure varies from 93 to 1955 meters above sea level. The average annual minimum temperature ranges from 12°C to 19°C and the average annual maximum temperature ranges from 22°C to 30°C. Chure annually receives rainfall from a minimum of 1138 mm to a maximum of 2671 mm throughout the year (Shrestha, 2015).

It is one of the world's youngest and most vulnerable mountain, constantly afflicted by mass erosion, landslides and other environmental degradations that make the region vulnerable (Singh, 2010). In recent decades, Nepal's vulnerability has increased due to abrupt high and unpredictable rainfall, as well as land-use changes. Furthermore, deforestation, unplanned and nonengineered road construction and farming on steep slopes have weakened the terrain and increased landslide susceptibility (SAWTEE, 2016). In 2014, the Nepal government named the Chure landscape a "Environmental Protection Area (EPA)" and established the "President Chure-Tarai-Madesh Conservation Development Committee", an overarching authority for administering the Chure area (Bishwokarma et al., 2016). Geographically, Chure is classified in three different types: Bhabar zone, Inner Terai and Churia Hills (Shrestha, 2015). Geologically, the Churia range is known as Siwalik and classified as Lower Siwalik, Middle Siwalik and Upper Siwalik.

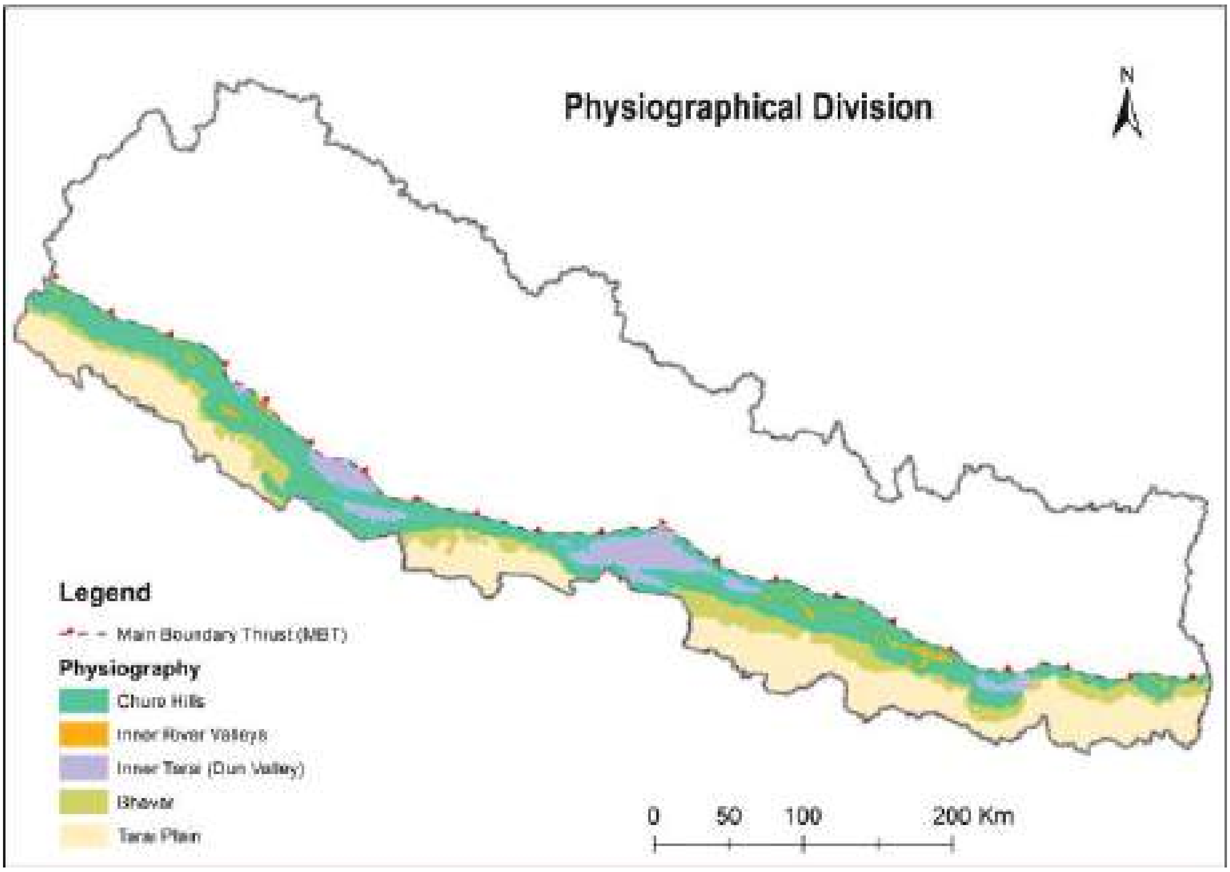

Figure 2. Map showing Chure Hills
Source: PCTMCBT (2018)

5.6.1 Case study sites

The case study sites were shortlisted in consultation with experts. The case study sites considered the following categories:

- The study area will fall under fragile Chure
- Frequent landslides occurred/occurring in the area
- Rural road construction activities are taking place, which are triggering landslides

5.6.1.1 Kamalamai Municipality

Kamalamai Municipality is the one of the larger municipalities of Nepal. It is an old settlement of Sindhuli. It is located on Bagmati province between latitude 26055'N to 27022'N and longitude 85015'E to 86025'E. There are Dudhauli municipality and Tinpatan rural municipality to East, Golanjor and Ghyanglekh rural municipality to North, Marin rural municipality in West, Sarlahi, Mahottari and Dhanusha districts in South of Kamalamai Municipality. The total municipality area is 482.57 km^2 and the total population is 76,553. The climate varies with elevation and other physical factors. Winter is the driest season while summer is the wettest season. Rice and maize are the major crops of Kamalamai Municipality. The altitudinal ranges of Kamalamai ranges between 278 and 1994 above mean sea level.

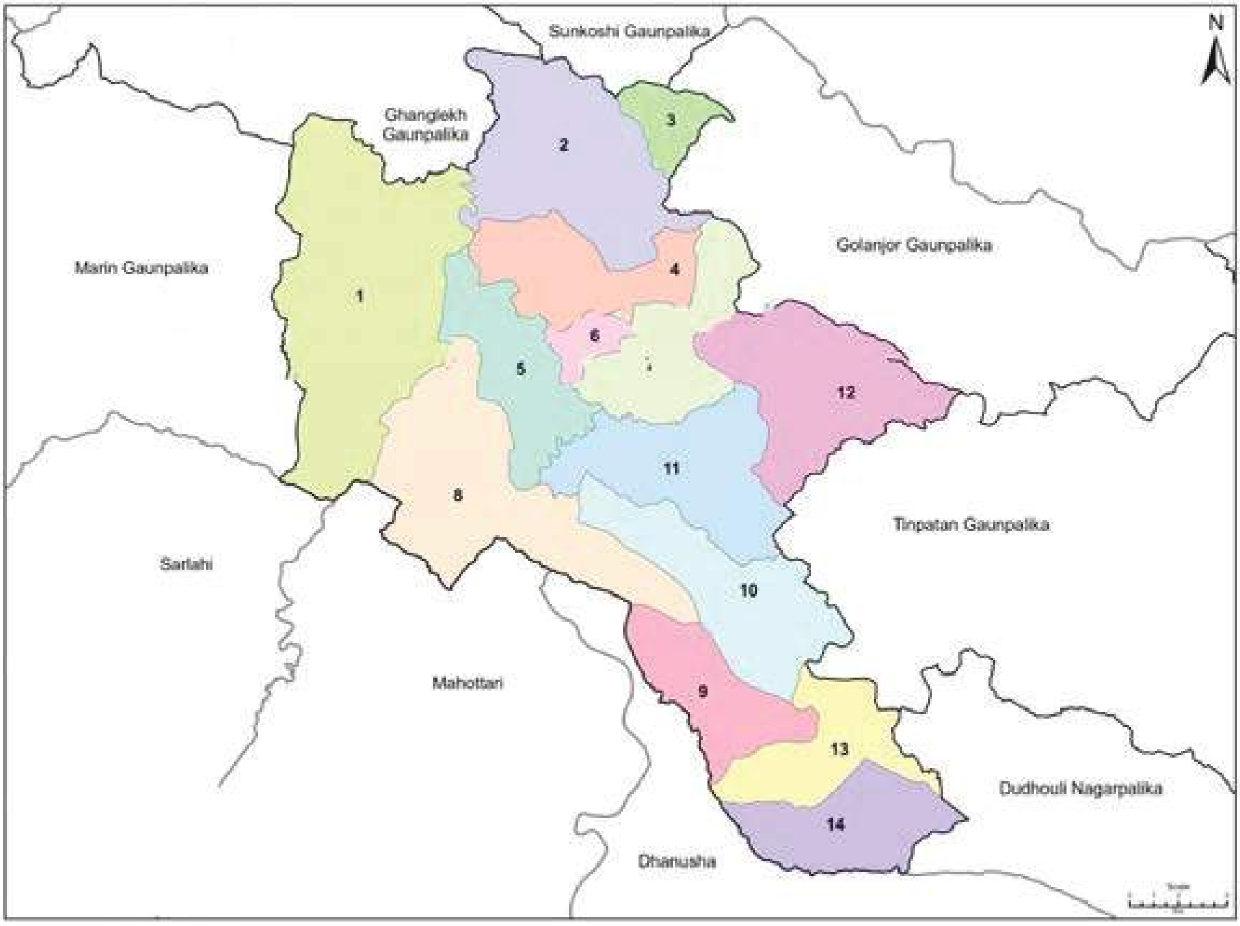

Figure 3. Kamalamai Municipality, Sindhuli

5.6.1.2 Bakaiya Rural Municipality

Bakaiya is a rural municipality in Nepal's Bagmati province within the Makwanpur district. It is located at 27°11'12" N to 27 28'31" N and 85°5'26" E to 84 24'5". According to the Bakaiya Profile (2019), the municipality covers 460 km^2 and has a population of 46,248 people (23,845 males and 22,403 females). Its altitudinal ranges are between 200 m and 2100 m above mean sea level. Bakaiya is surrounded by Bagmati Rural Municipality in East, Hetauda Municipality and Makwanpurgadhi Rural Municipality in West, Lalitpur District in North and Bhimphedi Rural Municipality, Rautahat District and Bara District in South.

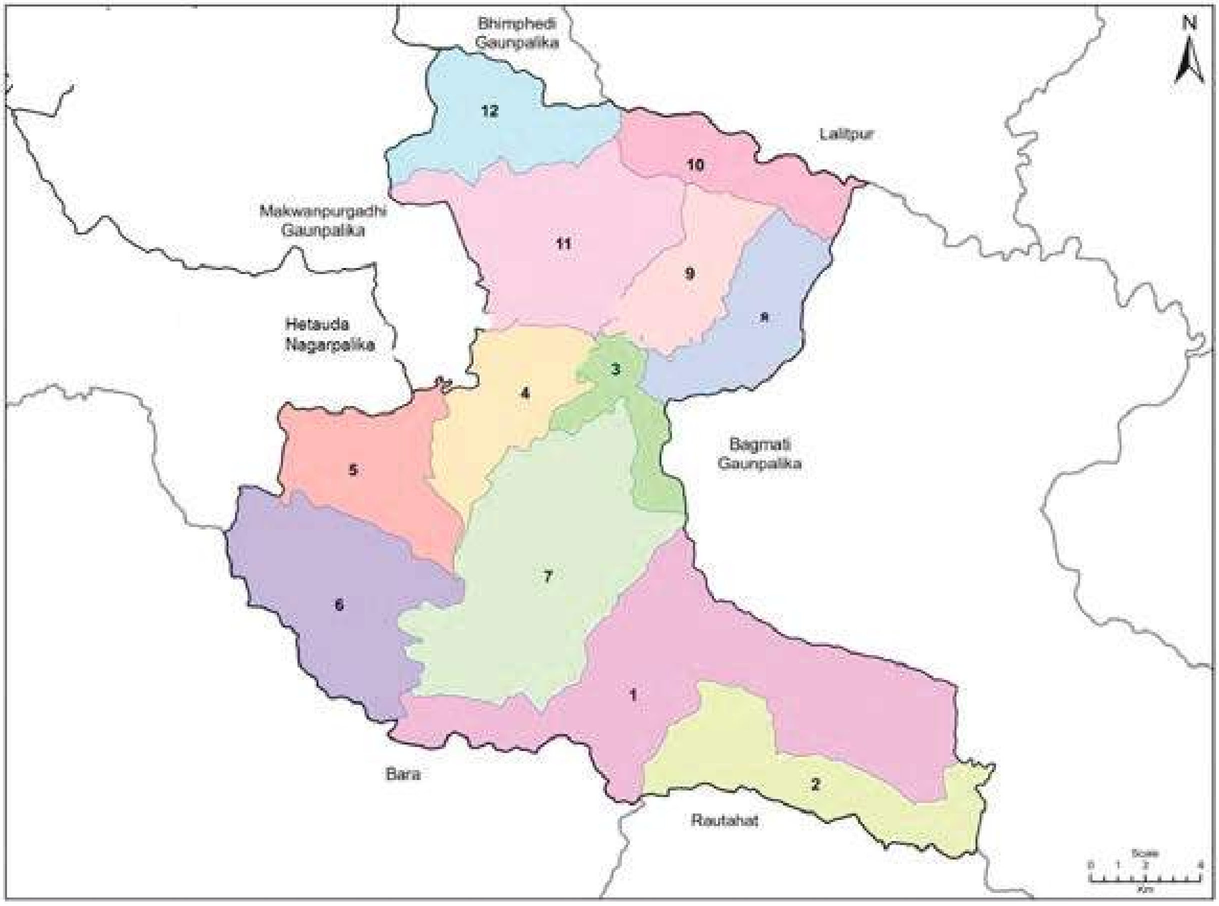

Figure 4. Bakaiya Rural Municipality, Makwanpur

6. Results and Discussion

6.1 Landslide status in Chure region

Geologically weak young Chure has always been vulnerable to landslides due to its crumbly nature. Between 2011 and 2021, it witnessed 734 landslides, which is approximately 30% of landslides in entire Nepal. In 36 districts under Chure region, 355 people lost their lives, 28 went missing and 2584 families were affected. The economic loss was NPR. 844,508,879, which is about half of the documented financial loss brought by landslides in Nepal (Table 1). This shows higher impacts in Chure as compared to other parts of Nepal and needs to be taken seriously.

Table 1. Landslide status province wise in Chure region

Provinces	No of landslides	Deaths	Missing	Affected	Economic loss (NPR.)
Province 1	204	68	6	1514	53,241,900
Madhesh	4	4	0	1	350,000
Bagmati	214	69	12	279	21,312,500
Lumbini	169	109	4	620	757,084,479
Gandaki	49	36	4	66	3,200,000
Karnali	35	21	1	30	8,650,000
Sudur Pashim	59	48	1	74	670,000
Total	**734**	**355**	**28**	**2584**	**844,508,879**

Source: MoHA (2022)

When the landslides in the Chure region were broken down by province, it was found that Bagmati province in the Chure region holds the top spot (214 landslides) and Province 1 occupies the second spot. When examining national data, it was recognized that Madhesh province experienced only four landslides (Table 1). We identified that all the four landslides in the Madhesh province belonged to Chure hills.

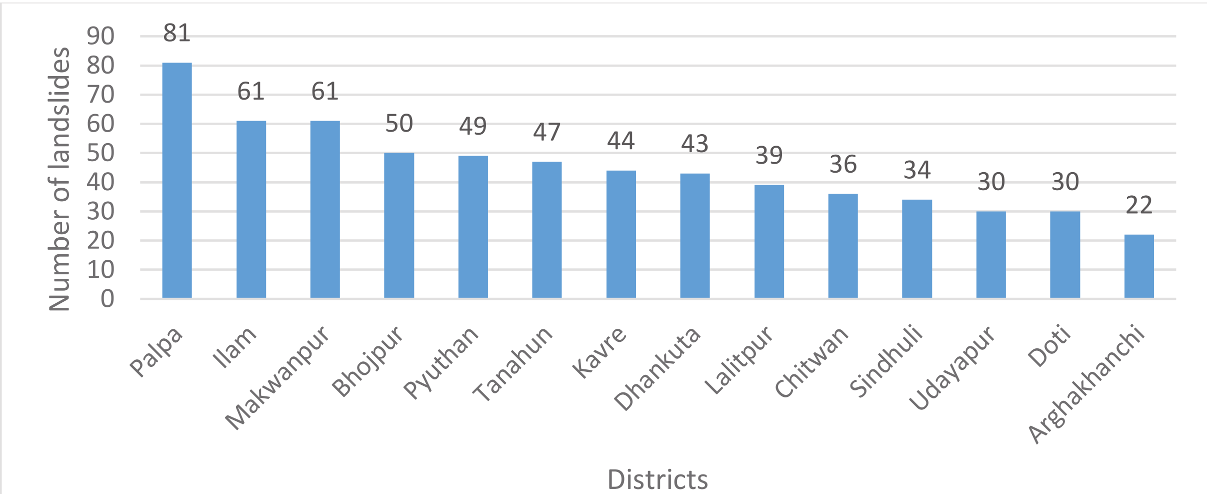

Figure 5. Chure districts with more than 20 landslides (2011-2021)
Source: MoHA (2022)

There were 14 districts in Chure that have observed more than 20 landslides (nationally documented) between 2011 and 2021. Among them, Palpa of Lumbini Province occupies top-most position with 81 landslides. Our study districts, that is Makwanpur and Sindhuli of Bagmati province occupy third (61 landslides) and eleventh position (34 landslides), respectively (Figure 5). Makwanpur and Sindhuli witnessed 3.9% of total landslides of Nepal between 2011and 2021 (MoHA, 2022).

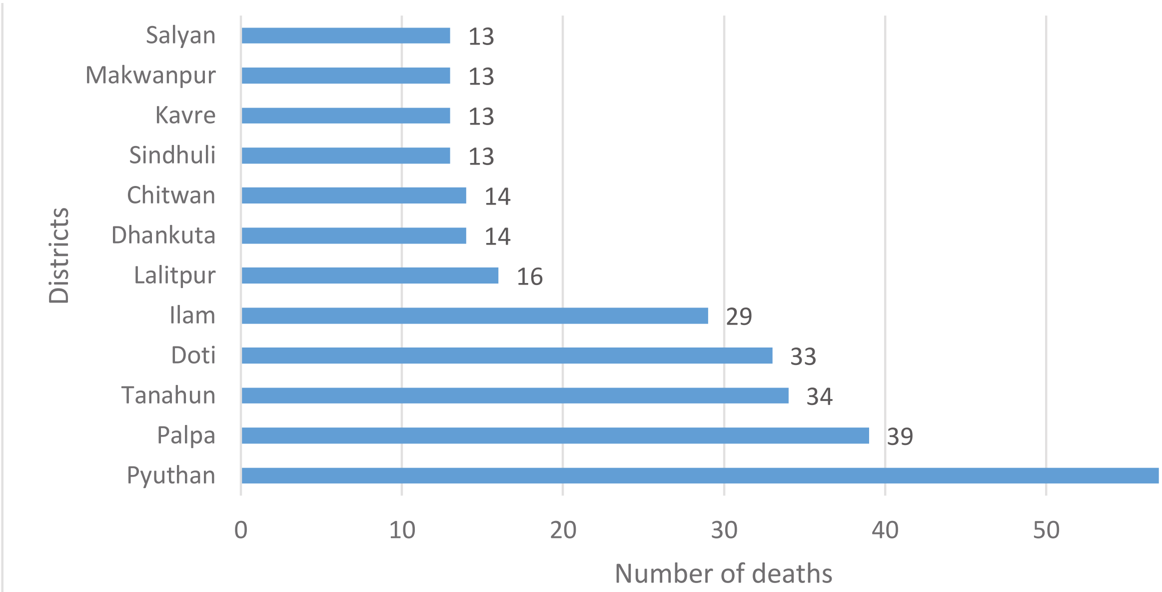

Figure 6: Chure districts with more than 10 deaths
Source: MoHA (2022)

Likewise in terms of casualties, 12 districts in the Chure region had more than 10 casualties, with Pyuthan having the most (57 reported deaths) and Palpa having the second-most (39 recorded deaths). With 13 deaths in each district, our study's locations in Makwanpur and Sindhuli hold the eight position (Figure 6).

Table 2. Chure districts having huge economic loss of more than NPR 2 million between 2011and 2021

Position	Name of districts	Economic loss (NPR.)
1	Pyuthan	749,169,479
2	Bhojpur	23,987,000
3	Ilam	16,335,000
4	Kavre	12,410,000
5	Dhankuta	9,619,900
6	Salyan	5,500,000
7	Lalitpur	4,872,500
8	Palpa	4,415,000
9	Makwanpur	3,700,000
10	Tanahun	3,200,000
11	Surkhet	3,150,000
12	Arghakhanchi	2,700,000
13	Udayapur	2,200,000

Source: MoHA (2022)

In terms of economic loss, the total loss in Chure region is one half of the total landslide-related loss in Nepal. Among the Chure districts with huge loss, Pyuthan occupies the first position with NPR 749,169,479. This accounts for 88.7% of the loss in the Chure region. Interestingly, Pyuthan is also the district in Chure with the largest casualties. Altogether, 13 districts of Chure suffered loss of more than NPR 2 million. Makwanpur, our study district, suffered a loss of NPR 3,700,000, which is about 0.4% of the economic loss in the Chure region (Table 2).

6.1.1 Landslide status in Sindhuli and Makwanpur (case study districts)

In a span of 10 years (2011–2021), 34 landslides have occurred in Sindhuli and 61 in Makwanpur district (Figure 10). These are documented landslide cases and there might be many undocumented landslides that may not have been included in the government portal. Both these districts are part of Chure region of Bagmati province where landslides incidents are the highest.

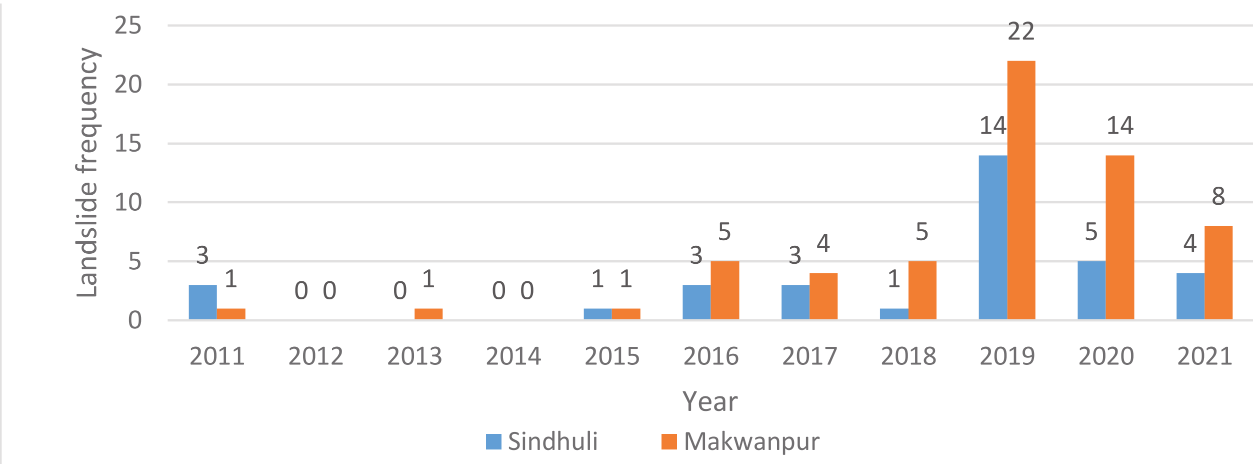

Figure 7. Landslides in Sindhuli and Makwanpur between 2011 and 2021
Source: MoHA (2022)

If we compare the landslide incidences between Sindhuli and Makwanpur districts, the landslides data were either one or non-existent in Makwanpur between 2011 and 2015. A gradual increase in landslides can be observed in Makwanpur from 2016 onwards and the highest number of landslides (22) occurred in 2019. The case is quite similar to Sindhuli district that had the highest landslides of the decade (14) in 2019 too (Figure 7). One interesting observation is that local government was formed after the 2017 local election and in most of the places the priority was road construction. The period 2020–21 was also the time of COVID-19 restriction and also when local road expansion was relatively less.

Table 3. Landslide impacts (2011-2021) in Sindhuli and Makwanpur

	Sindhuli	Makwanpur
Male deaths	3	3
Female deaths	5	4
Missing	1	6
Unknown deaths	4	0
Total deaths	13	13
Injured	19	14
Affected family	89	46
Estimated loss (NPR)	300,000	3,700,000
Landslides mentioned near road	9	24

Source: MoHA (2022)

In both Sindhuli and Makwanpur, 13 people lost their lives from landslides. Sindhuli had more affected families of 89 and Makwanpur of 86. More numbers of houses were damaged in Sindhuli (77) as compared to Makwanpur (2). However, the available financial details are bit questionable and data needs revision. As per the data of MoHA(2022), the estimated loss in Sindhuli is quite low (NPR 300,000) as compared to Makwanpur (NPR 3,700,000) (Table 3).

Another interesting information is that out of 34 landslides in Sindhuli, 9 were mentioned near roadside and in the case of Makwanpur out of 61 landslides, 24 were mentioned near roadside (Table 3). This type of information in a way implies that landslides near roadsides are increasing and the growing vulnerability of landslides near road. This calls for more planned construction and investment in slope stability and road safety. However, the information is brief and does not clearly mention whether these are highway roads, feeder roads or rural road. Yet, we can speculate that landslides near road have become frequent.

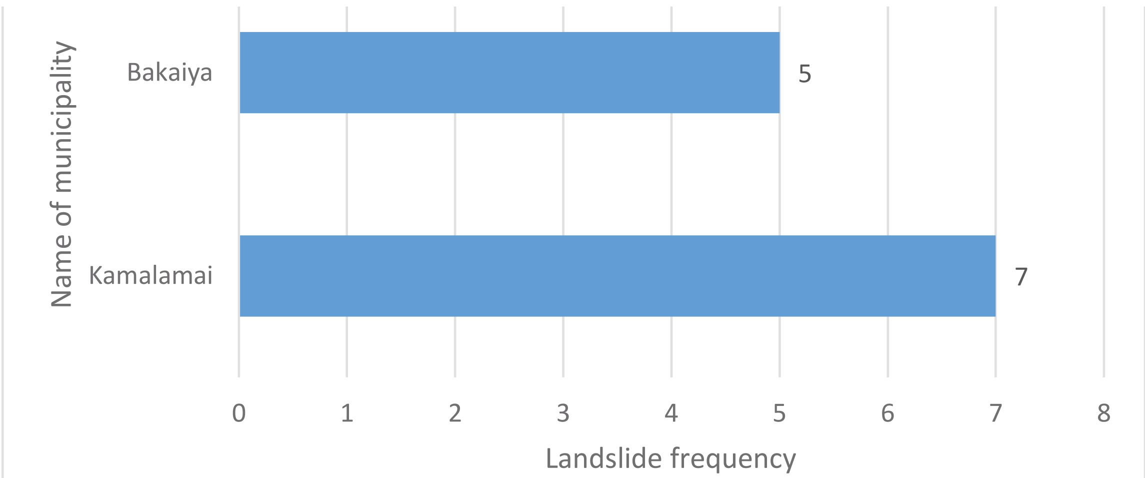

Figure 8. Major landslide incidences of Bakaiya and Kamalamai (2011-2021)

Source: MoHA (2022)

In the case of our study location, seven landslides in Kamalamai Municipality of Sindhuli district and five landslides in Bakaiya Municipality of Makwanpur district were documented between 2011 and 2021 in a disaster-risk reduction portal (Figure 8). Kamalamai had a total 5 deaths (3 males and 2 females) and 14 families were affected and 4 people were injured, respectively. In the case of Bakaiya, there are no records of casualties in the portal (MoHA, 2022). However, a leading national daily in 2017 reported the death of six family members[3] by landslides, which shows Bakaiya's landslide vulnerability.

Also, Bakaiya rural municipality of Chure region is likely to have more road-related landslides in the future since the dozer road constructions are increasing rapidly. As of 2018, 50 rural roads were built within this municipality of which most of them are across the district boundaries (Bakaiya, 2019). Kamalamai has also identified three regions and 2425 households that are vulnerable to landslides (Kamalamai Municipality, 2021).

6.2 Road status in Chure region

The Chure region had 363 rural road of 6576.62 km in 2018. When these roads were segregated province wise, it was found Lumbini province comprising Chure region had the longest rural road of 1815.9 km, followed by Bagmati province having 1348.37 km of rural road (Table 4). Also note that Chure region in Bagmati province had the highest number of landslides (214) and the one in Lumbini province had the third highest landslides (169) (Table 1).

Table 4. Details of road sector and length in Chure region province wise

Provinces	No of roads	Road length (km)
Province 1	53	994.04
Madhesh	10	141.7
Bagmati	95	1348.37
Lumbini	107	1815.9
Gandaki	15	340.79
Karnali	49	1216.29
Sudur Pashim	34	719.53
Total	363	6576.62

Source: PCTMCDB, (2018)

In Chure region, 17 districts had rural roads of more than 100 km. Surkhet had the longest rural road of 1113.1 km, which is about 95.1% of Karnali province (Table 4). Surkhet, however, had a record of 18 landslides between 2011 and 2021 (MoHA, 2022). This also showed that Chure region in Karnali province has lesser landslides as compared to other provinces. We further need to acknowledge the fact that only two districts (Surkhet and Salyan) of Karnali province fall under Chure region.

Sindhuli (459.35 km) and Makwanpur (436.02 km), our study locations, occupied fourth and fifth positions in term of rural road length (Figure 9). These are the top most Chure districts of

[3] https://kathmandupost.com/national/2017/08/13/six-of-a-family-members-missing-as-landslides-buries-house-in-makwanpur

Bagmati province having the longest rural roads and also the districts where roadside landslides are gradually increasing with Makwanpur having 61 documented landslides and Sindhuli with 34 landslides (Figure 7). These are only the official figures and there could be many landslides near road that may have remained undocumented. During our field visits, we observed landslide along the rural road of Bakaiya, Makwanpur and Kamalamai, Sindhuli. Though most stakeholders agree that haphazard road construction and landslides are related, there are still many who do not fully agree with this theory.

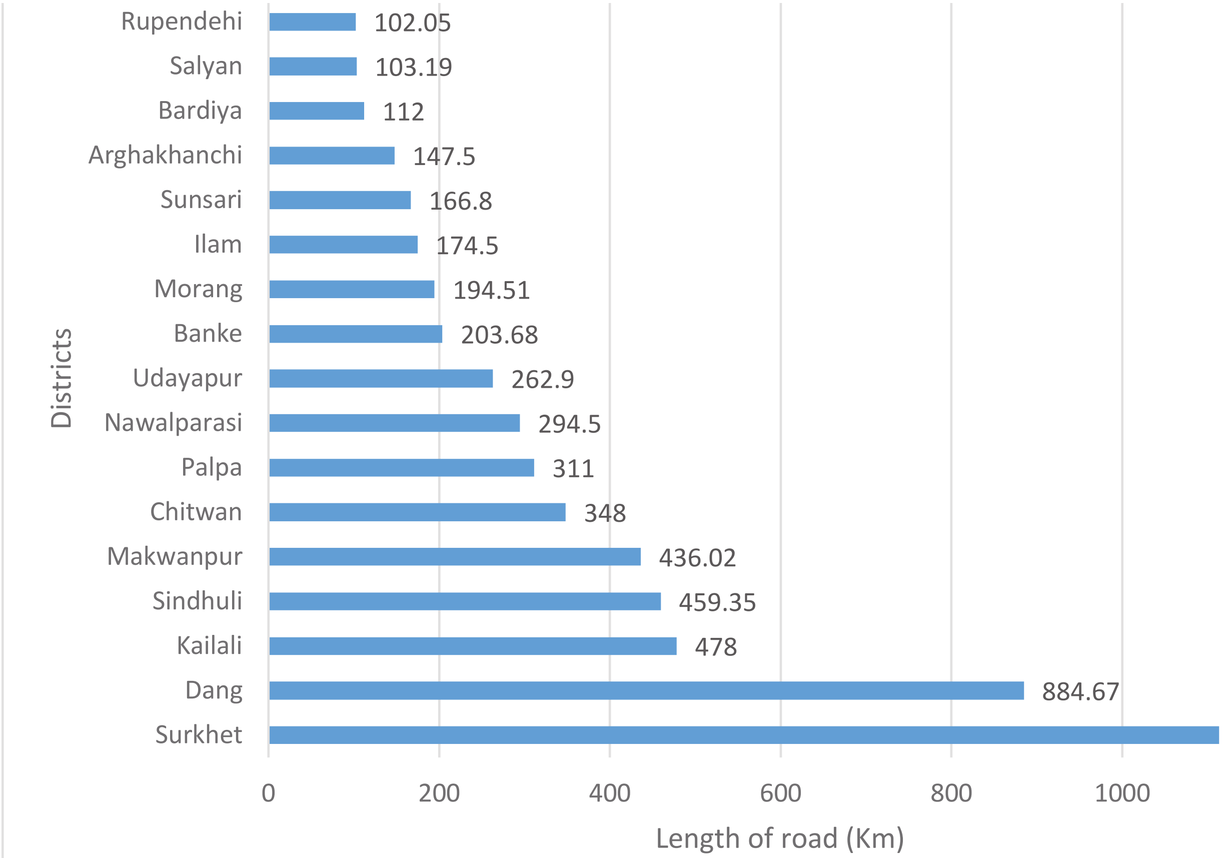

Figure 9. Rural roads having length more than 100 km

Source: PCTMCDB (2018)

6.2.1 Road types and accessibility in Bakaiya, Makwanpur and Kamalamai, Sindhuli

Road accessibility has been evaluated very differently by Kamalamai municipality in Sindhuli and Bakaiya rural municipality in Makwanpur. While Kamalamai classified road accessibility as motorable, trail, horse trails and the one lacking road access, Bakaiya classified road accessibility as blacktopped, gravelled, earthen, trail and others (Figures 10 and 11). Both profiles focus on the percentage of households with access to roads rather than the length of the roads.

In Bakaiya rural municipality of Makwanpur, 51% of households have access to earthen road and only 2% has access to black-topped road indicating that road development is still in early stage and requires more strengthening. These earthen roads are likely to be destroyed by monsoon rain and demand continuous maintenance. About 40% of the households still rely on trails, which means they lack access to motorable road. In the case of Kamalamai, 71% of the households have access to motorable road. However, this information does not reveal the type of road and 25% still rely on trails and 3% household do not have access to any type of road.

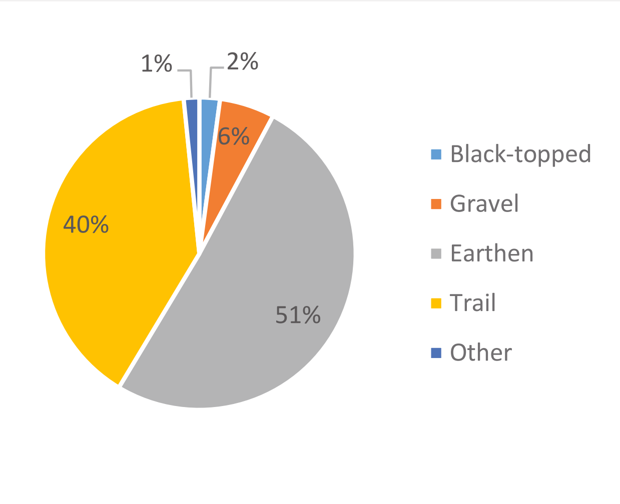

Figure 10. Road accessibility in Bakaiya

Source: Bakaiya (2019)

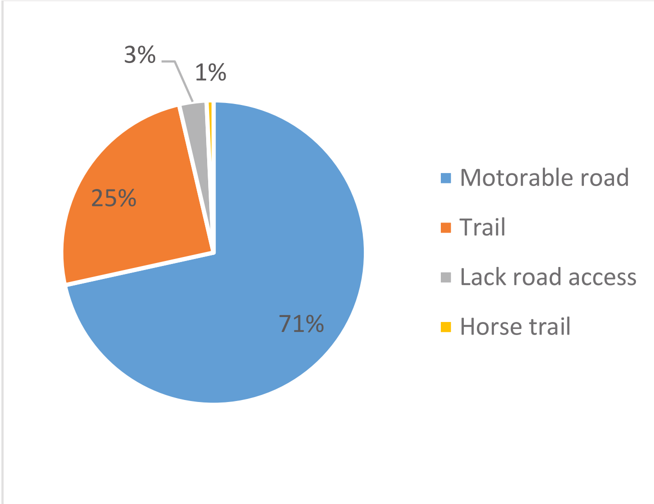

Figure 11. Road accessibility in Kamalamai

Source: Kamalamai Municipality (2021)

Multiple road tracks are being opened in Bakaiya and Kamalamai, which was found through field observation because roads are a community's top priority. Landslides frequently destroy these roadways as they are hastily opened without enough planning, especially during the monsoon. As a result, maintenance and repairs are rather expensive. Further, the monitoring aspect of rural roads being constructed (in terms of quality and follow up of guidelines of rural road standard) was found to be much weaker.

6.3 Field observation and reflections

The study team visited the case study sites in Sindhuli and Makawanpur districts and interacted with local stakeholders (local government officials, user group members, contractors and engineers) along with road users (farmers, students, teachers, businessmen, political leaders along with others). Also, the team visited the landslide of affected rural roads and met the concerned local stakeholders. First the study team visited the rural roads of Kamalamai Municipality and Bakaiya Rural Municipality (Maisthan-Ishwarpur Sadak of Kamalamai and Bhirkot-Bijaldanda Sadak of Bakaiya). During the road observation, landslides were observed in locations known as Tindhare and Hattisar of Kamalamai Municipality. In a location called Pathiparan, Kamalamai, certain landslides were found to be stable. Similar to this, roughly 10 to 12 large landslides were seen on Bakaiya's route, with Chure-Danda being the most notable.

Both the roads were constructed by the local road user committee and heavy machines were used to open the track without blasting. The dozers and the operators were from outside the local area. The local stakeholders were not familiar with the vulnerability of Chure Hills and ecosystem degradation due to road construction. The roads were built by the political and social influences rather than local need. The lack of funding prevented the construction of culverts and drainage systems on both of the rural roads that were visited. Budget constraints prevented the construction of a retaining wall and supportive gabion wire was employed instead. Even though the locals acknowledge that the usage of heavy machinery caused landslides, the roads nonetheless received top priority. It was revealed that the user committee pays little attention to the risks posed by poorly planned or non-engineered roads and instead focusses on what the public wants, most of which are political in nature.

6.3.1 Road: The development priority

Road is the first development priority of the community followed by drinking water, health services and education. Despite landslides and the vulnerable nature of Chure Hills, the local people and their leaders' aspire to construct road in their community. The political factor also plays an important role in decisions related to road construction as it assists in improving the position of political parties and leaders. The land prices along the road corridors have sharply increased and the local people want roads in their premises as roads improve mobility, local business and trade. Local communities are mostly not aware about the ecosystem degradation as a result of haphazard road construction. They accept that landslides occurred due to road construction, however, they do not understand the severity.

6.3.2 Poor implementation of the provision of IEE and DPR

The responsible agencies are not carrying out IEE and DPR is also not properly implemented. If DPR and IEE are properly followed, landslides can be minimized. On the one hand, IEE/EIA takes longer time (2 years approx.) to receive approval, while on the other hand local community seeks immediate action. Therefore, the user groups generally start road construction without IEE/EIA approval. To properly implement DPR, sufficient budget is required such as for making the road width 6 m with proper radius and gradient, for which most of the rural roads have no extra budget. The monitoring and supervision part is quite weak for proper implementation of both IEE and DPR. Elected leaders have a tenure of only 4–5 years. Therefore, they rush to complete the development work that they had promised prior to election.

6.3.3 Road benefits though poorly constructed

Local governments want to build roads to demonstrate their proclivity for development, politicians want to build roads to gain votes, the public wants roads for better connectivity and to avoid drudgery, farmers want roads for better access to markets and landowners want roads to increase the value of their land. Thus, road development, whether designed or non-engineered, appears to fit into the larger interests of a diverse set of stakeholders (Dixit et al., 2021).

6.3.4 Connection between rural road construction and landslides

While the evidences on monsoon-induced landslides and earthquake-induced landslides are well established, the linkage between road construction and landslides are more subjective. According to Dixit and Shukla (2017), the construction of roads in any given landscape could have various consequences on ecosystem and society. Surface runoff is common in the landscape before a road is built but runoff will be re-channelled to new areas after road construction. Road development also disturbs the phreatic balance of springs. When a flow channel is disrupted, water no longer flows towards a spring, and flow begins to decrease, eventually yielding less water. As a result, the decrease in spring flow caused by non-engineered road construction severely impacts community-based drinking water and local irrigation schemes, increasing local-level water and food insecurity. Such practices result in drainage failure, fractures and debris flow. As a result, roads are harmed immediately after they are built (MoFE, 2017).

From the filed observation of landslide-affected roads in Sindhuli and Makawanpur districts, it was also quite evident that the current cut-and-throw method has transformed the landscape, affecting drainage, slope stability, erosion and downstream sediment supply. While these externalities are genuine, the majority of Nepal's hill roads that run along river banks risk disruption. Rivers flowing along the banks of the curve cause toe cutting of the slope, erosion and saturation of the land mass causing landslides. When the study team of Oxford Policy Management juxtaposed 337 visible landslides sites across 35 hill districts with the nearest road in Google earth, 205 (61%) landslides had proximity to roads. The remaining 132 (39%) were on hills with no adjacent roads. A temporal analysis of Google Earth photographs from 2008 revealed that of the 205 landslides observed along the road, 179 (87%) had developed scars after road construction. The remaining 26 (13%) landslide scars existed prior to the construction of road (Dixit et al., 2021).

Though other factors such as natural (heavy rainfall, earthquake, weak rock and soil, geological fault, climate pattern) as well as anthropogenic (deforestation, improper land use practices, construction activities) are equally responsible, the non-engineered and unplanned road construction activities are triggering landslides in newly constructed rural roads, particularly in Chure Hills.

6.4 KIIs with stakeholders at national level

An interaction programme was organized in Kathmandu with national-level experts who provided valuable inputs in relation to infrastructure resilience and focussed on rural road construction built/being built at Chure Hills. The experts included Senior Geologist at Kathmandu-Terai/Madesh Fast Track Project, Nepali Army, Executive Director of Sustainable Infrastructure Development Foundation (SIDeF) and Geologist Engineer and Lecturer from Department of Geology, Tribhuvan University, Kathmandu.

Countries in developed regions of the world like Europe and North America are more technically adept at constructing robust infrastructure than Nepal and other South Asian nations. Furthermore, Nepal is more geologically fragile than any other South Asian nation. The Silwalik-Chure region has a very crumbly landscape. It needs to be handled more delicately. Despite having funds, management is the main issue in Nepal. Funding for development initiatives is typically not a problem in Nepal. Budgets are frequently halted because of poor management. The locals, however, seek more funds since they are unaware of this.

6.4.1 Cause of numerous roads construction

The federal structure in Nepal has provided more power to local governments where the officials/representatives are more interested in showing up the volume of work rather than on sustainability. Infrastructure such as road, health posts and schools have become the priority of local governments.

Road has also become a priority and the local elites prefer better roads for their children. Thus roads have become a part of personal aspiration. For example: Elites want their son/daughters who are staying abroad to travel in motorable road while returning home. Therefore, they demand local leaders to construct roads and the leaders are unable to deny as they usually promise road construction prior to election. Local people are aware of landslides but still roads have become their first priority.

6.4.1.1 Problems

- Ignorance of local stakeholders about triggering landslides due to non-engineered roads, and the concerned authorities not being able to orient them.
- Local government find difficulty in implementing DPR, though prepared. For example: rural roads normally do not construct drainage.
- Lack of study on slope stabilization and also lack of analysis of retaining structure. Even if we stop road construction in Chure Hills, we are likely to experience landslides in the next 20-30 years due to previous road disturbances.
- Retention of capable young engineers has become a problem in local government as they often travel abroad to seek better opportunities.
- Implementing authorities such as municipality/rural municipality exercise major power but lack capacity and proper implementation mechanism.
- Local leaders accept that landslides are an outcome of road construction but still seek faster development.
- There is also an issue of malpractice and corruption such as the nexus between dozer owner and local leader in road construction.
- Slope management is challenging and structural analysis in rural road is very poor.
- In deep-seated landslides, bioengineering may not work. There are many such landslides in rural areas and managing these slides are becoming problematic in Nepal.

6.4.1.2 Solutions

- Proper survey would have prevented landslides to some extent.
- DRR mainstreaming plan are yet to be focused. Sendai Framework are targeting to prepare DRR

strategic plan by 2022 in local government but the question is will they be able to take support from the right person.

- Training needs to include science teacher, high school students, elected representatives, ward secretary, environmental personnel and engineers. These are the people who will be aware and can contribute in the future.
- One of the solutions could be green road construction that involves gradual widening of road (up to 2 m and let it stay for 2 years for compaction) whereas length can be decided as per the budget and capacity. For 2 years, the experts can observe slopes and make future plans as per the outcomes.
- We need to take precautions prior to damage. For this the municipality has to prepare an inventory of the damaged and not damaged roads.
- Municipality transport plan and inventory of roads (old, new, to be built, to be maintained) have become more of a formality, but they needs to be gradually and forcefully implemented.
- There are many costly solutions but we need to identify cheaper sustainable solutions in rural areas.
- Prioritize cut and fill rather than cut and throw. Calculation is needed in mass wasting and its concurrent impact.
- One needs to focus on affordable technical solutions that are also sustainable. High tech in rural road is not recommended due to lack of budget, and technical knowhow. Local technology is highly preferred. Nature-based solution is highly recommended such as traditionally bamboos were used for slope stabilization. Now experts are attempting to use vetiver grass as its below ground biomass is more than above ground biomass (3 m of roots). It also grow faster (ready in 3-6 months).
- Local government with the help of federal or provincial government should develop risk-sensitive land-use plan.

6.5 Infrastructure resilience planning exercise at Bakaiya Rural Municipality

The resilience planning exercise for rural road infrastructure was carried out by local stakeholders in Bakaiya Rural Municipality. Based on the study objectives, this exercise assisted in identifying the most promising and viable option. Engineers, builders, road user committee members, municipality representatives and officials, farmers and political leaders were among the local stakeholders who took part in the event. They were briefed on the project and instructed on infrastructure resiliency. The local understanding of resilience with respect to road infrastructure and landslides was evaluated.

The stakeholders worked together to plan the resilience of four local roads in Bakaiya Rural Municipality, Makawanpur district. The challenges and consequences of road alignment landslides were also explored. It was determined which local stakeholders could help build resilient infrastructure. Local stakeholders identified potential solutions during the exercise and ranked them according to necessity or urgency. Rank 1 was marked as a top priority and Ranks 5 and 6 as less favoured. The duties of the potential stakeholders were detailed, along with the agencies responsible for carrying them out, and their capacity was rated as low, high or moderate.

7. Conclusion and Suggestions

7.1 Conclusion

The road access is more important in villages since rural roads connection has potential to improve livelihood of people. Today the network of roads has considerably expanded, but its sustainability has emerged as a major challenge. The resulting disasters in the vulnerable Chure Hills through erosion, floods and sediment flow lead to significant impacts on people, water use systems and built-in infrastructure, particularly the roads. Though road is one of the most prioritized in terms of budget, human resources and technology in the country, it has not been successful in marshalling its agency in constructing quality and safe roads in the country.

The unstable condition of Chure Hills should be recognized in areas where similar rural roads are causing huge landslides. Although Nepal's vulnerability ranking of landslides is not clear, landslides are at the heart of the country's climate vulnerability. The climate change will cause more dry spells and erratic precipitation in the future, threatening Nepal's vulnerability to landslides and this is more severe in the Chure region. This was revealed in the filed observation of the rural roads in two municipalities. Both natural- and human-induced phenomena were responsible for increasing landslides in the country. So we need to discuss more about human-induced landslides especially haphazard road construction and non-engineered roads because they require urgent attention. The following points are worth noting in connection to landslide management in rural road construction activities.

To understand the problems and challenges of landslides, it is necessary to understand the complexity of landslide hazards and their impacts on individuals, households and communities and on the local government actions.

- Though rural roads have several benefits to communities, these roads should not be built haphazardly, which are mostly non-engineered. The motive of demanding more roads is also questionable from vested socio-economic and political interests. This was truly reflected in the field visit and the interactions held with local stakeholders.
- The connection between road construction and triggering landslides is a big question along with the sustainability of roads and the extent of use of built roads (in rural context).
- Practices of engineering, norms, values are equally the key to well designed, built and maintained roads, irrespective of whether national roads or rural.
- The nexus of building non-engineered roads produces winners and losers. Winners involve contractors, businessmen, suppliers, political persons, frequent users and mayors with

connection to road construction, whereas losers are low-income families, marginalized groups who have very limited connection with it but suffer much from landslide impacts.

- Non-engineered road building is an outcome of political uncertainties and transition since the mid-1990s that created new dynamics.
- In some places municipal/ward representatives were operating dozers (directly/indirectly) under municipality constructed rural roads. There seems conflict of interest.
- The dozer drivers' work might not be fully observed by the respective users' committee, and the committee even did not have technical idea to check in line with DPR.
- Developing DPR and its implementation was found to be cosmetic. Further there was delay in approving DPR because no IEE was carried out. Moreover, it is time consuming to get IEE approval from the Ministry of Forest and Environment under federal jurisdiction.
- The low capacity of palikas is a major challenge. The low capacity is at three aspects: project planning and management, technology and policy. Many local officials and people in informal conversation argue that development should not be halted because of environmental concerns and that conservation can be done once development has been achieved. They do not seem to realize that opening a track and excavating without any basic engineering is not the path to sustainable development, rather such oversights can incur much higher costs to the state, people and nature.
- Good practices of local and indigenous knowledge is not getting attention that may be much supportive to managing landslides. If technical and scientific knowledge are to be blended in this, it will give long-term sustainability. The local stakeholders are self-capable to develop a resilience planning of their locality if someone facilitates genuinely.

7.2 Suggestions

7.2.1 **National level**

- Damage and loss: This data can provide evidence on economic and non-economic costs for pursuing risk reduction measures. It is also important to collect local data on landslide hazard, susceptibility and risks and incorporate them into design and construction of road, settlements, hydropower, irrigation and other infrastructure. Generic tasks can be carried out by the respective wards and the municipalities whereas more specific and technical tasks have to be carried out by hiring the experts.
- Dialogue and advocacy: The dialogue among stakeholders must cover different aspects of building engineered local roads [basic geological, engineering standards such a lopes, curves (the radius), balance of cut and fill], design, construction and maintenance of surface runoff, slope stabilization and use of bio-engineering methods. This also helps in addressing policy gaps.
- Data and information: Rainfall, hydrometeorology data of the hazard area at local level is absolutely needed to know the rainfall intensity, which likely to impact soil erosion and landslides. In close collaboration with Department of Hydrology and Meteorology (DHM) and its local office at the region, the local government can get these data and information.

- Strategic investment: In Nepal, rural roads are built faster and without pursuing phase construction practice. Even so, strategic roads need priority investment on slope stability.
- Risk-sensitive infrastructure: Currently, the Municipal and Provincial Transport Master Plans (MTMP, PTMP) are prepared without much consideration of the disaster risks. At the policy level, it will be important to make development interventions inclusive of disaster-risk reduction.
- Land-use planning: Rural road projects must include clear recommendations on land zoning that sets prospective areas for settlement, markets and areas recognized as buffer zones against landslides.
- Separate policy for Chure: There needs to be a separate policy for sensitive Chure region while developing infrastructures in this region.
- Project management: Strengthening Palikas' capacity in the various aspects (engineering, geology, environmental, economic and social) of road design, construction and monitoring is necessary. No road should be built without following Nepal Rural Roads Standards (NRRS) guidelines. The pool of knowledge from erstwhile Department of Local Infrastructure (DoLI), Department of Roads (DoR) and other interventions needs to be harnessed, synthesized in a process of coproduction in which provincial and Palika functionaries, private sector and the communities play a crucial role. Support is needed to build capacity of Palikas for local road building to geological, engineering, hydrological and environmental backstopping along with tools, skills and training.
- Local needs and priorities: Federal government are not able to pay full attention on the local needs and priorities. Some programmes are fairly top-down without giving due consideration to the local interests.
- Rehabilitation and relocation: It is necessary to understand cultural and livelihood factors involved in relocation and rehabilitation of landslide-affected families. Investment is necessary in better understanding of the barriers necessary for designing a rehabilitation plan.
- Budgetary provisions: These days, the priority of maintenance budget is on re-integrating road surface and not on slope stabilization. A separate heading under slope stabilization is necessary to ensure that a dedicated budget is available for landslide mitigation.

7.2.2 Local-level government

The local government should take these initiatives alone or along with the support from other local stakeholders:

- Permission to use dozer in restrict basis is absolutely necessary. Local government officials should not allow the operation of heavy machines (even indirectly). They should also follow strict criteria and keep in mind the conflict of interest (as many ward representatives have their own dozers).
- The old landslides (repetitive) and new (due to heavy rain or by the use of heavy machines) were found in the observation sights. So the solutions should be sought by separately analysing the types of landslides occurring in the road alignments.

- Local people treat Chure Hills similar to other hills or mountains of Mahabharat mountain range. A separate policy should be developed, which focusses on sensitive areas (such as Chure Hills).
- The DPR should be made practicable as per the local resources and the capacity of the local government (to avoid poor implementation). Moreover, the IEE approval process should be smooth and less bureaucratic.
- In many places, local people demanded the road in their settlements or field sights because of likely increment of their land price. Such things should be discouraged, which benefits only certain group of people.
- Promote nature-based solutions (e.g. Bio-engineering) along with practicable and appropriate local and indigenous knowledge and blend them with scientific knowledge.
- Develop and follow road master plan: Some municipalities have nature-based plans where as some do not have them. Even in those cases where such plans exist, the roads are not being built as per them.
- There is low level of connection and coordination between local government and federal government. Local government officials argue that their needs are not understood by the federal government. The development programmes and policies are mostly designed top-down.
- Clarity is needed between forest office (which is directly governed by federal government) and local government about development agenda and its implementation modality. Local officials argued that many forestry related federal rules are creating problems at local level for developmental activities.
- Encourage local community to develop resilience planning on their own and seek support from others if needed. Initiation must be taken by them as they know their community best.

References

1. Amatya, S. C. (2016). *Landslide Disaster Management in Nepal: A Near-future perspective* (pp. 15–21). Nepal-Japan Friendship Association of Water Induced Disaster (NFAD), Japan and Department of Water Induced Disaster Management (DWIDM), Kathmandu.
2. Bakaiya RM. (2019). *Municipal Profile (pp. 182–187)*. Bakaiya Rural Municipality, Makwanpur.
3. Bishwokarma, D., Thing, S. J., & Paudel, N. S. (2016). Political Ecology of the Chure Region in Nepal. *Journal of Forest and Livelihood*, 14(1), 84–96.
4. Bruneau, M., & Reinhorn, A. (2007). Exploring the Concept of Seismic Resilience for Acute Care Facilities. *Earthquake Spectra*, 23(1), 41–62. https://doi.org/10.1193/1.2431396
5. CISA. (2021). *Infrastructure Resilience Planning Framework (IRPF) (First)*. Cybersecurity and Infrastructure Security Agency.
6. Cutter, S. L., Ahearn, J. A., Amadei, B., Crawford, P., Eide, E. A., Galloway, G. E., Goodchild, M. F., Kunreuther, H. C., Li-Vollmer, M., Schoch-Spana, M., Scrimshaw, S. C., Stanley, E. M., Whitney, G., & Zoback, M. Lou. (2013). *Disaster Resilience: A National Imperative. Environment: Science and Policy for Sustainable Development,* 55(2), 25–29. https://doi.org/10.1080/00139157.2013.768076
7. Demenge, J. (2011). *The Political Ecology of Road Construction in Ladakh.* University of Sussex.
8. Dixit, A., & Shukla, A. (2017). *Reconstruction and Recovery of Earthquake-Damaged Jarayatar*. Institute for Social and Environment Transition-Nepal.
9. Dixit, A., Neupane, S., Bhandari, D., & Aacharya, B. K. (2021). *Political Economy of 2020 Landslides, Road Construction and Disaster Risk Reduction in Nepal*. April 2021, 16. https://www.preventionweb.net/publication/political-economy-2020-landslides-road-construction-and-disaster-risk-reduction-nepal
10. DoLIDAR. (2016). *Statistics of Local Road Network (SLRN).* 510.
11. DoR-GoN. (2007). *Roadside Geotechnical Problems: A Practical Guide to their Solution*. In Kathmandu: Department of Road, Government of Nepal. https://dor.gov.np/uploads/publication/publication_1472971151.pdf%0Ahttps://dor.gov.np/uploads/publication/publication_1472792371.pdf
12. DoR-GoN. (2018). *Strategic Road Network of Nepal*. HMIS-ICT Unit, Department of Roads, Government of Nepal.
13. FRA/DFRS. (2014). *Churia Forests of Nepal (2011 – 2013)*. Babarmahal, Kathmandu: Forest Resource Assessment Nepal Project/Department of Forest Research and Survey.
14. Froude, M. J., & Petley, D. N. (2018). Global fatal landslides 2004 to 2016. *Natural Hazards and Earth System Sciences*, 18, 2161–2181. https://www.arcgis.com/apps/webappviewer/index.html?id=98462998953c4f1fbd7caaa166373f63
15. Ghimire. (2013). Landslide Disaster Management in Nepal A Near-future perspective Prepared by Contents. *Scandinavian Journal of Caring Sciences*, 1(3), 1–17.

16. Haimes, Y. Y. (2009). On the Definition of Resilience in Systems. *Risk Analysis*, 29(4), 498–501. https://doi.org/https://doi.org/10.1111/j.1539-6924.2009.01216.x
17. ITAD. (2017). *Rural Access Programme Phase 3. Monitoring, Evaluation and Learning Component Review of Rural Roads Maintenance Planning In Nepal* (p. 20). ITAD, Brighton.
18. Kamlamai Municipality. (2021). *Municipal Profile* (pp. 70–72). Kamalamai Municipality, Sindhuli.
19. Lamsal, A. (2014). *Major Landslides in Nepal*. Kathmandu University.
20. Leibundgut, G., Sudmeier-Rieux, K., Devkota, S., Jaboyedoff, M., Derron, M. H., Penna, I., & Nguyen, L. (2016). Rural Earthen Roads Impact Assessment in Phewa Watershed, Western Region, Nepal. *Geoenvironmental Disasters*, 3(1). https://doi.org/10.1186/s40677-016-0047-8
21. McAdoo, B. G., Quak, M., Gnyawali, K. R., Adhikari, B. R., Devkota, S., Lal Rajbhandari, P., & Sudmeier-Rieux, K. (2018). Roads and Landslides in Nepal: How Development Affects Environmental Risk. *Natural Hazards and Earth System Sciences*, 18(12), 3203–3210. https://doi.org/10.5194/nhess-18-3203-2018
22. MoFE. (2017). *Vulnerability and Risk Assessment and Identifying Adaptation Options in Industry, Transport, and Physical Infrastructure* (pp. 3–4). Ministry of Forests and Environment, Government of Nepal. Kathmandu, Nepal.
23. MoHA. (2022). *Nepal Disaster Risk Reduction Portal: Landslide Data 2011-2021*. Ministry of Home Affairs, Government of Nepal. http://drrportal.gov.np/
24. MoHA. (2019). *Nepal Disaster Report 2019*. Kathmandu: Ministry of Home Affairs, Government of Nepal.
25. Mulmi, A. (2009). Green Road Approach in Rural Road Construction for the Sustainable Development of Nepal. *Journal of Sustainable Development*, 2, 149–165. https://hdl.handle.net/10535/6465
26. Nepal, N., Chen, J., Chen, H., Wang, X., & Pangali Sharma, T. P. (2019). Assessment of Landslide Susceptibility along the Araniko Highway in Poiqu/Bhote Koshi/Sun Koshi Watershed, Nepal Himalaya. *Progress in Disaster Science*, 3, 100037. https://doi.org/10.1016/j.pdisas.2019.100037
27. OECD. (2021). Building Resilience: New Strategies for Strengthening Infrastructure Resilience and Maintenance. In *OECD Public Governance Policy Papers* (Issue 05).
28. Pande, K. (2017). *Improving Rural Connectivity and its Impact on Sustainable Development Goals (SDGs) – Case of Nepal* (Background Paper for EST Plenary Session-3). Intergovernmental Tenth Regional Environmentally Sustainable Transport (EST) Forum in Asia, March.
29. Petley, D. N., Hearn, G. J., Hart, A., Rosser, N. J., Dunning, S. A., Oven, K., & Mitchell, W. A. (2007). Trends in Landslide Occurrence in Nepal. *Natural Hazards*, 43(1), 23–44. https://doi.org/10.1007/s11069-006-9100-3
30. Rayamajhi, S., Pokharel, R. K., & Tiwari, K. R. (2019). *An Assessment of the President Chure-Tarai Madhesh An Assessment of the President Chure-Tarai Madhesh Conservation Development Program.* November. https://doi.org/10.3126/forestry.v16i0.28362

31. Rossmanith, C. (2018). *On the Road to Development: The Impacts of Road Construction on Livelihoods in Manang*. Institute of Geography, University of Innsbruck.
32. Shrestha, A. (2015). *Status of Chure in Makwanpur District*. Kathmandu: Daayitwa.
33. Shrestha, B. P. (1981). *An Introduction to Nepalese Economy*. Ratna Pustak Bhandar.
34. Sidle, R. C., Ziegler, A. D., Negishi, J. N., Nik, A. R., Siew, R., & Turkelboom, F. (2006). Erosion processes in steep terrain - truths, myths, and uncertainties related to forest management in Southeast Asia. *Forest Ecology and Management*, 224(1–2), 199–225. https://doi.org/10.1016/j.foreco.2005.12.019
35. Singh, B. K. (2010). Assessment of the upstream Churia Hills and downstream Terai plains linkage: An environmental services perspective. *Banko Jankari*, *20*(1), 17–23.
36. Singh, B. P. (2018, July 6). From nowhere to nowhere: haphazard road construction is ravaging the Nepali countryside. *Nepali Times*. https://www.nepalitimes.com/banner/from-nowhere-to-nowhere/
37. Upreti, B. N., & Dhital, M. R. (1996). *Landslide Studies and Management in Nepal*. Kathmandu: International Centre for Integrated Mountain Development.
38. Upreti, B. R., & Shrestha, G. (2017). Linking Migration, Mobility, and Development for Strengthening Adaptation to Climate and Disaster Risks: Reflections from Nepal. In *Identifying Emerging Issues in Disaster Risk Reduction, Migration, Climate Change and Sustainable Development* (pp. 145–160). Springer.
39. Wan, C., Yang, Z., Zhang, D., Yan, X., & Fan, S. (2018). Resilience in Transportation Systems: A Systematic Review and Future Directions. *Transport Reviews*, 38(4), 479–498. https://doi.org/10.1080/01441647.2017.1383532
40. WB-GoN. (2013). *Nepal Road Sector Assessment Study*. Kathmandu: The World Bank and Government of Nepal.

Policy Brief: Radio Club Station within District Emergency Operations Centres

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CDRI

Coalition for Disaster Resilient Infrastructure

Abstract

The aim of this article is advocacy for policy change by Wireless Planning and Coordination (WPC) Wing of the Ministry of Communication, Government of India to allow Indians to possess amateur radio transceiver (a radio capable of both transmission and reception) with the caveat of transmission only by an amateur radio licensee, as in the US. Amateur radio is a fragile fail-proof communication system that does not depend on other support system. Currently, amateur radio operators (ham) go to disaster sites with their equipment and restore emergency communication. In the process time is lost, when every second makes the difference between lives and deaths. The second aim is installing amateur radio club station within district emergency operations centres (DEOCs). Then, ham will quickly go to communication breakdown disaster-affected DEOC and restore amateur radio emergency communication, reducing disaster mortality, morbidity and tangible infrastructure losses. A district collector can install an amateur radio station within DEOC by investing approximately Rs 1.62 lakh only. For about 739 Indian districts, an investment of approximately only Rs 22 crore is required. Funds are available from State Disaster Response Fund and other sources.

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Malaviya National Institute of Technology, Jaipur is the host institute. The views expressed in this paper reflect the opinions of the author and not necessarily the official views of TIEMS-IC, MNIT, or CDRI. The CDRI Fellow has no known conflict of interest in this project to disclose. Correspondence concerning this Policy Brief should be addressed to Kailash Gupta, The International Emergency Management Society – India Chapter, C 56 Opp. TPS, Shastri Nagar, Jaipur 302 016, India.

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1. Problem

Proper disaster response is not possible in the absence of effective communication. Evidence shows that during many disasters, communication systems are destroyed, because of inter- alia, communication towers collapsed, telephone cables snapped, mobile phone networks overwhelmed and electricity outages. This happens at a time when fail-proof communication system is required to save lives, because every second makes a difference between life and death. The consequences and significance of failing to respond immediately and effectively to communication problem during disasters result in avoidable disaster mortality, morbidity and tangible infrastructure losses.

The US 9/11 Commission (2004), set up after the Twin Tower attack in New York City in 2001, in its report concluded communication breakdown as the main bottleneck to respond. Communication infrastructure in India failed during many disasters, including 1999 Odisha Super Cyclone, 2001 Gujarat Earthquake (Gupta, 2004; Rathod, 2001), 2004 Indian ocean tsunami, and recently 2019 Odisha Cyclone Fani (Gupta, 2019).

2. Emergency Communication Alternatives and their Evaluation

Earlier, landline telephones were the norm for emergency response. However, with the advent of mobile phones, they have become obsolete and during disasters, they have become dysfunctional.

Telecommunication technologies, particularly mobile phone technologies are advancing by leaps and bounds. Nevertheless, they depend on communication towers and other infrastructure, which become dysfunctional during disasters.

Satellite phones offer emergency communication alternative, as they do not depend on the infrastructure on the land. Therefore, they ought to work during disasters. Bharat Sanchar Nigam Limited is the only authorized service provider of satellite phones in India. Satellite phones are costly and airtime usage cost is prohibitive. Evidence shows that satellite phones did not work during 2001 Gujarat earthquake (Gupta, 2004) and recently after 2019 cyclone Fani in Odisha (Gupta, 2019) because they were neither charged nor responders knew how to use them. The responders did not use satellite phones in their routine work. Unless and until a human uses an equipment regularly, it is absurd to expect that it will perform during a disaster.

Internet is now almost ubiquitous and so pervasive that it is required to perform many daily living functions. However, during many disasters, administrators and responders are unable to access Internet connection because of the reasons stated earlier and Internet servers crash due to overloading.

The Wireless Planning and Coordination Wing, Ministry of Communication, Government of India (WPC) has allocated radio frequencies for two-way communication to disaster administrators, responders, national and state disaster response forces, police, para military forces and other disaster responding organizations. WPC has allotted each of these stakeholders one frequency in VHF band, suitable for communication within limited distance. Amateur radio operators, popularly known as ham (singular and plural noun), are licensed to operate in VHF, UHF and HF frequency bands without any airtime charges. HF allows two-way communication across the globe.

Further, there is a problem of interoperability, meaning an agency can communicate within its own ranks, but not with other agencies, which hinders coordination. During disasters, many organizations, even unattached volunteers, have to work for effective disaster response. During many disasters, a number of ham with their portable VHF, UHF and HF radio stations go to responding organizations and restore emergency communication and resolve interoperability problems.

Conclusion: Despite advances in telecommunication technologies, systems fail during many disasters. International evidences have shown that ham continued to operate even during turbulent conditions providing telecommunication facilities to disaster responders. Therefore, this article proposes to install amateur radio club station or ham club station

(HCS) within about 739 Indian District Emergency Operations Centres (DEOC), popularly known as control rooms. In the case of a communication failure threatening situation (such as an approaching cyclone) or actual communication systems failure, ham will quickly go to the DEOC, nearest to the disaster site, and maintain emergency communication.

Amateur radio works, because ham regularly check their functionality by checking-in the amateur radio nets. Amateur radio nets are coordinated by some ham on fixed frequencies during fixed times daily or on a particular day of the week. Ham, number of them, call one after the other to the net coordinator – a ham volunteer - for check-in and get report of her/his sound propagation quality to ensure 24×7×365 functionality.

Rule 2(b) of the Indian Wireless Telegraph (Amateur Service) Rules, 1978 defines amateur service as, ". . . a service of self-training, inter-communication and technical investigations carried on by amateurs that is, by persons duly authorized . . . interested in radio technique solely with a personal aim and without pecuniary interest". Amateur radio is a technical hobby and ham provide emergency communication during disasters because of their passion.

International Telecommunication Union (ITU) regulates radio spectrum, including amateur radio. ITU is an UN agency for information and communication technologies to facilitate international connectivity in communications networks. ITU's work helps us make phone calls and access the Internet. ITU has allocated specified frequency ranges in VHF, UHF and HF bands for use by ham without airtime charges, because amateur radio is a fragile fail-proof system and it works when all other modes of communication fail.

3. Genesis of the Proposal

Disasters are getting significance because of increasing intensity and frequency. Disaster management requires disaster-resilient infrastructure. The Indian Prime Minister, Mr Narendra Modi, in the 2016 Asian Ministerial Conference on Disaster Risk Reduction proposed an international coalition of countries and other organizations. He launched Coalition for Disaster Resilient Infrastructure (CDRI) in 2019 at the UN Climate Action Summit.

CDRI awarded one of the first cohort CDRI Fellowships 2021-22 to the author for research on creating disaster- resilient emergency communication infrastructure. Malaviya National Institute of Technology, Jaipur, was the host institute and D. Boolchandani, professor of Electronics and Communication Engineering his mentor. The author co-opted in his team ham and interns, one of which worked remotely from the US.

The author conducted two in-person focus group meetings with 13 participants including ham, media personnel and lay people. In-person meetings were conducted with officials of WPC and National Disaster Response Force (NDRF). In this transdisciplinary participatory action research all other activities were done virtually due to the pandemic. Presentations were made in six international

conferences and Hamfest India 2021. Six papers have been published and two are in pipeline. This article is the synthesis of our research findings.

4. Current Practice

Currently, ham go to disaster site when called by authorities or pro-actively. They carry with them their transceiver (a radio capable of both transmission and reception), antenna and power supply (appliance to convert 230-volt AC to 12-volt DC to power transceiver), to the disaster sites and nearest DEOC. They then install antenna, temporary amateur radio stations (ARS) and restore amateur radio emergency communication. In the process, time is lost, when every second makes the difference between lives and deaths.

4.1 We give examples that will elucidate the role ham have played in recent disasters in India.

- On December 3, 2020, the Thiruvananthapuram District Disaster Management Authority (DDMA) wrote to the Amateur Radio Society of India, the representative body of Indian ham affiliated with the International Amateur Radio Union, requesting the establishment of an ARS as Cyclone Burevi was approaching.
- In May 2019, three ham travelled from Kolkata to Bhubaneswar in a car in anticipation of landfall of cyclone Fani with their amateur radio equipment (Bhattacharya, 2019), remained at the Bhubaneswar State EOC for 10 days and restored emergency communication. The cyclone Fani made landfall near Puri on 3 May, 2019, and State EOC was without electricity for 10 days.
- After Gujarat earthquake in 26 January 2001, nine ham from Mumbai and the author from Vadodara with their amateur radio equipment went to Bhuj DEOC and Gandhinagar state EOC and were the first to reach and respond. We restored amateur radio emergency communication the next day (Rathore, 2001). Mishra (2004) states that based on a committee report, the government recorded 13,805 fatalities (p. 56). However, non-government estimates are approximately 25,000. Many deaths could have been avoided, if ARSs were pre-existing,

5. Proposed Solution

Nollet and Ohto (2013), Victor et al. (2010) and Wilkosz (2004) assert thereliability and dependability of the amateur radio emergency communication system. We have used HCS within EOCs and hospitals in North Dakota and California states in the US.

In view of above, we have proposed as partof disaster-resilient infrastructure, HCS within ~ 739 DEOC of the country. They will provide facility for fail-proof amateur radio emergency communication system in the country. HCS can use transceiver even during electricity outage by plugging the system to a car battery. A ham can send messages in the form of voice, text,pictures, slow-scan television (SSTV),

automatic position reporting system (APRS) and other digital modes (Baruah,2015, 2020).

A modest ARS with transceiver, antenna, power supply and cables cost approximately Rs 1.62 lakh. Each district is required to have an EOC. The cost of installing ARSs in approximately 739 Indian DEOCs is about US$3 m or Rs 22 crore, a meagre amount for the whole of India.

A transceiver requires only a smalltable (similar for use of a laptop). An EOCnormally would have permanent staff and many existing EOCs have civil defence/ home guards attached with them. These personnel can be trained to get an amateur radio license. Therefore, there isno incremental cost for space and staff.

There is no dearth of resources for a mere Rs 1.62 lakh for installing a HCS within a DEOC. The possible funding sources include (but are not limited to) the following:

- The district collector has budgetunder many heads.
- HCS is an approved schemeunder the MP and MLA Local AreaDevelopment Fund.
- The mandatory CSR funds under Indian Companies Act, 2013, can be used for cost of HCS equipmentand training.

The Government of India Guidelines on Preparedness and Capacity Building under National and State Disaster Response Fund for 2022-23

(https://ndmindia.mha.gov.in/images/Gui delines.PDF) has allocated Rs 1301crore for NDRF and Rs 3043 crore forSDRF. The Guidelines in Section 11.2(i)NDRF Category-A (b) states, "Projects

aimed at setting up/ strengthening national level . . . including strengthening of "Emergency Operation Centres" and preparedness and response mechanism across the states" and in Category B (a) "Projects of the State Government(s) related to . . . emergency operations centres, training and capacity building."

Therefore, funds are available withstate governments for HCS within DEOCs. The easiest way to implement the proposed solution is for Home Secretary, Ministry of Home Affairs, Government of India exercising the authority under the Disaster ManagementAct, 2005 to issue directions to chief secretaries of states and administrators of union territories to install ARSs in eachDEOC and train staff to become active ham.

Presently, there is a government notification that only a ham may possess an amateur radio transceiver. The government has to make a policy change allowing possession of transceiver by anyIndian, with the caveat of transmission only by an amateur radio license, as in theUS.

The Disaster Management Act, 2005 in Section 30(2)(xxviii) requires DDMAs to "ensure communication systems are in order, and disaster management drills are carried out periodically." Rigid application in letter and spirit of this Section of the Act will ensure that the system remains functional.

Independent of the solution in Section 5.7, a few forward-thinking districtcollectors need to

- mobilize local ham,
- form a district ham club,
- apply to WPC for an HCS license with support of three general category amateur radio licensee for the club license,
- obtain the license,
- install ARS within DEOC,
- assign the responsibility ofmaintenance of ARS to a staff member of DEOC (preferably aham), and
- allow ham during specified hours to use club station.

These forward-thinking district collectors will set up a model for replication.

Installation of ARS within DEOCs will encourage citizen participation in disaster management. Ham, who are citizens, will be able to go quickly during disasters to DEOC and maintain amateur radio emergency communication,reducing mortality, morbidity andinfrastructure losses.

6. Output and Impact

The acceptance of proposedsolutions and implementation in letter andspirit will result in installation of ARS within DEOCs and starting of functioningdistrict HCS in some districts. In the course oftime, this may replicate with functioning HCS in many districts.

The impact of the project will be public good by saving lives through emergency communications during disasters. In any disaster, the mostvulnerable are the women, children, olderadults, differently abled and people with low socioeconomical status.The investment of having functioning HCS within DEOCs in the longrun will reduce mortality, morbidity and tangible infrastructure losses and will give maximum social benefit return comparedto any other disaster-resilient infrastructure investment.

7. Policy Recommendations andCall for Action

Recommendation 1. We recommend Wireless Planning and Coordination Wing of Ministry of Communication,Government of India (WPC) to make policy change allowing Indians to possess amateur radio transceiver, with the caveat of transmission only by anamateur radio licensee, as in the US.

Recommendation 2. We recommend Home Secretary, Ministry of Home Affairs, Government of India exercising the authority under the Disaster Management Act, 2005 to direct chief secretaries of states and administrators of union territories to install amateur radio stations in each district emergency operations centre and train local people to become active ham using the State Disaster Response Fund allocation.

Recommendation 3. We recommend a few pioneering collectors to form a districtham club, obtain amateur radio club station license, install amateur radio stations within their district emergency operations centre costing only about Rs 1.62 lakh and promote the amateur radio technical hobby.

References

1. 9/11 Commission. (2004). *The 9/11 Commission Report – The full final report of theNational Commission on Terrorist Attacks Upon the United States*. https://govinfo.library.unt.edu/911/report/911Report.pdf
2. Baruah, S. (2015). Radio based approach for disaster risk reductionand management using automatic packet reporting system (APRS®) and hamradio (amateur radio) digital communication technologies [Paper presentation]*IFAC-IDRiM Conference*, New Delhi
3. Baruah, S. (2020). A practical radio and internet based approach for disaster risk reduction and management through geospatial information studies using automatic packet reporting system (APRS®). Details available at https://www.qsl.net/vu2msy/APracticalRadioandInternetBasedApproachforDisa sterRiskReductionandManagementUsingAPRSbySandeepBaruahVU2MUE.pdf
4. Bhattacharya, R. (2019). Cyclone Fani: HAM operators to help Odisha communicate. *The Indian Express*. Details available at https://indianexpress.com/article/cities/kolkata/cyclone-fani-ham-operators-to- help-odisha-communicate-5707844/
5. Gupta, K. (2004). Role of ham radio operators in Gujarat earthquake. In Institution ofEngineers (India) (Ed.), *World Congress on Natural Disaster Mitigation, New Delhi February 2004* (Proceedings Vol. I, 181-187)
6. Gupta, K. (2019). Why to better manage disasters? *The WIMWIAN IIM Ahmedabad Alumni Magazine,* 1(4), 75-79. Details available at *https://wimwian.iima.ac.in/alumnioffice/wimwian-jun-2019.pdf*
7. Mishra, P. K. (2004). *The Kutch earthquake 2001: Recollections, lessons andinsights*. National Institute of Disaster Management. Details available at https://nidm.gov.in/PDF/pubs/KUTCH%202001.pdf
8. Nollet, K. E., & Ohto, H. (2013). When all else fails: 21st century amateur radio as anemergency communications medium. *Transf Apheres Sci. 49*(3), 122-427. http://doi.org/10.1016/j.transci.2013.08.002
9. Rathod, N. (2001). Gujarat earthquake disaster communication report. *Ham RadioNews, VII* (1), 16-18
10. Victor H. Cid, V. H., Mitz, A. R., & Arnesen, S. J. (2010). *Keeping Communications Flowing during Large-scale Disasters: Leveraging Amateur Radio Innovations for Disaster Medicine*. Cambridge University Press
11. Wilkosz, W. R. (2004). Amateur radio emergency service: Are communication lines the missing link to homeland security? *Journal of Law, Technology, & Policy*, No. 1

Flood-Resilient Floating Community Housing

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Coalition for Disaster Resilient Infrastructure

Abstract

Constant seasonal flooding in the north-eastern delta region affect people's houses and livelihood. This problem is seen in various regions of India but very few measures have been developed to overcome this problem. The solutions that are practiced are short-term and mainly displace people from their place. Human settlements have always been found near the river. Earlier, these settlements that lived near the rivers had the capacity to tackle floods as a disaster. The Mesopotamia settlements have lived on water and managed to tackle floods as a surviving factor. The problem of floods in the north-eastern region is due to River Brahmaputra as it causes floods along its course. The major effects can be felt in the rural part of India. Due to these floods, people live on the roads as they are at a higher height or move to high areas. Once the floods recede, people again move to their same place. Frequent floods have made people to adaptive to water but no infrastructure are in place to help them in their plight. People manage transportation through boats. However, there is no electricity at night and people face other problems. Floods cut off these people from the world.

To address this natural disaster at a community level, one has to design infrastructure that can combat this natural disaster as it can against any other disaster. The research proposes the idea of a Floating or Amphibious house that can begin to float at the time of floods. These houses will be self-sufficient in terms of energy and sustenance. These can withstand independently without the need for external agencies. The material for these houses will be light in weight and be able to withstand natural calamities and be able to suffice human needs. These houses, in general, will be energy neutral and every service will be provided individually along with community-level services of collective sewage pots, etc. During the disaster, these houses will float and will remain intact in the same place. The energy cut during the calamities will not affect these houses since these houses will be self-sufficient and self-reliant. The natural water drinking area will also be floating and provide clean water at the time of disaster. In India, many rural and urban areas face floods, but the proper infrastructure is not available be it in terms of physical, ecological or social.

Funding

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1. Introduction

The temperature of the earth has been rising globally, which can be attributed to global warming. The rise in the earth's temperature has led to melting of glaciers and ice sheets, making the volume of the sea increasing and resulting in the expansion of the water surface. Another troubling development we are witnessing is a massive shift of land water to oceans because of more human consumption of water and groundwater being recharged at a slower rate. This is causing scarcity of fresh water. Concretization of cities is another issue contributing towards groundwater not recharging. All these factors are contributing to the alarming rise in sea levels, thus affecting many cities today and in the coming years. Since 1880, the global sea level has risen about 8 to 9 inches, i.e. 21 to 24 cm. The rise in the sea level depends on CO2 emission. Even if the CO2 emissions are controlled by 2030, it is projected that the sea level will continue to rise as high as 0.3 m by 2100 as a result of high emissions. The rise in sea levels in the near future will be especially detrimental for coastal, metropolitan and urban areas ; these include Guangzhou in China, New Orleans and New York in the US, Mumbai in India, Osaka in Japan, and many more. As a very bleak future is in store for all of us, we need to urgently innovate in every field which suppresses or is dealt with by solving these consequences.

The need of the hour is to let the innovators and researchers study and implement terms of floating and amphibious architecture (Wang & Wang, 2015), design and engineering.

1.1 Why floating and amphibious architecture?

Reclamation of land requires time as well as expenditure. Floating structures are flexible and can be easily carried away in disasters. They are suitable for the deep sea and can adjust as per changing water levels, thus making better vertical movement. Floating structures are earthquake resistant as they are not directly connected to the land. They are environment friendly and can be modular and implemented on a larger scale.

1.2 Structure systems in floating architecture

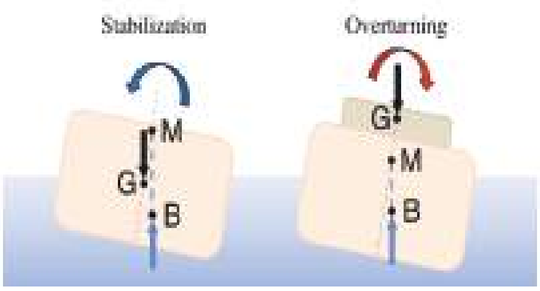


Figure 1. Floating body stabilization and overturning
Source: Wang & Wang (2015)

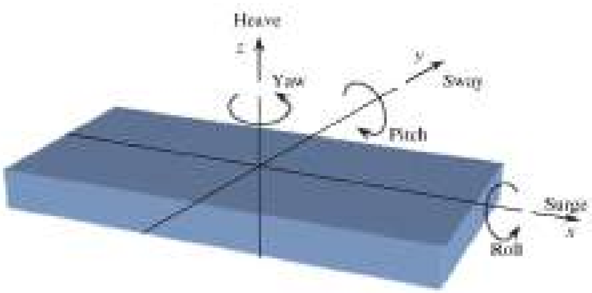


Figure 2. Motions in floating structure
Source: Wang & Wang (2015)

The structure of a floating system during applied loads well as rotations in all the three directions. The degree of freedom is six namely as shown in the figure

- Surge: Translation in the x-direction (forward and backward)
- Sway: Translation in the y-direction (side to side)
- Heave: Translation in the z-direction (up and down)
- Roll: Rotation about the longitudinal x-axis
- Pitch: Rotation about the transverse y-axis
- Yaw: Rotation about vertical z-axis

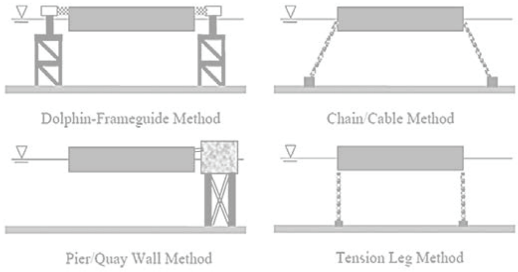


Figure 3. Types of mooring systems
Source: Wang & Wang (2015)

Mooring can restrict these degrees of freedom, and sway, surge and yaw can be neglected. The movements and oscillations caused by the dead and live loads are balanced by the force acting from below the structure called buoyant force. Though, roll and pitch could be caused due to eccentric loads.

Flood is another problem that the low-lying areas around rivers are experience. Human settlements have always chosen land near rivers to facilitate better water opportunities used in irrigation and drinking, cooking, etc. The regular floods were capable to adapt doing stilt housing. The construction of dams has increased these floods in terms of occurrence as well as level of flood.

Researchers around the world are working on designing and implementing completely floating as well as amphibious architecture. The research on floating and amphibious architecture is majorly based on two methods:

- At micro level, creating a prototype of small buildings as per detailed structure and testing,
- At macro level, visualizing and implementing floating cities, arenas, sea farms, etc.

The prototypes are being tested and implemented but mass production along with acceptability and community knowledge is lacking. Climate change is real and needs to be addressed. The design work should now be planned such that implementation can be done on a bigger scale, especially in the urban fabric along with planning for rural low-lying areas experiencing frequent floods. The policies must be changed, formed and accepted. The analysis of urban coastal cities and their buildings along with rural low-lying areas along the river will help in creating strategies for implementation for retrofitting, replacing and possible spaces to be moved on water.

Living with water has been a concept for ages but the technological improvement has made it more viable and beneficial. The parameters of supporting the infrastructure with self-sustenance have to be worked out along with the analysis. This will be more of a multi-disciplinary infrastructure planning, be it social, physical or ecological along with working for energy and food.

Currently, the floating architecture research implementation is majorly seen in Europe and United Kingdom. Such types of research are very less in South Asian countries, particularly India, despite having a long coastline and many endangered cities and low-lying rural areas experiencing frequent floods. In India, the research should be done in collaboration with industrialized systems along with cultural and traditional aspects of the place, be it materials, energy or food.

Some of the leading researchers, architectural firms, societies and institutes working on floating and amphibious architecture in the western countries are as follows:

- Elizabeth English, Buoyant Foundation Project, Canada
- Jacques Rougerie, Jacques Rougerie Foundation, France
- Koen Olthuis, Waterstudio NL, The Netherlands
- CM Wang, Very Large Floating Structure author, Civil Engineer, Singapore
- Łukasz Piatek, Poland
- Saif Ul Haque, Bangladesh
- Deep Blue Institute, Berkeley, California
- Blue 21, Delft, The Netherlands
- Society of Floating Solutions, Singapore
- Resilient Rotterdam, The Netherlands
- Institutes of Marine Time Engineering Science and Technology, The Netherlands
- The Sea Steading Institute, UK
- Richard Coutts: Baca Architects, UK

In this study, we propose that the focus should be on the micro level and test prototypes as per the context and culture of the place of implementation. It can be replicated to make floating or amphibious communities living with water, futuristic coastal floating communities, and floating settlements as a whole. The research will work in whole to part mode, starting from micro to macro planning.

The overall research questions are as:

- For coastal cities and low-lying areas of rural India along the river: identifying and analysing them for possible interventions of amphibious and floating architecture as per the lifespan of the buildings.
- A new form of infrastructure planning will include the parameters in response to rising sea levels and natural disasters such as flood.
- The parameters of culture, sustainability, self-dependency, resilience, viability, and ecological and economic factors are to be dealt with while designing.
- Analyse and design floating and amphibious possibilities, in terms of living, energy and food.
- Structural and material interventions as per the context and exchange of knowledge with the local people.
- Innovative interventions to catalyse the wake of living with water.
- Possible regional-level intervention in response to lowering CO2 emissions.
- Possible systems for desalination of seawater or treating the wastewater for lowering the shortage of fresh water.

The research will work as per the Sustainable Development Goals while designing, implementing, and beyond.

This dissertation is a part of whole research for floating and amphibious architecture in flood mitigation as well as in response to climate change with special focus on the rise in sea levels. The objective of the research is to develop an amphibious housing prototype. The research will be helpful in terms of making the architectural design more valuable and contributable. The simulation of energy-neutral systems for a prototype of a floating house will make it more viable and easier to understand the cost benefits over the long run.

The overall research of which this dissertation is a part:

1. For flood-prone areas, which are not near the coastline but experience frequent floods and also coastal line areas. Preparing master plans for possible implementation of measures in the future to maintain the spatial and temporal adaptations in regional infrastructure –

    - Identifying the low-lying areas with usual flood episodes and documentation of the conditions of the building. The interventions will be designed in a way that it will enable autonomous maintenance and refurbishment activities that cause minimal disruption and thus reduce the cost of adaptation in the area.
    - The analysis of the buildings will be based on the life span of the buildings along with the type of the building. This analysis will help to categorize the buildings for either retrofitting with amphibious foundation or completely replacing it with new amphibious buildings.
    - After analysis, the strategies for design as per parameters of culture, sustainability, self-dependency, resilience, viability and ecological and economic factors will be formalized.
    - Design as per technology and exchange of knowledge of local materials and techniques with the people of the community.
    - Resource planning and interventions will be planned to maintain autonomous maintenance and refurbishment activities to make them affordable.

2. Creating completely new floating designs near the shoreline around the coastal cities for accepting living, working, and being on the water:

    - Analysing the cities with possible voids for new development, which can be made on water rather than the land of the coastal city, like making floating office spaces, recreational spaces, etc.
    - Utilizing the same land for healing the other impacts of climate changes (for example making urban forests in the city, open spaces).
    - Creating possible floating villages for the production of food, energy and even desalination of ocean water.
    - Creating possible community villages for acceptance of living on the water, making it self-reliant, sufficient and achieving net zero on water.

These two measures will work in both flood mitigation and climate change adaptation.

1.3 Methodology

Qualitative Research

- Doing literature studies and case studies for energy-neutral systems in small-scaled floating and amphibious houses. (Data collection through secondary sources including research papers, books, etc.)
- Frame out the requirements of the typical floating house and do simulations for energy-neutral systems. (Work to be executed and designed as per data, which include primary sources.)
- Compile the results and presentation.

Figure 4. Proposed framework

Implementation Research

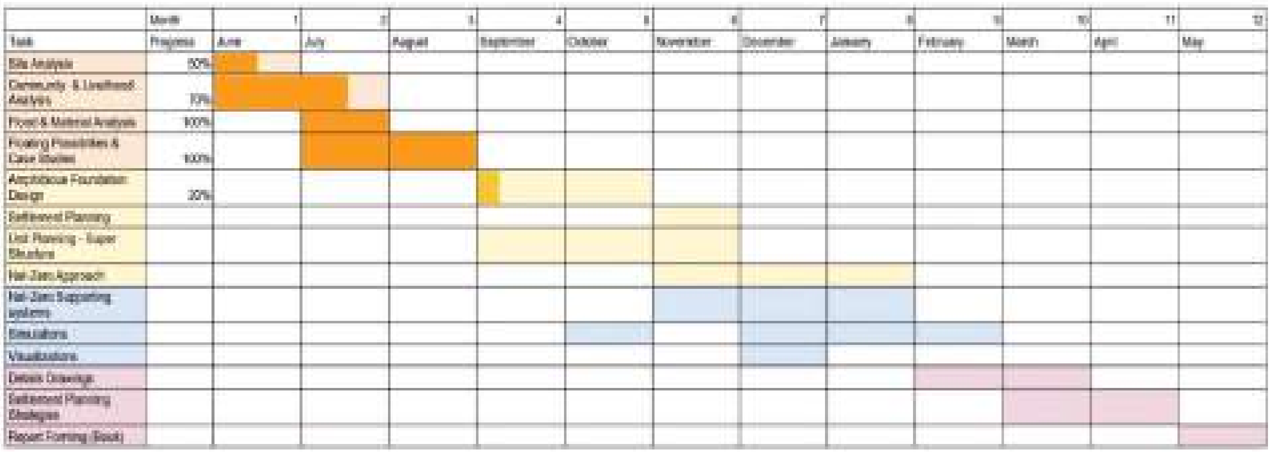


Figure 5. Gantt Chart

- Implementing the studied techniques and process
- Visualizing the data to support the implementation

2. Majuli Island – Fresh Water Island

Majuli is a major biodiversity hotspot in Assam. It is the largest inhabited river island in India. The Island of Majuli is separated from the mainland of Assam by 2.5 km. The island has a population of about 160,000 inhabitants (Census 2011) of which 70% belong to tribal communities such as Mishing, Deuri, Kachari, and Koch-Rajbongsi. The Government of India nominated Majuli island for enlistment as a UNESCO World Heritage site, in the Cultural Landscape category.

The island has been shrinking over time due to riverbank erosion and excessive flooding. Like the rest of Northeast India, it has a complex composition of different ethnicities, religions, castes and scheduled tribes. These communities have through decades developed livelihoods, knowledge systems, and technologies based on the environmental risks of the river.

Figure 6. Majuli Island
Source: GIS, Authors

The uniqueness of Majuli lies in its diverse agroecology and the combination of tribal and non-tribal cultures. Their tacit knowledge and adaptive water management strategies are systematically marginalized by large-scale, centralized flood and erosion control measures by the government that dissociates local people from their traditional adaptation programmes. Majuli's weather and water conditions are well-known to the communities living there. They have 'lived with the floods' for several years and are comfortable with normal flooding that both destroys and replenishes their agricultural fields with fertile alluvium. Their lifestyle highlights that there are different perceptions of water conditions as communities like Majuli have evolved with coping measures and adapted over time. Moreover, they provide a linear history of change and how communities have formed a lifestyle from fluctuating conditions.

In today's era of climate change – where several coastal and island communities are dealing with a severe rise in water levels – water management needs to be diversified and decentralized with an adequate appraisal of indigenous knowledge that can be used towards designing adaptive strategies. As mentioned earlier, given the prospect of global sea-level rise, there is an urgent need to develop a more sophisticated toolbox

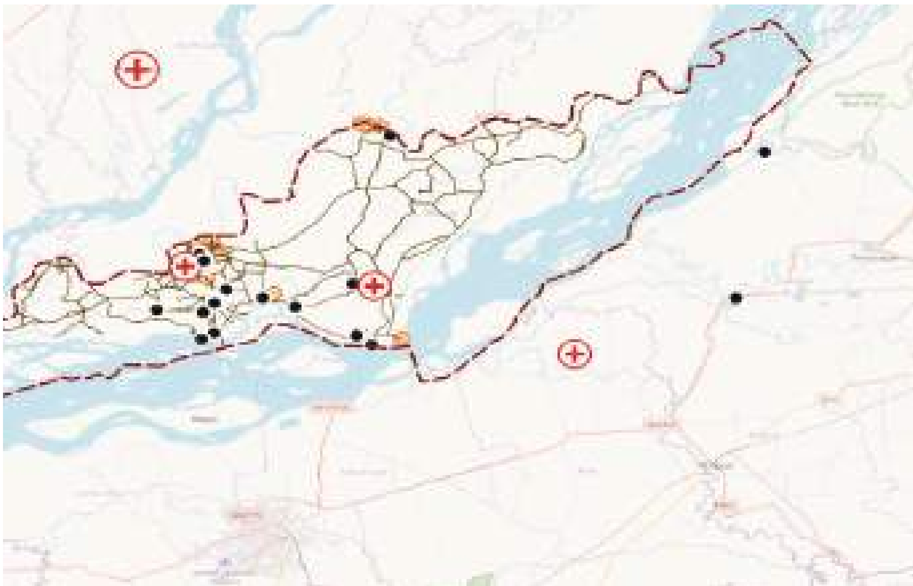


Figure 7. Settlement pattern and amenities
Source: GIS, Authors

for adaptation. Analysing Majuli's traditional adaptive strategies, despite their different dynamics and causes, can potentially inform other vulnerable communities that are experiencing similar fluctuating weather and water conditions.

Figure 8. Majuli Map 1986

Figure 9. Majuli 1973

Figure 10. Majuli 1996

Figure 11. Majuli Island 2001

Figure 12. Majuli Island 2013

Figure 13. Majuli Island 2020

2.1 Bamboo as building material

Globally, India is the second largest producer of about 130 species of bamboo. It is regarded as "poor man's timber" because its mechanical properties are suitable for structural applications in terms of high strength to weight ratio, ductility of fibrous microstructure, low cost, faster production and simple manufacturing processes. The physical and mechanical strength of oriented strand lumber made from Asian bamboo has better value compared to its wooden counterparts.

2.1.1 Problems

Majuli, the largest river island in the world, is seriously affected by the erosion of River Brahmaputra and River Subansiri. At Majuli Island every year floods and flood-induced erosion claim people's and animals' live, demolish houses, submerge 80% of the land and destroy villages. The river island is receding every year: Of an area of 1345 km2 in 1891, no more than 640 km2of land was left in 2008. Since 1991 out of 244 villages, 35 have been razed by the rivers.

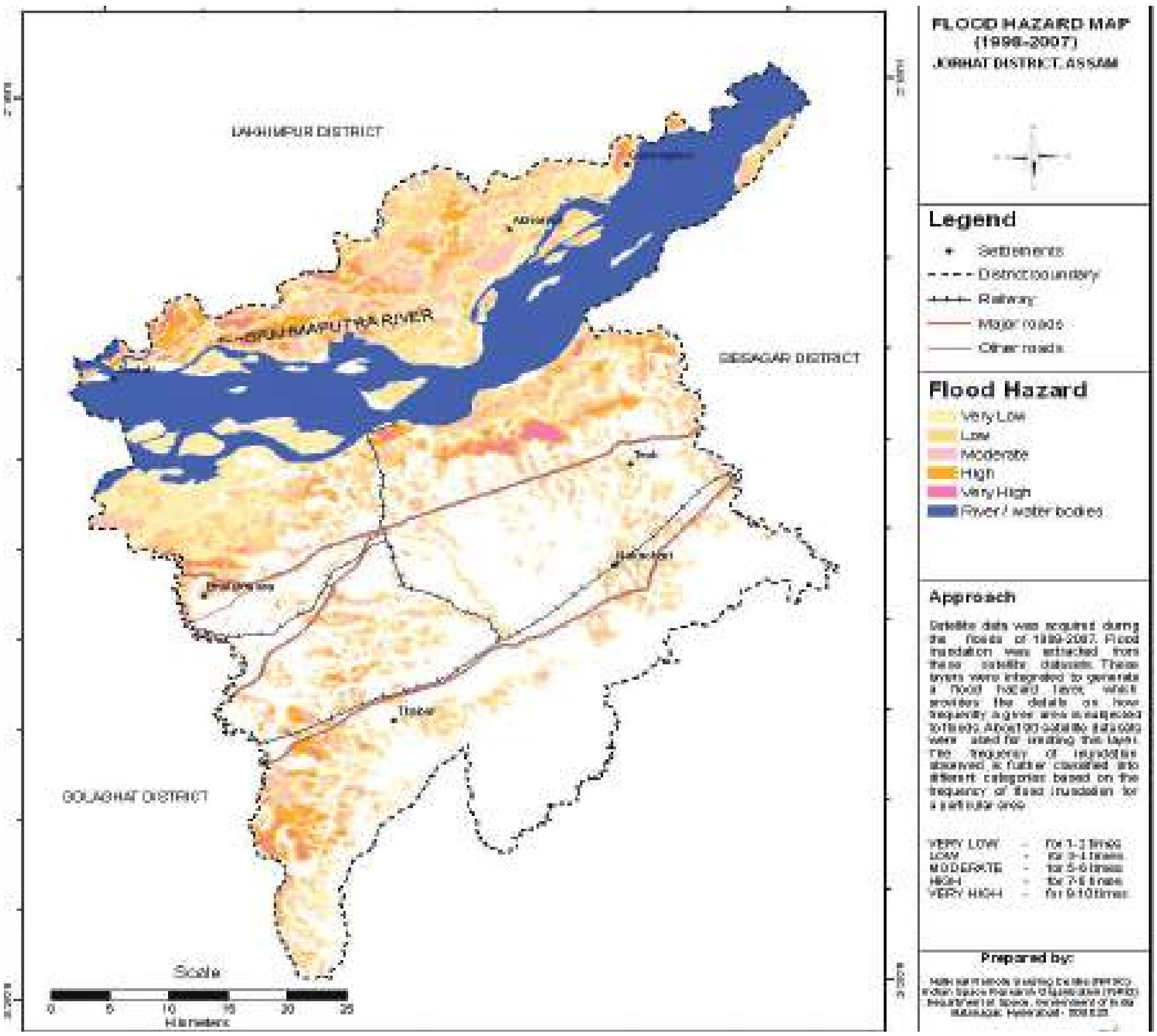


Figure 14. Flood-prone areas
Source: Assam (2008)

Figure 15.(a) Destroyed sandbags

Figure 15. (b) RCC porcupines

Livelihood Loss: Loss of lives and damage to property creates a sense of insecurity in the minds of the people.

Increasing Population: The density of population on the island in 1901 was 24 persons per km2, which went up to 146 persons in 1991. As of 2001, the density of the population is 364 persons per km2. This figure is higher than the 340 persons per km2in entire Assam.

Floods: Today, Majuli faces the dual fury of flood and bank erosion. Floods occur more than once a year. Recurring floods have been affecting the ecological balance, physical landscape, as well as biodiversity in the island. The flood causes havoc among people and their livestock living on the island. Schemes have also been taken up to relieve the drainage congestion in the cities and other important areas.

2.1.2 During floods

Floods occur every year, which is considered a blessing but only if it is in a controlled manner since it brings more fertile soil for agriculture. But when these floods become uncontrolled, the destruction is huge and causes various problems. It destroys both the houses and the crop. The major problem during the floods is of water and sanitation. The villages with 50-70 houses usually lack sanitation facilities. People defecate in open; this creates diseases and an unhygienic situation. During floods

Figure 16. . Bamboo houses under water
Source: Ayang Trust

Figure 17. Aftereffects of flood
Source: Ayang Trust

even these options are not available, which creates a major problem within the villages and people experience skin diseases. Waterborne diseases are also very common in these areas.

Figure 18. Sanitation issues

Apart from floods destroying the houses, they also leave debris that needs to be cleaned to avoid problems and diseases.

Transportation is also a major problem during floods. People use boats for commutation but not everyone owns a boat. The problem is more acute with the differently abled people, as they are unable to travel and remain confined in the house. These are some pictures of the Majuli during the floods.

Figure 19 . Flooding visuals in the neighbourhood

2.2 Flood control measures

The following measures and enable in controlling floods:

- Construction of embankments and flood walls
- River training and bank protection works
- Anti-erosion and town protection works
- River channelization with pro-siltation device
- Drainage improvement/sluices
- Raised platform
- Flood forecasting and warning
- Flood zoning

In 1954, the Government of India declared National Policy on Flood comprising three phases as follows:

1. The immediate: Include revetments, spurs and embankments at selected sites.
2. The short term: Include in its fold construction of embankments and channel improvement covering large parts of affected areas.
3. The long-term: Include the building of storage reservoirs on certain rivers, and additional embankments if found necessary.

To date, the Water Resources Department has taken up works primarily for the general development of the rural sector and for the protection of major townships.

Figure 20. Current course

Phase I:

- Construction of nose of the existing land spurs.
- Permeable screens in the form of R.C.C porcupines (1390 no.)
- Improvement of the road with embankment (50 km)
- Construction of new embankment (18 km)
- Bank revetment work (1.5 m)

Phase II:

- Permeable spurs to be constructed in specific locations in the above reaches (21 no.)

Phase III:

- Land spurs (10 no.) along with bank revetment.

Figure 21. Road as embankment

Figure 22. Road as embankment

Table 1: District Authorities

Government Agency	Resources	Function
Brahmaputra Board	Local office and headquarters in Majuli	Majuli Protection Plan
Majuli Cultural Landscape Management Authority (MCLMA)	Local office in Majuli	Preservation of Majuli's cultural landscape
The Water Resources Department	Office in Guwahati	Welfare services for scheduled tribes and castes
The Fishery Department	Office in Garamur, Majuli	Water services, Seed bank program, Fish and pig culture
The Char-Anchal Development Agency	Office in Garamur, Majuli	Tourism development
The Circle Office	Office in Kalambari, Majuli	Administration
The SDO (Civil) Office	Office in Garamur, Majuli	Administration
The Assam State Assembly Library	Guwahati, Assam	
Gram Panchayat representatives of Salmora, Dakhinpat, and Rawnapar panchayats	Majuli	Village representatives from major villages in Majuli
MIPADC: Majuli Protection and Development Council	Local units in Majuli and Guwahati	Majuli protection, aided with the World Heritage dossier preparation
AJYP: Assam Yuva Parishad	Local units in Majuli	Demands to introduce comprehensive self-government system in Assam
TMPK: Takam Mishing Poring Kebang	Local units in Majuli	Student's organization focused on socioeconomic and political issues of the Mishing Tribe.
KMSS: Krishak Mukti Sangram Samiti	Local units in Majuli	Local organization focused on issues of public distribution systems, land rights, and governmental and corporate corruption.

3. Community: Bijoy Sapori, Majuli Island

Bijoy Sapori is one such village that experiences floods every year; this village is located centrally between a riverine and River Brahmaputra. It comes in Garamur town area of Majuli.

Figure 23. Location map of Bijoy Sapori

Source: Google Earth

Figure 26 shows the geographical location along with the section of the area showing levels. The village has a population of 2000–2500 with 50-60 houses. People live in a joint family along with a good landing pattern of 0.5 bighas to 1 bigha on average. The landscape involves beetle trees, fruit plants and other medicinal plants. The usual structure of the village involves agricultural fields along the river with community ponds surrounding the houses. These community ponds have fish for food and the houses are on the raised platform. Some are built completely on the silts while some are on the ground itself with a raised platform.

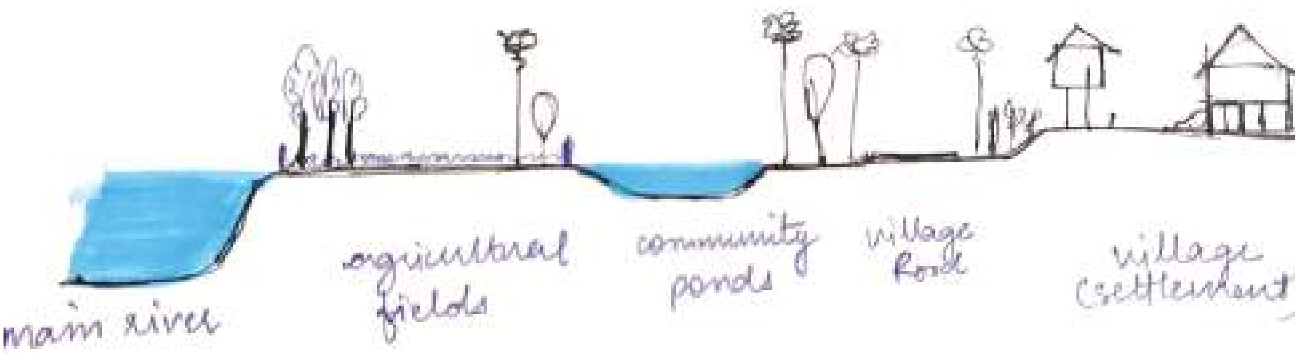


Figure 24. Section sketch

The settlement pattern is linear and parallel to the river with the road on the side of the river. The architecture of the village was bamboo with thatch roof but is now being replaced with modern construction materials. Mixed mode of construction is also preferred and much better than complete modern materials. The houses are categorized into concrete houses (modern construction), concrete and bamboo (mixed mode) and bamboo houses.

Figure 25. Plan sketch

Figure 26. Community pond

The concrete houses have everything made in concrete and brick. This creates higher levels of discomfort in the occupants due to heat.

In a mixed mode of construction, the structure along with the silts are made of concrete, while the walls, floors and roof are made of bamboo, wood and aluminium sheets.

The houses with bamboo are completely made of bamboo, with only a bamboo foundation mixed with concrete or brick.

The living and kitchen areas are together while another structure is built to store for food grains and for washing if any. The space beneath the living structure is used by the women for weaving and domestic animal shelter. The grain structure is much higher than the usual structure to avoid the effects of the high level of floods, while the space beneath it is used for storing agricultural instruments and machinery.

Figure 27. Concrete and bamboo

Figure 28. Village visuals

Housing Typology

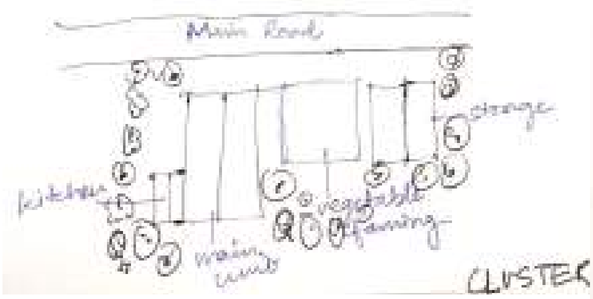


Figure 29. A single house plot

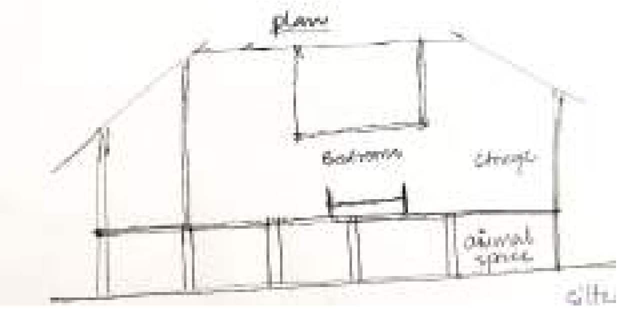


Figure 30. Section

The entrance to the house is through a wooden staircase to a porch where all the family members sit in the evening. This also serves as a place where guests are seated. The living space or bedroom is common. Bamboo furniture is used within the houses. The rooms are separated through bamboo partition walls.

Figure 31. Front elevation

Figure 32. Bedroom

Figure 33. Kitchen area

Utensils are washed outside the kitchen and in open. Usually, water is pumped from the handpump placed at the level of the house, while some houses that cannot afford these pumps bring water from the neighbourhood or government water facilities.

Figure 34. Washing utensil area

Figure 35. Storage

The interesting part of these vernacular houses is the patterns and indigenous bamboo art used. These have both aesthetic value and function value. The following figures depict some of the patterns being used in the houses.

Figure 36. Floor mat pattern

Figure 37. Furniture mat pattern

Figure 38. Wall mat pattern

Figure 39. Ceiling mat pattern

Figure 40. Ventilation jali pattern

Figure 41. Floor mat pattern

The landscape of the village is highly beneficial for the villagers in terms of economy and thermal comfort. The government water facilities are being set up, which are powered by solar panels.

Figure 42. External landscape)

Figure 43. Village water facility

4. Floating Infrastructure Implementation

The term "amphibious" means that the house must preserve the same functionality in both dry and flooded conditions. This means it must be able to shift from floating on water to on land interchangeably. This feature and cost are the greatest challenges. The timeline illustrates the stages of challenges posed by amphibious housing.

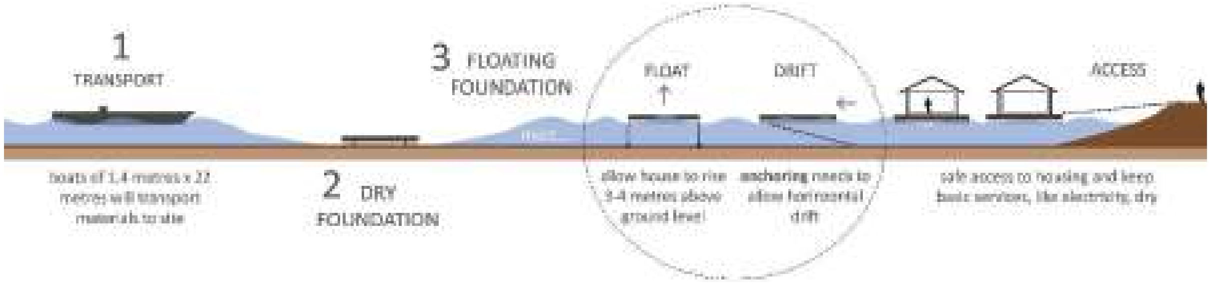


Figure 44. Foundation forces

The stability of the floating house must be preserved while water depth rises and falls. The sinking of the building in the muddy, swampy soil can restrict the uplifting forces needed for floating. The structure must always be able to float fast enough so that no water flows on the top of the base and into the house. Anchors will connect the floating foundation to the soil, limiting horizontal drifting.

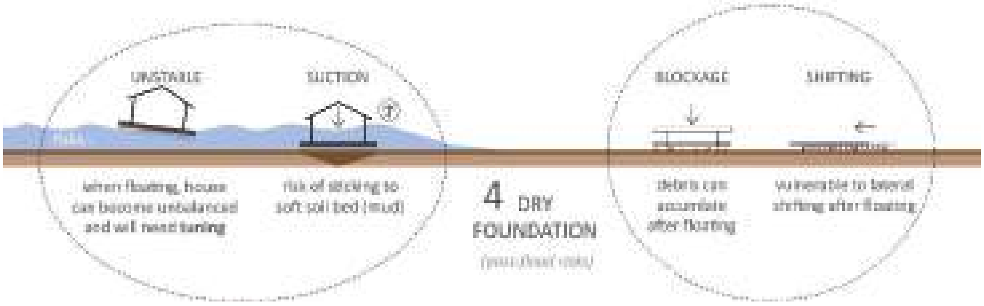


Figure 45. Post flood risks

After a flood when the house descends, debris, such as a tree trunk, can get stuck under the base and cause the house to be inclined and creating problems for the inhabitants. This can be combated by using jacks to uplift and remove debris and wedging for positioning. There is a risk that the house will not return to an acceptable position. The chains/ropes must be designed in such a way that the whole structure will always end up within a range of acceptable positions, minimizing lateral shift.

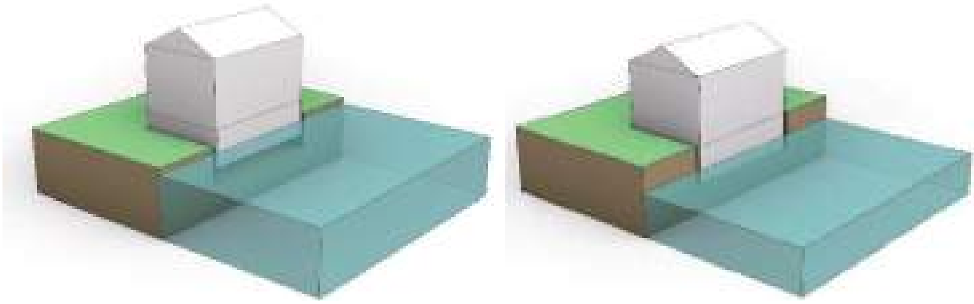


Figure 46. Amphibious foundation option 1

4.1 Conceptual Design for Floating Foundation

In this research, the study drives the design to make it vernacular, using existing materials on the location. So, a hybrid design strategy is adopted. Initially, the design was prepared with empty barrels and cast concrete method.

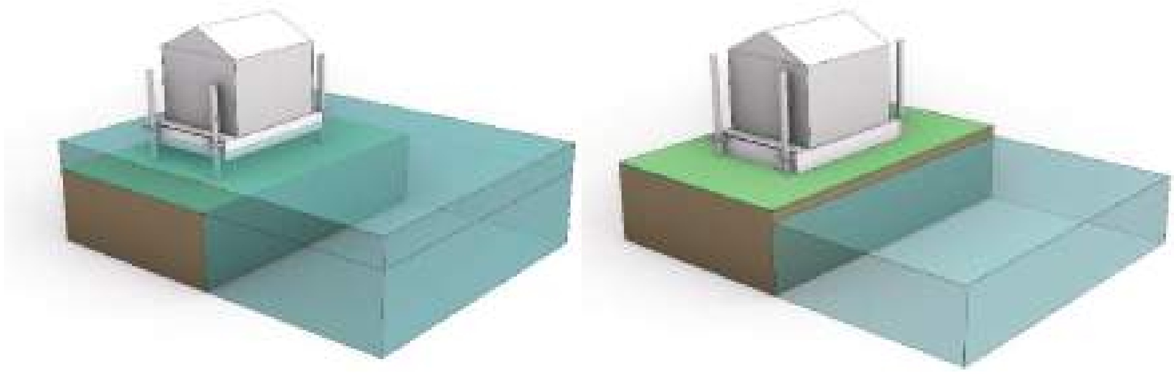


Figure 47. Amphibious foundation option 2

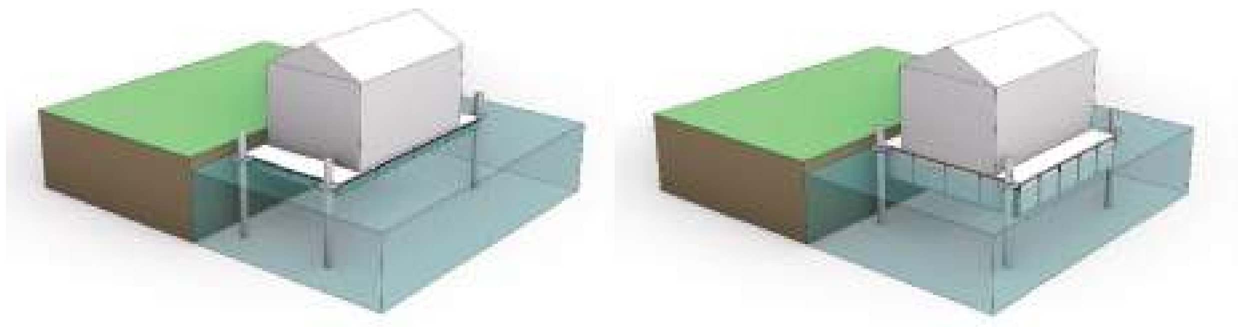


Figure 48. Amphibious foundation option 3

The initial stage is to understand the existing types of floating foundations that can be adapted to the amphibious structure for both social and economic benefits. The foundations are usually modular based, so it is easy to transport and assemble on the site. The other type is locally made with the existing resources. The following figures show the study of different typologies. Starting with the container steel barges, modular barges, floating pontoons, concrete, and the vernacular style.

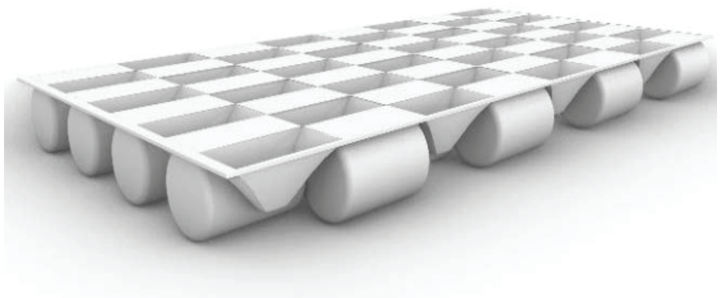


Figure 49. Concrete with drums amphibious foundation

Later, the concrete is changed to bamboo structure, to be feasible for its buildability on site and with the abundance of bamboo in that region. This design gives more stability to withstand the superstructure. It is also a modular design so it is easy to suit the community requirements. The egg crater-like design gives an advantage over the force from the river flow and the void spaces give a possibility for harvesting hydropower. The stability test and force will be carried out on this design and modifications will be adopted.

Figure 50. Platform

Figure 51. Floating vernacular platform)

4.2 Single unit design

Functional requirements include the following:

- Living
- Bedroom
- Kitchen and toilet
- Learning/sleep area
- Typical single-unit design

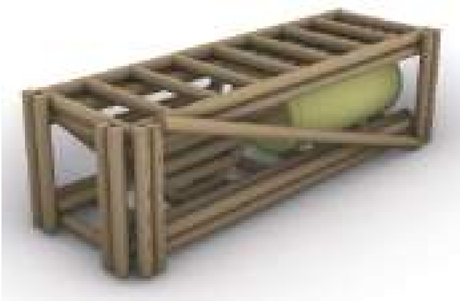


Figure 52. Bamboo and drum

These are the designed platform, plastic barrels with bamboo. The anchored bamboo is mixed with concrete footing. The superstructure is made of bamboo patterns in accordance with the culture-specific patterns.

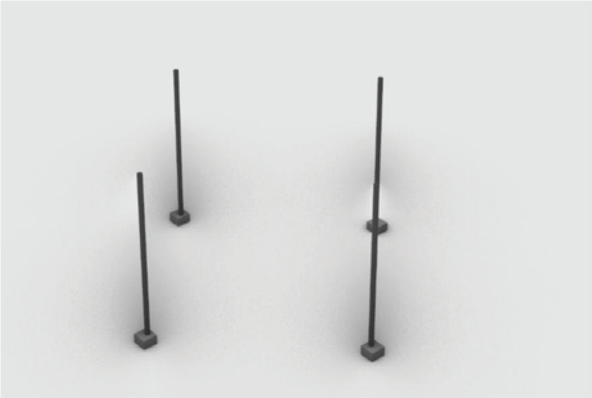


Figure 53. Bamboo columns with concrete footing

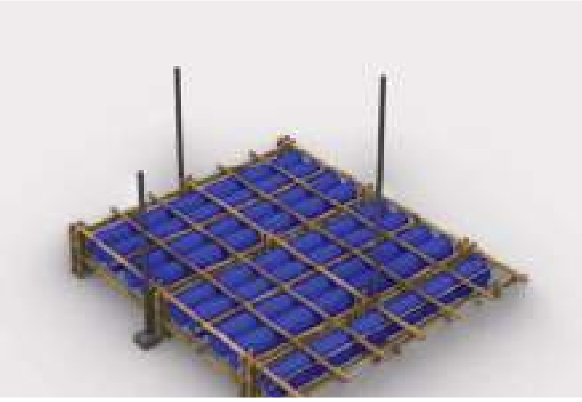


Figure 54. Amphibious foundation

Figures 55 and 56 depict the visuals of the typical house that can be scaled up to create a community.

Figure 55. Superstructure with bamboo traditional patterns

Figure 56. Upper floor

Figure 57. 3D View of the structure

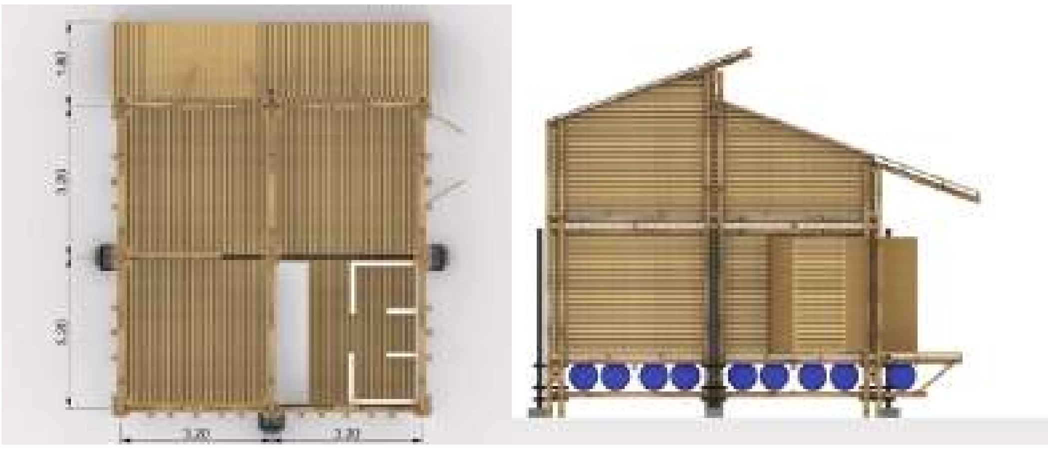
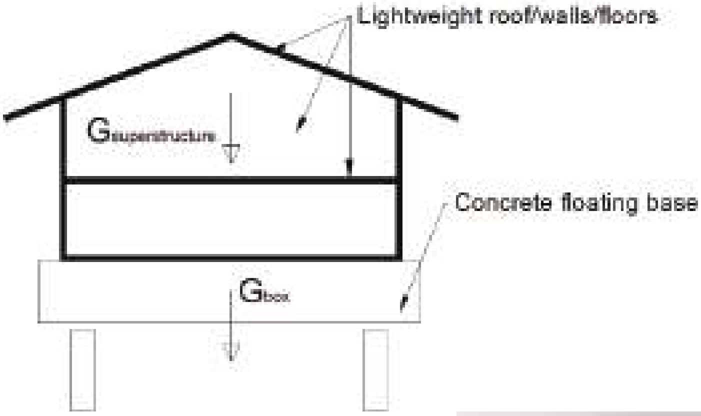


Figure 58. Plan and section

Figure 59. Elevation and floating situation

Size of the unit	- 6.80m × 8.40m
Usable space	- 4 modules × 3.20 m × 3.20 m
Total usable space in one unit	- 70 m2 (for 6-8 ppl)
Size of floating foundation	- 6.80 m × 8.40 m
Foundation depth	- 1.20 m
Diameter of a barrel	- 0.590 m
Height of a barrel	- 0.869 m
Volume of barrel	- 0.51271 m3
Weight of a barrel	- 9.979 kg
Fully immersed barrel lift capacity	- 502.731 kg
Half immersed barrel lift capacity	- 251.3655 kg
¾ th immersed barrel lift capacity	- 377.04825 kg
54 barrel lift capacity	- 13,573.737 kg (half immersed)
Draft height	- 0.355 m
Foundation weight	- 813.19 kg
Superstructure weight	- 5,082.731 kg
Family of 6 members(avg)	- 300 kg
Family of 8 members(avg)	- 420 kg
Weight of utilities and others	- 1000 kg
Total weight of the structure	- 6,895.921 kg + live load
Free board height	- 0.7 m under the above weight



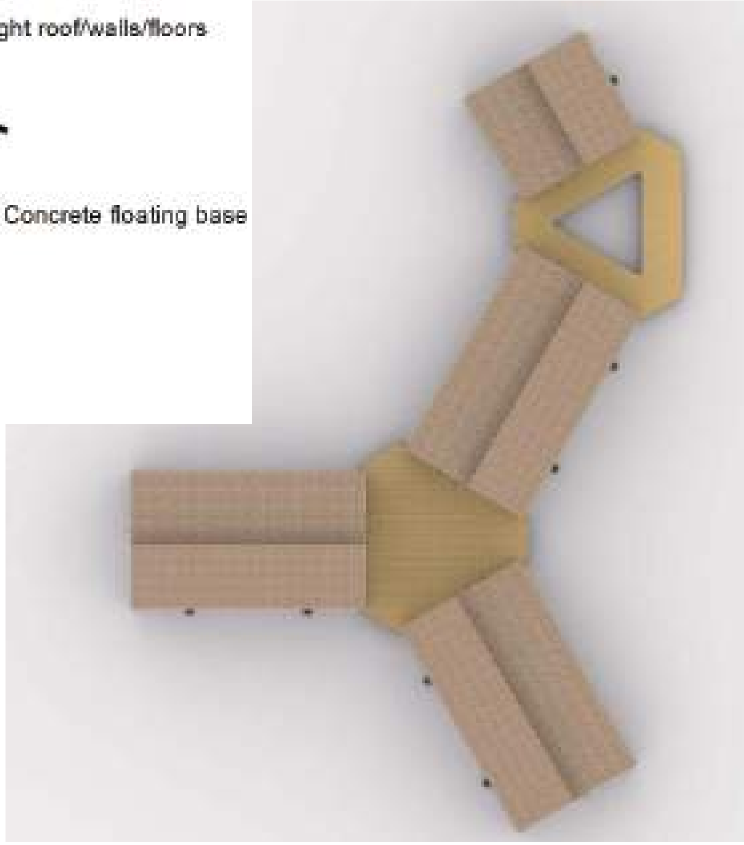


Figure 60. Cluster formation plan

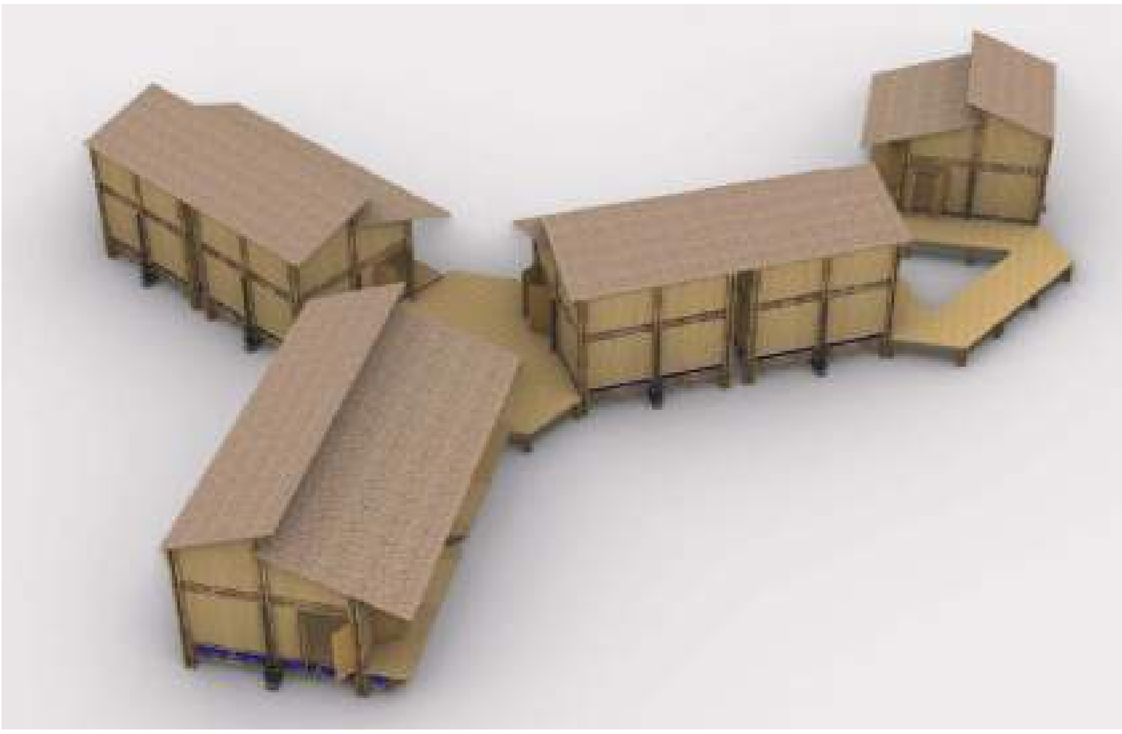


Figure 61. Cluster Formation – 3D

4.3 Net-zero water

- Rainwater collected per day 108 L with an area of 10 m2 with 360 mm of rainwater highest in the month.
- Usually, a flood lasts for 7 days, so the tank capacity is as per holding water for 7 dry days. Although during flood fresh rainfall also happen, so the total capacity of 800 L is enough.
- This water would cater to the ablution and sanitation of the community.
- Each sanitation block will have rainwater harvesting tank capacity of 400 L
- The wastewater from washrooms cannot be discarded directly into the flood waters or in open during dry days. Thus, this water will be treated to avoid waterborne diseases.

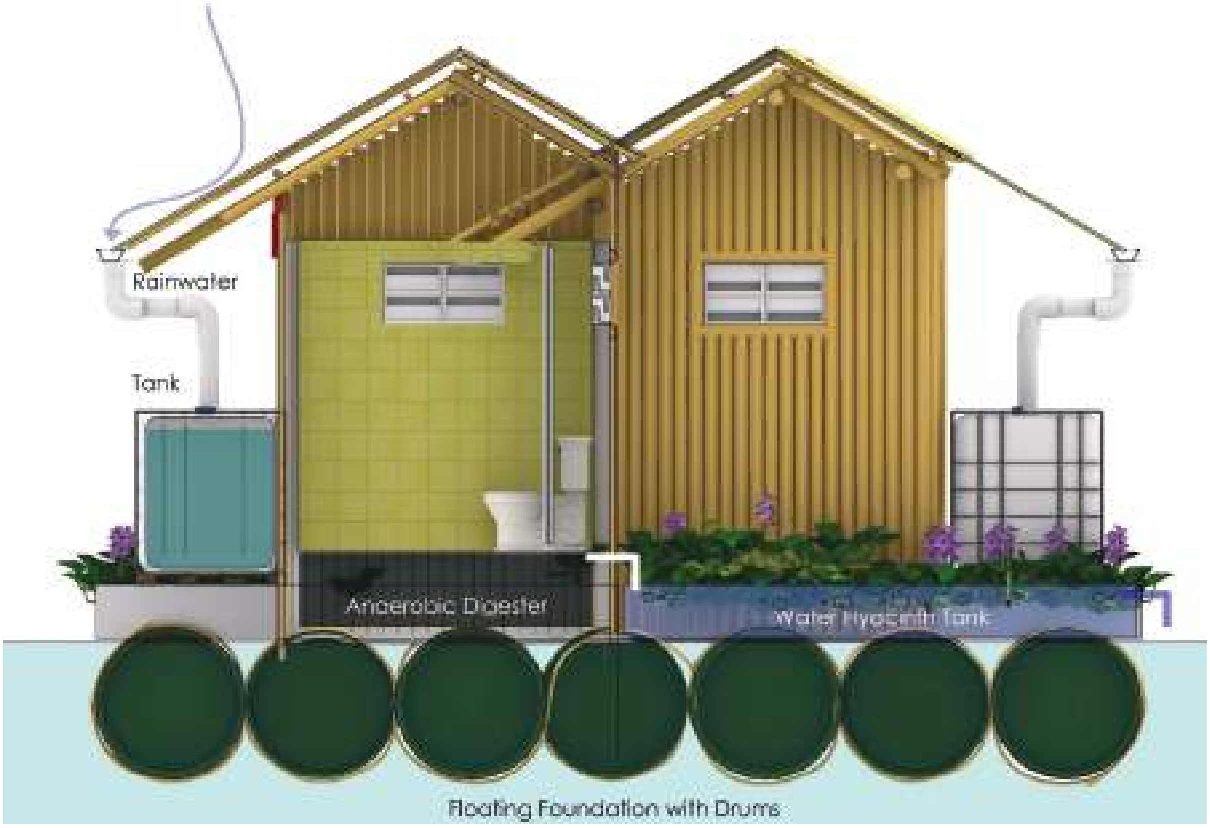


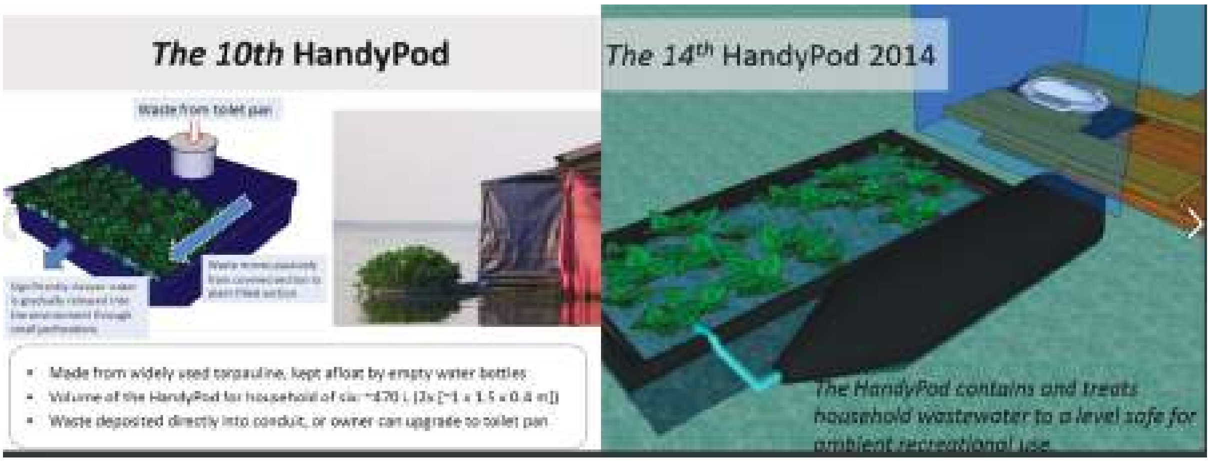
Figure 62. Sanitation block section

Wastewater treatment will be done in two stages. The first will start when the wastewater is flushed into the tank beneath the toilet. This tank gives a few days of septic containment. This is where the anaerobic digestion will take place.

The second stage will start when after containment of the first tank fills and passively moves to the next tank where water hyacinth is present. These respond to waste as food and perhaps clean the water.

4.4 Handy pod

Handy pod is appropriate for almost all challenging sanitation environments, including floating, flood-prone, high groundwater table, beach sand, and impermeable soil (rock/clay) environments.



The "Pod" features require minimum to no maintenance, excellent treatment, easy assembly, long life use, stability in extreme storm events, no moving parts, no odour, no mosquitoes and no chemical or electrical inputs. It is a desirable product that, with the provision by local businesses and with smart subsidy financing programmes for economically poor households, can enable wide adoption of sanitation in challenging environments.

4.4.1 How is the wastewater treated?

The Handy Pod is composed of two stages of treatment sized for the number of people using the latrine, be it a school or a household. The first stage receives the waste and pour-flush water from the latrine pan. This stage provides several days of septic containment which then, with additional pour-flush usages, flows passively by gravity into a second three-day containment stage of treatment. This second stage involves thousands of different species of naturally occurring microbes responding to the waste as food, including significant predation on the pathogens. This second container has an extensive internal surface area; on this surface area, a microbial biofilm develops, which absorbs the chemicals and particulates that sustain the metabolism and ecology of the microbes. Due in part to the warmth of the tropical climate, a tremendous amount of microbial activity takes place in both the stages. In particular, the second stage design for microbial biofilm activity provides a treated effluent that results in “safe ambient water” next to the second stage’s discharge pipe.

4.4.2 Water sanitation flow

Inputs

1. Freshwater from rainwater storage
2. Freshwater from ground

Outputs

1. Urine Separating Toilets - Urine and Stool Water
2. Urine - Struvite Reactor - Storage
3. Stool Water - Anaerobic Digester - Water hyacinth - Storage

5. Conclusion

Floating architecture is the future solutions of the problems of sea-level rise and is currently the solution for flood-prone areas. Its implemented as a form of amphibious platform. The retrofitting can be done after careful investigation of the existing structure while for the new structure amphibious option ability can be integrated with the built structures. These structures are now needed to be integrated with the government disaster-resilient structures.

One such structure can be created in each village of flood-prone areas where this structure can act as a healthcare, education, community centre or even gram panchayat centre for the villagers during the dry season while as a disaster-resilient shelter during the disasters. The idea of creating a multifunctional space will make it more relevant to implement and cost-effective. The innovation and technology have to be integrated to create it self-sustainable and self-reliant. The energy-neutral systems can be possible for these floating houses.

The people living in low-lying areas along the river and around the coastline cities will be most beneficial from these floating architecture. Also, the low-income group of industrialized countries who face the impacts of rising sea levels especially in South Asia will be benefitted. To make these amphibious or floating house viable, energy systems that would make these systems net zero promotes them and contribute to the sustainable development goals. Further research will be done on the implementation on site a prototype of the community centre.

References

1. Begum, H. (2020). Climate Change and Natural disaster : A Case Study of Flood affected Women of Assam, North-east. *International Journal of Academic Research and Development*, 05(01), 67-70. Details available at http://www.academicjournal.in/archives/2020/vol5/issue1/5-1-31.
2. Bhattacharjee, S., & Mukherjee, N. (2017). Floating houses: A design for flood resilience innovations in Bangladesh. *Proceedings of 33rd PLEA International Conference: Design to Thrive, PLEA 2017*, 3(October), 5149–5156.
3. Greenprint Schoonschip. (2021). Details available at https://greenprint.schoonschipamsterdam.org/
4. Habibi, S. (2015). Floating building opportunities for future sustainable development and energy efficiency gains. *Journal of Architectural Engineering Technology*, 04(02), 3–9. https://doi.org/10.4172/2168-9717.1000142
5. Kapsalaki, M. (2012). *Economic - efficient design of residential net zero energy buildings with respect to local context*. Details available at https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwii7-2hvv3LAhUhCpoKHQsFCA4QFggdMAA&url=https://repositorio-aberto.up.pt/bitstream/10216/68186/1/000155028.pdf&usg=AFQjCNEC5Yu9LIokgd5EA4iqv3thrcMHmA&sig2=1Zmg2g7shH
6. Kumar, Ankur, V., & Singh, N. R. (2018). Disaster resilient design strategies through vernacular practices: Case study of Majuli Island and Bakkhali, India. *Proceedings of the Annual International Conference on Architecture and Civil Engineering*, 216379, 538–547.
7. Maclay Architects. (2015). *Net Zero Energy Feasibility Study Full Report*, Efficiency Vermont: USA. 1-90.Details available at: https://www.efficiencyvermont.com/Media/Default/docs/white-papers/efficiency-vermont-net-zero-energy-feasibility-study-final-report-white-paper.pdf
8. Mäkinen, S. (2015). *Future Floating Community for Singapore 2030*. Details available at https://aaltodoc.aalto.fi/handle/123456789/19662
9. Moosa, A., Do, K., & Jonescu, E. (2020). Design response to rising sea levels in the Maldives: A study into aquatic architecture. *Frontiers of Architectural Research*, 9(3), 623–640. https://doi.org/10.1016/j.foar.2020.04.002
10. Neuman, R. (2020). Paving the waves. *World Conference on Floating Solutions*, Rotterdam, NL. Details available at https://www.pavingthewaves.org/
11. Occurrences, E. (n.d.). *Documentation_on_Past_Disasters, their impact, Measures taken, vulnerable areas in Assam*. 1–32. Details available at: http://www.mati.gov.in/docs/Training%20Materials%20DMC/Disaster%20Concepts/doc umentation_on_past_disasters.pdf
12. Owen, C. L. (2004). *Aquatecture Macro-design Projects on the Theme : " Water " Mobile Offshore Industry.* Details available at https://id.iit.edu/wp-content/uploads/1986/06/Aquatecture_patterned-energy.pdf
13. Petrie, G., Quirk, J., Stopnitzky, S., Weigner, P., Aljets, P., Suarez, L., Jacobus, E., Goldhaber, B., Ryjikov, E., Taylor, M., Green, S., & Khaleel, H. (2014). *The Floating City Project* (Issue March 2013).

14. Pool, M. (2020). Paving the waves. *World Conference on Floating Solutions*, Rotterdam, NL. Details available at https://www.pavingthewaves.org/
15. Prosun, P. (2011). The LIFT House : An amphibious strategy for sustainable and affordable housing for the urban poor in flood-prone Bangladesh. *In A Thesis presented to the University of Waterloo in fulfillment of the thesis requirement for the degree of Master of Architecture Waterloo.*
16. Roy, N., Pandey, B. W., & Rani, U. (2020). Protecting the vanishing geo-cultural heritage of India: Case study of Majuli Island in Assam. *International Journal of Geoheritage and Parks*, 8(1), 18–30.
17. Sarma, A. (2014). Landscape degradation of river island Majuli, Assam (India) due to flood and erosion by River Brahmaputra and its Restoration. *Journal of Medical and Bioengineering*, 3(4), 272–276.
18. Schoonschip Amsterdam. (2021). Details available at https://schoonschipamsterdam.org/
19. Voos, K., & Musall, E. (2013). *Zero energy house*. In D.-I. Cornelia Hellstern, Dipl.-Ing. , Kim Ahrend, Jana Rackwitz (Eds.), Kösel GmbH & Co. KG, Altusried-Krugzell.
20. Wang, C. M., & Wang, B. T. (2015). *Large Floating Structures : Technological Advances*. Details available at http://swbplus.bsz-bw.de/bsz416043380cov.htmhttp://dx.doi.%5Cnorg/10.1007/978-981-287-137-4

Intertwined Natures Adaptation to Climate Change Using Green and Blue Infrastructure in Lambayeque, Peru

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Under CDRI Fellowship Programme 2021-22

CDRI
Coalition for Disaster Resilient Infrastructure

Universidad de Piura

Abstract

This project presents the design of green and blue resilient infrastructure in Chongoyape, Lambayeque, Peru. The final product is the intertwining of design processes, which results from the active reading of the place. The methodology used in the project comprises research through design, resulting in spatial explorations in the form of mapping and transformative models. The aim of this project is to answer the research question: How can green and blue infrastructure be designed in Chongoyape for the town to be climate adaptive? An important part of the methodology focuses on the exploration of site specificity as a design tool to achieve sustainability in socio-ecological systems, which claims the capacities of resilience and adaptation as its essential components. The this project in Chongoyape is proposed from the need to mitigate the social, infrastructural and economic damages caused by El Niño-related events. Nature-based solutions are presented as a solution to respond to this panorama. Furthermore, the validation of the project is realized through phasing of the project and participatory actions.

Acknowledgments

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The completion of this project could not have been accomplished without the assistance of Andrés Wong, especially regarding logistical ventures, and, María Alejandra Chinguel and Valeria Chávez, for their effort in helping during the initial stages of the project.

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1. Introduction

The economic growth of the last decades in Peru has led to visible migrational movement towards urbanized areas. In the northern region of Lambayeque, this is illustrated by the gathering of the population in Chiclayo, the capital of the region. This comprises human interaction outside of the natural and rural environments, which accounts for almost 50% of the total territory of Lambayeque.

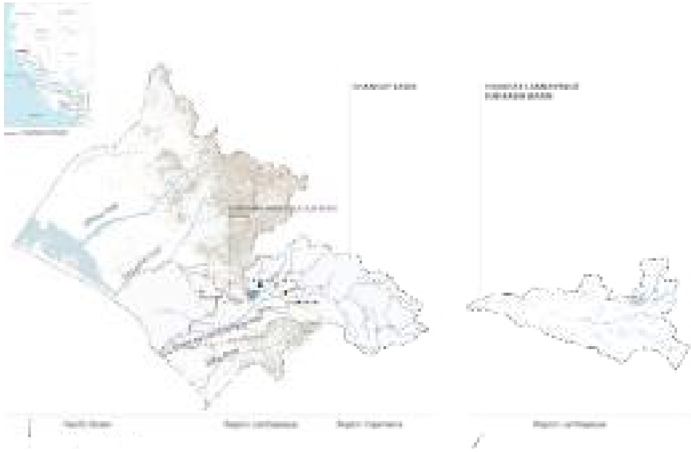


Figure 1. Location of Chancay-Lambayeque sub-basin, Lambayeque region, Peru

1.1 Flood risk

Every 2 to 7 years, Peru is affected by El Niño phenomenon from December to March. This results in heavy rains, flooding, mudslides, the extreme rise in temperature, diseases outbreak such as cholera that in the past led to epidemics. The drastic temperature changes caused endemic fauna and flora to succumb. Additionally, the national GDP decreases by 5-7%, which in current numbers accounts for 10 000 millions US dollars (Wong, 2018).

Table 1. Average catchment rate of main rivers of the region, compared with El Niño phenomenon 1998

River / Anual Catchment Rate	Average	El Niño Phenomenon 1998
Chancay-Lambayeque	850 Hm3/year	3000 Hm3/year
La Leche	165 Hm3/year	1800 Hm3/year
Zaña	850 Hm3/year	1200 Hm3/year

Source: Made by author with data from Hydrological Development Plan of Lambayeque Region

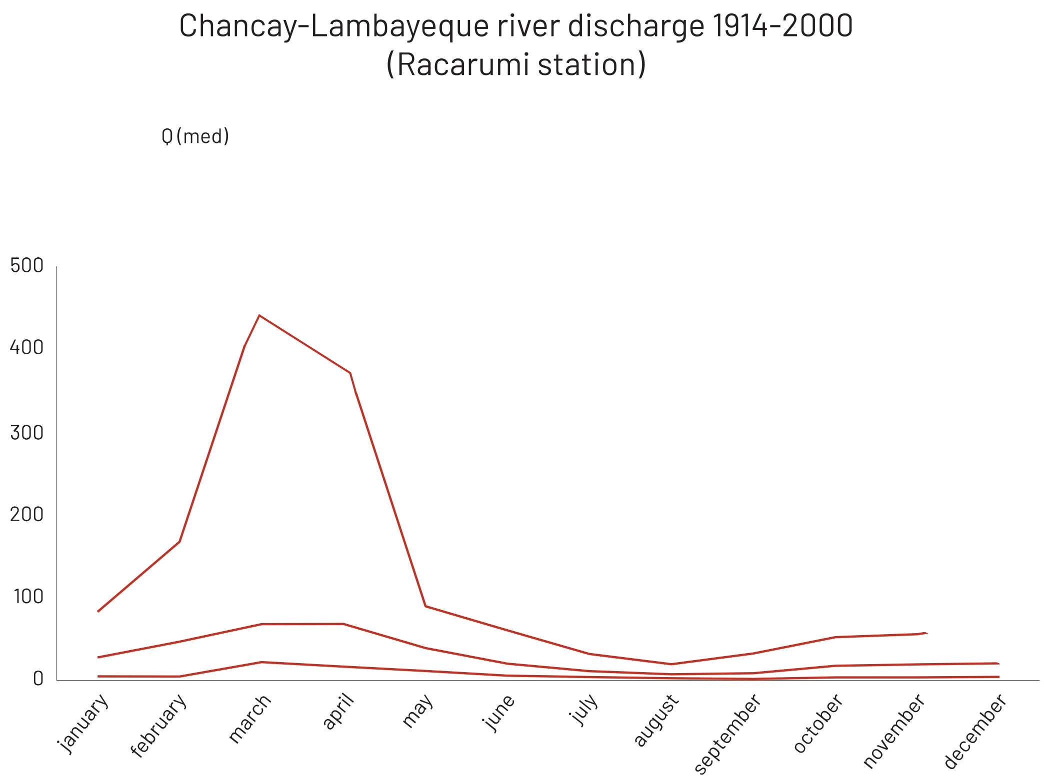


Figure 2. Chancay-Lambayeque river discharge 1914-2000 (Raca Rumi station)

Source: Made by author, 2022, with data from Asesores Técnicos Asociados (2002)

The overarching aim of intertwined natures is to design resilient green and blue infrastructure in Lambayeque, as well as to create an understanding of water as an ecological, economic and social asset, instead of unveiling negative impressions of destruction about it. Furthermore, the concept of resilience and adaptive capacity inform the research project resulting in a sustainable project that is able to absorb unexpected changes. Moreover, the second objective of the project is to create collaboration bonds between academia and common citizens in order to create awareness and educate local communities by making the information available and easy to grasp for all.

El Niño phenomenon is a recurrent natural disaster affecting Peru. However, it is devastating consequences are still suffered, given that the solutions proposed by the national government are not sustainable. The current disaster response plan lacks an integrative strategy and is not successful most of the time. It focuses on canalizing water courses, cleaning lower parts of the rivers and relocating people who live in hazardous zones. These plans are reactive and mainly focus on hard-engineering structures with no proper research about improving the ecological matrix. From the aforementioned context, an enormous opportunity for building nature-based infrastructure arises, combining theoretical principles such as resilience and adaptive capacity into spatial interventions, taking into account the interactions and processes of human and non-human species. Moreover, by aiming to educate and create awareness as well as achieving a new equilibrium in the territory, a sustainable development is proposed.

1.2 Three natures

The title of the research project shares the title and its origins with the MSc thesis 'Intertwined Natures. Towards Territorial Cohesion & Flood Risk Adaptation in Lambayeque, Peru'. The title originates from the theory of the 'Three Natures' coined by John Dixon Hunt, in which 'the first nature refers to wilderness and natural landscapes, the second nature refers to agriculture, urban development, and infrastructure. The third nature refers to highly designed landscapes, comprising ideas and experiences, which are reflections of the processes of the first and second natures' (Wong, 2018, p.17), resulting in spatial interventions, which is translated into the final proposed design.

Figure 3. First and second natures of the surroundings of Chongoyape

Source: Made by author, 2021

Figure 4. Landscape, infrastructure, built tissue related to the water system

Source: Made by author (Photographs in the diagram were taken by the author)

1.3 Chongoyape as a testing ground

Chongoyape is considered the entrance point of the Chancay-Lambayeque river in the Lambayeque region. In fact, when meandering through the neighbouring Cajamarca region, it is called Chancay river.

Chongoyape has an altitude of 209 meters above sea level and a population of 18,364 inhabitants (INEI, 2017). Its main challenges regarding natural phenomena are river flooding and mudslides.

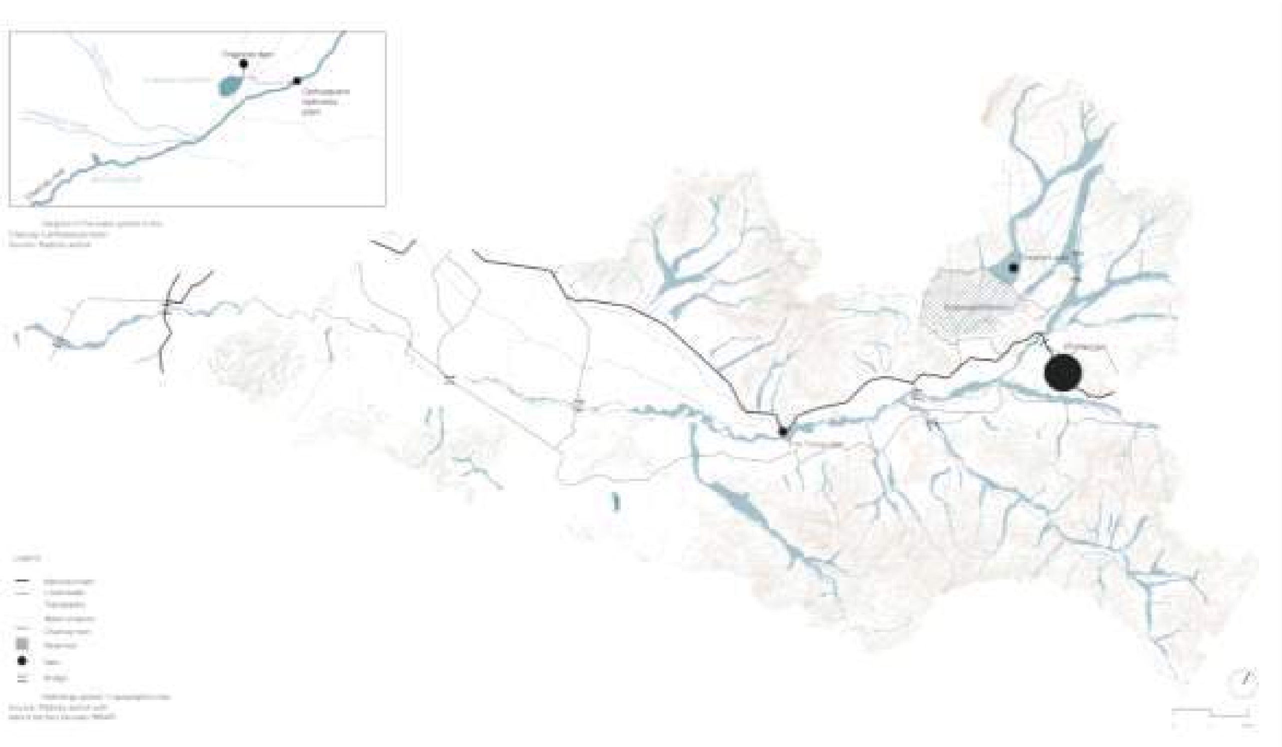


Figure 5. Hydrology system of the Chancay-Lambayeque sub-basin

Source: Author (2018)

In order to understand the features of the site in a systematic and multiscalar way, the tool of site specificity is introduced to understand the territory. Site specificity places the experiences and physical attributes of a given landscape on the same level of importance. By placing experiences, not just programmes or events, in such an assertive scene, the human agency is taken as a crucial piece of the ecosystem.

2. Research Problem

Economic development led to massive population movement to urban environments, causing a myriad of challenges such as climate variability, occupation of hazardous areas, heat island effect, alteration of hydrological regime increasing vulnerability in the case of climate change and natural disasters. This scenario is directly linked to the current COVID-19 pandemic. According to the Biodiversity and Pandemic report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, the risk of pandemics grows at an exponential speed, which are mainly caused by anthropogenic changes, manifesting themselves in five new diseases in humans each year. One of the greatest risk factors are changes in land use, due to the intensification of agriculture and livestock, since by breaking the natural balance, zoonotic infections –infections capable of mutating from animals to humans– are increasing at an alarming rate (IPBES, 2020).

'Natural disasters have mainly triggered water related issues such as floods, increase of river flows, extreme rainfall –10 times higher amount than average–drought, pollution, among others' (Wong, 2018, p.33). According to Tucci (2009) floods resulting from natural disasters are the main vulnerability suffered by developing countries. Moreover, natural disasters intensified due to climate change, leaving behind productive land, infrastructure, and devastated towns, affecting mostly vulnerable population.

In the Peruvian case, El Niño affects the country resulting in heavy rains, floods caused by higher levels of river streams, landslides, extreme temperature, diseases such as cholera and finally, large losses of endemic fauna and flora (Wong, 2021a).

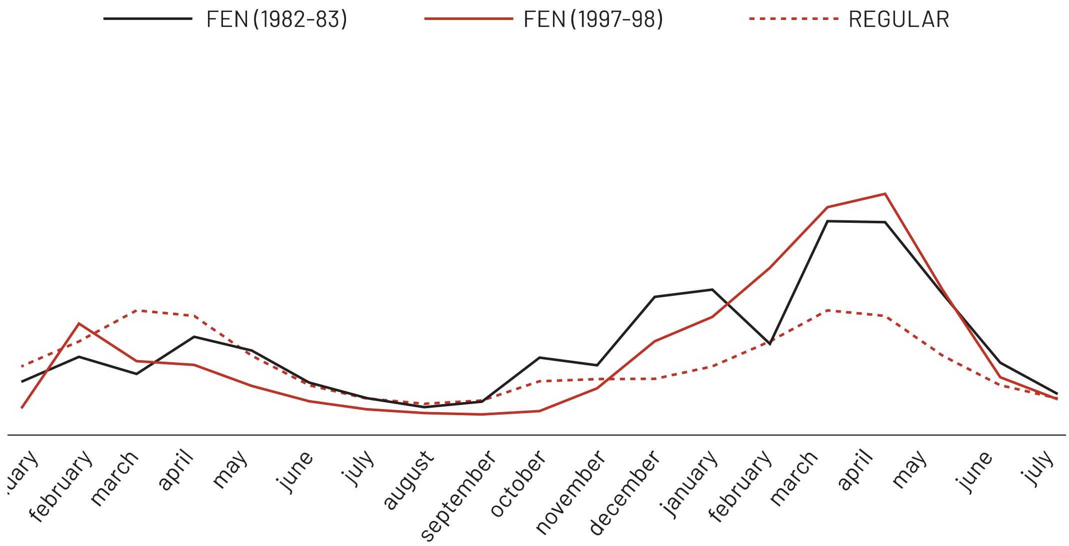


Figure 6. Chancay-Lambayeque river discharge during El Niño Phenomenon (FEN) 1982–83, 1997–98

Source: Made by author, 2022, with data from Estudio Geoambiental de la Cuenca del Río Chancay-Lambayeque Boletín 33 Serie C, Geodinámica e Ingeniería Geológica

Due to climate change, new and more acute climate patterns emerge. In 2017, 'Coastal El Niño' hit Peru and Ecuador. Its consequences were even more extreme than the ones resulting from El Niño phenomenon: 14 out of the existing 25 regions of the country were declared in state of emergency, leaving more than 200 casualties, 1097859 affected population and thousands of houses and critical infrastructure collapsed, leaving entire communities isolated. Moreover, several disease outbreaks occurred, declaring 9 regions in the state of health emergency, while vast productive areas were flooded resulting in large economic losses, given that agriculture is the main economic activity. The total economic loss accounted for 3104 million US dollars.

The dichotomy of the water-related challenges of the region of Lambayeque can be summarized as follows: on the one hand, the region suffers from excess of water, mainly driven by natural phenomena, getting more acute due to climate change. On the other hand, the region is part of the Peruvian coastal dry forest zone, which means that most of the territory is located in a desertic climate, which, in turn, can be translated into drought seasons. The acuteness of the last remark is particularly important to a great degree since the main economic activity in the regions is agriculture. Moreover, the dominant crops cultivated are rice and sugar cane, which need high amounts of irrigation to thrive.

Figure 7. Dichotomy of water-related challenges: flooding and drought
Source: Made by author for IFoU presentation, 2021 (Photographs were taken by the author)

The Lambayeque region was one of the most ravaged during Coastal El Niño 2017, where images from despair from the natural disaster were combined with the lack of planning and overuse of hard engineering infrastructure. From the former panorama, the following research question came to light: How can green and blue infrastructure be designed in Chongoyape for the town to be climate adaptive?

Figure 8. Diagram of an exaggerated section of the Chancay-Lambayeque sub-basin
Source: Made by author, 2022

3. Aim, Objectives, and Scope of the Research Study

The research question of this project was presented in the former point: How can green and blue infrastructure be designed in Chongoyape for the city to be climate adaptive? The overarching aim of Intertwined Natures is to design resilient green and blue infrastructure in Lambayeque, and to create an understanding of water as an ecological, economic and social asset, instead of unveiling negative impressions of destruction about it. Furthermore, the concepts of site specificity and landscape legibility are taken into account in order to develop a truthful landscape urbanism project. These accompanied by resilience and adaptive capacity inform the proposed design of a capacity to adapt and transform while facing unexpected changes, such as the ones resulting from flooding or drought.

The second objective is to break barriers between academia and common citizens, creating collaboration bonds through a website and social media channels, in order to create awareness and educate local communities, by making the information available and easy to grasp for all. The objective of the webpage is to share data, design experiments, local tales, photographs and video journeys, in a language that is easily understood by the whole community. Moreover, by aiming to create a regional identity and awareness as well as achieving a new equilibrium in the territory, more sustainable development is proposed. Finally, the innovative method of interlinking theoretical principle and design interventions makes this research project a powerful tool for propagating this kind of ventures, solving hypothesis from the academic world to challenges in the real world.

4. Methodology

The departure point for this research project is to put forward the idea of landscape urbanism in the form of green and blue infrastructure design in the region of Lambayeque, specifically in the town of Chongoyape, in order to mitigate flooding; taking into consideration the array of tools, methods and interventions that arise from the coalition of urbanism, landscape architecture and ecology in order to understand the urban, rural and natural landscapes as living ecologies and agents of change.

4.1 Research through design

Research through design – also called 'research on design'– is a process approach. This means that the research develops through research questions, methodology, collection of data, analysis of data, designing and reporting of the results. (den Brink, 2017; Nijhuis & de Vries, 2020). Observation, digital surveys, interviews and mapping were used as data collection instruments in order to gather local information, not just from the site itself but from the people that inhabit that place. This is a methodology where design is used as an umbrella for research, as a way of exploring spatial possibilities in order to generate innovative results, where the term 'design is understood as a form of research' (Nijhuis & de Vries, 2020, p.87), and relates to a research method in which planning and design are the main features (ibid.).

The objective of the project is related to climate change adaptation, more specifically to achieve a new equilibrium in Chongoyape. In this particular case, design exploration is comprising The Agency of Mapping in a way that mapping is not just understood as tracing, but as a way of getting to know the site, considering 'mapping as an active agent of cultural intervention' (Corner & Hirsch, 2014, p. 200).

The proposed nature-based solutions will be achieved through research and design methodology, where design is used as an umbrella for research to explore possibilities and generate innovative results.

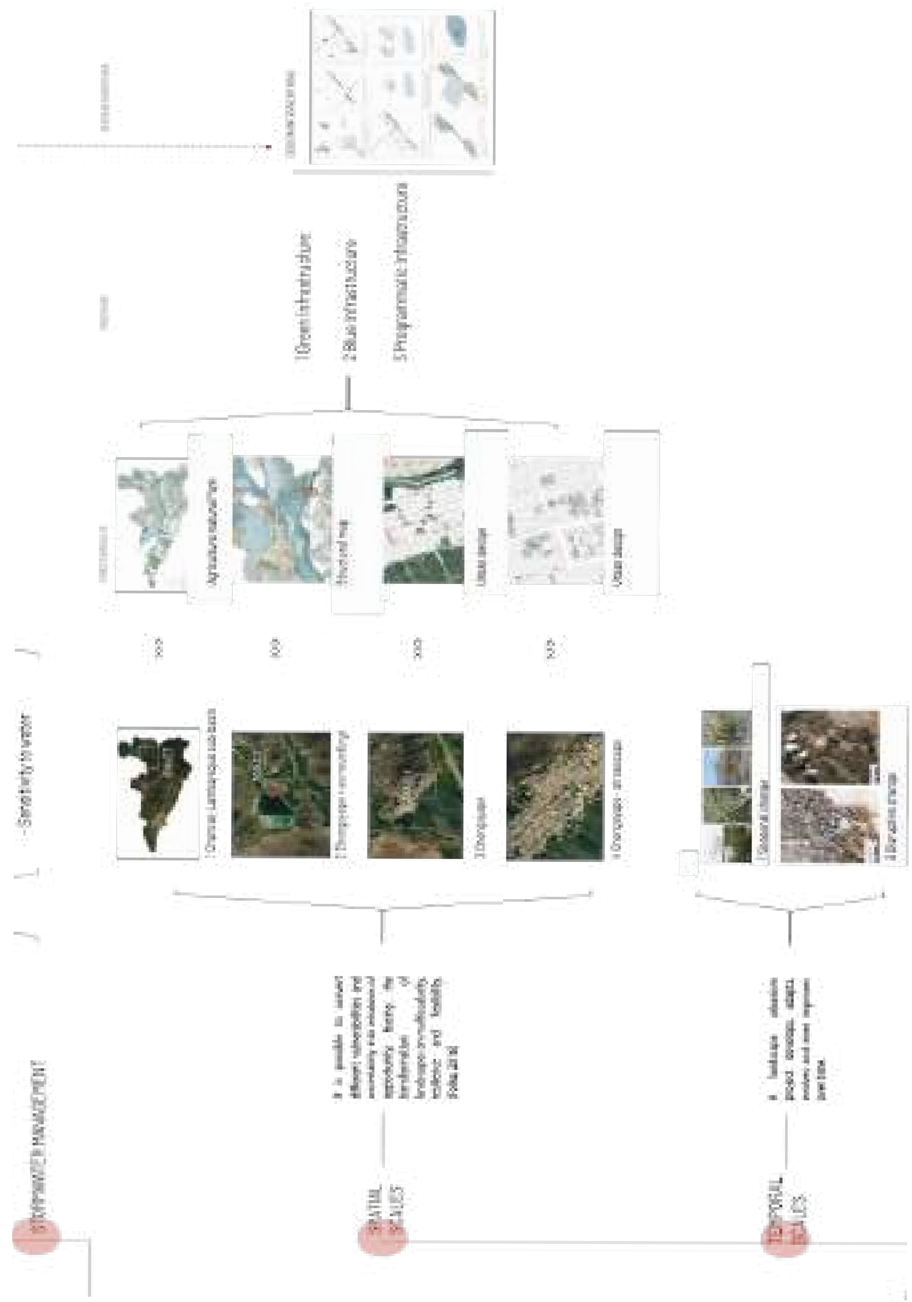


Figure 9. Research through design methodology comprises spatio-temporal scales. The diagram shows the expected results from each of the scales, finishing with the main design interventions

Source: Made by author, 2022

4.2 Methods

Design-based research aims for a systematic exploration of the place with the following research strategies

4.2.1 Description

Description comprises direct observation, field study and literature review.

The method of covert observation of humans and non-humans subjects in Chongoyape was realized in four different sessions. It was a naturalistic way of observation.

Field study aimed to create a visual journey, comprising photographs and drone footage. It started on June 2021 and continued until December 2021. The visual journey part is composed of photographs and drone footage, which is shared through the project's website and social media channels.

Literature review is classified in five categories: resilience and adaptive capacity; green and blue infrastructure; research through design; reference projects; Peruvian legislation. This section started on June 2021, and it will continue enriching the current project until June 2022. The overarching aim of the literature review section is to inform the project with theoretical concepts that explore nature-based solutions.

4.2.2 The agency of mapping

Mapping at the sub-basin and Chongoyape surroundings scales is mainly based on the Master thesis 'Intertwined Natures' (Wong, 2018). However, a few maps have been updated with new data, as the figures shown below, given its pertinence for the current study.

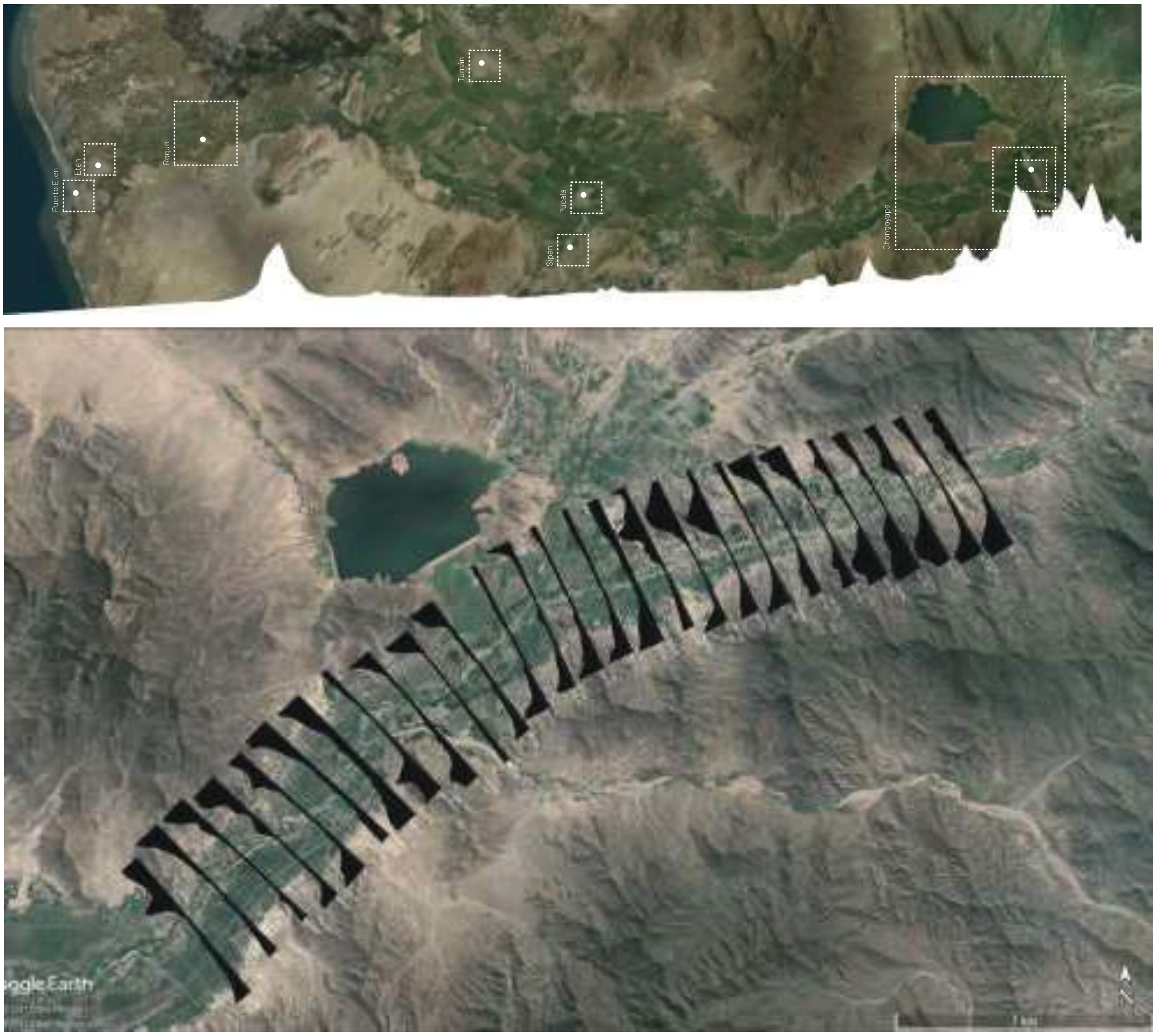


Figure 10. Exaggerated section showing urban settlements along the Chancay-Lambayeque valley

Source: Made by author, 2021

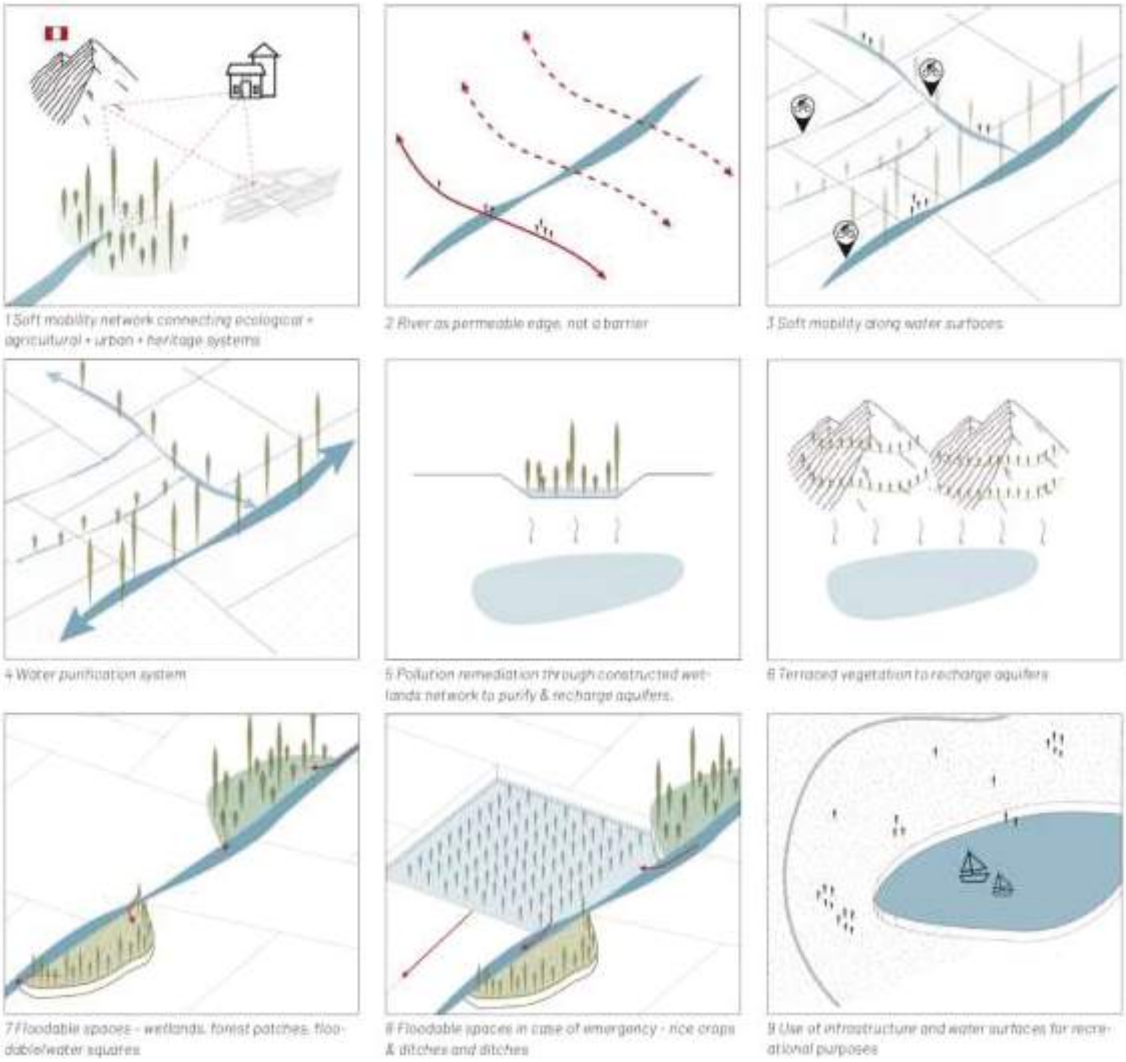


Figure 11. Sections along the river in order to determine risk prone zones

Source: Made by author, 2021

The main focus of this research project lies on the spatial scales of the Chongoyape settlement and the Chongoyape streetscape. It was not possible to find any cadastral or AutoCad maps or plans, so a recognition of the territory took place. The redrawing of the Chongoyape spatial scales are mainly based on satellite maps –Google Maps and Apple Maps–, drone footage and pictures taken by the author during field studies.

4.2.3 Evaluation and diagnosis: landscape assessment

The analysis is the previous part to design. This part of the process allows for the diagnosis of the site, resulting in a suitability analysis which is the basis for the design of the future explorative models.

4.2.4 Participatory action research

Results of this section followed from the formal analysis and social participation activities such as digital surveys and interviews conducted in Chongoyape and by phone.

As has been pointed out in Sustainable Large Parks: Ecological design or designer ecology?, "design processes can be potent agents of change" (Lister, 2007, p. 51). Design processes should be aligned to local conditions in order to reconciliate the diversity of agents that coexist in the site. Collaborative sessions and workshops are a form of design process that were considered at the beginning of the current research project. Because of the Covid-19 pandemic, in-person workshops were cancelled during the first quarter of the Fellowship period. Instead the collaboration took place in the form of digital surveys. Two digital surveys were launched during the Fellowship year. On the one hand, the first digital survey aimed to understand the general knowledge of the population regarding El Niño phenomenon, climate change and their effects in the local social fabric and infrastructure. Also, this survey hinted to possible nature-based solutions that were later going to be proposed in Chongoyape. The second digital survey aimed to be part of the validation of the design project in the form of transformative models, by discussing four sites where green and blue resilient infrastructure were proposed in order for the community to comment on the viability of the project and to share their thoughts and critiques. It is important to mention that in order to cover all age ranges, during the second digital survey, some of the surveys were filled out by the author with the responses of older persons while we were talking by phone or by Zoom.

The purpose of the Chongoyape case study is to explore and discuss feasible ways for designing resilient climate change-related infrastructure, from the smaller spatial scale – streetscape – to the sub-basin scale. Furthermore, the evaluation of the project explores, as it name indicates, the assessment of the 'Intertwined Natures', understanding the different types of landscapes and actions, and the different grading of manipulation that can be embedded in each of them. Phasing of the project is used to understand which are the spatial interventions and policies that might be implemented first, and which interventions are concatenated with others.

5 Results and Discussion

5.1 Visual journey

The visual journey is the result of one of the parts of the observation method, specifically of the

Figure 12. Comparison of seasonal change of endemic flora. Pictures shown were taken in winter and spring
Source: Made by author, 2021

5.2 Resilience and adaptive capacities

This section is the result of the literature review method. The following text is part of the paper presented on IFoU (Wong, 2021a).

Resilience and adaptive capacity thinking are closely related to sustainable development. For the current project this is based on the design of green and blue networks which take the parcels close-by to the river axis, turning them into protected areas, creating an Agriculture–Natural Park. By giving this river corridor the status of regional park, it will oblige farmers farming adjacent to the river to use natural pesticides and fertilisers, improving the soil next to the river, which in turn, will improve the overall water condition. In return, the production is designated with an organic label which are valued much higher than the resulting from 'regular' practices. Furthermore, rice producers next to the river will improve its crops by having regular water flow into their parcels, however, in the case of natural disaster emergency their crops can be used as part of the floodable emergency water system that incorporates the space for river overflow. The overarching aim of the park is to facilitate movement through the valley and to be the integrator among natural and human-made landscapes –while protecting biodiversity– into the expansion of existing growing cities. Moreover, it becomes the link that rural communities need to thrive economically. (Wong, 2018) As part of the nature-based solutions, a network of constructed wetlands is designed, as well as vegetation strips along water streams and terraced indigenous vegetation that are crucially important in the upper part of the sub–basin. Additionally, constructed wetlands are the main mechanism to remediate pollution in the sub-basin and water storage in the case of drought. Forest patches are the main source of restoration of the water table, currently in danger for the construction of illegal wells. Finally, the main crops of the region are rice and sugar cane, which need plenty of water. A strategy for self-organizing, a fundamental requirement of long-term sustainability (Lister, 2007), in the upper part of the sub-basin is the diversification of crops to ones that do not need much water to sustain themselves, such as sweet potato, arracacha, strawberries, root crops and, native fruit trees such as mango and passion fruit, to name a few.

By proposing these strategies, the sub-basin can adapt to unexpected changes without changing paths, which means that the recurring images from despair resulting from El Niño phenomenon would belong to the past. Moreover, by generating a multiscalar plan for the sub-basin, the perception and engagement at local and regional scales would be improved with either ecological performative agendas or architectural activities. The agendas and programmes are particular to the site, given that they correspond to the specific conditions of Lambayeque, where the natural, rural and urban landscapes ought to be adaptive to flooding from natural disasters and for the sporadic drought, given its geographic location within the ecosystem of dry forest. Finally, by facing the adaption to future complexity, the performative ecology in the form of green and blue networks nourishes resilient and adaptive capacities within the Chancay-Lambayeque sub-basin.

Conclusion of text presented for the conference paper presented on IFoU 2021 (Wong, 2021a).

5.2.1 Flood resilience approach

The “4-domains” approach (4DA) enables the project with four dimensions resulting from rainfall events, and shows how these can be designed and managed for the system to not change courses. The 4DA ‘is applied to define the sequencing of spatial strategies in correspondence to four types of rainfall events’ (Bacchin, 2015).

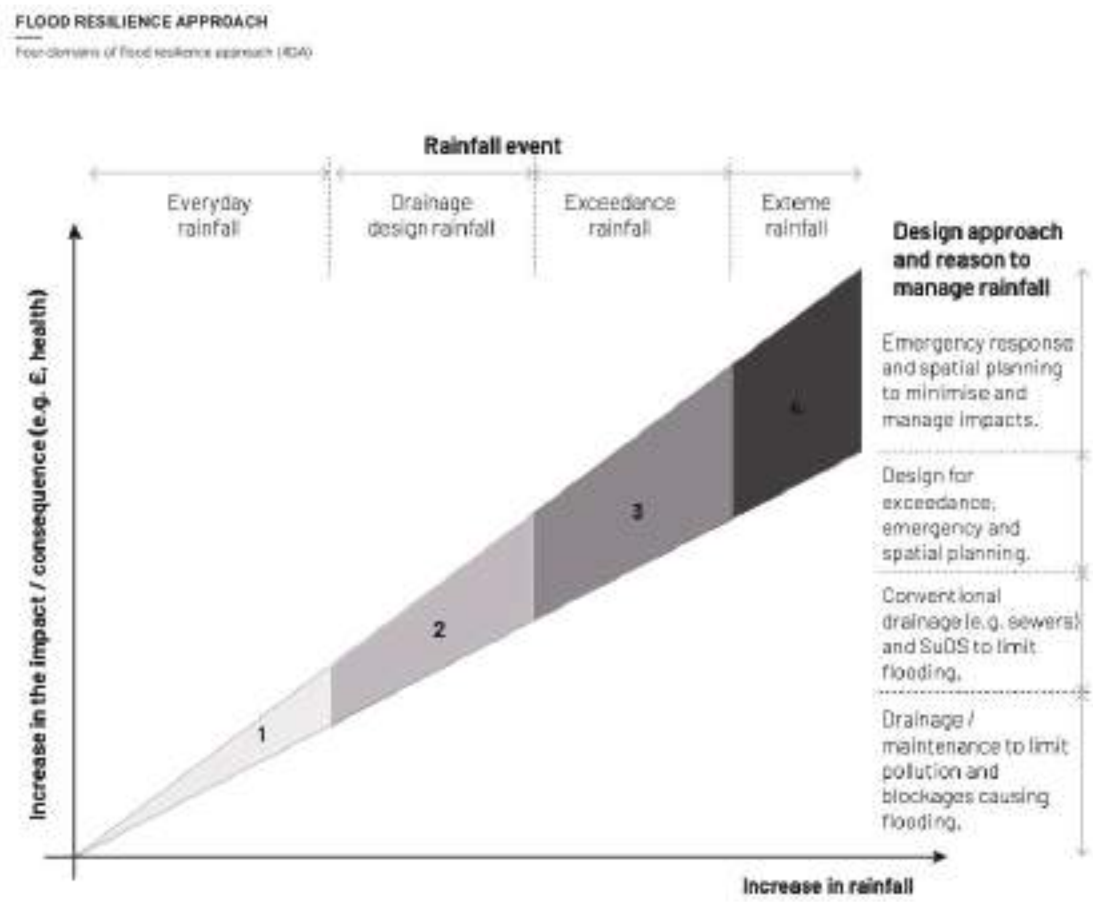


Figure 13. The '4 domains' of flood resilience approach (4DA)

Source: Redrawn by author, 2022, from Ashley, et. al. (2015)

First Domain: No exceedance water. Operations mainly comprised maintenance of existing water network and implementation of drainage networks.

Second Domain: Controlled exceedance of surface water. LID and SUDS practices are used to limit flooding. Some of the interventions are rain gardens, infiltrations planters, pervious pavements and constructed wetlands, to name a few.

Third Domain: 'Manage exceedance pathways along with overall improved spatial quality of the streetscape' (Bacchin, 2015). Runoff exceedance are managed with the use of multifunctional spaces such as green reservoirs, floodable public spaces, underground water retention structures. Other open recreational spaces are redesigned to be multifunctional (ibid.)

Fourth Domain: Controlled flooding. Emergency measures.

The 4DA approach is illustrated in Section 5.4 Transformative models.

Low Impact Design (LID) and Sustainable Urban Drainage System (SUDs) practices are mentioned as part of the strategies of the four domains of flood resilience approach.

Figure 14. Low Impact Design (LID) + Sustainable Urban Drainage System (SUDs) practices: filter, infiltrate, store, evaporate

Source: Redrawn by author, 2022, from Kuzniecow Bacchin, T. (2015); www.susdrain.org; Richter in www.costelloinc.com

5.3 Site specificity as a tool

This section, as the one presented before, is the result of the literature review method.

The following text is part of the conference paper presented on IFoU 2021 (Wong, 2021a).

Corner & Hirsch (2014) describe specificity of site as an approach that considers its 'environment, culture, politics and economies, as programme unto itself'. For the study, this position is merged with the one from Berrizbeitia (2007) where the specificity of site places the experiences and physical attributes of a given landscape on the same level of importance. By placing experiences, not just programmes or events, in such an assertive scene, the human agency is taken as a crucial piece of the ecosystem.

Site specificity was used as a design tool in Chongoyape, to inform the final project with knowledge arising not only from the physical attributes of the site but also from the intangible ones. Consequently, the project resulted in a series of transformative models as a way of exploration to respond to future states of flooding. It should be considered that the essence of this tool is not to claim to be a specific configuration destined for success, since multiple variables come into play within each unique ecosystem, where the greater or lesser manipulation of the landscapes might result in an array of interventions. Furthermore, the results are designed experiments that accommodate growth and change in the light of future adversities.

Figure 15. Dry forest showing xerophile vegetation, and endemic species such as carob and molle trees, been the former the most emblematic specie of the Peruvian dry forest

Source: Made by author, 2021

The use of the site specificity tool in the case study allowed to accomplish a thorough reading of the territory where new relationships of co-dependency were drawn within the region taking the Chancay-Lambayeque river as the carrying structure, proposing an agriculture-natural park, where both ecological –for protecting coastal dry forests and endemic fauna – and programmatic –in the form of architectural seed projects– dimensions are managed as performative agendas, along with functions, formal and spatial attributes, and processes (Czerniak, 2006) in order to achieve a new sustainable equilibrium of coexistence with exceedance of water resulting from unexpected climate- related events. Furthermore, the design tool informed the new equilibrium and afforded the project with the capacities of resilience and adaptation, which are at the core of sustainability. This way the project can withstand perturbations in the future, maintaining or adapting a stable state without changing courses.

Conclusion of text presented for the conference paper presented on IFoU 2021 (Wong, 2021a).

Figure 16. Palo verde (Cerdium praecox), endemic specie of the Peruvian coastal dry forest. The image shows a comparison during winter and spring

Source: Made by author, 2021

Carob tree
(Prosopis pallida)

Tap Roots
Roots can grow up to 2-3 times the canopy diameter to look for groundwater.

Roots absorb underground water up to 50 meters.

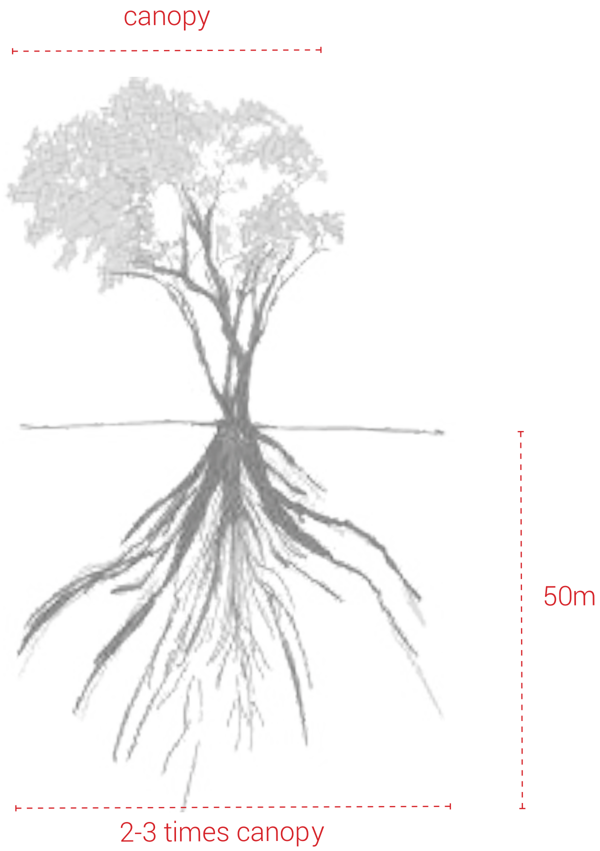


Figure 17. Endemic flora. Carob tree (Prosopis pallida) –algarrobo in Spanish– is the most representative specie of the Peruvian coastal dry forest

Source: Made by author, 2021

The proposed transformative models (see Section 5.4) take into consideration this particularity of the landscape in order to design green and blue resilient infrastructure that are able to perform as the existing mechanisms encountered in the site. Carob tree reforestation in forest patches is not only important for the collective memory of the inhabitants, but also for cleaning and replenishing underground water table given that its roots can absorb water up to 50 m underground. To accomplish this, carob tree's roots grow up to 2 or 3 times the diameter of its canopy to look for groundwater (see Figure 17). Moreover, carob trees can survive on their own without much maintenance.

Furthermore, national endemic species such as white-winged guan and the spectacled bear are being protected in restricted areas, as well as a myriad of birds.

Figure 18. Agriculture system of the Chancay-Lambayeque sub-basin, with a special focus on rice crops in Chongoyape. Pictures on the right show how the productive landscape patterns mutate from one season to the other.

Source: Made by author, 2021

Finally, other particularity of the place is illustrated in Figures 16 and 17. Agriculture is one of the main economic actives of the region. Most of the crops found in the region are: rice, sugar cane, yellow corn, cotton, asparagus and fruits such as mango and grapes and berries. A percentage of the agricultural production is exported. As mentioned in the research problem, water-related challenges in Chongoyape are contradictory in nature with excess and lack of water. By mapping where the heavily water-dependent crops are located –in this case, rice– the proposal can focus on those places to accommodate water excess in case of a greater amount of stormwater or river exceedance. Moreover, Figure 17 analyses the growth of a rice seed, the amount of water it needs, the months where more irrigation water is allocated for this kind of crops, as well as the temperature of Chongoyape. It can be inferred from this analysis that the stages where the crops need more water are exactly aligned with rainy season and even with the months where El Niño usually occurs; on the assumption that it is a mild phenomenon. This analysis further informed the use of rice crops in the case of extreme emergency, transforming this agricultural land into resilient infrastructure, able to adapt to sudden change. Moreover, this proposed green and blue infrastructure was able to accommodate uncertainties arising from natural phenomenon.

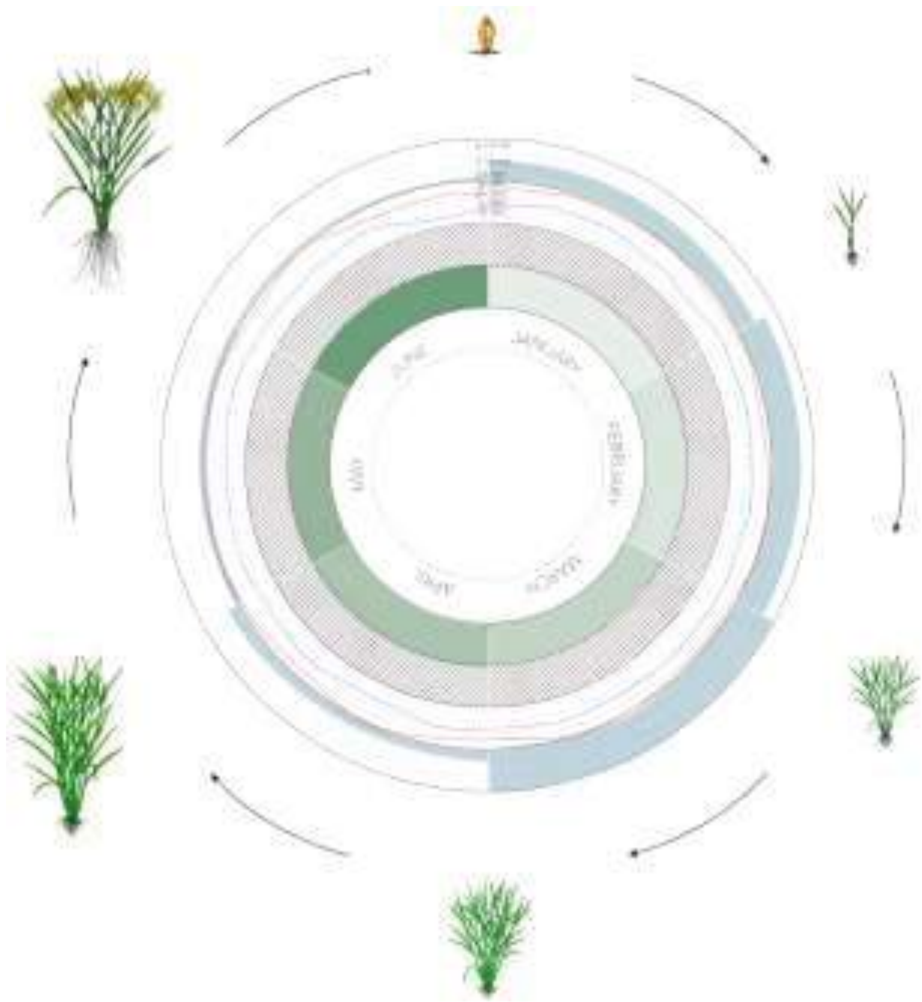


Figure 19. Agriculture system. Growth of rice crop showing the amount of water it needs, the months where more irrigation water is allocated for this kind of crops, as well as the temperature of Chongoyape

Source: Made by author, 2021

5.4 Transformative Model

This section is the result of the agency of mapping and the evaluation and diagnosis: landscape assessment methods.

The following text is part of the conference paper presented on IFoU 2021 (Wong, 2021a).

Site specificity is a way of understanding the landscape by engaging with it. This research does not aim to find a universal solution to flooding or climate change, since an overarching element of the research takes in consideration the specificity of each place. In the same line, Nijhuis & de Vries point out that the research through design 'is not about absolute truth finding' (ibid., p. 101), but as a strategy where thinking and producing are synchronously movements. 'Research through design can be regarded as a powerful research strategy in which complex spatial problems are approached in a creative and integrated manner. The targeted search plays a central role in a process in which thinking and producing go hand in hand' (Nijhuis & de Vries, 2020, p. 100) . It is worth noting that the so mentioned exploration of the site can be also translated as a transformative model, as used by Erixon et. al. (2013), where the design is a tool for generating discussion about a topic.

5.4.1 Design principles

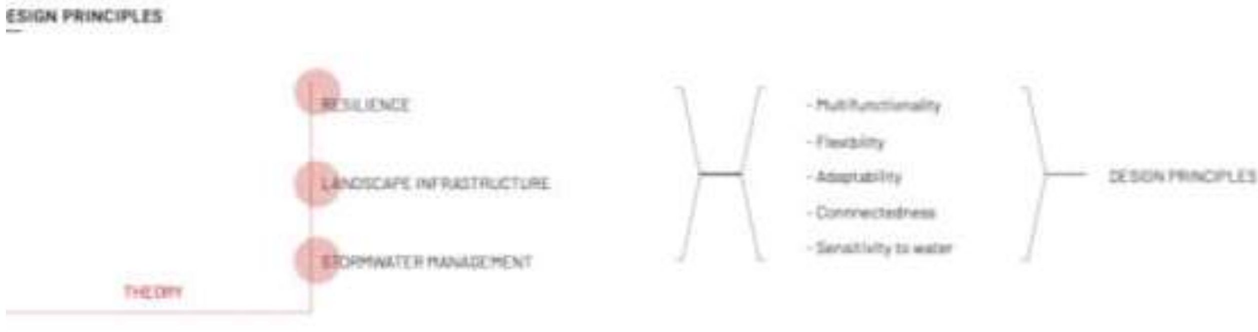


Figure 20. Design principles to be used in the project resulted from the theoretical framework

Source: Made by author, 2022

5.4.1.1 Resilience

Resilience is the capacity to adapt or transform while facing unexpected/extreme change (Folke et. al., 2010).

Excerpt from Wong (2021a): Unlike the architectural object, a landscape urbanism project develops, adapts, evolves and even improves over time. Moreover, it will possibly suffer change in its composition or structure over time (Pickett et. al., 2004). For the present project, the course of time comprises two components: first, the course of time through seasons or in some latitudes in the form of rainy or dry seasons. Second, time as uncertainties arising from extreme events such as El Niño , Niño Costero, among others.

5.4.1.2 Multifunctionality

'The strength of multifunctional landscapes is their ability to afford the needs of diverse users, thus appealing to diverse constituents with various recreational, cultural and ecological needs/ objectives. Multiple uses also facilitate efficient use of time and space.' (Kato & Ahern, 2009, p.799)

5.4.1.3 Flexibility

This concept is related to timeframes and contingency design. In the case of need, extreme flooding for example, these paces can be used for a certain period of time, without damaging other parts of the system.

5.4.1.4 Adaptability

Refers to human action that sustain, innovate, and improve development on current pathways. It is more related to the spatial structure of the system. Throughout changing circumstances, an adaptive system should be able to maintain its regime as usual if one element collapses or needs to be intervened (Folke et. Al. 2010; Wong, 2018).

The dynamic characteristic of ecosystems urges to design dynamic processes as resilient and adaptive systems that are able to steer paths in case of any known or unknown disturbances, in order for them to 'adapt to changing conditions over time' (Berrizbeitia, 2007, p. 183). In this context, resilience is measured by how much uncertainty and change an ecosystem might absorb before changing paths or regimes (Czerniak, 2007; Erixon et. al., 2013). In the Chancay-Lambayeque sub-basin that would be translated into the amount of rainfall that the river can accommodate –after a natural disaster– before 'flipping' into a new behaviour of flooding. In addition to this, 'watersheds are integrators of diverse processes' given that subterranean water from aquifers, aquitards, aquiclude and aquifuges accrue sediments and minerals that can be helpful or polluting agents downstream of the basin (Pickett et. al., 2004,p. 376).

5.4.1.5 Connectedness

It can be argued that this concept "regulates" the elements of the system. From the elemental notion of ecology, without connections such as nourishment and outlet sources the biotic and abiotic elements would not function correctly and would die (Wong, 2018).

5.4.1.6 Sensitivity to water

This principle is related to Water-Sensitive Urban Design that allows, as far as possible, all the components of natural water cycles to occur in urban environments (Wong, 2006).

5.4.2 Design interventions

Strategies and design interventions for Chongoyape were adapted from previous work from the author (2018).

The spatial strategies are classified in blue infrastructure, green infrastructure, and programmatic infrastructure. The intertwining of these strategies aims for a resilient territory (see Figure 21).

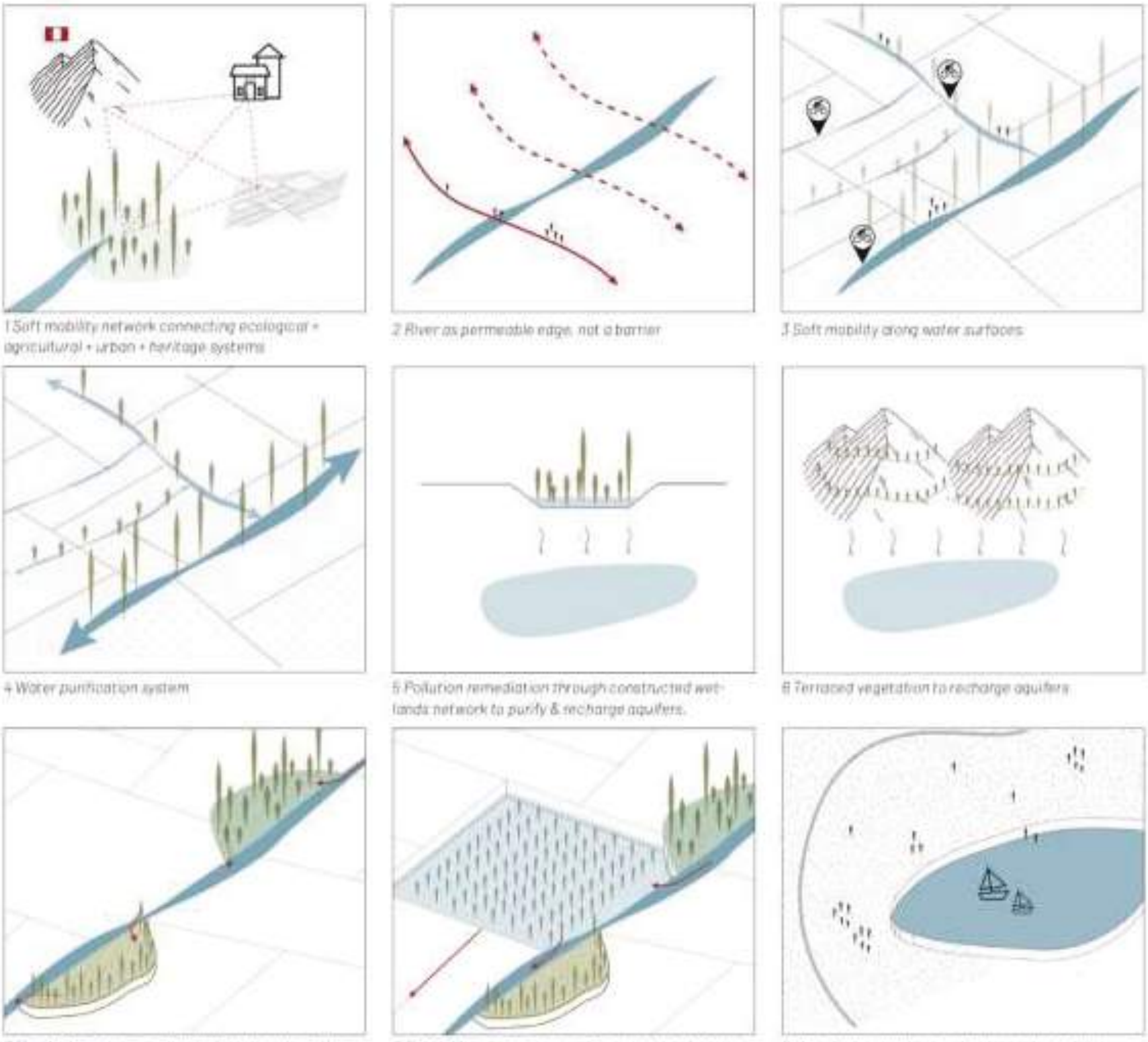


Figure 21. Strategies and design interventions for Chongoyape

Source: Made by author, 2018

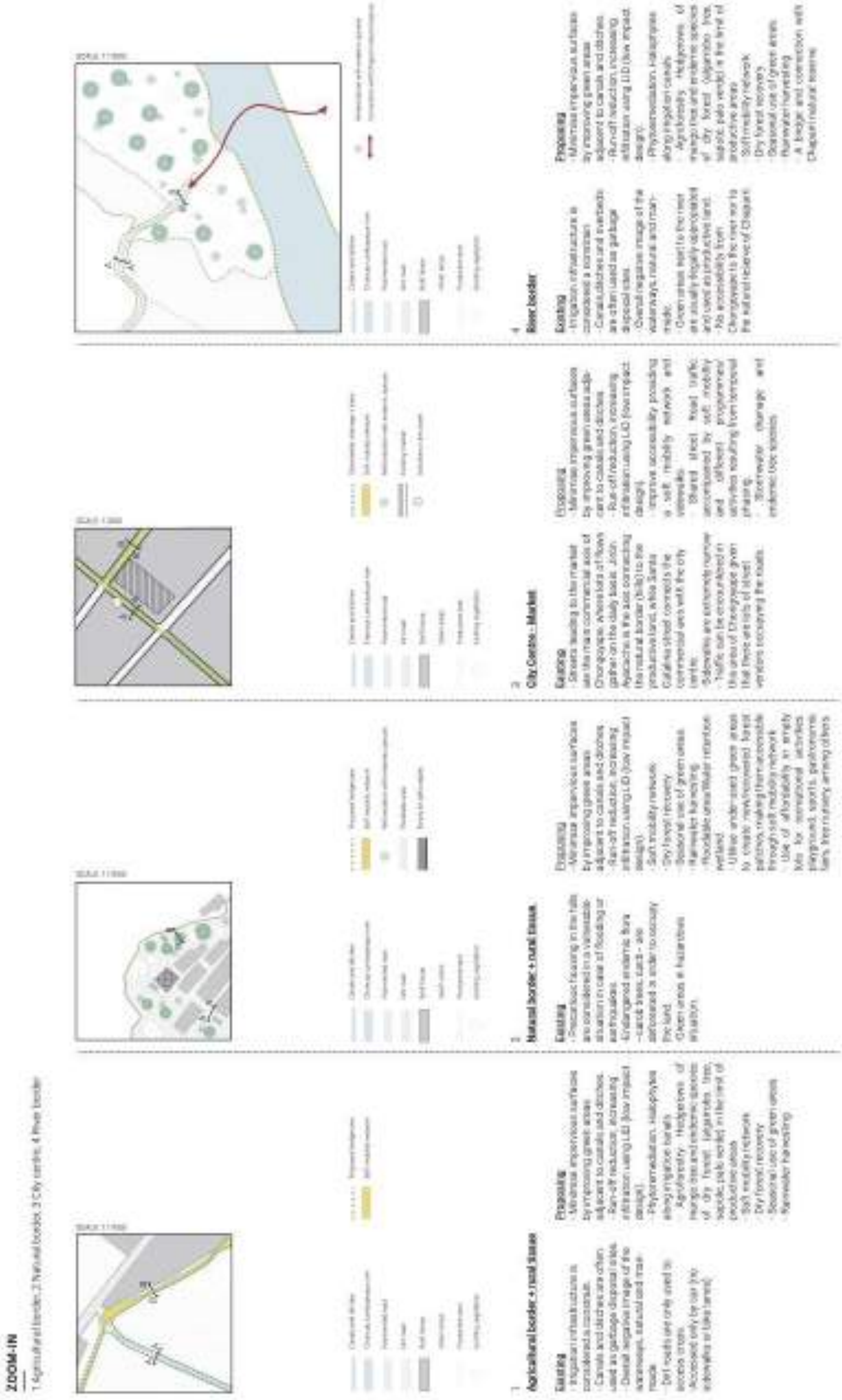
Figure 22. Structural map of spatial scale: Chongoyape and surroundings

Source: Adapted by author, 2022, from Wong, 2018.

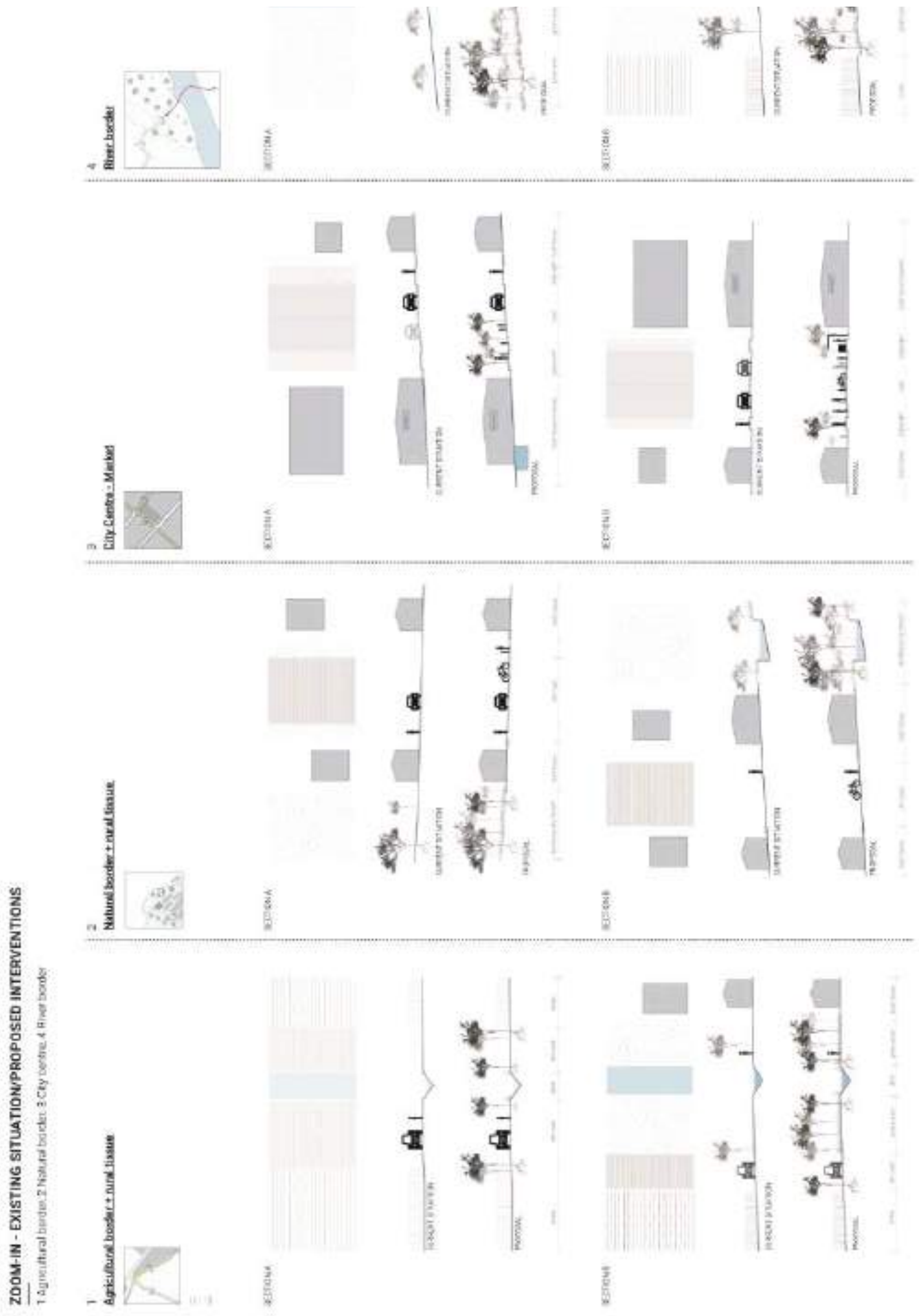
The following spatial scale shows Chongoyape and four zoom-ins, which present the place in a more detailed view in order to propose nature-based solutions. The detailed sites were selected to illustrate the array of morphologies found in place.

Figure 23. Chongoyape. Location of zoom-ins

Source: Apple Maps, accessed on February 2022. Edited by the author



The design of the zoom-ins is explained through transformative models in the form of a section, and a collage (see Figure 27 and forward). On the one hand, the section is divided in three parts:



proposed interventions are located in the upper part. It also gives information about the water resilience approach used in each intervention. The middle part explains the ecological benefits and finally, the bottom part highlights the social benefits of the design interventions. On the other hand, the collage show the current situation of the site and the proposal.

ZOOM-IN

1 Agricultural border, 2 Natural border, 3 City centre, 4 River border

SCALE: 1/1000

1

Agricultural border + rural tissue

Existing
- Irrigation infrastructure is considered a constrain.
- Canals and ditches are often used as garbage disposal sites.
- Overall negative image of the waterways, natural and man-made.
- Dirt roads are only used to access crops.
-Accessed only by car (no sidewalks or bike lanes)

Proposing
- Minimise impervious surfaces by improving green areas adjacent to canals and ditches.
- Run-off reduction, increasing infiltration using LID (low impact design).
- Phytoremediation. Halophytes along irrigation canals
- Agroforestry. Hedgerows of mango tree and endemic species of dry forest (algarrobo tree, sapote, palo verde) in the limit of productive areas
- Soft mobility network
- Dry forest recovery
- Seasonal use of green areas.
- Rainwater harvesting

SCALE: 1/1000

2

Natural border + rural tissue

Existing
- Precarious housing in the hills are considered in a vulnerable situation in case of flooding or earthquakes.
-Endangered endemic flora –carob trees, cacti– are deforested in order to occupy the land.
-Green areas in hazardous situation.

Proposing
- Minimise impervious surfaces by improving green areas adjacent to canals and ditches.
- Run-off reduction, increasing infiltration using LID (low impact design).
- Soft mobility network
- Dry forest recovery
- Seasonal use of green areas.
- Rainwater harvesting
- Floodable area/Water retention: wetland
- Utilise under-used green areas to create new/recovered forest patches, making them accessible through soft mobility network
- Use of affordability in empty lots for recreational activities: playground, sports, gastronomic fairs, tree nursery, among others.

SCALE: 1/500

3

City Centre - Market

Existing
- Streets leading to the market are the main commercial axis of Chongoyape, where lots of flows gather on the daily basis. Jirón Ayacucho is the axis connecting the natural border (hills) to the productive land, while Santa Catalina street connects the commercial axis with the city centre.
-Sidewalks are extremely narrow
- Traffic can be encountered in this area of Chongoyape given that there are lots of street vendors occupying the roads.

Proposing
- Minimise impervious surfaces by improving green areas adja-cent to canals and ditches.
- Run-off reduction, increasing infiltration using LID (low impact design).
- Improve accessibility providing a soft mobility network and sidewalks.
- Shared street. Road traffic accompanied by soft mobiltiy and different programmes/ activities resulting from temporal phasing.
- Stormwater drainage and endemic tree species

SCALE: 1/1000

4

River border

Existing
- Irrigation infrastructure is considered a constrain.
- Canals,ditches and riverbeds are often used as garbage disposal sites.
- Overall negative image of the waterways, natural and man-made.
- Green areas next to the river are usually ilegally appropiated and used as productive land.
- No accessibility from Chongoyape to the river nor to the natural reserve of Chaparri.

Proposing
- Minimise impervious surfaces by improving green areas adjacent to canals and ditches.
- Run-off reduction, increasing infiltration using LID (low impact design).
- Phytoremediation. Halophytes along irrigation canals
- Agroforestry. Hedgerows of mango tree and endemic species of dry forest (algarrobo tree, sapote, palo verde) in the limit of productive areas
- Soft mobility network
- Dry forest recovery
- Seasonal use of green areas.
- Rainwater harvesting
- A bridge and connection with Chaparri natural reserve

Figure 24. Existing conditions of zoom-ins

Source: Made by author, 2022

Figure 25. Existing and proposing conditions of zoom-ins

Source: Made by author, 2022

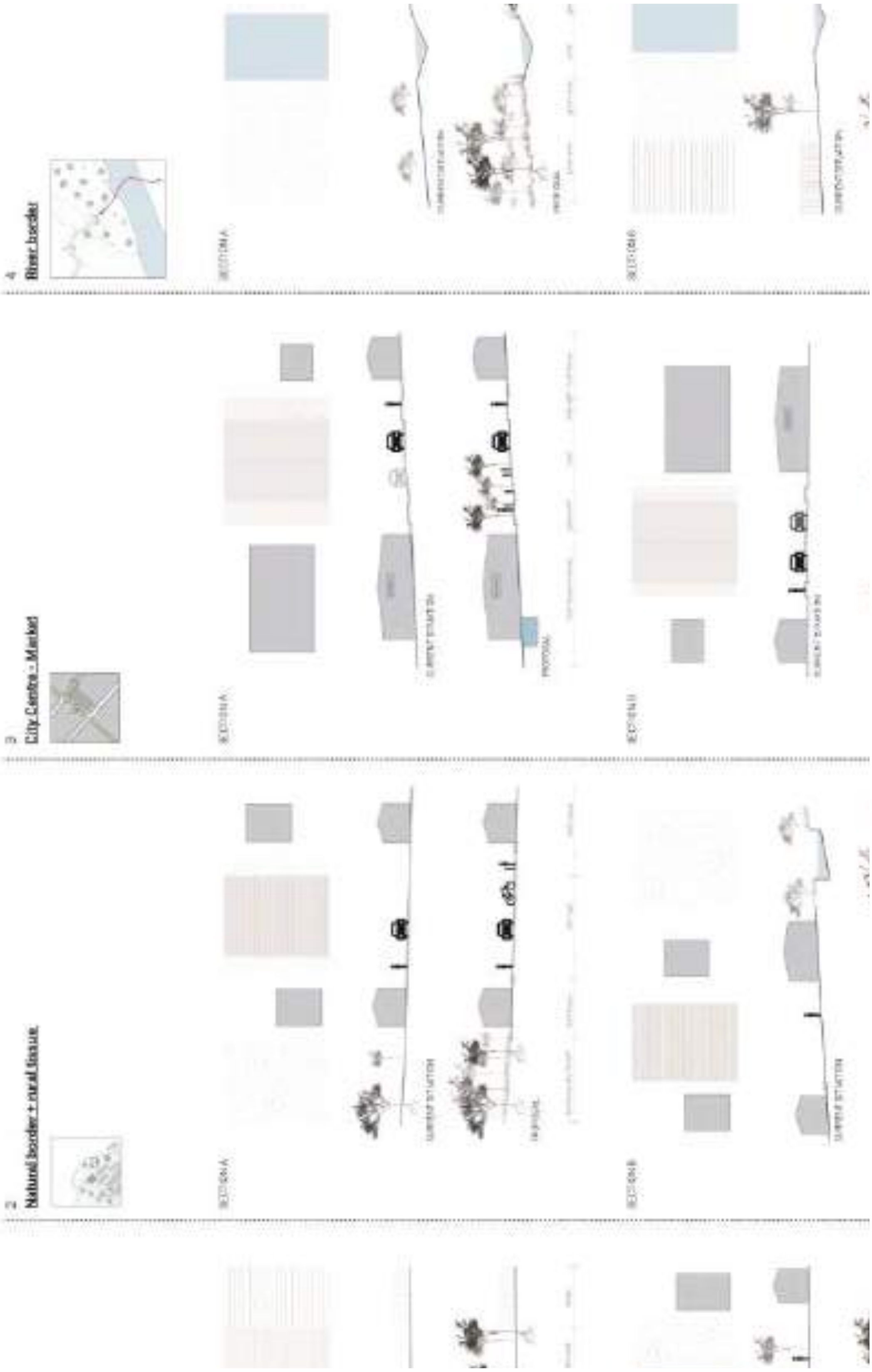


Figure 26. Zoom-ins

Source: Made by author, 2022

Zoom-in 1: agricultural border + rural tissue

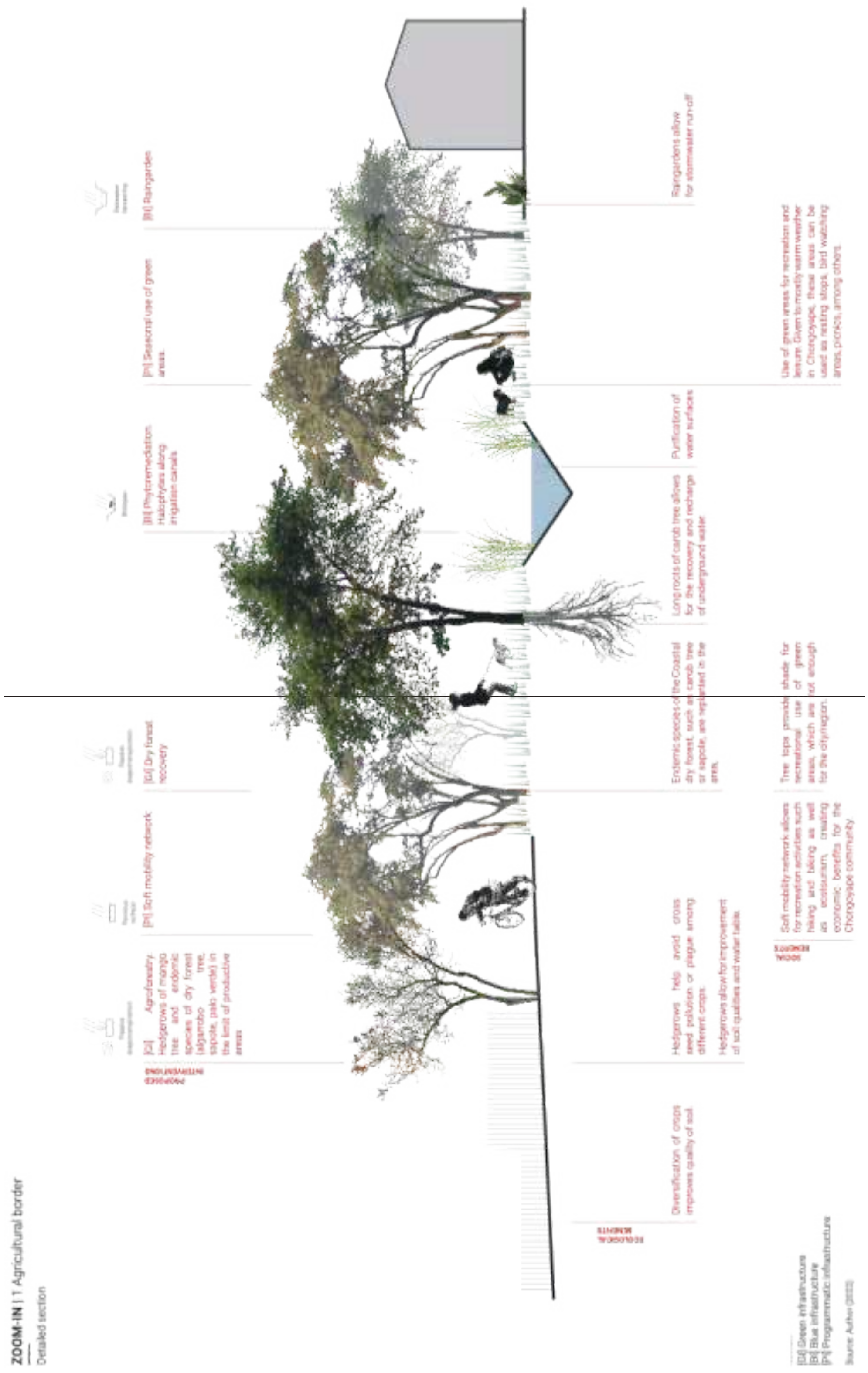


Figure 27. Zoom-in 1, detailed section

Source: Made by author, 2022

Figure 28. Zoom-in 1, existing situation

Source: Google Maps, accessed in February 2022

Figure 29. Zoom-in 1, transformative model

Source: Made by author, 2022

Zoom-in 2: natural border + rural tissue

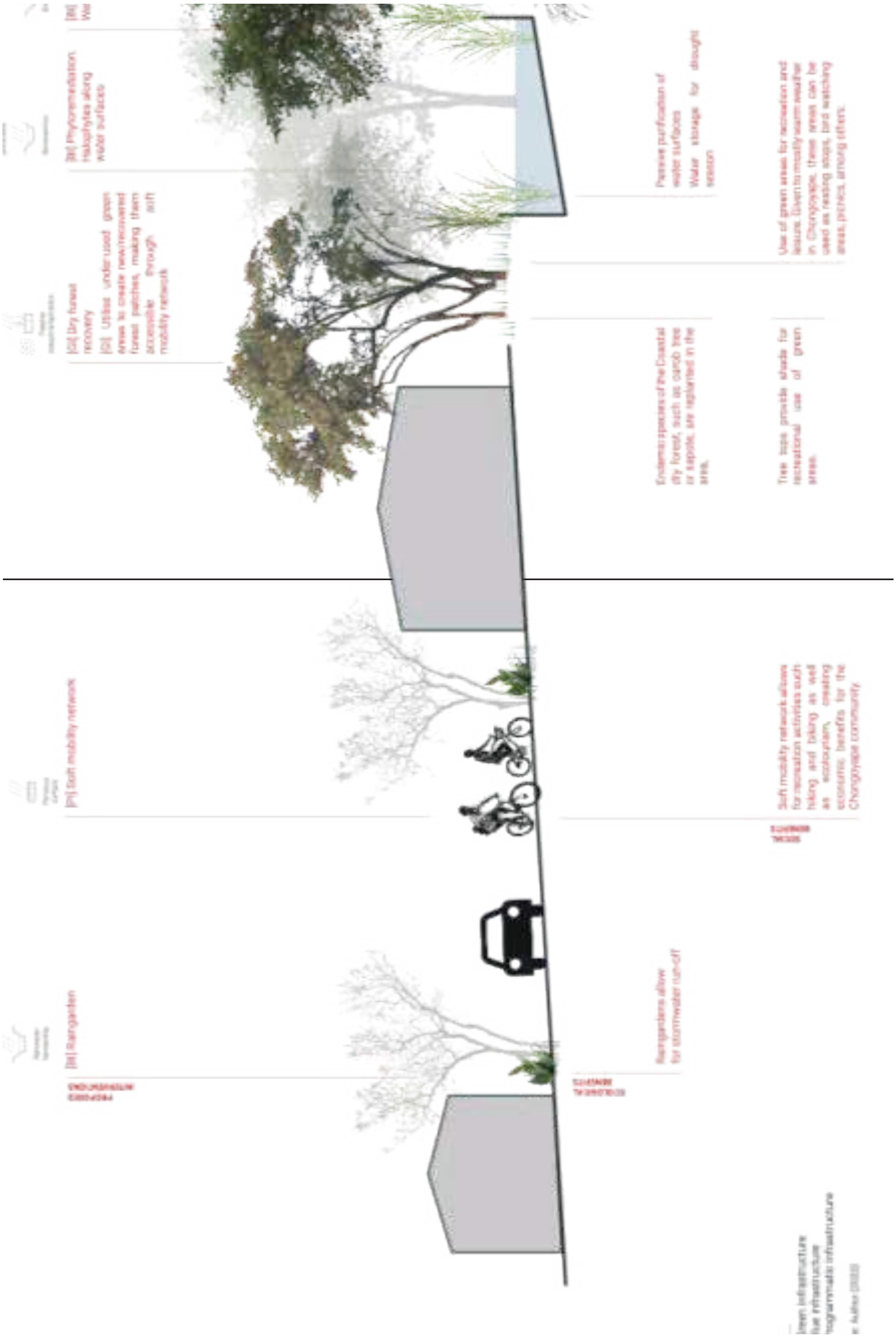


Figure 30. Zoom-in 2, detailed section

Source: Made by author, 2022

Figure 31. Zoom-in 2, existing situation

Source: Google Maps, accessed in February 2022

Figure 32. Zoom-in 2, transformative model

Source: Made by author, 2022

Zoom-in 3: city centre + market

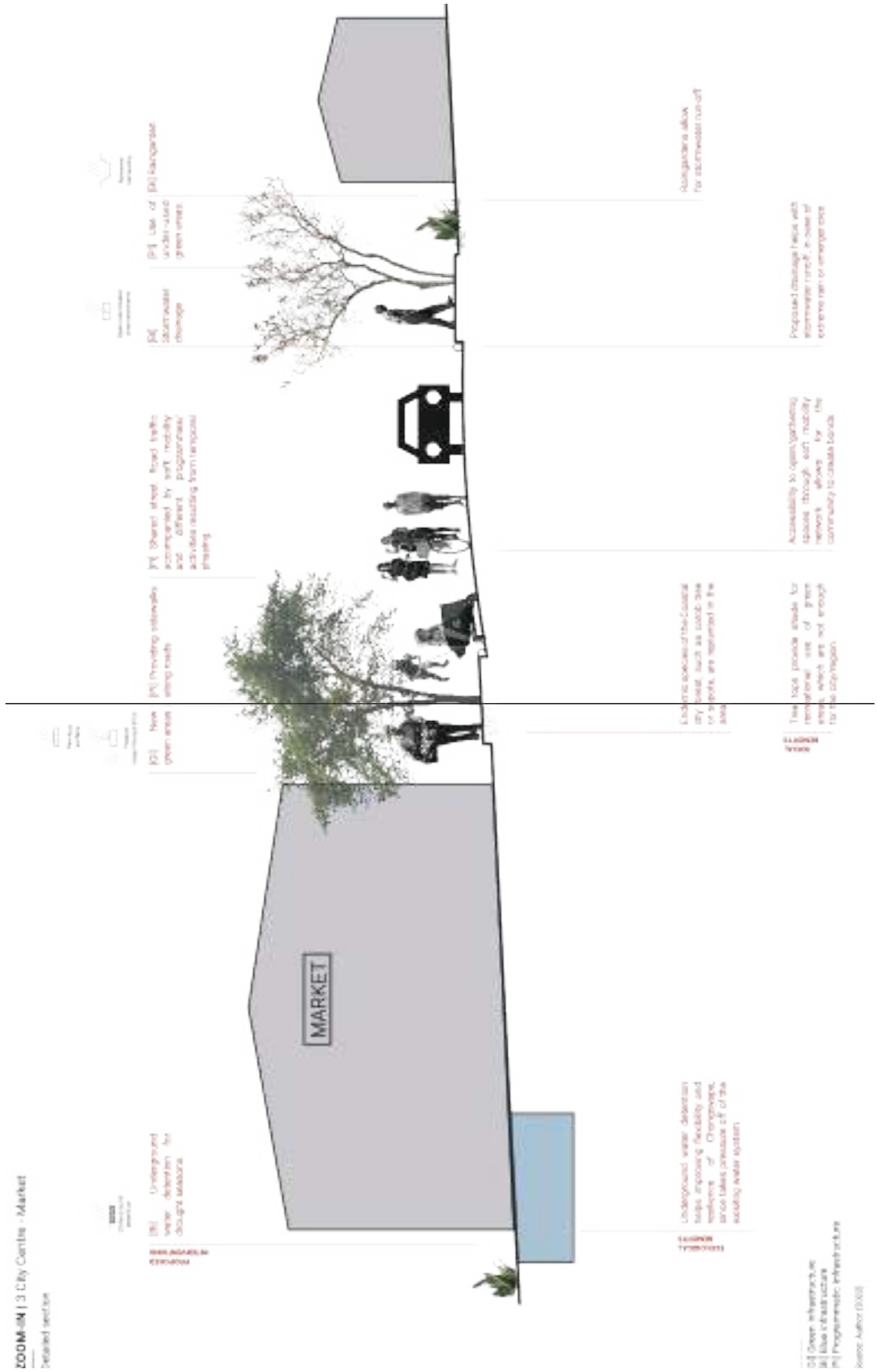


Figure 33. Zoom-in 3, detailed section

Source: Made by author, 2022

Figure 34. Zoom-in 3, existing situation

Source: Google Maps, accessed in February 2022

Figure 35. Zoom-in 3, transformative model

Source: Adapted by author, 2022 from Wong, 2018

Zoom-in 4: river border

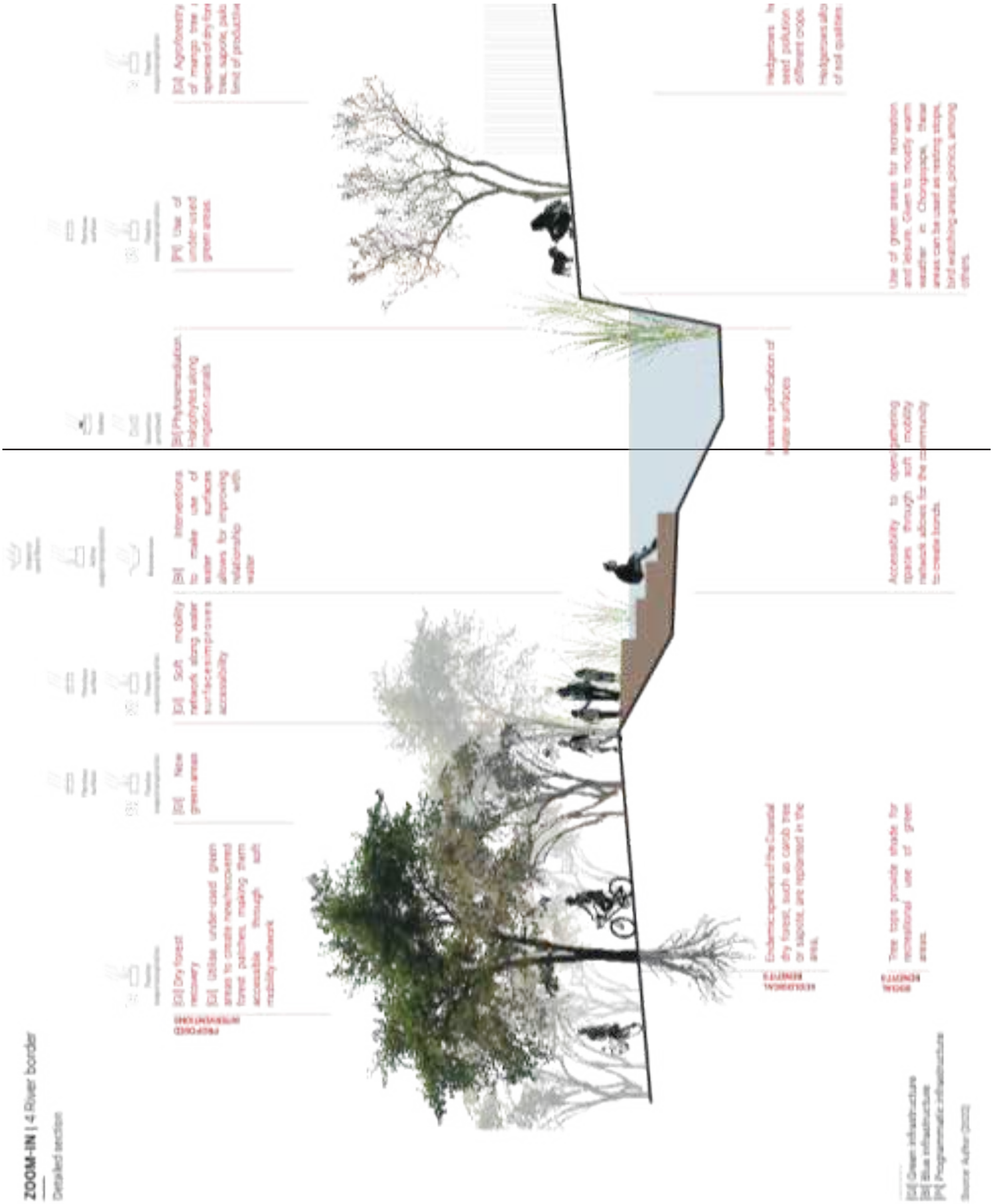


Figure 36. Zoom-in 4, detailed section

Source: Made by author, 2022

Figure 37. Zoom-in 4, existing situation

Source: Author, 2018

Figure 38. Zoom-in 4, transformative model

Source: Adapted by author, 2022 from Wong, 2018

To summarize this section, the 4-domains approach of flood resilience is explained as follows with a few examples:

First Domain: Depending on the state of the dry forest, it will be proposed to be maintained or to be recovered.

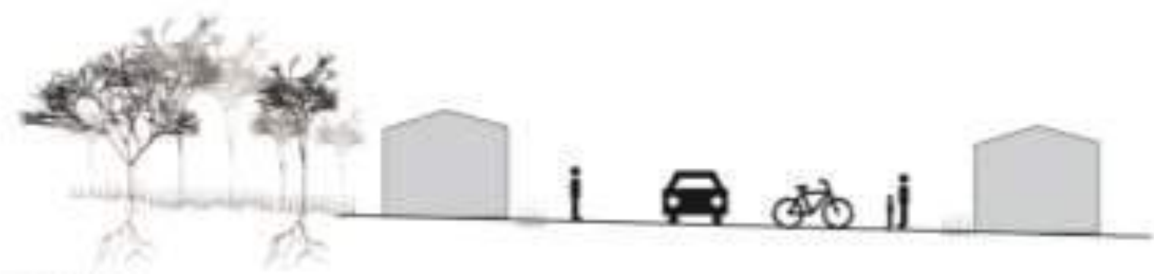


Figure 39. 4-domains approach of flood resilience (4DA), first domain shows the recovery of a deciduous dry forest pocket

Source: Made by author, 2022

Second Domain: Some of the interventions are rain gardens, infiltrations planters, pervious pavements, and constructed wetlands, to name a few. Raingardens, which aim for stormwater harvesting to retain water for drought seasons. Ecological benefits of this nature-based solution is that it allows for stormwater runoff. On the other hand, the social benefit is that rain garden can be managed by the community itself.

- Water retention. A constructed wetland in the upper part of Chongoyape, so in the case of a mudslide, given its location on the edge of the hill, it will allow for flooding in this area before it gets to the town itself.

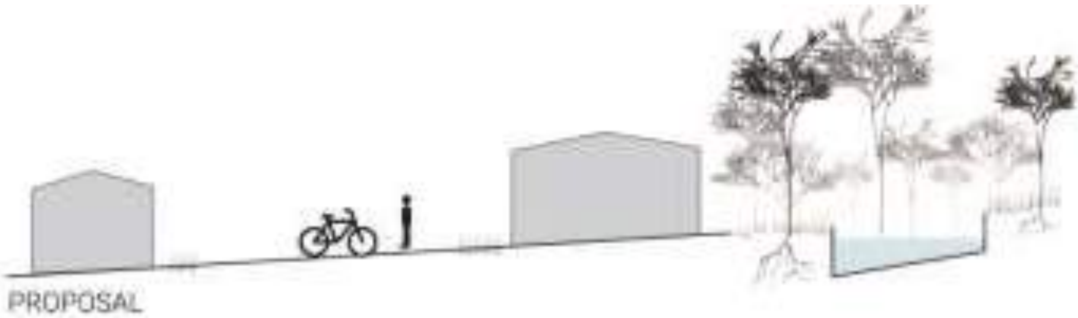


Figure 40. 4-domains approach of flood resilience (4DA), second domain shows the design of the constructed wetland

Source: Made by author, 2022

Third Domain: Some of the interventions are green reservoirs, floodable public spaces, underground water retention structures.

- Floodable public spaces are designed as forest patches along the Chancay-Lambayeque river.
- Underground water retention is proposed under the new market structure.

Figure 41. 4-domains approach of flood resilience (4DA), third domain shows the design of an underground water retention

Source: Made by author, 2022

Fourth Domain: This domain refers to controlled flooding.

- Emergency measures, creation of a connecting path with temporary bridges and escape routes.
- Use of floodable spaces in the case of emergency, rice crops and forest patches.

Figure 42. 4-domains approach of flood resilience (4DA), fourth domain shows the design of a floodable space in the form of a forest pocket

Source: Made by author, 2022

5.5 Project validation

This section is the result of the phasing of the design combined with the participatory action research method.

5.5.1 Phasing of the design

Validation of the project explores, as it name indicates, the assessment of the 'Intertwined Natures', understanding the different types of landscapes and the different grading of manipulation that can be embedded in each of them. Phasing of the project will be the start of this section, in order to place the project in a more realistic context. The image on the left shows the improvement on ecological and social dimensions with 17 years apart.

This is a way to corroborate the effectiveness of the design and the theoretical principles embedded in it, multifunctionality, flexibility, adaptivity, connectedness and sensitivity to water are going to be addressed throughout the case of targeting water as a system, from beginning to end.

Scenario thinking as a way to validate resilience aims for the understanding of complexity, uncertainty and possibilities arising from the scenario theory, in order to put it into practice, where the main concept regarding scenario is the following: 'a scenario is not a future reality, but rather a mean to represent it with the aim of clarifying present action in the light of the possible desirable future' (Durance & Godet, 2010, p. 1488). Furthermore, scenario thinking goes hand in hand with the transformative model approach, which aims at exploration of innovative solutions, taking into consideration the specificity of the site.

The use of phytoremediation techniques (see Figure 43) such as planting halophytes along irrigation canals improves purification of water surfaces.

Forest patches are the main source of restoration of the water table, currently in danger for the construction of illegal wells.

Agroforestry. Hedgerows of mango tree and endemic species of dry forest (algarrobo tree, sapote, palo verde) in the limit of productive areas. Hedgerows help avoid cross seed pollution or plague among different crops. Moreover, it allows for improvement of soil qualities and water table.

Diversification of crops: Main crops of the region are rice and sugar cane, which need plenty of water. One of the strategies is to slowly change to crops that do not need much water to sustain themselves, such as sweet potato, arracacha, strawberries, root crops and, fruit trees such as mango and passion fruit to name a few.

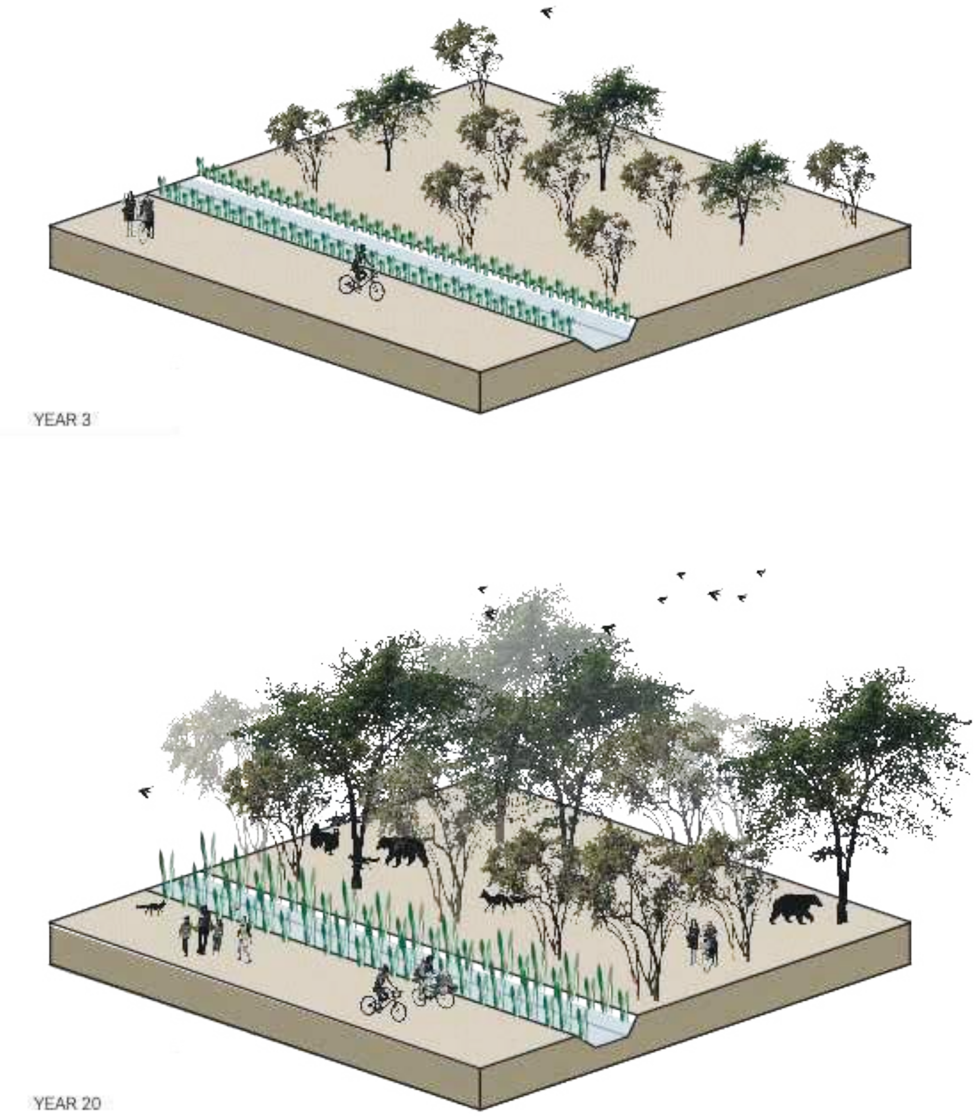


Figure 43. Phasing of the design intervention, showing year 3 and year 20

Source: Made by author, 2022

Constructed wetlands network, vegetation strips along water streams and terraced vegetation (see Figure 44) are crucially important in the upper part of the sub-basin. Constructed wetlands are the main mechanism to remediate the pollution in the upper part of the sub-basin, and water storage in the case of drought.

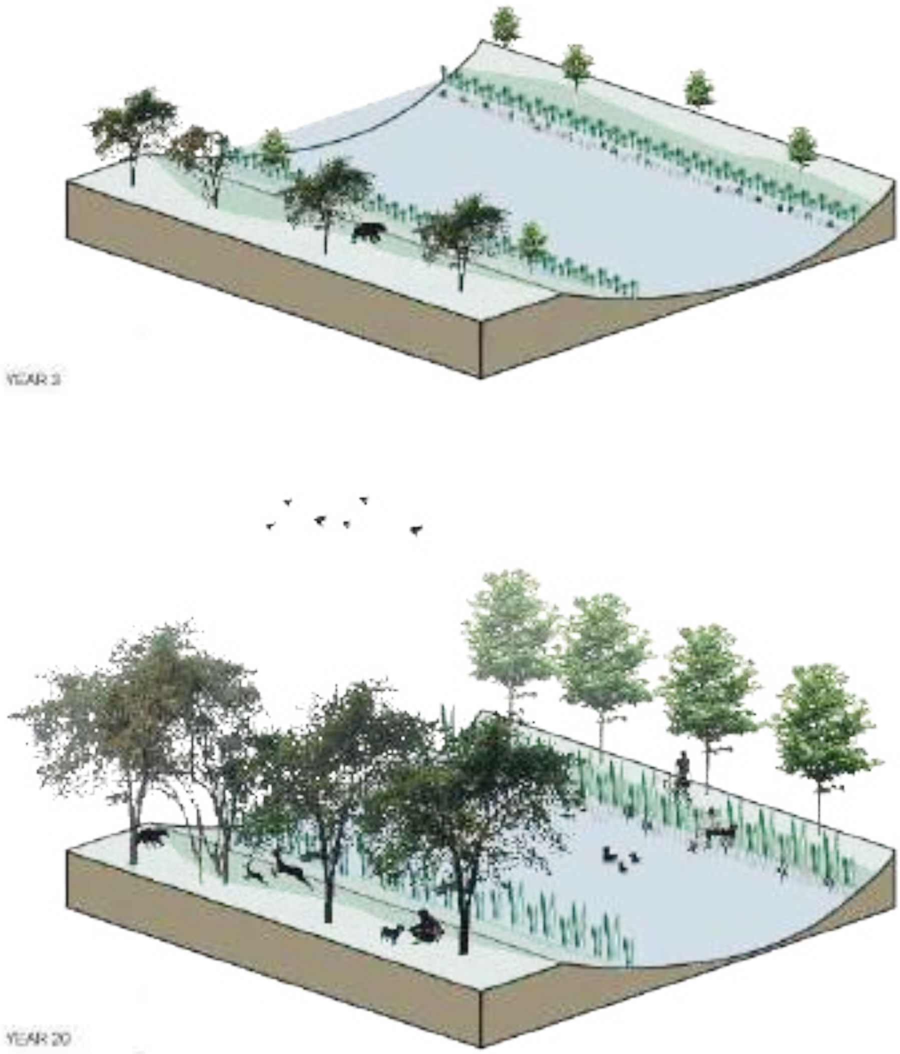


Figure 44. Phasing of the design intervention, showing year 3 and year 20

Source: Made by author, 2022

5.5.2 Participatory action

Participatory design has proven to be a challenge during the Covid-19 pandemic, since at the beginning of the research project, June 2021, most citizens were still working from home, including the education sector; moreover, meetings from outside your close circle are prohibited. Quarantine measures were relaxed the following months, however, strikes against the national government over the past months also affected the possibilities to access the site.

This situation was overcome with interviews and digital surveys. Some of the interviews were conducted in person, during field work visits while others were realised over the phone. Digital surveys were conducted mainly by digital mediums, which was the best option. However, some of the digital surveys were conducted over the phone, especially with people that needed extra assistance.

Digital survey 1

Conducted in October 2021. Total universe: 222 participants.

The survey was divided in three parts, depending on the location the questions addressed: questions regarding the Lambayeque region, questions about the capital of the region, Chiclayo –most populated and dense city in the region– and finally, questions about Chongoyape.

From the responses to these questions, a few hypothesis were answered. The fact that most of the people (91%) are aware of the lack of public spaces within the region; which was as high as 99% in the case of public spaces in Chongoyape. Furthermore, it was quite interesting to know that most of the people knew that climate change affects their everyday lives, however, not many knew that nature-based solutions could be used in order to improve flood risk resulting from natural phenomenon.

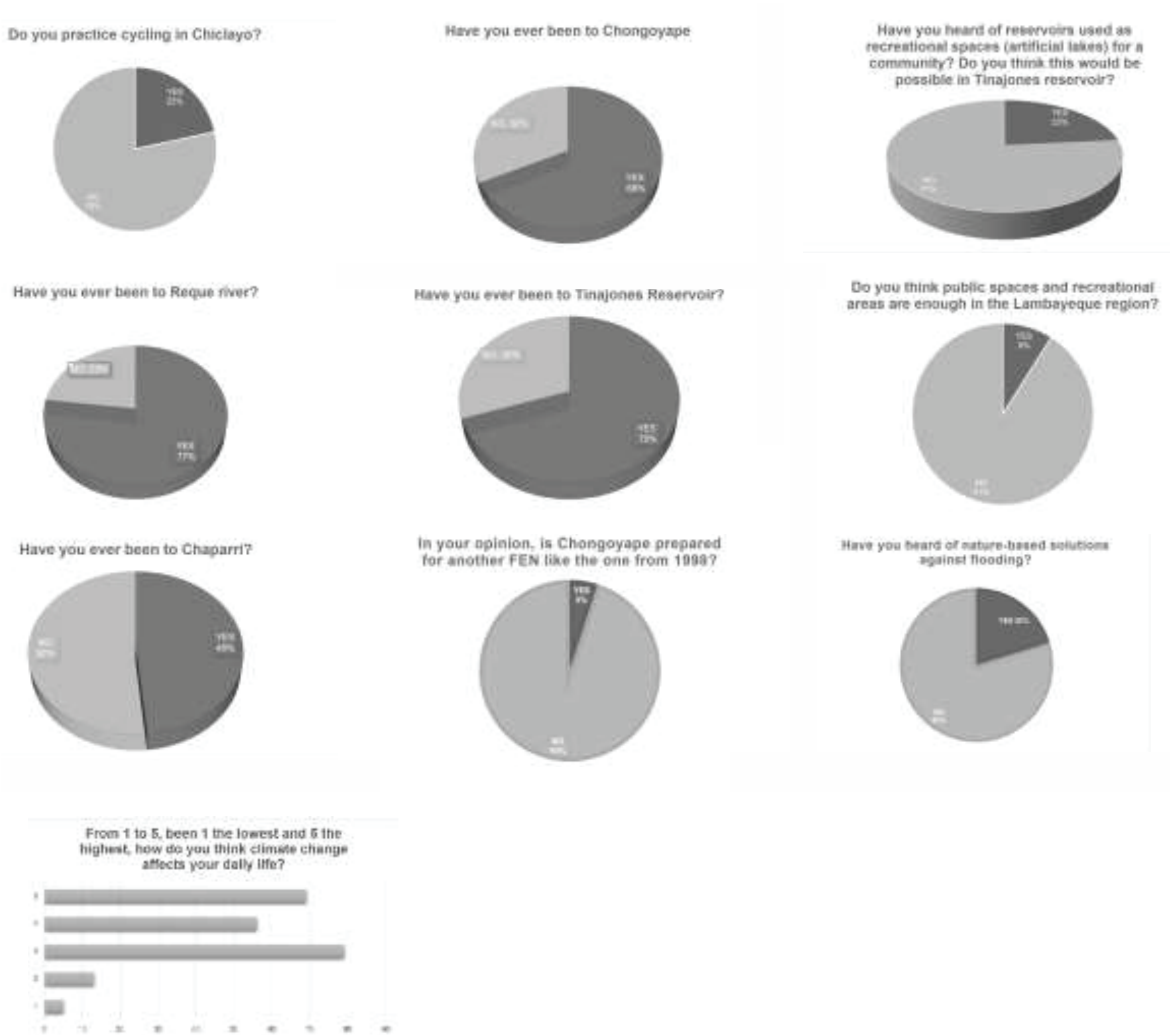


Figure 45. Responses to the digital survey 1

Source: Made by author, 2021

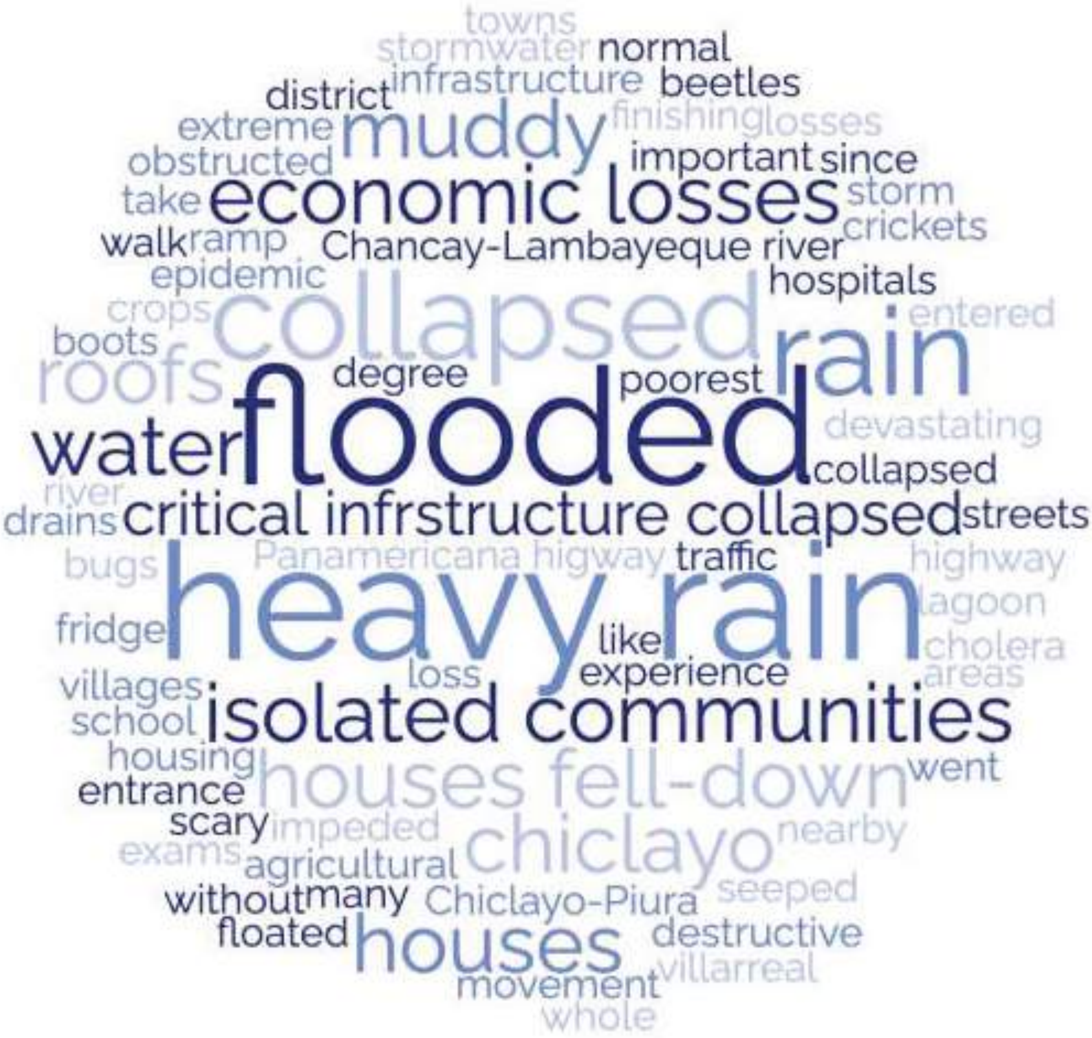


Figure 46. Summary of main words when referring to El Niño and the struggles the community has to overcome every time it occurs

Source: Made by author, 2021

When asked about the openness of existing water infrastructure, which is part of Chongoyape's identity, most of the participants said they had never been there. Allowing to infer that the water infrastructure of the region is managed as "hidden infrastructure". Moreover, when asked about nature-based solutions, most of the participants said they did not know the term. However, in the detailed responses, there is a clear empirical knowledge of what should be done, not with the exact name of nature-based solutions but, for example, knowing that the openness of the reservoir should be done in a responsible and ecological way, in order to protect natural resources, water bodies and drinking water, and human dimensions, mainly for safety reasons. This last remark goes hand in hand with the programmatic response of the project, since the reservoir functions as 'hidden infrastructure' people that swim there take it as an adventure, which means there have been accidents over the years. Finally, this survey helped to understand the main challenges of Chongoyape, from the perspective of the inhabitants, which in turn, helped inform the transformative models.

Digital survey 2

Conducted in March-April 2022. Total universe: 248 participants.

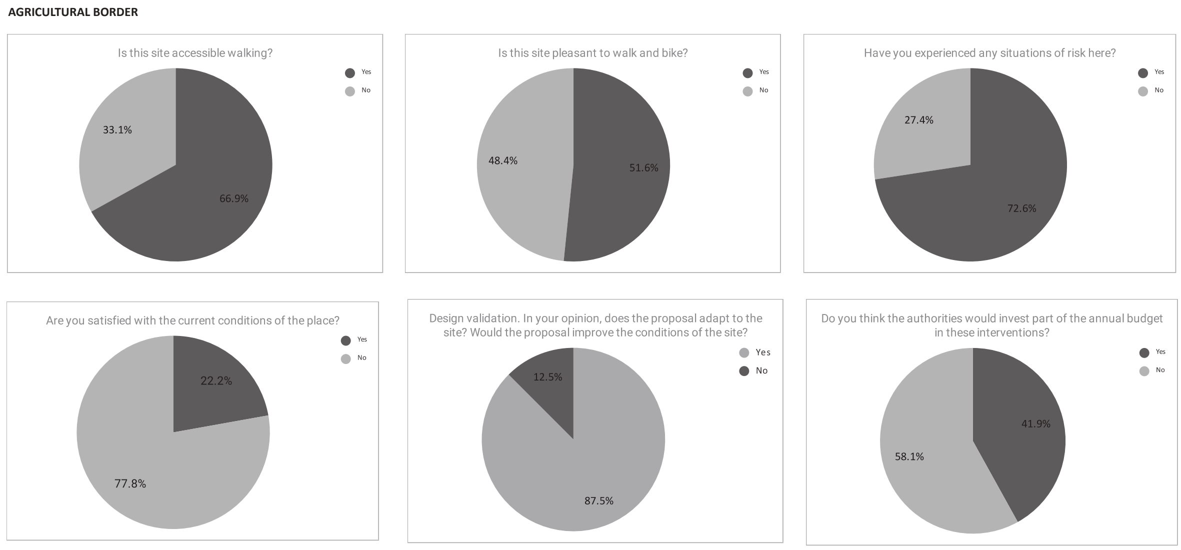


Figure 47. Responses to the digital survey 2, for the Zoom-in 1: Agricultural border + rural tissue

Source: Made by author, 2022

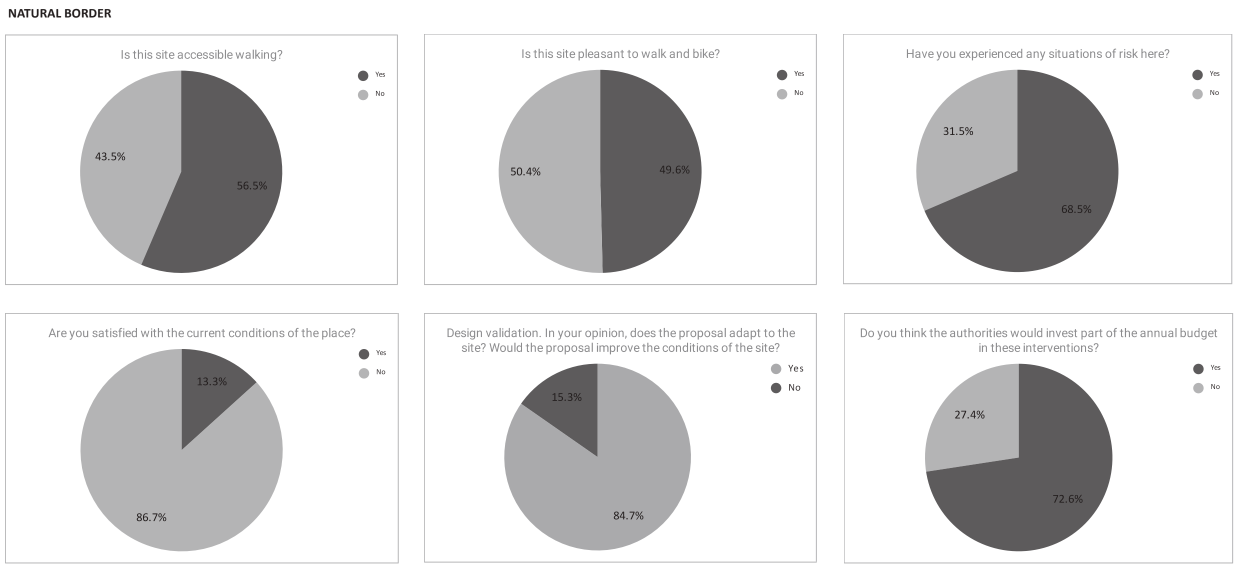


Figure 48. Responses to the digital survey 2, for the Zoom-in 2: Natural border + rural tissue

Source: Made by author, 2022

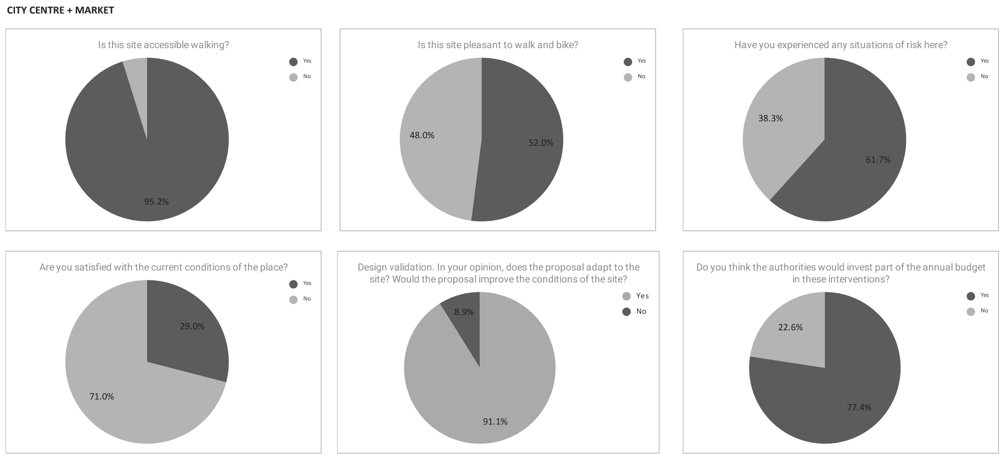


Figure 49. Responses to the digital survey 2, for the Zoom-in 3: City centre + market

Source: Made by author, 2022

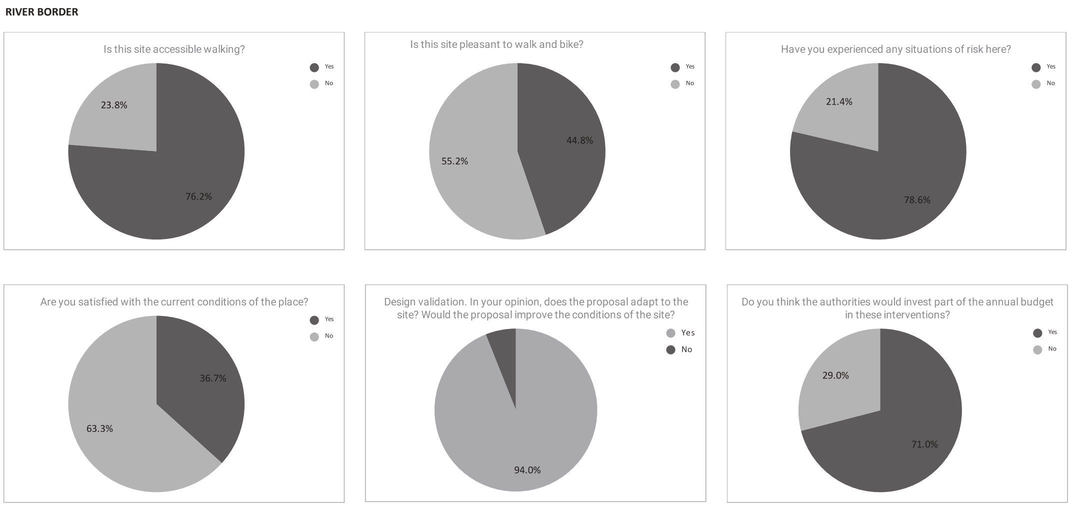


Figure 50. Responses to the digital survey 2, for the Zoom-in 4: Chancay-Lambayeque river border

Source: Made by author, 2022

Positive results were shown with digital survey 2, which was used for validating the design. When specifically asked about the adaptation of design, to the site and how it would improve the specific site the responses were the following: for Zoom-in 1, 87.5% of the responses correspond to 'yes' and 12.5% of the responses correspond to 'no'; for Zoom-in 2, 84.7% of the responses correspond to 'yes' and 15.3% of the responses correspond to 'no'; for Zoom-in 3, 91.1% of the responses correspond to 'yes' and 8.9% of the responses correspond to 'no'; for Zoom-in 4, 94% of the responses correspond to 'yes' and 6% of the responses correspond to 'no'. This is translated into 'in favour' of the spatial intervention or 'against'. The current research project aimed for higher participatory design which was over clouded by the Covid-19 pandemic; however, having an average of almost 90% –89.325% to be exact– of acceptance rating, in addition to the empiric knowledge of the general community about nature-based solutions makes me feel optimistic of a sustainable future for Chongoyape, where flood mitigation is achieved through green and blue resilient infrastructure.

6. Enablers and Barriers

Enablers

The management team of CDRI was always quite helpful and engaging.

Even though the advice from the mentor and TEG member was always taken into account after the revisions, there was freedom to decide what would suit better for the research project.

Quarterly revision were especially helpful since it allowed me to know if the research was going in the right direction or some items needed change. Receiving useful feedback regarding the research topic or if the research problems was being understood; and later on, if the design was been showed clear enough or if needed any readjustments.

Barriers

Lack of response from part of governmental agencies. I tried to contact them via email and by telephone. The objective was to get input and feedback from the design part, not just from the community but from the upper part of the decision-making process ladder as well; however, this was not achieved.

The Covid-19 pandemic made the participation part of the project troublesome; however, this was overcome with digital surveys.

Internal conflicts in the country such as a transport strike, made it impossible to travel to Chongoyape during the last couple of months. Before this happened, there was some hope that parts of the digital surveys were going to be done in person, at least with a reduced number of people. However, this was not possible.

7. Conclusion and Way Forward

From the aforementioned context, diagnosis and design, it is imperative to come back to the main research question: How can green and blue infrastructure be designed in Chongoyape for the city to be climate adaptive? Transformative models in the smallest spatial scales answer the question given that change at these scales 'enables resilience at larger scales' (Folke, 2010). Moreover, the small-scale functions as 'driver for innovation, and thus for slow change and adaptation at larger scales' (Erixon et. al., 2013, p. 278).

The following text is part of the conference paper presented on IFoU 2021 (Wong, 2021a).

It can be concluded that a network of green and blue infrastructure is necessary to improve – and even guide– access to natural areas that over time have been disappearing to accommodate highly urbanized environments (Bacchin, 2015; Wong, 2018). The use of the site specificity tool allowed for the recognition of ways of living which were not considered during the initial site visits, where only the physical attributes were recognized. As this study suggests the site specificity tool improved the perception of the place, granting the appropriate knowledge to propose a design able to accommodate complexity.

Conclusion of (Wong, 2021a).

Additionally, the design of green and blue resilient infrastructure in the smaller spatial scales in Chongoyape made the conceptual term ‘resilience’ a visual one, by illustrating interventions that can be executed in places that the inhabitants of Chongoyape use on their everyday lives. This, in turn, improves the legibility of the sites and makes the community eager to appropriate the spaces, which in turn, can help promote bottom-up approaches. ‘Moreover, the early involvement of the whole array of stakeholders gives them a sense of ownership, which allows for appropriation of spaces and for the community to be a strategic part of the monitoring and maintenance processes’ (Wong, 2021a). Finally, given the dichotomy of the water challenges in Chongoyape and the vulnerability of the place to El Niño-related events, it is of outmost importance to educate the future generations and forge cooperation bonds with the local community to inform resilience.

Next steps. The average of acceptance of the design validation was 89.325% however, there was some part of the community that did not feel the design adapted or would improve the site. Next steps for the current project would be to hold in-person workshops to explain the transformative models, since there are still some barriers when conducting digital surveys. Moreover, recommendations from the community would be taken into account to improve the design, in order to achieve a participatory design process.

Finally, a way forward would be to replicate the methodology used in the current project for other places in the Chancay-Lambayeque sub-basin, especially in town where the latitude changes considerably compared to Chongoyape, as Sipán and Etén, located in the middle and final part of the sub-basin, respectively. This way new spatial interventions would be introduced, and an integrative system would be designed to mitigate flooding and climate change-related events in the whole Chancay-Lambayeque sub-basin.

It is important to mention that once the feedback of the final deliverables is received, a final paper will be sent to Urbanism journals for publication.

References

1. Ashley et. al. (2015). Innovative socio-technical solutions bringing multifunctional values to urban citizens. *JPI-Urban Europe Green/Blue Infrastructure for sustainable, attractive cities report,* D1.6
2. Berrizbetia, A. (2007) *Re-Placing Process in Large Parks* (ed. Czerniak, J, & Hargreaves, G.). Nueva York: Princeton Architectural Press
3. Brink, A. van den (Ed.). (2017). *Research in Landscape Architecture: Methods and methodology.* Routledge/Taylor & Francis Group.
4. Corner, J., & Hirsch, A. B. (2014). *The Landscape Imagination: collected essays of James Corner*, 1990-2010. New York: Princeton Architectural Press
5. Durance, P., & Godet, M. (2010). Scenario building: Uses and abuses. *Technological Forecasting and Social Change,* 77(9), 1488–1492. https://doi.org/10.1016/j.techfore.2010.06.007
6. Erixon, H., S. Borgstrom, S., & Andersson, E. (2013). Challenging dichotomies - exploring resilience as an integrative and operative conceptual framework for large-scale urban green structures. *Planning Theory & Practice*, 14(3), 349-372.
7. Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand- Krajewski, J.-L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., & Viklander, M. (2015). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, 12(7), 525–542.
8. Folke, C. (2016). Resilience (Republished). *Ecology and Society*, 21(4). doi:10.5751/ES- 09088-210444
9. Gobierno Regional de Lambayeque. (2013). *Memoria Descriptiva del Mapa de Vegetación – Descriptive Memory of Vegetation Map*
10. Gobierno Regional de Lambayeque. (2013). *Estudio de Biodiversidad: Flora – Biodiversity Survey: Flora*
11. Hung Y. Y., Aquino, G. & Waldheim, C. (2011). *Landscape Infrastructure : Case studies by SWA*. Basel: Birkhauser.
12. IPBES Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2020) *Workshop on Biodiversity and Pandemics*. Details available at https://ipbes.net/pandemics
13. Kuzniecow Bacchin, T. (2015). Performative nature. Urban Landscape infrastructure design in water sensitive cities. A+BE | *Architecture and the Built Environment.*
14. Kuzniecow Bacchin, T., Ashley, R., Sijmons, D., Zevenbergen, C., & Timmeren, A. van. (n.d.). Green-Blue Multifunctional Infrastructure: An Urban Landscape System Design New Approach. *ICUD 2014: Proceedings of the 13th IAHR/IWA International Conference on Urban Drainage*, Sarawak, Malaysia, 7-12 September 2014.
15. Lister, N. (2007) Sustainable Large Parks: Ecological design or designer ecology?. In J., Czerniak & G., Hargreaves (Eds.). *Large Parks*. New York: Princeton Architectural Press.

16. Nijhuis, S., & de Vries, J. (2020). Design as research in landscape architecture. *Landscape Journal*, 38(1-2), 87-103.
17. Ministerio del Ambiente. (2014). *Perú, Kingdom of Forests*. Biblioteca Nacional del Perú: Lima
18. NOAA. What are El Niño and La Niña? *National Ocean Service website*, https://oceanservice.noaa.gov/facts/ninonina.html
19. Tucci, C. (2009) 'Mitigating of water related natural disasters in developing countries' in Feyen, J., Shannon, K., Neville, M., & International Urban Water Conference International Urban Water Conference (2008 : Heverlee, Belgium). Water and
urban development paradigms : Towards an integration of engineering, design and management approaches : *Proceedings of the international urban water conference*, Heverlee, Belgium, 2008. Boca Raton, Fla: CRC
20. Wong, T. H. F. (2006). Water sensitive urban design—The journey thus far. *Australasian Journal of Water Resources,* 10(3), 213–222.
21. Wong, T. H. F., & Brown, R. R. (2009). The water sensitive city: Principles for practice. Water Science and Technology, 60(3), 673–682. Wong, C. (2018). *Intertwined Natures. Towards Territorial Cohesion & Flood Risk Adaptation in Lambayeque, Peru.* Delft University of Technology.
22. Wong, C. (2021). A sense of place. Site specificity as a way to foster resilient urban landscapes. *The Evolving Scholar* | IFoU 14th Edition.
23. Wong, C. (2021b). Naturalezas entrelazadadas. Adaptación al cambio climático mediante infraestructura verde y azul en Lambayeque, Perú. *Proceedings of ISUF-H*.

GIS-Based Landslide Susceptibility Mapping by AHP Method, A Case Study, Bamyan, Afghanistan

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Coalition for Disaster Resilient Infrastructure

Disclaimer:

We hereby declare that this research titled “Disaster Resilience Building Construction Practices on Hilly Slopes of Bhutan-A Research Compliance and Recommendation for National Adaptation” is an original work and we have not committed, to our knowledge, any academic dishonesty or resorted to plagiarism in writing this research report. All the sources of information and assistance received during the course of the study are duly acknowledged.

Abstract

Landslides are one of the critical phenomena that frequently lead to loss of human life and property, as well as cause severe damage to natural resources and infrastructure. Bamyan province is a landslide-prone zone because of its rush topography, climate conditions, seismic potential and geology. Every year landslides in Bamyan result in significant economic and social losses (deaths, injuries and property destruction).

This article presents a landslide susceptibility analysis in Bamyan, Afghanistan using AHP (Analytic Hierarchy Process) method. To provide the landslide susceptibility, determination of the effective factors in landslide occurrence is very important. For this purpose, the most important factors affecting the occurrence of landslides in this province were identified through ground observations and comparison of pervious research. Thereafter, 12 factors that affect the landslide occurrence were selected including, lithology, distance to drainage, slope, distance to fault, rainfall, land cover, distance to village, drainage density, elevation, aspect, distance to road and land surface temperature. According to the relation between the above factors and landslide distribution, the weight value and rating value of each factor were calculated using AHP. Finally, the susceptibility maps of the study area were provided using Arc GIS software through weighted overlay method. The final map shows that very high risk, high risk, moderate risk and low risk zones respectively, cover 2.88%, 58.34%, 29.52% and 9.26% of the Bamyan areas. On the other hand, lithology, drainage and slope are recognized as the most effective factor on the occurrence of landslide.

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1. Introduction

Landslide, one of the most damaging natural disaster phenomena, occurs every year across the world, especially in mountainous area. Landslides of various scales occur because of natural and anthropogenic factors around the world and cause human and financial losses (Aksaray et al., 2011). Occasionally, an enormous landslide buries a town or city, killing thousands of people. Landslides cause billions of dollars in damage every year, about equal to the damage caused by earthquakes in 20 years. Most of the time, landslides cause damage because people lack awareness (Pourghasemi et al., 2013)analytical hierarchy process, and statistical index models and an assessment of their performances. The study area covers the north of Tehran metropolitan, Iran. When conducting the study, in the first stage, a landslide inventory map with a total of 528 landslide locations was compiled from various sources such as aerial photographs, satellite images, and field surveys. Then, the landslide inventory was randomly split into a testing dataset 70 % (370 landslide locations.

A landslide is the movement of mass of rock, debris or earth down a slope. It results from the failure of the materials, which fall down the slope due to force of gravity. It is also known as slope failure slumps or landslips (Yazdadi and Ghanavati, 2016)as well as causing severe damage to natural resources. Kordan watershed located in the Alborz province, which including areas that are prone to landslide. The area under investigation is located from 50 ° 45' to 05' ° 51' east longitude and 35° 55' to 36° 05' North with expansion of about 488 km2 and elevation ranges from 1320 to 3900 m. The purpose of this study is to identify factors in landslides and zonate landslide hazard of Kordan watershed using AHP (Analytical Hierarchy Process. Outward and downward movement of mass consisting of rocks, slope instability and soil due to natural or anthropogenic causes is termed as landslides. These events are associated with pre and post-earthquake, soil erosion, rainfall and anthropogenic activities (Koley et al., 2020). The term "landslide" comprises all varieties of mass movements of hill slopes. It can be defined as the inwards and outwards movement of slope forming materials composed of rock, earth, soil, mud and debris or combination of all these materials along surfaces of separation by sliding, flowing and falling, slowly or rapidly under the influence of gravity (Koley et al., 2020; Yazdadi and Ghanavati, 2016)as well as causing severe damage to natural resources. Kordan watershed located in the Alborz province, which including areas that are prone to landslide. The area under investigation is located from 50 ° 45' to 05' ° 51' east longitude and 35° 55' to 36° 05' North with expansion of about 488 km2 and elevation ranges from 1320 to 3900 m. The purpose of this study is to identify factors in landslides and zonate landslide hazard of Kordan watershed using AHP (Analytical Hierarchy Process. Landslides cause adverse effects on human lives and economy worldwide. Steep slopes characterize mountainous terrains, fractured, folded and high relative relief weathered rocks. Expansion of urban and humanmade structures into potentially hazardous area leads to extensive damage to infrastructure and occasionally results in loss of life every year (Kamp et al., 2008)2005 Kashmir earthquake triggered several thousand landslides throughout the Himalaya of northern Pakistan and India. These were concentrated in six different geomorphic-geologic-anthropogenic settings. A spatial database, which included 2252 landslides, was developed and analyzed using ASTER satellite imagery and geographical information system (GIS.

Landslide susceptibility mapping has greatly helped designers and engineers to select suitable locations for development projects, and the results of such studies can be used as basic information to assist managers and environmental planning. Finally, potential hazards can be avoided by identifying areas with high landslide potential (Pourghasemi et al., 2012)landslide locations were identified by aerial photographs and field surveys, and a total of 78 landslides were mapped from various sources. Then, the landslide inventory was randomly split into a training dataset 70 % (55 landslides. The results of research conducted in different countries show that landslides occur under the influence of various human and natural factors, but the effect of every factor is different according to geomorphology, geology, climate and regions (Saleem et al., 2019). Some of the studies conducted on landslide risk zoning are as follows: Naseri (2016), Kamp et al. (2008)2005 Kashmir earthquake triggered several thousand landslides throughout the Himalaya of northern Pakistan and India. These were concentrated in six different geomorphic-geologic-anthropogenic settings. A spatial database, which included 2252 landslides, was developed and analyzed using ASTER satellite imagery and geographical information system (GIS, Kanwal et al. (2017)which contain Landsat 8 imagery and distance from roads; (2, Moradi et al. (2012), Feizizadeh and Blaschke (2013), Hamid Reza Pourghasemi et al. (2012)landslide locations were identified by aerial photographs and field surveys, and a total of 78 landslides were mapped from various sources. Then, the landslide inventory was randomly split into a training dataset 70 % (55 landslides, Koley et al. (2020), Yazdadi and Ghanavati (2016)as well as causing severe damage to natural resources. Kordan watershed located in the Alborz province, which including areas that are prone to landslide. The area under investigation is located from 50 ° 45’ to 05’ ° 51’ east longitude and 35° 55’ to 36° 05’ North with expansion of about 488 km2 and elevation ranges from 1320 to 3900 m. The purpose of this study is to identify factors in landslides and zonate landslide hazard of Kordan watershed using AHP (Analytical Hierarchy Process, DV.COM (2014), Alam (2020)Bangladesh has been experiencing hill cutting problems and subsequent landslide occurrence in its southeastern hilly region. Since 2000, landslides have caused over 500 deaths, mostly in informal settlements in southeast Bangladesh. The most significant single event was the 2007 landslide causing 127 deaths in Chittagong’s informal settlements. The landslide events took over 110 people in Rangamati on 12 June 2017. In the scenario of rising deaths by landslides in the southeastern region, this research aimed to understand communities’ landslide hazard knowledge, reasons for living in at-risk areas, risk perception and preparedness. This research applied both quantitative (i.e., structural questionnaire and Aksaray et al. (2011). These researches have been conducted in Afghanistan, India, Pakistan, Iran, Korea, Italy, Bangladesh and Turkey and aimed to identify the effective factors that cause landslide and specify the efficiency level of those factors.

In order to provide landslide susceptibility maps, various methods such as fuzzy logic, statistic methods and Analytic Hierarchy Process (AHP) can be used (Yazdadi and Ghanavati, 2016)as well as causing severe damage to natural resources. Kordan watershed located in the Alborz province, which including areas that are prone to landslide. The area under investigation is located from 50 ° 45’ to 05’ ° 51’ east longitude and 35° 55’ to 36° 05’ North with expansion of about 488 km2 and elevation ranges from 1320 to 3900 m. The purpose of this study is to identify factors in landslides and zonate landslide hazard of Kordan watershed using AHP (Analytical Hierarchy Process. Since the 1970s, researchers have been searching for suitable methods for assessing the spatial distribution of landslide hazards based on GIS techniques. Of the various methods proposed by researchers to assess the landslide phenomenon, one of them is AHP. This method was used by

Saaty (1980), Bernasconi et al. (2010), Yazdadi and Ghanavati (2016)as well as causing severe damage to natural resources. Kordan watershed located in the Alborz province, which including areas that are prone to landslide. The area under investigation is located from 50 ° 45’ to 05’ ° 51’ east longitude and 35° 55’ to 36° 05’ North with expansion of about 488 km2 and elevation ranges from 1320 to 3900 m. The purpose of this study is to identify factors in landslides and zonate landslide hazard of Kordan watershed using AHP (Analytical Hierarchy Process, Achour et al. (2017) and Devara et al. (2021). AHP gained wide application in site selection, suitability analysis, regional planning and landslide susceptibility analysis (Ayalew et al., 2005). For the purpose of the present research, the AHP method has been selected. Using this method, each layer used in landslide susceptibility zoning is broken into smaller factors. Then these factors are weighted based on their importance, and eventually the prepared layers are assembled and the final map is produced. This is done based on three principles: decomposition, comparative judgment and synthesis of priorities (Malczewski, 2006). In this method, weight of each layer depends on the judgement of expert, so that the more precise is the judgement, the more compatible is the produced map with reality (Moradi et al., 2012).

The Bamyan province in Afghanistan is a landslide-prone zone because of its own characteristics including the mountainous topography, climate conditions, seismic potential, geology and geomorphology. Based on the report “Afghanistan natural disaster incidents”, in 2020 most landslides occurred in northern, central and western provinces of Afghanistan. Landslides are one of the most frequent hazards in Bamyan, resulting in significant economic and social losses (e.g., deaths, injuries and property destruction). Figures 1, 2, 3, 4, 5 and 6 show the occurrence of landslide in different times in different parts of Afghanistan. For instance, the landslide that occurred on 23 September 2018 in Shibar district of Bamyan resulted in significant economic and social losses (e.g., deaths, injuries and property destruction)(Shroder, 2016). Unfortunately, no comprehensive landslide research has been conducted in Afghanistan yet. A few researches have been conducted but are limited to a province or a district, which is not enough. Therefore, to date, statistics on the number of landslide events, in terms of location and time, and statistics of landslide damage are not available for the country. However, according to a survey conducted by the Afghanistan - Natural Disaster Incidents with the financial support of the OCHA in 2020, the number of families affected by natural disasters in Afghanistan is 16,446, the number of victims is 109,430, the number of damaged homes is 8303 and the number of destroyed houses is 2717 (OCHA, 2020).

Figure 1. Yakawalang, Bamyan, landslide in Dara Ali
Photo Credit: Local People, Sept 2015

Figure 2. Same landslide but photo took in October 2021

Figure 3. Kotal Surkhak, Yakawalang landslide in October 2021

Figure 4. Second landslide in Dara Ali, Bamyan in October 2021

Figure 5. Photo of Abe Barek, Badakhshan landslide
Photo: Fardin Waeze/UNAMA (UN, 2014)

Figure 6. Photo of Abe Barek, Badakhshan landslide
Photo: Fardin Waezi/UNAMA (UN, 2014)

Another landslide occurred in Barak district of Badakhshan province on 2 May 2014 due to heavy rain and attracted the attention of the world due to its great intensity and destruction. The human casualties of this event were between 300 and 2700 people. Furthermore, according to the observation made through high-resolution satellite imagery, such as World View, between 7 June 2013 and 5 May 2014, about 78 infrastructures were damaged and destroyed (Zhang et al., 2015; Unitar, 2014). Similarly, according to a report published by Radio Azadi on 11 February 2015, all kinds of natural disasters occur annually in different parts of the country at different scales (Radio Azadi, 2015).

Identifying landslide-prone areas is one of the first steps in natural resource management and development planning. Landslides occur under the influence of various natural and human factors, and evaluating the impact of each of these factors has a significant role in predicting the probability of their occurrence and zoning (Zhang et al., 2015). Identifying the effective factors in the occurrence of this phenomenon and their potential in the management of natural resources and reducing the damage caused by them is very important (Yazdadi and Ghanavati, 2016)as well as causing severe damage to natural resources. Kordan watershed located in the Alborz province, which including areas that are prone to landslide. The area under investigation is located from 50 ° 45’ to 05’ ° 51’ east longitude and 35° 55’ to 36° 05’ North with expansion of about 488 km2 and elevation ranges from 1320 to 3900 m. The purpose of this study is to identify factors in landslides and zonate landslide hazard of Kordan watershed using AHP (Analytical Hierarchy Process.

The purpose of this study is to identify the effective factors and provide landside susceptible map of Bamyan province using AHP model and GIS technique. In order to provide landslide susceptibility map, various methods such as fuzzy logic, statistic methods and AHP can be used. In the past, AHP has been used by Devara et al. (2021) and Abedini and Tulabi (2018)Frequency Ratio (FR. AHP is a theory of measurement that deals with quantifiable and intangible criteria and has been applied to numerous areas, such as decision theory and conflict resolution. Using this method, each layer used in landslide susceptibility zoning is broken into smaller factors. These factors are then weighted based on their importance, and eventually the prepared layers are assembled and the final map is produced. It is based on three principles: decomposition, comparative judgement and synthesis of priorities (Pourghasemi et al., 2012)landslide locations were identified by aerial photographs and field surveys, and a total of 78 landslides were mapped from various sources. Then, the landslide inventory was randomly split into a training dataset 70 % (55 landslides. In this method, the weight of each layer depends on the judgement of expert, which means the more precise is the judgement, the more compatible is the produced map with reality.

1.1 Description of the study area

Bamyan is a historical site and one of the 34 provinces of Afghanistan. It is located in the central part of Afghanistan (Figure 9). Geographically, the Bamyan province is located between 34°49'17" N latitude and 67°49'38" E longitude. The average altitude of Bamyan province is 2600 m from sea level. The total area of Bamyan province is 14148 km^2 and the total population is 387,300. Bamyan has seven administrative units: Bamyan centre, Yakawalang, Waras, Panjab, Shiber, Saighan, Kahmard (CSO, 2013).

Altitude change in this province ranges from 2000 to 5044 m. Two popular mountain scenery extended to Bamyan are Hindu Kush and Baba. These two mountain scenery are covered with snow most of the time and are the source of surface and ground water for the region. The main geographical characteristics of this region are steep rivers, valleys and mountains with high elevation. The climatic zone of alpine relief in Bamyan is characterized by a short cold summer and a long rigorous winter, with most precipitation occurring as snow. Bamyan is covered with snow the whole winter. The Bamyan province has a very complex geology. The oldest to the youngest geological materials can be found in this province. However, sedimentary rocks cover most area of this province. Because of long winter and cold climate, the province has less vegetation coverage. This province has mostly bare land. Together, these factors, in addition to human factors, cause landslides. However, most of the landslides that occur in Bamyan province are similar in flow. The Bamyan landslides include loose soil, rock, organic material, water and look like a slurry downslope ward. They include both fine and coarse grain particles. The causes of landslides here are heavy precipitation or quick snowmelt in the slopes with less vegetation. Most of the landslides happen after heavy participation in spring or snow melting in summer. Exact statistics are not available on the number landslides and its victims and financial losses.

Some of the local media have reported some of the disasters that have occurred in the region. As per a report published by Shia Association News, on 23 September 2018 because of landslide in the Shibar district, Bamyan province, three members of a family were killed and one was injured. In addition to the casualties, about 40 sheep, 4 cows and 9 acres of agricultural land were destroyed (Shia Association News, 2018). According to a report by Afghanistan Voice Agency, on 8 May 2014 in Sorkh Juy village of Dara-e-Fooladi, which is 20 km away from Bamyan centre, about 100 families fled their homes due to a possible landslide (AVA, 2014). The Afghanistan natural disaster incidents between 2012 and 2020 said that due to natural disasters, 4 people were killed, 19 people were injured, 1241 families were affected and 79 houses were destroyed (OCHA, 2020). The photos of the landslide in Bamyan province are shown in Figures 1, 2, 3 and 4. For more detail, Google Earth photographs of the occurred landslide in Bamyan province are presented in Figures 7 and 8.

Figure 7. Google Earth photo of Dara Ali, Yakawalang landslide

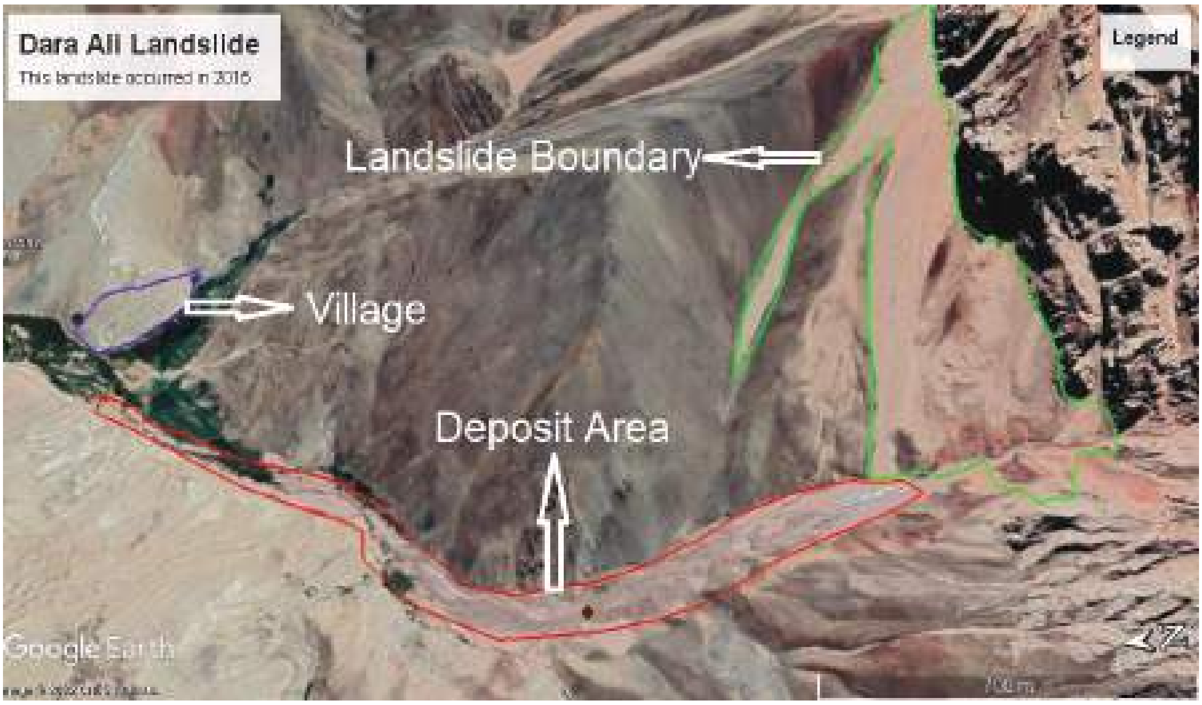

Figure 8. Google Earth photo of second occurred landslide in Dara Ali, Yakawalang

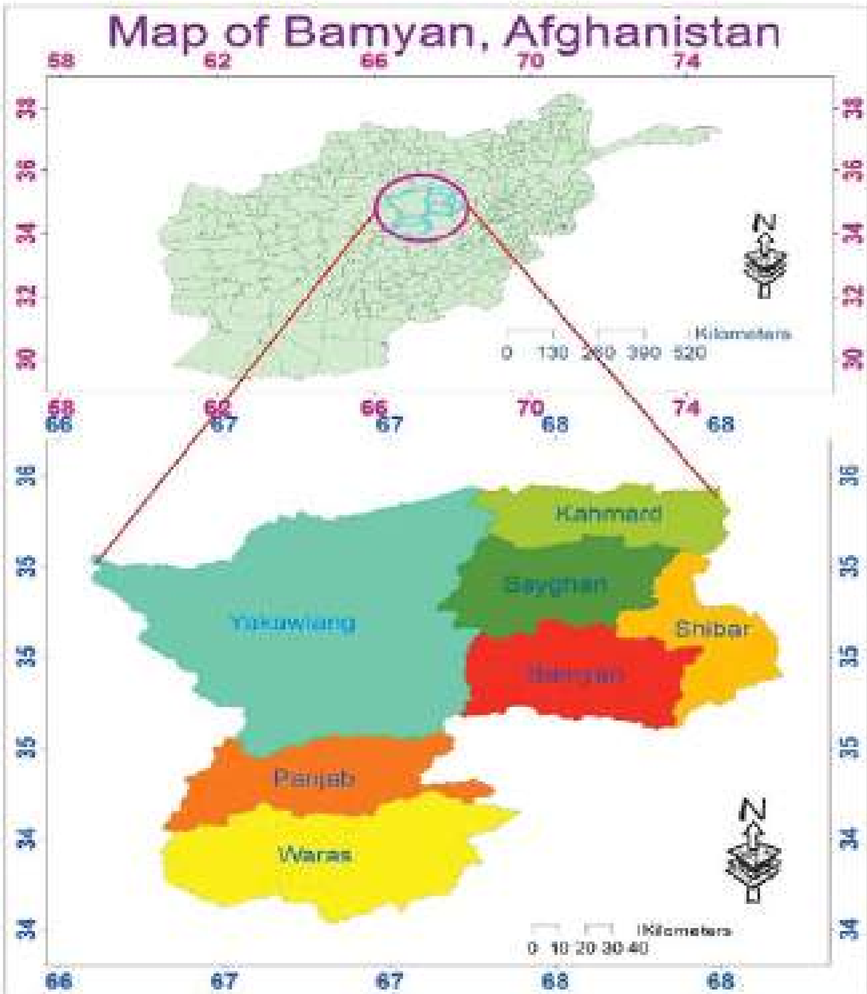

Figure 9. Bamyan, Afghanistan

2. Research Problem

In countries such as Afghanistan, Pakistan, India, Nepal, Bangladesh and Bhutan, landslides are generally caused by the Hindu Kush and Himalayan mountain ranges (USAID, 2017). Afghanistan has high mountains, steep slopes, highly fractured bedrock overlain by weak sediments, torrential rain storms and high seismicity, which means that slope failures in the country are plentiful and of many diverse types. High-speed rockfalls and rock slides are profuse below cliffs that occur throughout the high rugged mountains, and failures occur repeatedly of the common sedimentary rocks and sediments, especially where shales and unstable losses occur in the northern and central parts of the country. Loss of property and life from landslides and snow avalanches has also been extreme in the country, with many tens to hundreds killed in recent years. In addition, many of the landslides have blocked rivers and caused inundation upstream. Such landslide dams are inherently unstable if the impounded lake grows large enough because the dam may not hold and abrupt landslide lake outburst floods can result. Lake Shewa in Badakhshan, for example, formed the second largest such landslide dam in the world, with serious implications should it ever burst out into the River Panj tributary to the Amu Darya. At present, large quantities of water are being issued from the middle front face of the dam and several small slumps of dam face material have occurred in recent years. The Lake Shewa dam front has stood for thousands of years without total failure. But it still needs monitoring. In other cases, the common seismicity is related to rock slides and the destruction of travertine dams that produce floods downstream. This phenomenon can occur in Bamyan province in near future as this province has the needed features for this event.

Mass movements of nearly all types occur in Afghanistan but in the high relief of the rugged Hindu Kush mountain of central Afghanistan, mass movement threats to lives and property which necessitate intensive study by the researchers to elucidate future problems for development. Based on USAID observation in 2017, the northern and central parts of Afghanistan experience most landslide hazards. According this observation, Bamyan province has the Landslide Susceptibility Index of 19.8 K (population at landslide risk). The Bamyan province in Afghanistan is a landslide-prone zone because of its own characteristics including the mountainous topography, climate conditions, seismic potential, geology and geomorphology. Another important factor that causes landslides in Bamyan is its rough topography.

3. Aim, Objectives, and Scope of the Research Study

The overall objective of this research is to provide the landslide susceptibility map of Bamyan and contribute to mitigate landslide risk. The specific objectives are as follows:

- Preparation of landslide inventory map
- Provide landslide susceptibility map of Bamyan province using AHP method and GIS techniques
- Contribute to mitigate landslide risk by establishing reliable methods for determining the risk

4. Methodology

In the first step, landslide-prone areas were explored through aerial photographs and Google Earth. Then, for better understanding of the landslide-prone areas, a committee, consisting of geologist, geodesist, environmentalist and geographer, visited some areas. Since the study area is very large, the team visited locations where the landslides occurred. After a comprehensive review, the committee, based on geological, geomorphological, hydrological, human and environmental characteristics of the study area, used comparative studies and results of other researchers. To achieve the goal, 5 criteria and 12 sub-criteria were identified. Based on the selected criteria and sub-criteria, data were collected from different sources and shown in Table 1.

Table 1. Data source

Data	Description	Source
GDEM	Resolution (15 m)	USGS Earth Explorer https://earthexplorer.usgs.gov/
Aspect	Extracted from GDEM	USGS Earth Explorer https://earthexplorer.usgs.gov/
Faults	Extracted from Geological	USGS Earth Explorer https://earthexplorer.usgs.gov/
Slope	Extracted from GDEM	USGS Earth Explorer https://earthexplorer.usgs.gov/
Drainage	Extracted from GDEM	USGS Earth Explorer https://earthexplorer.usgs.gov/
Lithology	FAO Map Catalog	https://data.apps.fao.org/map/catalog/srv/eng/catalog.search?fbclid=IwAR1vErVybmOh8ynaVcM04jfSdhqooFPc3VJQ43iGjfdox5vI4hK_yVBAh-A#/home
Rainfall	PERSIANN yearly Data Resolution 0.25×0.25 degree	CHRS Data: https://chrsdata.eng.uci.edu/?fbclid=IwAR1rr5o5qNfU_ZurS1t70hWqoo8AljGNQg3NBlcQ4XGzmX3Xpsr-V76VzCU
LU&LC	Spatial resolution (10 m) provided from Sentinel-2	Esri 10m Land Cover: https://livingatlas.arcgis.com/landcover/?fbclid=IwAR3kzwQiNMQ35VED6ie4BMX3wTtoK3Vtzchx47BfBalOkoyPDSX02N9yixA
Roads	Open Street Map (OSM)	Geoinformatics World: https://geoinformaticsworld.com/vector_data/?fbclid=IwAR3THZHGbsf47kcTC2gBbojjYhM4z8NE11Ql8skQ9DXKIb48jaTxcJhrVU0
LST	Extracted from Landsat 8	USGS Earth Explorer https://earthexplorer.usgs.gov/
Villages	Open Street Map (OSM)	https://extract.bbbike.org/
Boundary of study area	DIVA GIS	https://www.diva-gis.org/gdata
Location of active landslides	Field survey	The coordinates of active landslides collected using handheld GPS.

Afghanistan is one of the poorest countries in the world in terms of research database. The 40 years civil war has left Afghanistan with no research database. All data used in this study are secondary data and collected from various Internet sources. Unfortunately, sometime this kind of data are not suitable for specific research in a small area as these are global data meant for globally research. It means that their scale and resolutions are not suitable for a small region. However, in this study, in addition to the collected secondary data, some primary data were also collected through field visit. For example, landslide-occurred areas were visited in order to assess the geological, morphological, climatic, hydrological and environmental characteristics of the area. Handheld GPS were used to take the coordinates and camera to take photos. Then all these information were used for validation of secondary data and final landslide susceptible map.

Next, all the data were pre-processed for next use. It means that some functions such as clip, mosaic, vector to raster were applied using Arc GIS 10.5 software. First, the digital elevation model of the region classified six elevation classes based on the natural failures that exist in the heights of the region. Slope layers and slope direction were prepared from the digital elevation model of the area. Similarly, all other digital layers such as lithology, land surface temperature, precipitation, LU&LC, distance to villages, distance to faults, distance to drainage, drainage density, distance road, distance to rivers were prepared. Finally, all the vectors layers were converted to raster layers.

In the next step, weigh value was assigned for each criteria, sub-criteria and classes. This step was performed according to the instructions of the AHP method. The AHP is a structured technique that deals with complex decisions developed by Saaty in 1980. This technique is based on pair-wise comparison of the contribution of different factors and gives various scenarios to the decision-makers. As there is no linear relationship between the landslide and the factors influencing them, therefor the usual statistical approach cannot solve all the problems. In this respect, AHP model provides conditions that can determine the landslide susceptible map with more details (Ghanavati, 2012).

4.1 Landslide susceptibility analysis

In this research, the AHP method was used to specify the weight value of each involved criteria, sub criteria and classes for landslide zonation mapping in Bamyan province. In the first step, the hierarchical structure should be drawn (see Figure 10). In this figure, we faced a four-level hierarchy including goal, criteria, sub-criteria and classes. Making the subject or problem into a hierarchical structure is the most important part of the hierarchical analysis, because in this part, by analysing difficult and complex problems, the hierarchical analysis transforms it into a simple form that can correspond to the human mind and nature. In other words, the process of hierarchical analysis simplifies complex problems by breaking them into hierarchically interrelated elements whose relationship between the main purpose of the problem and the lowest level of the hierarchy is clear. AHP method breaks down complex problems into simple ones that are easy for the users to understand. A comprehensive description about AHP can be found in Saaty (1980) and Bernasconi et al. (2010).

1. The goal, criteria, sub-criteria, alternative
2. The goal, criteria, factors, sub-factors, alternative

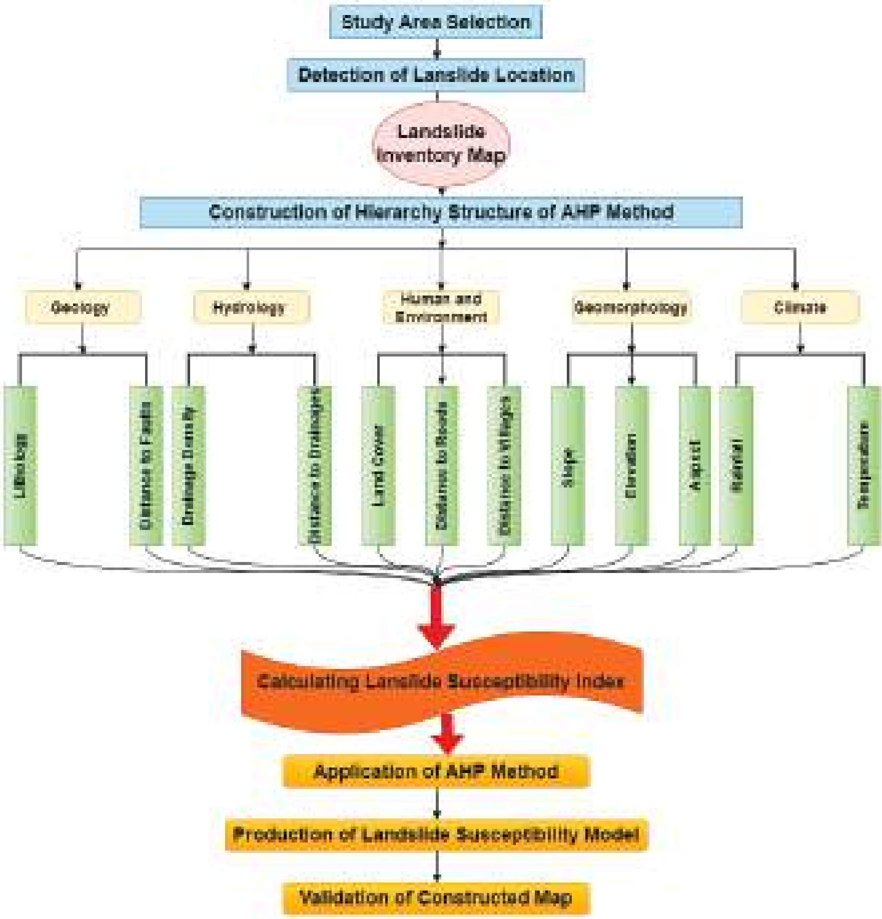

Figure 10. Hierarchical analysis process, constructing a hierarchy for landslide susceptibility mapping

AHP has gained wide application in site selection, suitability analysis, regional planning and landslide susceptibility analysis (Ayalew et al., 2005). It has been successfully employed in landslide susceptibility mapping by several researchers (Ayalew and Yamagishi, 2005multivariate statistical analysis in the form of logistic regression was used to produce a landslide susceptibility map in the Kakuda-Yahiko Mountains of Central Japan. There are different methods to prepare landslide susceptibility maps. The use of logistic regression in this study stemmed not only from the fact that this approach relaxes the strict assumptions required by other multivariate statistical methods, but also to demonstrate that it can be combined with bivariate statistical analyses (BSA; Moradi et al., 2012; Moradi et al., 2012; Malczewski, 2006). AHP involves building a hierarchy of decision elements (factors) and then making comparisons between possible pairs in a matrix to give a weight for each factor and also a consistency ratio as described by Devara et al. (2021). This will describe the importance of each factor relative to every other factor (Moradi et al., 2012). In AHP, each factor is rated against every other factor by assigning a value between 1 and 9, if the factors have a direct relationship. Conversely, the value varies between the reciprocals 1/2 and 1/9 (Table 1) (Saaty, 2000).

4.2 Preparation of landslide inventory map

In order to check the accuracy of the final map, the landslide inventory map was provided with the help of aerial photographs and ground surveys. Since the study area is very large and visiting every single occurred landslide point is difficult, accordingly, the landslide inventory map was prepared only for Yakawalang district of Bamyan province (Figure 11).

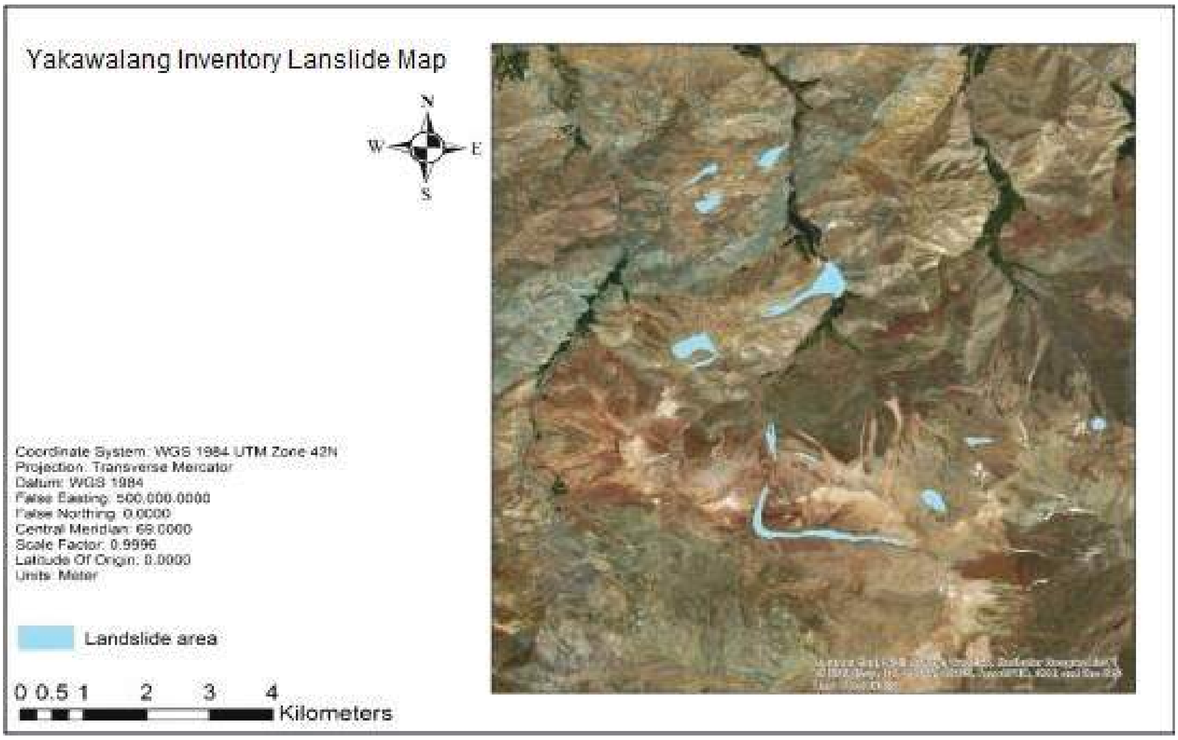

Figure 11. Landslide inventory map of Yakawalang district

4.3 Determining the weight value for factors, sub-factors and classes of sub-factors

The important steps of the AHP process are (1) constructing a hierarchy structure, (2) defining the weight value of each criteria and (3) combining the criteria. In the first step, factors and their spatial representation should be associated with a common scale to make comparisons possible. In the second step, a pairwise comparison matrix is constructed and each factor is compared with the other factor, relative to its importance. For instance, in the current research, the lithology factor has the most effect and it will get the highest number of caparison to all other factors. The basis for judging is Table 2. According to Table 2, the degree of superiority of one factor over another factor is determined by the degree of effectiveness of this factor to the goal. In the hierarchical analysis process, maximum weight is given to the layers that have the greatest impact on goal. In order to estimate the weights of each factor and show the effect of each factor on landslide, a committee consisting of experts in geology, geography, environmental science and geodesy was formed. Then, according to the weighting and preference table presented by Saaty (2000), each factor and its preference over other factors were determined. The quality of the comparison was described by the consistency ratio (CR), which is calculated as the ratio of CI and random index (RI), as indicated in Eq.(1).

$$CR = CI/RI \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Therefore, here the consistency index of a matrix of comparisons is calculated based on Eq.(2).

$$CI = \frac{\lambda_{max} - n}{n - 1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Here, in Eq. (2) is the average of (λ) and *n* is the number of criteria. As in this research the number of criteria are 12. then *n* will take the value of 12. A matrix with a satisfactory consistency level should yield a CR of less than 0.10. The low consistency ratio (<0.10) indicates that the computed weight for each factor is acceptable. Using a weighted linear combination (WLC), the landslide susceptibility map was derived. It is one of the most applicable function that can be used for decision-making in GIS (Malczewski 1999). In WLC, the 12 factor layers are overlayed and multiplied by their corresponding weight values. Finally, the overall score is calculated.

$$V_H = \sum_{k=1}^{n} W_k(g_{i,j}) \quad (3)$$

In this formula is the final weight, is the weight of each criteria and is the weight of each related class of criteria.

Table 2. Scale of preference between two parameters in AHP

Preference Factor	Degree of Preference	Explanation
1	Equally	Two factors contribute equally to the objective
3	Moderately	Experience and judgement slightly to moderately favour one factor over another
5	Strongly	Experience and judgement strongly or essentially favour one factor over another.
7	Very strongly	A factor is strongly favoured over another and its dominance is showed in practice
9	Extremely	The evidence of favouring one factor over another is the highest degree possible of an affirmation
2, 4, 6, 8	Intermediate	Used to represent compromises between the preferences in weights 1, 3, 5, 7 and 9
Reciprocals	Opposites	Used for inverse comparison

Source: Saaty (2000)

Table 3. Pair-wise comparison matrix, factor weights and consistency ratio of landslide influencing factors

Criteria	Geology	Hydrology	Morphology	Manmade and Environmental	Climate	Weight
Geology	1	3	4	6	8	0.481
Hydrology	0.333	1	3	4	7	0.265
Morphology	0.25	0.333	1	3	4	0.141
Humanmade and Environmental	0.16	0.25	0.333	1	3	0.076
Climate	0.125	0.143	0.25	0.333	1	0.039
Consistency ratio= 0.04						

Table 4. Pair-wise comparison matrix, sub-factors weights and consistency ratio of landslide influencing sub-factors

Criteria	Lithology	Distance to Drainage	Slope	Distance to Fault	Rainfall	LU&LC	Distance to Village	Drainage Density	Elevation	Aspect	Distance to Road	LST	Weight
Lithology	1	2	3	4	5	6	6	6	7	7	8	9	0.23
Distance to drainage	0.5	1	2	2	3	4	6	6	7	7	8	8	0.17
Slope	0.33	0.5	1	2	3	4	5	5	6	7	7	8	0.14
Distance to fault	0.25	0.25	0.5	1	2	3	5	5	7	7	7	8	0.12
Rainfall	0.2	0.33	0.33	0.5	1	2	2	3	4	5	6	6	0.08
LU&LC	0.16	0.25	0.25	0.33	0.5	1	2	2	4	4	5	6	0.06
Distance to village	0.16	0.16	0.2	0.2	0.5	0.5	1	2	3	3	4	5	0.06
Drainage Density	0.16	0.16	0.2	0.2	0.33	0.5	0.5	1	2	2	3	3	0.04
Elevation	0.14	0.14	0.16	0.14	0.25	0.25	0.33	0.5	1	2	2	3	0.03
Aspect	0.14	0.14	0.14	0.14	0.2	0.25	0.33	0.5	0.5	1	2	2	0.02
Distance to road	0.12	0.12	0.14	0.14	0.16	0.2	0.25	0.33	0.5	0.5	1	2	0.02
LST	0.11	0.12	0.12	0.12	0.16	0.16	0.2	0.33	0.33	0.5	0.5	1	0.02
Total	3.27	5.17	8.04	10.77	16.1	21.86	28.61	31.66	42.33	46	53.5	61	1.00
Consistency ratio = 0.05													

Table 5. Weights and consistency ratio of landslide influencing classes

Sub-factor	Sub-factor Classes	Weight	Sub-factor	Sub-factor Classes	Weight
Aspect	N	0.09	Lithology	Sedimentary	0.09
	N-E	0.08		Metamorphic	0.06
	w	0.07		Volcanic	0.03
	N-W	0.06	Distance to Fault	0–1000	0.09
	E	0.05		1000–2000	0.07
	S-E	0.04		2000–3500	0.05
	S	0.03		3500–5000	0.03
	N-W	0.02		5000–10500	0.01
	Flat	0.01	Rainfall	290–350	0.01
Land cover	Ice/snow	0.02		350–430	0.03
	Dense vegetation	0.04		430–510	0.05
	Sparse vegetation	0.06		510–600	0.07
	Built-up/Bare land	0.09		600–700	0.09
Distance to village	0–2000	0.09	Distance to Road	0–2000	0.09
	2000–4000	0.07		2000–5000	0.07
	4000–8000	0.05		5000–10000	0.05
	8000–15000	0.03		10000–20000	0.01
	15000–30000	0.01		20000–33000	0.03
Distance to drainage	30–600	0.09	Slope	0–9	0.03
	600–1500	0.07		9–18	0.04
	1500–2500	0.05		18–35	0.02
	2500–3500	0.03		35–50	0.07
	3500–7100	0.01		50–74	0.09
Elevation	0–2500	0.01			
	2500–3000	0.03			
	3000–3500	0.05			
	3500–4000	0.07			
	4000–5044	0.09			

5. Results and Discussion

The resulting landslide susceptibility map generated through the AHP method is shown in Figure 12. It was reclassified into four relative susceptibility zones: low risk, moderate risk, high risk and very high risk. According to Figure 13, the susceptibility condition is very high in Yakawalang district, Punjab district, some portion of Shiber, Saighan, Kahmart districts. Landslides are active in all districts of Bamyan province, but the area of risk are different. For example, Yakawalang, Punjab and Bamyan centre experience maximum landslides, but other districts such as Waras, Shibar, Sighan and Kahmard have relatively less landslides. Moderate landslide susceptible zones are shown to be widely distributed again in Yakawalang, Punjab, Kahmart, Saighan, Shiber and some parts of Bamyan city. The low landslide susceptible areas are mainly in Waras, some portion of Bamyan city, Yakawalang and Shiber. From Table 6, it can be observed that 9.26% of the total area was found to be of low landslide susceptibility, 29.52% of the study area is under moderate risk, 58.34% is under high risk and 2.88% is under very high risk. The results of landslide zoning maps can be used as basic information to assist environmental management and planning.

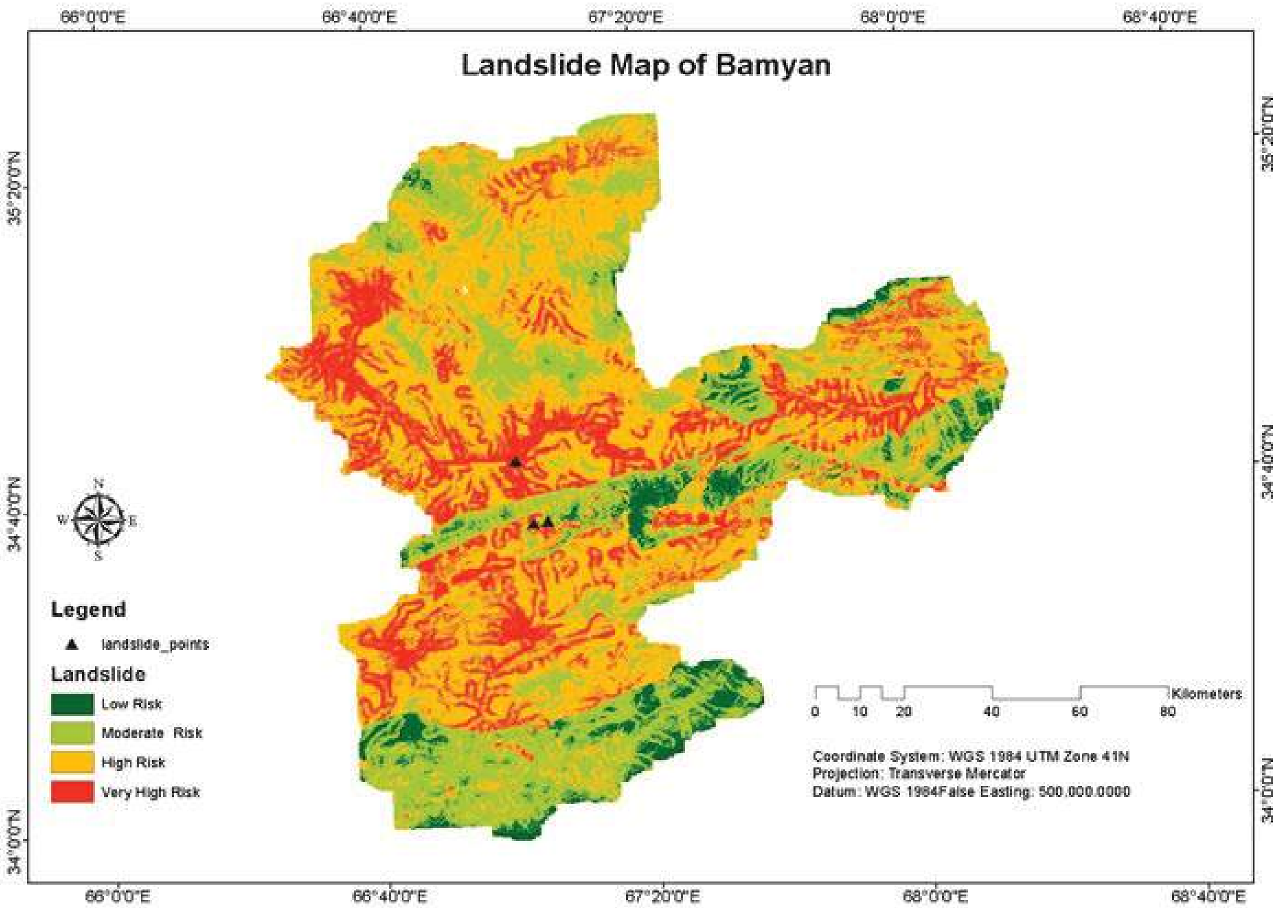

Figure 12. Landslide susceptibility map generated using analytic hierarchy process

Table 6. Percentage and area of landslide risk areas

Landslide Susceptibility Zones	Area (in km2)	Percent
Low risk	1309.705	9.26
Moderate risk	4175.072	29.52
High risk	8251.572	58.34
Very high risk	407.638	2.88

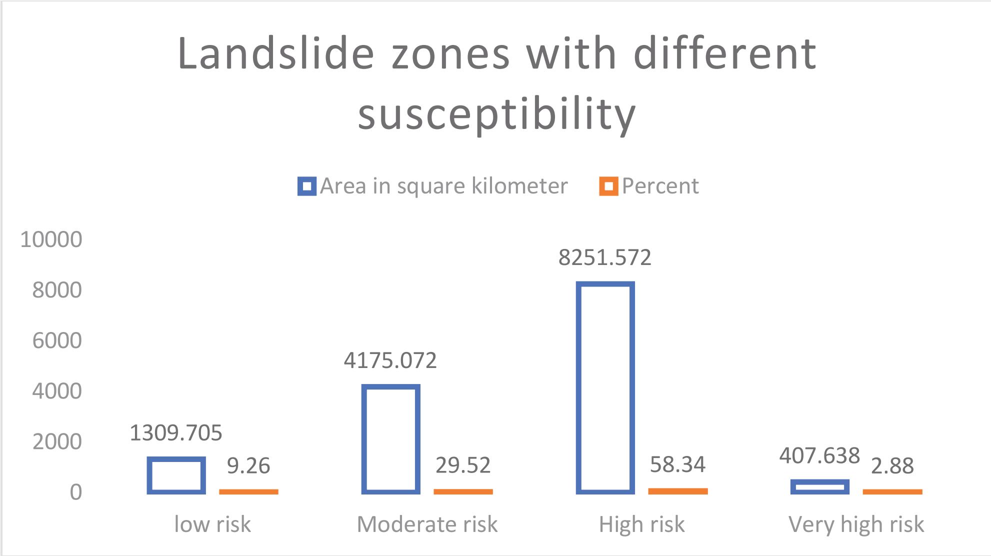

Figure 13. Area of landslide susceptibility zones (in km2 and percentage)

5.1 Rainfall

Rainfall plays a significant role in landslides. It increases the water level of groundwater, which in turn increases the static pressure and pore water pressure in slope materials. Most landslides occur after heavy rainfalls and, thus, rainfall is one of the main parameters in producing landslide maps. Water infiltrates rapidly upon heavy rainfall and increases the degree of saturation and potential of landslide occurrence (Moradi et al., 2012). In this study, the yearly rainfall data with spatial resolution of 0.25×0.25 degree for year 2017, 2018 and 2019 was obtained from Centre for Hydrometeorology and Remote Sensing data portal. Then the average of these three years was calculated in Arc GIS and divided in five classes as shown in Figure 14. The given weight for this factor is 0.08.

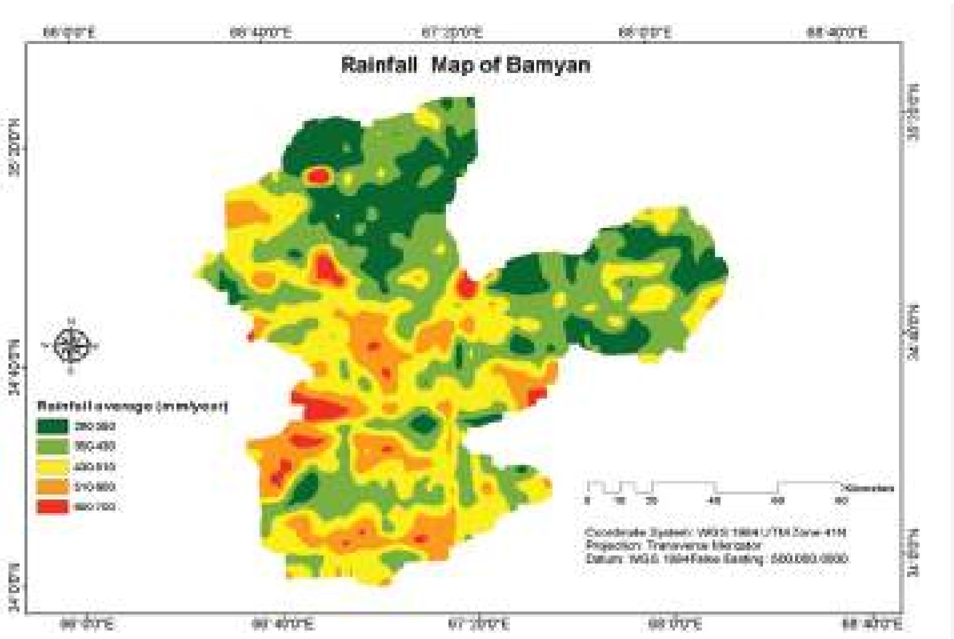

Figure 14. Rainfall map of Bamyan

5.2 Surface temperature

Surface temperature plays an important role in melting refrigerators. Chips flowing from melting refrigerators destroys geologically non-resistant materials and leads to landslide (Yazdadi and Ghanavati, 2016)as well as causing severe damage to natural resources. Kordan watershed located in the Alborz province, which including areas that are prone to landslide. The area under investigation is located from 50 ° 45' to 05' ° 51' east longitude and 35° 55' to 36° 05' North with expansion of about 488 km2 and elevation ranges from 1320 to 3900 m. The purpose of this study is to identify factors in landslides and zonate landslide hazard of Kordan watershed using AHP (Analytical Hierarchy Process. To find out about the effects of temperature on the occurrence of landslides, the temperature map of the study area was extracted from Landsat 8 image using the formula , where BT is the top of atmosphere brightness temperature, λ is the wavelength of emitted radiance and the values for landsat8 band 10 and band 11 are 10.8 and 12, respectively. In this study for this factor, a weight of 0.02 is assigned.

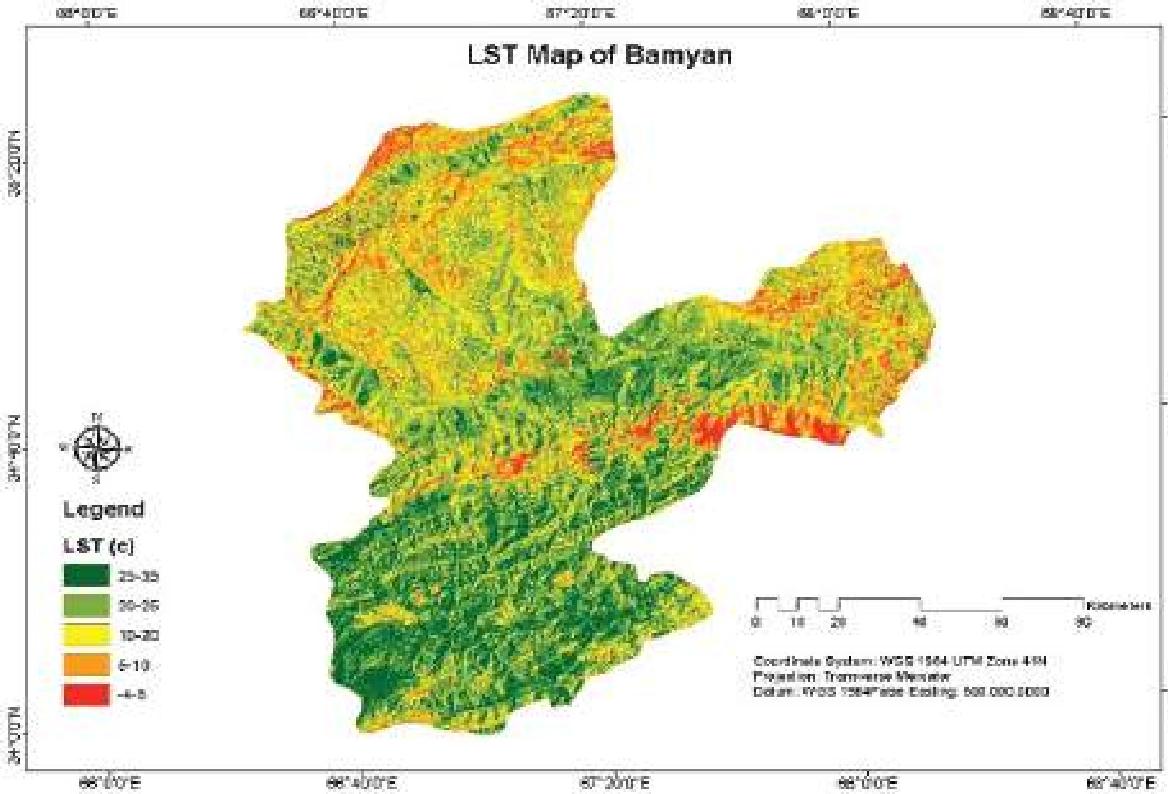

Figure 15. Land surface temperature (LST) map of Bamyan

5.3 Elevation changes

Elevation changes in each area considered as an effective factor in creating mass movements. This factor controls the direction of runoff and the density of the drainage network, and has a significant effect on the amount of soil moisture (as an effective factor in mass movements). In addition, elevation changes play a significant role in making steep slope (Schlagel et al., 2016)diverse geologic settings result in slopes susceptible to various forms of failure that pose considerable risk to the nation's growing population. Poor land management, such as overgrazing, deforestation, flood irrigation, unmaintained dirt roads, and unplanned urban sprawl exacerbate slope-stability problems and hazards. Landslide-susceptibility modeling (LSM. In this research, the Elevation data (GDEM) was collected from USGS earth explorer. In this research, a weight of 0.03 was assigned to this factor. Based on geological breaks, the elevation is classified in five classes.

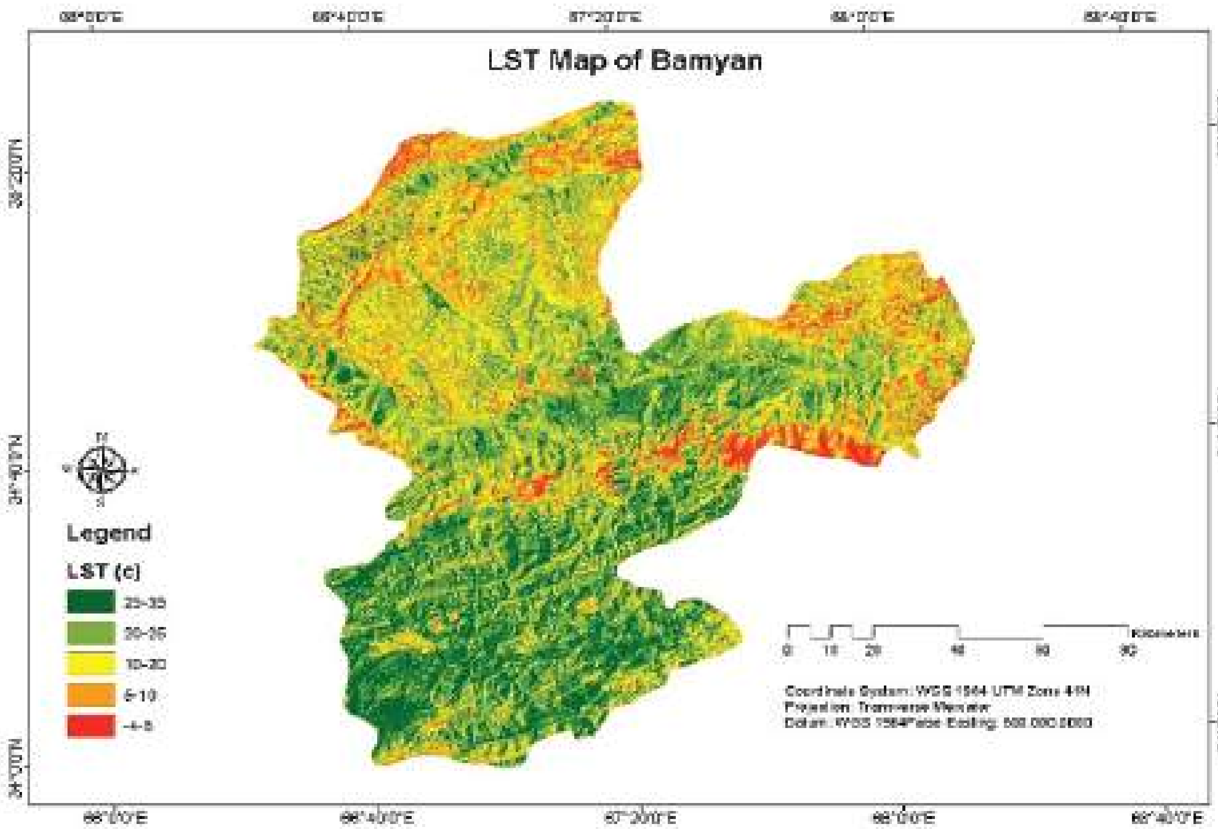

Figure 16. Elevation map of Bamyan

5.4 Slope

Investigation of slope status is important because the mechanism of many displacements related to surface materials and transport processes is a function of the slope. In this regard, it can be said that due to very high altitude range, the highlands are very young and steep, so they have a severe and significant erosive appearance. Therefore, the most effective dynamic factors can be found in mountain axes (Schlagel et al., 2016diverse geologic settings result in slopes susceptible to various forms of failure that pose considerable risk to the nation's growing population. Poor land management, such as overgrazing, deforestation, flood irrigation, unmaintained dirt roads, and unplanned urban sprawl exacerbate slope-stability problems and hazards. Landslide-susceptibility modeling (LSM; Pourghasemi et al., 2013)analytical hierarchy process, and statistical index models and an assessment of their performances. The study area covers the north of Tehran metropolitan, Iran. When conducting the study, in the first stage, a landslide inventory map with a total of 528 landslide locations was compiled from various sources such as aerial photographs, satellite images, and field surveys. Then, the landslide inventory was randomly split into a testing dataset 70 % (370 landslide locations. For preparing landslide susceptibility map, the slope map was divided into four slope categories and a weight of 0.14 was assigned to this factor. According to the landslide inventory map, most landslides occur in 30–50 degree of slope ranges. Theoretically, landslides do not generally occur in areas less than 5 degree.

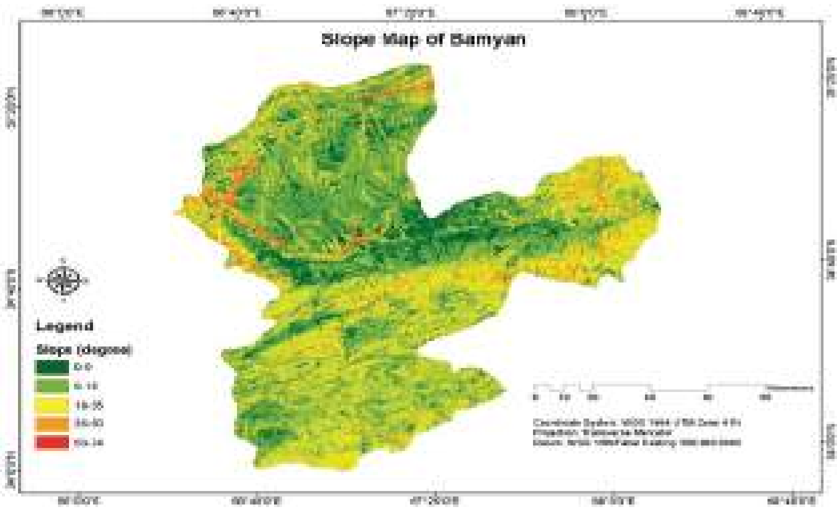

Figure 17. Slope map of Bamyan

5.5 Aspect

Aspect was weighted most heavily to the southeast and northwest to account for higher failure rates observed presumably due to fault-face orientation and moisture-microclimate regimes (Aksaray et al., 2011)"(Aksaray et al., 2011. Aspect is one of the determining factors in the mass movements of marl formations. The northern and western slopes have more moisture, and the number of landslide is more. In the eastern and southern slopes, due to maximum energy absorption and minimum water remaining in the soil, least mass movement is observed (Shroder et al., 2011b). In this study, the aspect map is generated from GDEM. For providing the landslide susceptibility map, a weight of 0.02 is assigned to this factor.

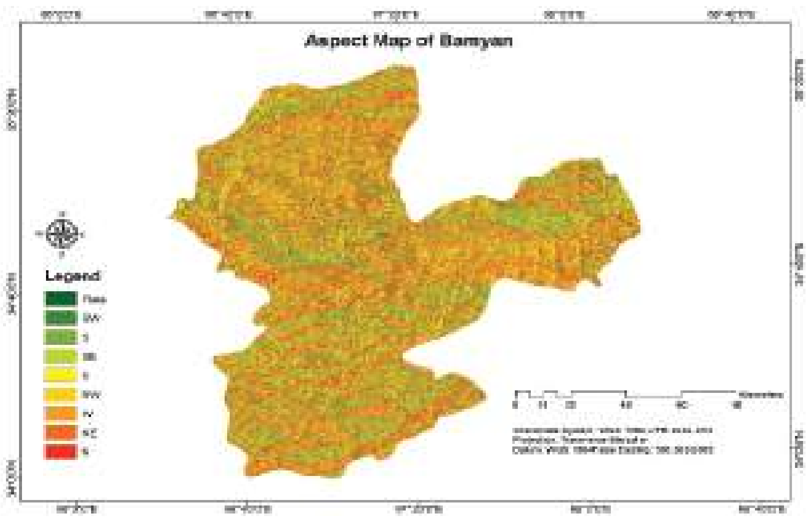

Figure 18. Aspect map of Bamyan

5.6 Land cover

The land cover type is very important for landslide studies, especially in areas that are covered with intense vegetation. As in tea plantations, intensely vegetated areas exhibit more saturation and greater instabilities than forest. Land cover analyses showed that landslides commonly occurred in the barren area. Barren slopes are more prone to landslides. In contrast, vegetative areas tend to reduce the action of climatic agents such as rain (Yazdadi and Ghanavati, 2016)as well as causing severe damage to natural resources. Kordan watershed located in the Alborz province, which including areas that are prone to landslide. The area under investigation is located from 50 ° 45' to 05' ° 51' east longitude and 35° 55' to 36° 05' North with expansion of about 488 km2 and elevation ranges from 1320 to 3900 m. The purpose of this study is to identify factors in landslides and zonate landslide hazard of Kordan watershed using AHP (Analytical Hierarchy Process. In this study the land cover data was collected from Esri data portal with spatial resolution of 10 m. For this purpose, the land cover map of the study area was classified into four classes such as water, dense vegetation, sparse vegetation and built up, bare land. For providing the final susceptibility map of the study area a weight of 0.06 was assigned to this factor.

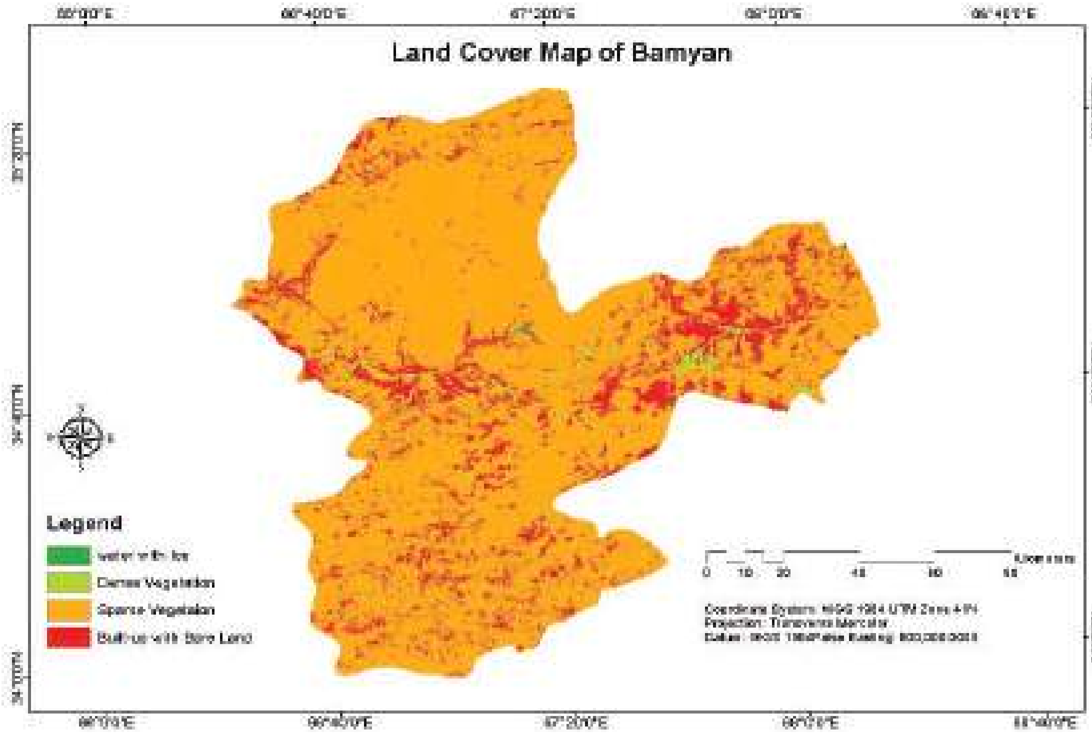

Figure 19. Land cover map of Bamyan

5.7 Human activities

Human activities always play a critical role in environmental change. In many cases, the location of these land uses is so inadequate that it causes distraction in the natural ecosystem (Aksaray et al., 2011). In this study the village density or human activity was considered as an effective factor in landslide susceptibility mapping. For this factor a weight of 0.06 was assigned to this factor.

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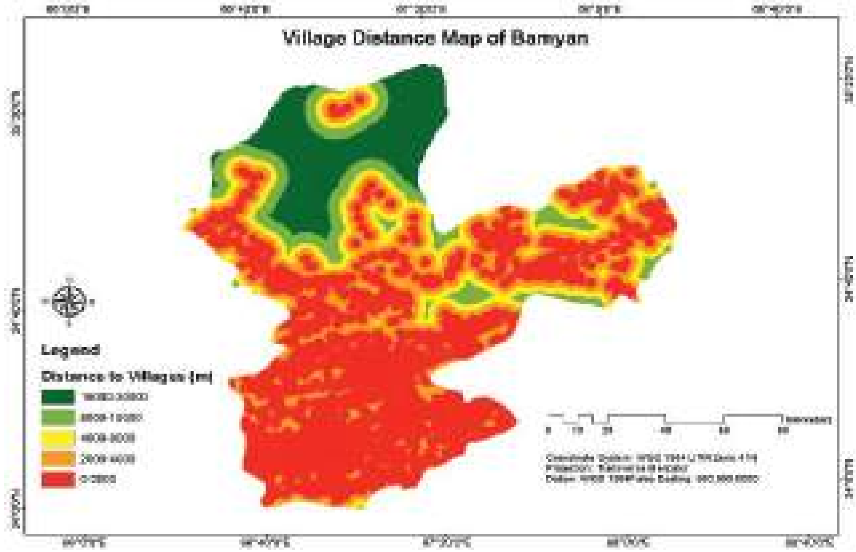

Figure 20. Village density map

5.8 Distance to roads

The distance to road is one of the main parameters in preparing landslide susceptibility maps. Roads can be one of the reasons of landslides. Roads change the nature of topography, decrease the shear strength of toe of slope and cause tensile stress. Naturally, slope may be stable, but road construction can have undesirable effect on it. The road causes infiltrating of water in slopes and enforces extra stresses due to traffic loads. In this region, many landslides have occurred because of unsystematic road construction in marl sediment alluvial (Aksaray et al., 2011). In this study, roads are classified into five classes based on specified distance. For the purpose of making the landslide susceptibility map, a weight of 0.02 is assigned to this factor.

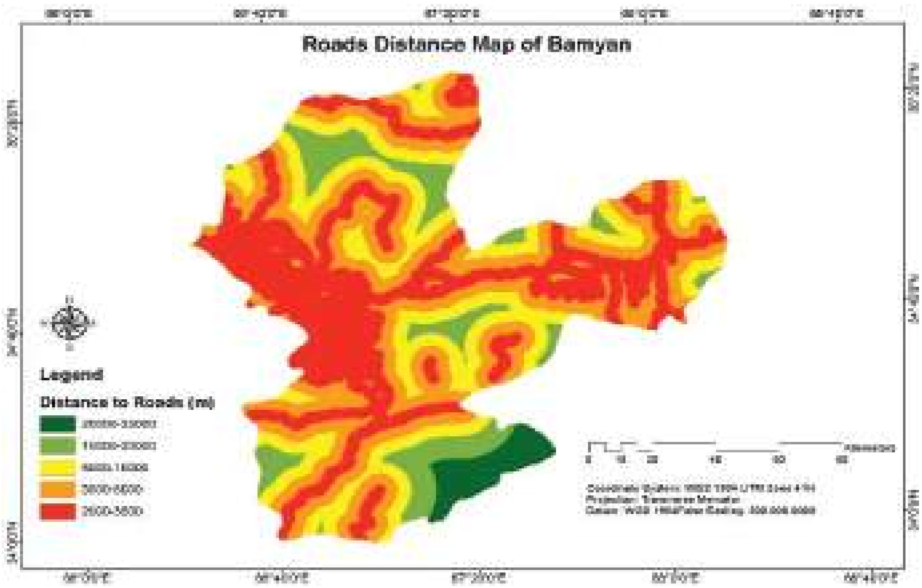

Figure 21. Road distance map

5.9 Distance to drainage

Distance to drainage is one of the effective factors for the stability of a slope. The saturation degrees of the materials directly affect slope stability. The proximity of the slopes to the drainage structures is also an important factor in terms of constancy. Drainage may harmfully disturb stability by eroding the slopes or by saturating the lower part of material until the water level increases (Moradi et al., 2012). Many slippery phenomena are caused by erosion and subsurface of slopes by high-velocity flood, surface runoff and river flows. Erosion of the slope over the time and by water and flood flows causes the balancing forces of the slope to be disturbed. This action increases the effect of destructive shear forces and ultimately causes slope instability. Instability usually begins with a set of tensile cracks at the top of the slope and over time leads to the fall or slipping of part of the slope. For the current purpose, distance to drainage with different buffer zones start from 30 m to 3500 m created and classified into five classes. For the purpose of creation of final landslide susceptibility, a weight of 0.17 was assigned to this factor. Distance to drainage after the lithology factor is the second important factor that affects landslide occurrence.

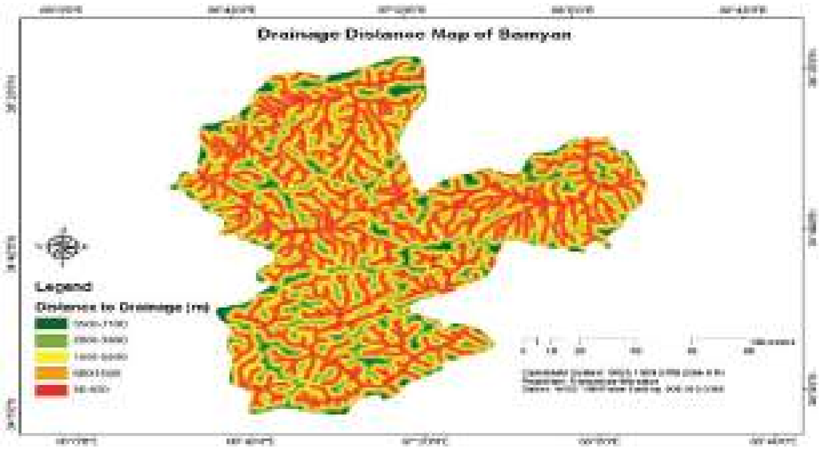

Figure 22. Drainage distance map

5.10 Drainage density

In general, water flows have a direct effect on landslide events in terms of their volume. The larger the volume of water, the greater is the impact on geologically unstable materials such as soil, clay and silt. The drainage density is calculated and classified into five classes. A weight of 0.04 is considered for this factor. Therefore, groundwater exchanges directly the appearances of surface water by supporting drainage base flow. Groundwater disturbs surface water by providing moisture for riparian vegetation, and monitoring the trim strength of slope materials, thereby affecting slope stability and erosion processes. Most of the time the volume of the drainages increases because of rainfall in the spring season and glacier and snow melt in the summer season. In smaller, low-order streams, groundwater also provides much of the increased discharge during and immediately following storms. The effect of streams to landslide increases all of these events (Yazdadi and Ghanavati, 2016as well as causing severe damage to natural resources. Kordan watershed located in the Alborz province, which including areas that are prone to landslide. The area under investigation is located from 50 ° 45’ to 05’ ° 51’ east longitude and 35° 55’ to 36° 05’ North with expansion of about

488 km2 and elevation ranges from 1320 to 3900 m. The purpose of this study is to identify factors in landslides and zonate landslide hazard of Kordan watershed using AHP (Analytical Hierarchy Process; Moradi et al., 2012). The drainage density is classified into five classes. For providing the final landslide susceptibility map, a weight of 0.04 is assigned to this factor.

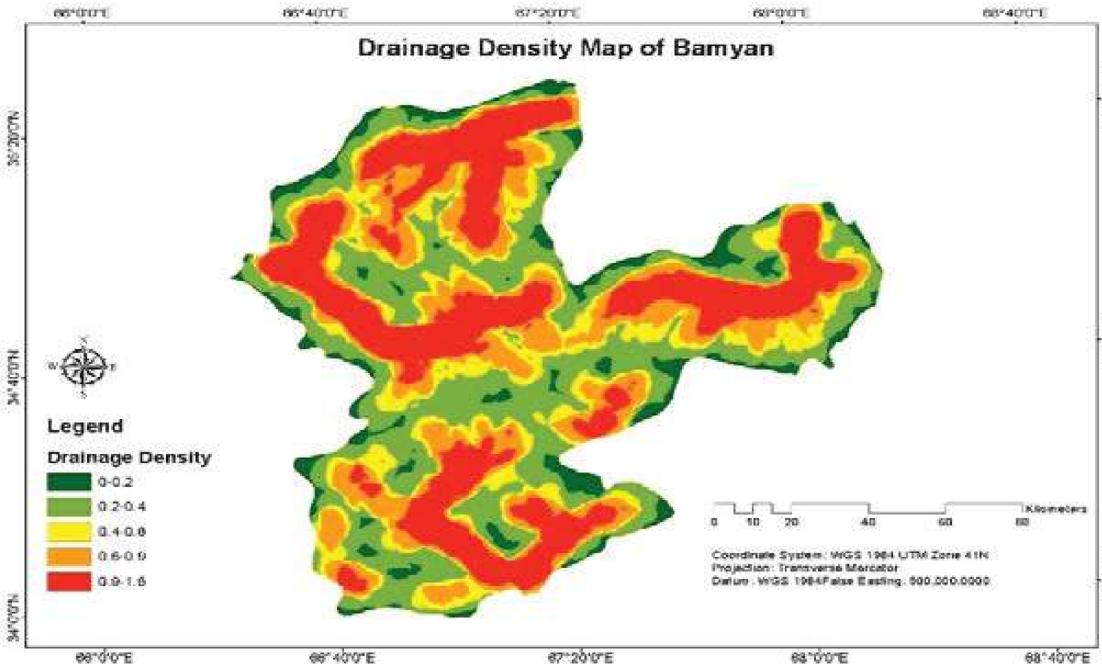

Figure 23. Drainage density map

5.11 Lithology

The main cause of slippery mass movements is the layers of loose marl formation. If the aggregation is composed of clay, the clay causes these layers to absorb rainfall and become slippery after expansion and saturation. Lithology is one of the most important parameters in landslide studies because different lithological units have different degrees of susceptibility. Due to the lack of detailed geological data in this study area, the lithological map of the study area has been divided into three major categories: sedimentary, volcanic and metamorphic. In this classification, the maximum score belongs to quaternary rocks and sediments and cover a major portion of the study area. This means quaternary rocks and sediments are more reliable to landslides. Because of geological reason, quaternary rocks and sediments are very young, not very stiff and unstable (Pourghasemi et al., 2013analytical hierarchy process, and statistical index models and an assessment of their performances. The study area covers the north of Tehran metropolitan, Iran. When conducting the study, in the first stage, a landslide inventory map with a total of 528 landslide locations was compiled from various sources such as aerial photographs, satellite images, and field surveys. Then, the landslide inventory was randomly split into a testing dataset 70 % (370 landslide locations} . As mentioned in this research, because of lack of detailed geological data in Afghanistan, the geology of the study area has been divided into three classis as shown in Figure 18. Sedimentary rocks cover most area of the study area. Resistance of sedimentary rocks to external factors such as slope, moisture, etc. is low, and hence the highest weight is assigned to this factor.

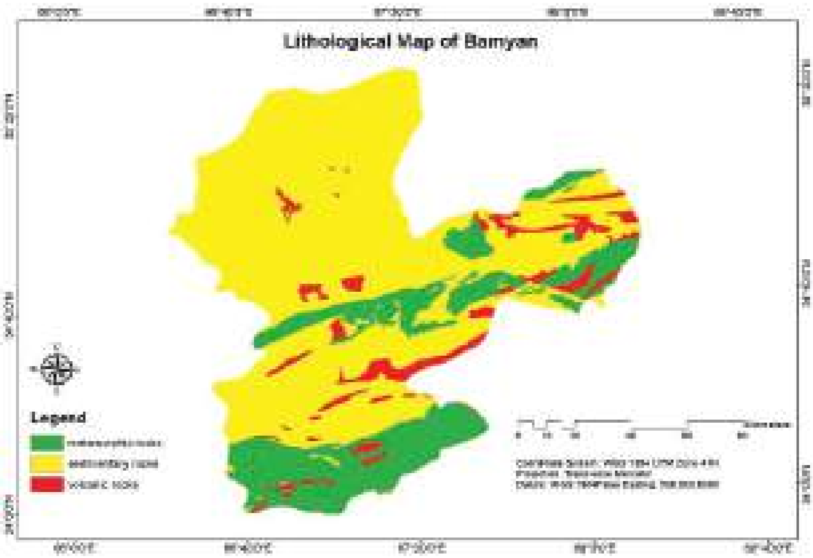

Figure 24. Lithology map

5.12 Distance to fault

For the fault factor, different effects can be imagined in the occurrence of slips in the slopes. Fragmentation and shear in the fault zone, water infiltration from these areas into the slopes, discontinuities around faults and erosion differences in the slopes are some of the effects. Fault movement acts as a trigger for landslides occurrence in the region. Landslide occurrence after an earthquake proves how effective is geological faults in landslide occurrence. In fact, the movement of faults causes the movement threshold to reach the slope. Tectonic movements play an intensifying and accelerating role in the occurrence of landslides. To investigate the relationship between landslides and fault factor, a map of the distance from the fault and the density of the fault was prepared. As is known, the impact threshold of faults is often up to a radius of 2 km. About 90% of landslides are located within this range. The fault is extracted from the geological map and classified into five classes. The range of distance is from 1000 m to 10500 m. For providing the final susceptibility map, a weight of 0.12 is assigned to this factor (see Figure 25).

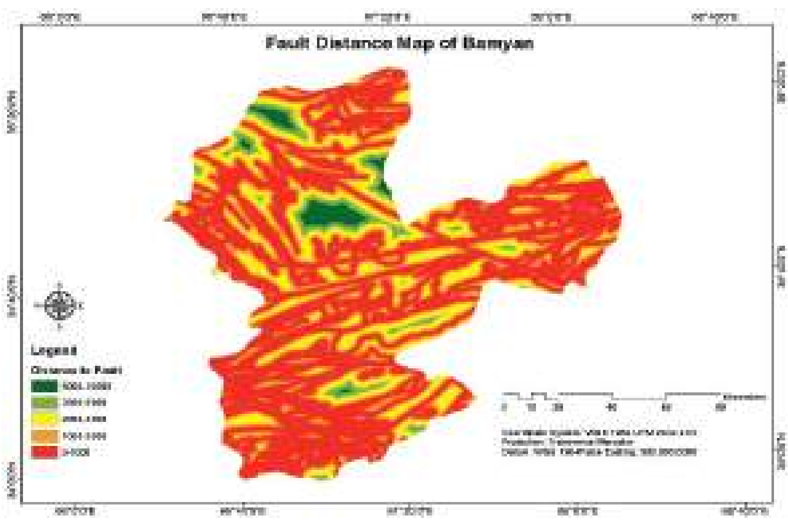

Figure 25. Map of distance to faults

To manage and minimize landslide hazards, research on landslide mapping is essential. Many methods have been proposed by researchers for providing landslide susceptibility maps. In this research, the landslide susceptibility map of Bamyan province was provided by using AHP method.

Bamyan city is a landslide-prone zone because of its physical appearance including steep topography, climate situations, located on earthquake zone, geology and geomorphology. In this research, using field survey, 20 landslides areas have been specified. Majority of these landslides occurred because of failure of geological materials, steep slope, erosion due to river and unsystematic road construction in marl sediment deposited.

Finally, in order to validate the accuracy of the final landslide susceptibility map, it was compared with the landslide inventory map of the study area. The results revealed that the active landslide zones had a high connection to the high and very high susceptibility class of map. The AHP map shows that approximately 80% of the active landslide zones were located at high and very high susceptibility zones of map. High and very high susceptibility zones are commonly matched sedimentary rocks. These rocks are composed of marl rocks that are very sensitive near water. The low susceptibility zones are associated with metamorphic and volcanic rocks and dense vegetation coverage. In this area the failure of the geological material, steep slope, river erosion considerably increases the potential of land sliding. Based on this research, it is presented that the high and very high susceptibility landslide zones identified by the AHP method can calculate potential landslide areas in the reality. The result of this research shows that if the field is accurately examined, then the HP method will give high accuracy results.

6. Enablers and Barriers

During the research and the completion of the research, it was concluded that the GIS and remote sensing is a powerful tool and knowledge in the preparation of landslide susceptibility map. In addition, the AHP method is a suitable method with the ability of pair-wise comparison. Overall, the AHP method has the power to compare one factor against all other factors and specify the level effectivity of each factor. On the other hand, lack of data and poor security situation of the country were obstacles during the research.

7. Key Takeaways from CDRI Fellowship Programme

It is true that today's developments in different fields are the result of researches that have been conducted in the past. Overall, this programme is a very useful and comprehensive and has the following benefits: it is a great programme to motivate researchers, it is very important for those researchers who cannot do such research at their own expense, it is a transnational programme that brings together researchers from different countries and provides a platform for the exchange of scientific research experiences. Overall, we found this research programme very useful in solving problems scientifically and sustainably.

8. Conclusion and Way Forward

Landslides are the most disastrous natural hazards across the world and also in Afghanistan. Their assessment should been done before the construction of all types of engineering projects. A correct assessment of the probability of landslide occurrence is therefore required for road projects such as A1 highway. As can be seen, the economic value of landslide damage, even at a very small scale in a sensitive area, such as transit roads or residential, agricultural and industrial sites, is very significant and high if it occurs. Failure to pay attention to them in order to stabilize or relocate and lack of accurate and scientific studies during the construction of roads or residential and commercial places can inflict irreparable damage to the country's economy. Therefore, creating a regional strategy for the protection of human and natural resources and reducing the damage caused by its occurrence is very important and necessary to achieve sustainable development goals. Providing a suitable model and a susceptible landslide map can be helpful for corresponding environmental and urban development planner authorities. Currently, Bamyan province is suffering from the lack of a comprehensive plan to deal with the damage caused by landslide. The results of this research will help decision-makers to identify landslide areas and implement construction projects correctly.

One of the advantages of the AHP method is that the factors affecting the occurrence of landslides are prioritized by comparing pairs between the given weight factors and the degree of impact of each factor on the landslide event. Hence, this leads to a more reliable result. For these reasons, the AHP model is used by planners to solve the complex management problems. On the other hand, GIS technique, due to its ability to manage large volumes of spatial information, is a powerful tool for this type of preliminary study. Therefore, the combination of GIS technique and AHP model makes it possible for planners to choose the most appropriate option through pair-wised comparison of influencing factors.

The study area was zoned in the form of different information layers based on the factor affecting the landslide event, and finally the occurrence of landslide zones was identified from a very low risk to very high (Table 3). Among the effective factors, lithology, distance to drainage, slope and distance from fault respectively with 0.23, 0.17, 0.14 and 0.12 weight have been identified as the most important factors in landslide formation in the study area. The role of others factors is reduced in relation to their impact on landslides and their weights are described in Table 4. The results of the final map shows that 9.26% of the study area belong to low risk, 29.52% belong to moderate risk, 58.34% belong to high risk and 2.88% of the study area are under very high risk (see Table 5).

The landslide susceptibility maps presented in this research constitute an important tool for decision-makers, planners and engineers. They can make rapid and well-grounded decisions to minimize and avoid the damage and losses caused by existing and future landslides, or avoid the highly susceptible zones, by suitable preventive measures and mitigation procedures.

References

1. Abedini, M., and Tulabi, S. (2018). Assessing LNRF, FR, and AHP models in landslide susceptibility mapping index: a comparative study of Nojian watershed in Lorestan province, Iran. *Environmental Earth Sciences*, *77*(11), 1–13. https://doi.org/10.1007/s12665-018-7524-1
2. Achour, Y., Boumezbeur, A., Hadji, R., Chouabbi, A., Cavaleiro, V., and Bendaoud, E. A. (2017). Landslide susceptibility mapping using analytic hierarchy process and information value methods along a highway road section in Constantine, Algeria. *Arabian Journal of Geosciences*, *10*(8). https://doi.org/10.1007/s12517-017-2980-6
3. Aksaray, A. Y., Aksaray, R., Model, D., Hierarchy, A., & View, P. (2011). *A GIS-based comparative study of frequency ratio , analytical hierarchy process , bivariate statistics and logistics regression ... December 2013*.
4. Alam, E. (2020). Landslide hazard knowledge, risk perception and preparedness in southeast Bangladesh. *Sustainability (Switzerland)*, *12*(16). https://doi.org/10.3390/SU12166305
5. Amir Yazdadi, E., & Ghanavati, E. (2016). Landslide Hazard Zonation by using AHP (Analytical Hierarchy Process) model in GIS (Geographic Information System) Environment (Case study: Kordan Watershed). *International Journal of Progressive Sciences and Technologies (IJPSAT*, *2*(1), 24–39. http://ijpsat.ijsht-journals.org
6. Ayalew, L., & Yamagishi, H. (2005). The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda-Yahiko Mountains, Central Japan. *Geomorphology*, *65*(1–2), 15–31. https://doi.org/10.1016/j.geomorph.2004.06.010
7. Ayalew, L., Yamagishi, H., Marui, H., & Kanno, T. (2005). Landslides in Sado Island of Japan: Part II. GIS-based susceptibility mapping with comparisons of results from two methods and verifications. *Engineering Geology*, *81*(4), 432–445. https://doi.org/10.1016/j.enggeo.2005.08.004
8. Bernasconi, M., Choirat, C., & Seri, R. (2010). The analytic hierarchy process and the theory of measurement. *Management Science*, *56*(4), 699–711. https://doi.org/10.1287/mnsc.1090.1123
9. Devara, M., Tiwari, A., & Dwivedi, R. (2021). Landslide susceptibility mapping using MT-InSAR and AHP enabled GIS-based multi-criteria decision analysis. *Geomatics, Natural Hazards and Risk*, *12*(1), 675–693. https://doi.org/10.1080/19475705.2021.1887939
10. AVA. (2014). Afghanistan Voice Agency News. *Fifty families in Bamyan have fled their homes for fear of landslides available:* https://avapress.com/fa.
11. Feizizadeh, B., & Blaschke, T. (2013). GIS-multicriteria decision analysis for landslide susceptibility mapping: Comparing three methods for the Urmia lake basin, Iran. *Natural Hazards*, *65*(3), 2105–2128. https://doi.org/10.1007/s11069-012-0463-3
12. Kamp, U., Growley, B. J., Khattak, G. A., & Owen, L. A. (2008). GIS-based landslide susceptibility mapping for the 2005 Kashmir earthquake region. *Geomorphology*, *101*(4), 631–642. https://doi.org/10.1016/j.geomorph.2008.03.003
13. Kanwal, S., Atif, S., & Shafiq, M. (2017). GIS based landslide susceptibility mapping of northern areas of Pakistan, a case study of Shigar and Shyok Basins. *Geomatics, Natural Hazards*

and Risk, *8*(2), 348–366. https://doi.org/10.1080/19475705.2016.1220023

14. Koley et al. (2020). *GIS based Landslide Hazard Zonation Mapping by Weighted Overlay Method on the Road Corridor of*. 1–32.
15. Malczewski, J. (2006). GIS-based multicriteria decision analysis: A survey of the literature. *International Journal of Geographical Information Science*, *20*(7), 703–726. https://doi.org/10.1080/13658810600661508
16. Moradi, M., Bazyar, M. H., & Mohammadi, Z. (2012). GIS-based landslide susceptibility mapping by AHP method, a case study, Dena City, Iran. *Journal of Basic and Applied Scientific Research*, *2*(7), 6715–6723.
17. Naseri, M. K. (2016). Related papers Statistical Landslide Susceptibility Mapping by Analysis in Takhar Province of Afghanistan. *International Journal of Engineering and Technical Research*, *Volume-5*(Issue-1).
18. OCHA. (2020). Afghanistan Natural Disaster Incident Reports [2012 through 2020]. United Nations Office for the Coordination of Humanitarian Affairs (OCHA). Accessed at: https://data.humdata.org/search?q=natural+disaster+incident&ext_search_source=main-nav.
19. Pourghasemi, H. R., Moradi, H. R., & Fatemi Aghda, S. M. (2013). Landslide susceptibility mapping by binary logistic regression, analytical hierarchy process, and statistical index models and assessment of their performances. *Natural Hazards*, *69*(1), 749–779. https://doi.org/10.1007/s11069-013-0728-5
20. Pourghasemi, Hamid Reza, Pradhan, B., & Gokceoglu, C. (2012). Application of fuzzy logic and analytical hierarchy process (AHP) to landslide susceptibility mapping at Haraz watershed, Iran. *Natural Hazards*, *63*(2), 965–996. https://doi.org/10.1007/s11069-012-0217-2
21. Radio Azadi. (2015). Concerns about landslide risk in Bamyan province. available: https://da.azadiradio.com/a/26473546.html
22. Saaty, TL(1980). The Analytical Hierarchy Process, Mcgraw Hill, New York.
23. Saleem, N., Enamul Huq, M., Twumasi, N. Y. D., Javed, A., & Sajjad, A. (2019). Parameters derived from and/or used with digital elevation models (DEMs) for landslide susceptibility mapping and landslide risk assessment: A review. *ISPRS International Journal of Geo-Information*, *8*(12). https://doi.org/10.3390/ijgi8120545
24. Schlagel, N. A., Johnson, W. C., Johnson, W. C., Dere, A. L. D., Dere, A. L. D., Shroder, J. F., & Shroder, J. F. (2016). *Multi-Criteria Analysis of Landslide Susceptibility, Afghanistan*. *January 2018*. https://doi.org/10.1130/abs/2016am-281520
25. Shia Association News. (2018). *four people killed and injured due to landslide in Bamyan*. available: https://af.shafaqna.com/FA/291107
26. Shroder, J. (2016). Hydro-Hegemony in Afghanistan and Surrounding Countries. In *Transboundary Water Resources in Afghanistan*. Elsevier Inc. https://doi.org/10.1016/b978-0-12-801886-6.00014-8
27. Unitar. (2014). The Ab Barak Landslide : Past and Future. *UNOSAT*, *August 2014*. available; https://unosatmaps.web.cern.ch/AF/FL20140430AFG/UNOSAT_Ab_Barak_landslide_report.pdf

28. USAID. (2017). *Afghanistan: Landslide Susceptibility Index*. available: https://immap.org/product/afghanistan-landslide-susceptibility-index/
29. Varo, J., Sekac, T., & Jana, S. K. (2019). Landslide Hazard Zonation from a GIS Perspective and Urban Planning Solutions in Central –Division of Fiji Islands. *International Journal of Innovative Technology and Exploring Engineering*, *8*(12S), 352–361. https://doi.org/10.35940/ijitee.l1091.10812s19
30. Zhang, J., Gurung, D. R., Liu, R., Murthy, M. S. R., & Su, F. (2015). Abe Barek landslide and landslide susceptibility assessment in Badakhshan Province, Afghanistan. *Landslides*, *12*(3), 597–609. https://doi.org/10.1007/s10346-015-0558-5

Innovative Structural Protection System for Resilient Community against Multiple Hazards

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Coalition for Disaster Resilient Infrastructure

Abstract

Lifeline structures such as hospital buildings must remain functional not only during but also after any natural, accidental or humanmade disaster. Some of the major hospital buildings in India have experienced ageing, which has hampered their structural performance against excitations from earthquake and wind excitations. To improve the resilience of hospital buildings, new technologies are, therefore, required to be introduced, which must also have higher fire rating. Unfortunately, in the past several earthquake-triggered collapse of hospital buildings and fatalities caused due to fire accidents were reported. Hence, through the research work carried out under this fellowship of the Coalition for Disaster Resilient Infrastructure (CDRI), innovative structural protection system for resilient community against multiple hazards has been developed. Specifically, novel lightweight and fire-resistant fibre-reinforced bearings (FRBs) for retrofitting of the hospital buildings under multi-hazard scenarios have been designed, fabricated and tested numerically as well as experimentally against the anticipated loading scenarios.

To base the investigation initially, rapid visual survey (RVS) of some of the major hospital buildings in the National Capital Territory (NCT) of Delhi was conducted for assessment of their present in-situ structural condition. Based on the observations RVS inferences were made about the requirements of their enhancement in resilience against the three hazards: earthquake, wind and fire scenarios. Base isolation for retrofitting the hospital buildings was concluded to be the most suitable alternative, supplemented with improved fire-resistance of the isolation systems. It was followed by developing analytical force-deformation relations and implementing them in finite element (FE)-based numerical simulation. Further, such FE simulations using equivalent linearization help translate this technology in real-life applications through structural designs. For load-bearing and framed structures, new types of FRBs have been conceived, developed and designed in this CDRI Fellowship project.

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1. Introduction

In order to control the dynamic response in low- to mid-rise structures subjected to earthquake excitation, seismic base isolation is used in construction projects in both new or old structures (Matsagar and Jangid, 2004). Among several types of base isolation systems that are categorized into elastomeric isolators, sliding type isolation systems and roller bearings, the present research is on existing fibre-reinforced bearings (FRBs) and the development of a new patentable FRB. Some of the earlier investigations have shown the effectiveness of the FRBs in seismic isolation of new structures (Becker and Mahin, 2012). The present project taken forward the effectiveness of the FRBs in seismic isolation of new structures in terms of the state-of-the-art and state-of-the-practice.

1.1 Base isolation for seismic retrofitting of structures

For existing structures, Matsagar and Jangid (2008) proposed the feasibility of employing the base isolation technology preliminarily by initiating such an effective scheme. However, owing to several impediments in the implementation of such a relatively new technology it could not be utilized in real-life structures except in a few exceptional cases where retrofitting using base isolation was employed. Thus, it necessitated conducting research on the development of new types of isolation systems that could easily be used in retrofitting operations of existing structures. Retrofit strategies are required for both the types of load-bearing and the framed buildings. Generically, the design of seismic retrofitting needs to be site- and case-specific for any particular project, especially for hospital buildings. Moreover, the developed technological solution should be effective for practical implementation in real-life buildings. It should offer ease of construction, speedy activities and minimal if not nil interference with routine use of the structure being retrofitted.

1.1.1 Outcomes from survey

It is noted from the rapid visual survey (RVS) that the current structural health of several hospital buildings is direly worrisome. As the hospital administrations do not permit sharing/publicizing the details; therefore these have been excluded from the present research study. However, the outcomes of the survey essentially highlight a desperate need to improve the hazard resilience of these lifeline structures. The RVS has brought to attention structural interventions that are required for hospital buildings to improve multi-hazard resilience of the hospital buildings that satisfy continued operations without affecting the routine patient care.

1.1.2 Resilience of hospital buildings from multiple hazards

While some organizations consider seismic retrofitting of hospital buildings against independent dynamic excitation from an earthquake, protection from wind-borne excitation is rather a rare premise of consideration. It is mandatory for the hospital building to satisfy fire rating requirement. However, fire resistance of construction materials, especially in the case of the new device(s) implemented, needs to be ascertained both at the material level and at the structural level. It has been mandated that the superstructure of the hospital buildings will essentially require to be designed fire-resistant adequately.

1.2 Present status of seismic base isolation

In the ten seismic base-isolated building projects completed in India, conventional and imported bearings have been used in the new construction projects. No seismic retrofitting project using the base isolation technique has yet been completed to the best of our knowledge in the country thus far. Therefore, successful completion of this CDRI Fellowship project is considered crucial for the multi-hazard resiliency of hospital infrastructure.

It is assumed that the reluctance on using base isolation in new hospital buildings and retrofitting old ones is arguably because of the higher construction costs involved. Developments in fibre-reinforced bearings (FRBs) have not taken place at par with laminated rubber bearings, so their popularity in field applications is inferior. Making a lightweight and low-cost isolation system, albeit facilitating multi-hazard resilience, is hence deemed a viable option in overcoming the present challenges of failures experienced in hospital buildings under the multiple (independent/dependent) hazards being considered.

Technology development and translational research conducted in this CDRI Fellowship project have promisingly led to patentable end-products of two variants of the tri-axially braided functionally: graded natural fibre-reinforced bearing devices and retrofit processes for immediate field applications in real-life hospital buildings. Thus, lab-to-land tech-transfer goal has been adequately achieved. Some other advantages of the base isolation technology are also adequately highlighted in the process. Along with achieving the calculated multi-hazard resilience of the lifeline infrastructure, four sustainable development goals have been also met directly or indirectly.

It is necessary to develop a structural solution in the form of a multi-hazard retrofit measure of new and existing hospital buildings that satisfy the disaster resilience requirements, and are adequate for their continued (uninterrupted) functionality. Additionally, while improving resiliency by retrofitting operations in existing hospital buildings, regular functionality needs to remain unaffected. The advantage of the seismic retrofit using base isolation technology needs to be exploited in ensuring longevity, ease of monitoring and maintenance during the service life of the building using the novel lightweight and fire-resistant fibre-reinforced bearings. The novel lightweight and fire-resistant FRB design using natural fibres have potential application in the retrofit operation of (a) load-bearing , (b) framed structures or both. The two variants of these bearings are able to serve the purpose of retrofitting by inserting the bearings in the existing hospital buildings without interrupting their functionality and improving multi-hazard resilience manyfold. Hence, conducting numerical analysis, investigators proposing design procedures as well as industry-partner conducting tests on the natural FRBs manufactured based on the innovative design are highly relevant technological developments that were undertaken through this CDRI Fellowship project.

The foremost technical objective of this research study was to develop a simple mathematical hysteretic model for the nonlinear force-deformation behaviour of the UFREI, which can be practically implemented. Further, effective stiffness and damping parameters of the UFREIs have to be obtained by equivalent linearization of the newly proposed mathematical model. To achieve these objectives, a three-dimensional (3D) FE model of the UFREI is created and validated from existing experimental results and earlier numerical investigations (Munjal et al., 2019). A novel trilinear hysteretic model (THM) is developed subsequently, which is able to appropriately represent the force-deformation behaviour of the UFREI. Further, the effective parameters of the UFREI are estimated through equivalent linearization of the proposed THM. The variations in the force-deformation behaviour of the UFREI with the change in its properties are studied by conducting detailed and rigorous FE simulations. Then, a suitable normalization of the force-deformation curve is achieved, such that one single curve can represent the hysteretic behaviour of all UFREIs with any specified inherent properties. Thereafter, a normalized THM is obtained that exhibits high accuracy in predicting the hysteretic behaviours of a large variety of UFREIs. Finally, the newly proposed THM is utilized to generate a simple procedure for the design of the UFREIs under any site-specific conditions, and is implementable in real-life design projects.

The construction industry needs to undertake a theoretical investigation for the multi-hazard retrofitting of hospital buildings through translational research. Hence, for technology demonstration, a case study on real-life hospital building was undertaken. A three-dimensional (3D) numerical model was developed and validated with results reported in the standard literature and subsequently, a finite element (FE) analysis of the structure with UFREI was carried out. Subsequently, the variation in the effective stiffness and damping parameters of the isolator was obtained with the change in the (a) UFREI's shape factor, (b) UFREI's aspect ratio and (c) shear modulus of the elastomer used in the UFREI. Conclusions are then drawn on the behaviour of the UFREIs ranging across a variety of geometric and material properties that are useful for effective field implementation of the present technology.

Conducting rapid visual survey (RVS) of some major hospital buildings in National Capital Territory (NCT) Region of Delhi, particularly those serving for several years has been the first step to preparing the justified background for undertaking this project. Such a survey conducted will ably help in understanding their current structural health through visual inspection. To conduct a rapid visual survey (RVS), the guidelines of the National Disaster Management Authority (NDMA) was followed for the purpose. The outcomes from the survey analysed have been synthesized to comprehend the vulnerability of the hospital buildings in the NCT of Delhi.

The subsequent approaches undertaken in this CDRI Fellowship Project include:

(i) Finite element (FE)-based numerical investigation for retrofitted hospital buildings

(ii) Analytical investigations in developing mathematical models of the FREIs

(iii) Experimental investigations for mechanical characterization of the FREIs

The 3D FE model of the UFREIs is created using Abaqus/CAE 2020 (Simulia, Dassault Systems). Initially, a square UFREI of the width of 100 mm and a total depth of 104.9 mm is modelled. The force-deformation characteristics of the model are validated as per the results presented by Das et al. (2015). Das et al. (2015) performed FE analysis on the UFREI with similar geometry and validated their model with experiments. In the considered isolator, there were 19 layers of rubber with a shear modulus of 0.7 MPa and each layer was 5 mm thick. Carbon fibre-reinforced polymer (CFRP) sheets with a thickness of 0.55 mm are used as the reinforcing layers having Young's modulus of 4400 MPa and Poisson's ratio of 0.2. The 3D FE analyses thus conducted helped in developing of the retrofitting technology for the existing hospital buildings practically under multiple loading scenarios.

2. Numerical Modelling and Finite Element Analysis

The 3D FE model of the UFREI was developed by constraining alternate layers of rubber and fibre-reinforced sheets together (refer to Figure 1). Two additional external steel plates have been modelled: the bottom plate is fixed and the top plate applies the horizontal displacement to the isolator. Since the isolator is unbonded, the steel plates are not constrained to the isolator, i.e., free to roll. To simulate the unbonded nature of the FREI, a penalty surface interaction model with a friction coefficient of 1 is assigned to the contact surfaces between the steel plates and the isolator. Corresponding to the shear modulus of the rubber, a hyperelastic material model is used; in this, Mooney-Rivlin model, the material constants considered are: C10 = 0.34 MPa; C01 = 0.01 MPa; and D1 = 0, respectively for distortional and volumetric response.

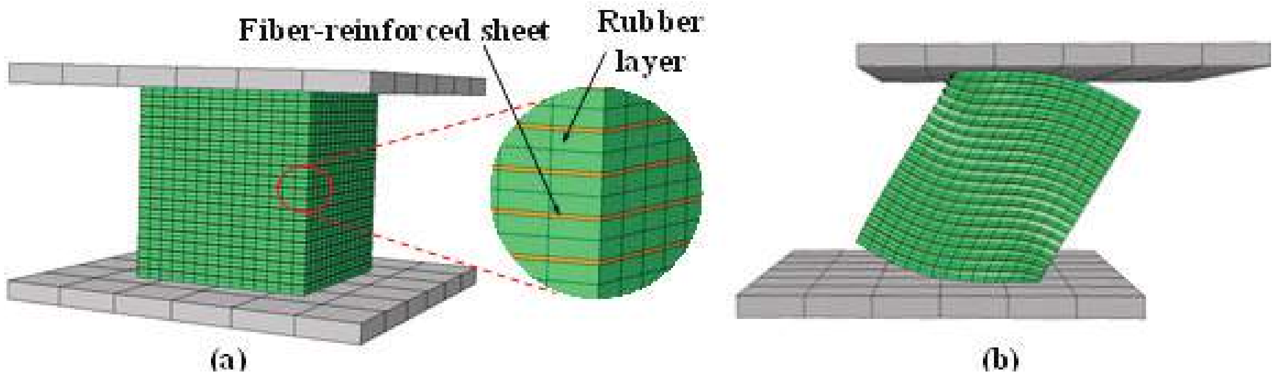

Figure 1. Finite element model of square UFREI, (a) in undeformed state, and (b) in deformed state at 60 mm horizontal displacement

The FE model of the rubber layers is formed using hybrid, 8-node brick elements without reduced integration (C3D8H). The fibre-reinforcement layers are modelled through an 8-node quadrilateral, in-plane, general-purpose continuum shell with reduced integration using hourglass control (SC8R). The mesh size is decided after conducting appropriate mesh convergence studies.

The 3D FE model of the UFREI is validated with the results reported by Das et al. (2015). A horizontal cyclic displacement with amplitude increasing from 10 mm to 60 mm and a frequency of 1 cycle/s is applied on the top loading plate, along with a constant vertical pressure of 1.2 MPa. Figure 2 shows the hysteretic behaviour of the modelled UFREI as compared to both, that is the numerical and the experimental results reported by Das et al. (2015). It is observed that the force-deformation behaviour of the modelled UFREI is in good agreement with the results published by Das et al. (2015). The dynamic performance of the UFREIs is measured by its effective horizontal stiffness and its effective damping ratio at any particular amplitude of horizontal displacement. The errors of the current FE model compared to the model reported by Das et al. (2015) are found to be 1.85% and 5.90%, in the effective stiffness and damping, respectively, for maximum horizontal displacement of 60 mm.

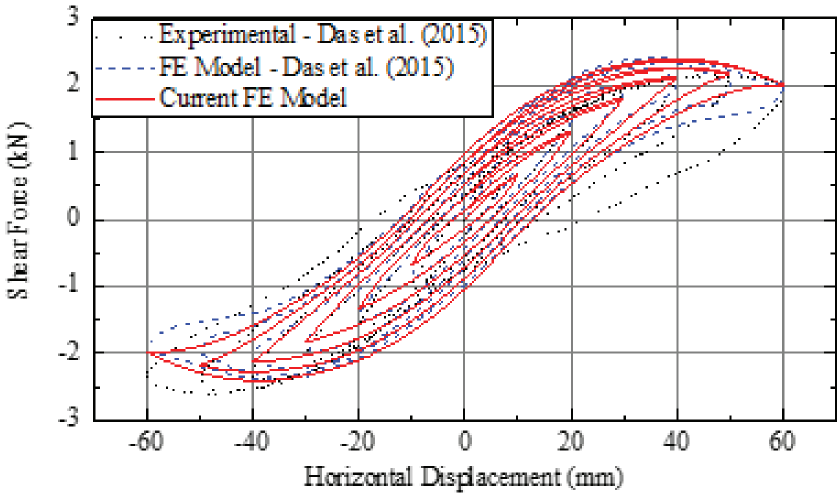

Figure 2. Validation of hysteresis loop obtained from current FE model with Das et al. (2015)

3. Numerical Study

The effective horizontal stiffness and the effective damping ratio of the UFREI are two important parameters for assessing the performance of the isolators under horizontal loads such as those induced during earthquakes. However, due to the non-availability of any closed-form analytical model for these parameters, it is difficult to judge the stiffness and damping values of the UFREI of any arbitrary geometry or material. Therefore, a parametric study is conducted in the current work to analyse and present the variation in the effective stiffness and damping of the UFREIs with the change in (a) its shape factor, (b) its aspect ratio and (c) the shear modulus of the elastomer. These three parameters are selected here because the hysteretic behaviour of the UFREIs is majorly governed by these parameters. To establish comparability amongst the different models a constant vertical pressure of 1.2 MPa is assumed to act on the isolator, and a horizontal cyclic load is applied to the loading plates with an amplitude of 0.63 tr, where tr is the total depth of the rubber layers. The amplitude is assumed as a multiple of tr to ensure that the rollover deformation of the isolators remains similar, which has a prominent effect on the nonlinear behaviour of the force-deformation curve of the UFREI.

4. Results and Discussion

Figure 3 presents variations in the effective horizontal stiffness and effective damping ratio of the UFREI with the change in the above-stated properties of the isolator. It is observed that the effective horizontal stiffness of the UFREI increases with the increase in the shape factor, aspect ratio and shear modulus of the elastomer of the isolator. However, the rate of increase in the effective stiffness with the increase in the aspect ratio is significantly higher. This implies that for a marginal decrease in the depth of the isolator, there is a rapid increase in the horizontal stiffness of the UFREI. In the case of an increase in the shear modulus of the elastomer, the change in the effective stiffness is not as significant as observed in the other two cases of shape and aspect ratios. The effective damping ratio of the UFREI reduces when the shape factor or the aspect ratio of the isolator increases. However it remains unchanged with the change in the shear modulus of the rubber used in the isolator. It is again observed that the rate of decrease in the damping ratio is significantly higher when the aspect ratio of the UFREI increases. Moreover, Figure 3 shows that after a certain level of increase in the shape factor, the change in the effective damping ratio of the UFREI is insignificant.

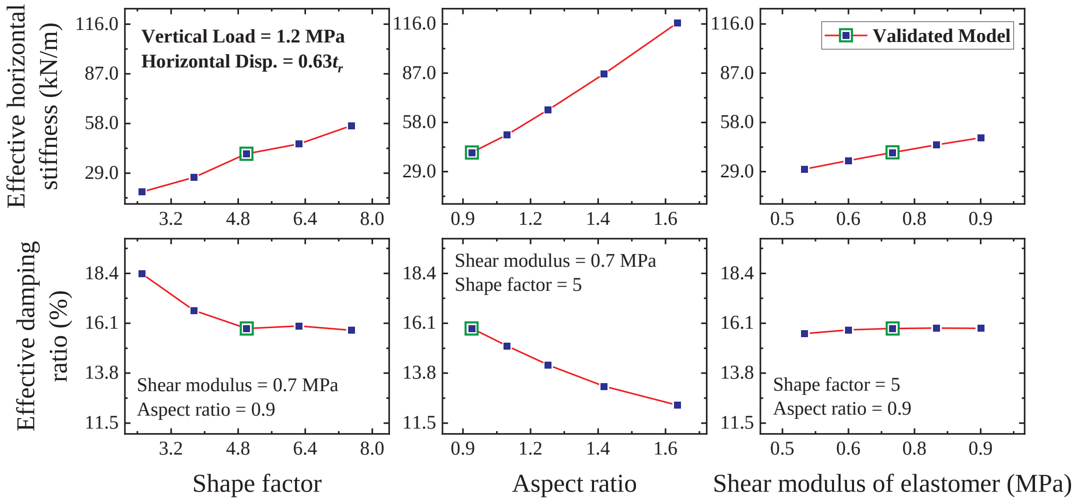

Figure 3. Variation in effective horizontal stiffness and effective damping ratio of the UFREI with the change in its shape factor, aspect ratio, and the shear modulus of elastomer

The shape factor of an isolator is the ratio of the loaded area to the free area of one elastomer layer and the aspect ratio of a square isolator is the ratio of its width to the total depth of the isolator. The shape factor and the aspect ratio define the geometry of the UFREI, which plays a crucial role in its dynamic behaviour. The dynamic characteristics of the UFREI under horizontal loading are also dependent on the shear modulus of the rubber, which is a measure of the material property of the isolator. The validated 3D FE model has a shape factor of 5, the aspect ratio of 0.95 and the shear modulus of the elastomer as 0.7 MPa. In the present study, three sets of UFREIs are investigated: (a) where the shape factor varies from 2.5 to 7.5, (b) the aspect ratio varies from 0.95 to 1.65 and (c) the shear modulus of the elastomer varies from 0.5 to 0.9, with all the other parameters maintained same as the validated model in each case. The observations made from this study and conclusions arrived at are useful in the design of the UFREIs used in construction projects.

5. Enablers and Barriers

Barriers to conducting the survey and challenges: Due to COVID-19 pandemic, the hospitals were in tremendous pressure and some parts were inaccessible. Also entry at several hospitals was prohibited and in other places, it was restricted. Hence, hospital administration had to be taken into confidence in order to conduct the investigation; especially, in recording information.

Manufacturing of the novel base isolation devices: The new devices pose a challenge in their manufacturing due to the unavailability of required resources.. However, the industry partner in this project, M/s Resistoflex Dynamics Private Limited took a keen interest in manufacturing these new devices. M/s Resistoflex Dynamics Private Limited successfully manufactured the new type of

UFREIs based on known technology. Furthermore, this will enable the successful implementation of the patentable UFREI with completely new technology.

Numerical and experimental works: As proposed originally in the proposal, the activities were performed as planned and successfully accomplished. The outcomes of this research work undertaken through the CDRI Fellowship project have been present in this article and will be useful in the real-life implementation in the future.

6. Conclusion and Way Forward

Unbonded fibre-reinforced elastomeric isolators (UFREIs) are lightweight and thereby cost-effective seismic isolation devices. Therefore, relatively more flexible UFREIs can effectively be introduced in structures for protection from strong earthquake ground motions. In this study we developed a 3D FE model of the UFREI and validated it with existing data from the literature. Further, the 3D FE model was used to study the dynamic behaviour of the UFREIs under varying geometric and material properties. One can conclude that the dynamic performance of the UFREI under cyclic loading is quite sensitive to the aspect ratio of the isolator. Therefore, the total depth of the isolator is one of the most important design variables that dictates its dynamic performance. Also, the shape factor has a significant effect on the stiffness and damping parameters of the UFREI. However, the rate of change in the dynamic parameters of the isolator is lesser in case of the change in its shape factor as compared to changes in the aspect ratio. The shear modulus of the elastomer has minimal effect on the effective stiffness and damping of the UFREI as compared to other geometric properties of the isolator.

Unbonded fibre-reinforced elastomeric isolators (UFREIs) are advanced base isolation devices that pose a lot of advantages against the conventional steel-reinforced elastomeric isolators (SREIs). The UFREIs are lightweight and more economical to install or retrofit in various types of structures as they are not explicitly fixed to the structures. Moreover, due to the unbonded nature of the isolators, they exhibit an interesting rollover deformation, which increases the flexibility of the isolator in the horizontal direction. In this project, we developed a trilinear hysteretic model (THM) to represent the nonlinear force-deformation behaviour of the UFREIs. First, the force-deformation behaviour of the UFREI was obtained using an experimentally validated 3D FE model of the isolator. With this, a novel THM was developed, where the nonlinear force-deformation behaviour of the UFREI could be represented by utilizing only four parameters. Further, equivalent linearization was undertaken to obtain the effective stiffness and damping parameters of the UFREI, based on the proposed THM. We have suggested an innovative normalization technique such that the normalized THM can predict the force-deformation behaviour of any UFREI with considerable accuracy. This allowed the formulation of a simple design procedure for the UFREIs.

Fibre-confined elastomeric isolator (FCEI) is a new product, hence further research is required to make it useful in various projects with specific requirements thereon. Codes and standards will be able to incorporate FCEIs once the technology becomes well-proven and established, which requires more research. For example, the buckling behaviour of the FCEI is yet to be studied, the outcomes of which have implications on their design.

References

1. Becker, T. C., & Mahin, S. A. (2012). Experimental and analytical study of the bi-directional behavior of the triple friction pendulum isolator. Earthquake Engineering and Structural Dynamics, 41, 355-373.
2. Matsagar, V. A., & Jangid, R. S. (2004). Influence of isolator characteristics on the response of base-isolated structures. Engineering Structures, 26, 1735-1749.
3. Matsagar, V. A., & Jangid, R. S. (2008). Base isolation for seismic retrofitting of structures. Practice Periodical on Structural Design and Construction, 13, 175-185.
4. Munjal, P., Jagtap, P., Alam M. S., & Matsagar V. A. (2019). Fiber-reinforced elastomeric isolators in seismic base isolation of buildings. 7th International Colloquium on Performance, Protection & Strengthening of Structures under Extreme Loading & Events (PROTECT 2019), Whistler, British Columbia, Canada, 16-17 September.

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