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Flood loss functions as decision support for guiding resilient urban development: a case study of Gaur Municipality, Nepal

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Abstract

Flood loss functions convert damage and loss of function into economic losses, providing critical information on expected damages from future floods. This article presents the outcomes of a study assessing the economic impacts of an extreme flood event in Gaur Municipality, Nepal, utilizing flood simulation results from a hydrodynamic model. A detailed questionnaire survey was conducted covering all parts of the municipality to collect data to assess the economic impacts of flooding on different types of buildings (e.g., adobe, masonry, and RCC frame) and agricultural lands. Subsequent statistical analysis considering building plinth height, number of stories, building age, etc., showed flood depth and duration to be the most sensitive parameters for the damage. Sets of linear and logarithmic depth-damage functions were generated and compared to predict damages for different buildings and crops. The study revealed a significant economic burden on the municipality from potential extreme floods, with estimated structural damage to residential and commercial buildings reaching NRs 225 million (US$ 3.21 million). This figure is expected to rise with time due to urbanization growth and subsequent wealth accumulation within the municipality area. The developed flood damage functions predict damages, while the flood loss map, highlighting regional vulnerability, aids in planning development activities within the municipality and provides economic justification for long-term investments in flood protection measures. This study is intended to serve as a decision support tool that could pave the way for informed and resilient urban development.

Keywords: *building resilience, depth damage curves, economic impact, flood loss functions, Terai.*

1. Introduction

Flooding is a major concern in numerous regions around the globe (Blanchard-Boehm et al., 2001; Horritt & Bates, 2002; Kundzewicz et al., 2014). The detrimental effects of floods include direct fatalities and illnesses, alongside indirect repercussions such as displacement and extensive destruction of crops, infrastructure, and property (Carroll et al., 2010; Khushi et al., 2024). Accurate flood impact estimates are crucial for evaluating mitigation measures' cost-effectiveness, facilitating land use planning, and guiding infrastructure development (Dottori et al., 2023; Zeleňáková et al., 2020). Moreover, flood loss maps assist stakeholders in prioritizing investments and empower authorities and communities to prepare for disasters (Percival et al., 2020).

Annually, floods and landslides in Nepal contribute to over 175 fatalities on average, accompanied by economic losses surpassing USD 140 million (Marsh, 2020). A total of 4160 floods were documented in Nepal between 1971 and 2016, resulting in human casualties and significant damage to infrastructure (Chidi et al., 2022). Latest data for the first six months of the year 2024 shows 181 disaster related deaths and estimated loss of NPR 2 billion (https://bipadportal.gov.np/damage-and-loss/). Furthermore, Nepal ranks tenth globally in relative physical exposure to flooding, indicating potential damage to physical assets equivalent to 1.4% of its GDP (Luo et al., 2015). Among 200 countries, Nepal ranks 4th, 11th, and 30th in relative vulnerability to climate change, earthquake, and flood hazards, respectively (Khanal, 2020). In addition to the loss of lives and property damage, psychological distress, a sense of insecurity, and intangible losses inflict profound anguish and suffering upon individuals residing in flood-prone areas.

Many studies and analyses have shown that damage reductions due to forecast improvements can range from a few percentage points to as much as 35% of annual flood damages (Dale et al., 2014; Meyerson, 2004). Furthermore, allocating funds for relief and rehabilitation frequently competes with developmental initiatives. Cannon et al. (2000) emphasize the importance of comprehending the interaction between hazards and the vulnerability of the elements at risk, suggesting that natural disasters stem from the convergence of natural hazards and the susceptibility of individuals and property (Cannon, 2022).

Recent flood events have highlighted the significance of maximum water levels during slowly rising river floods in causing damage. In these cases, the gradient of the flood wave is slight, so there are no damaging effects due to flow velocity impacts (Büchele et al., 2006). The primary cause of damage observed in many studies stemmed from the gradual rise of water levels (Adams & Pagano, 2016). Building surveyors in the UK found flow velocity to be the least influential factor in assessing flood damage among various flood characteristics (Soetanto & Proverbs, 2004). Flow velocity emerged as the least influential factor in their assessment of various flood characteristics' impact on damage. Flood water depth, duration, and velocity govern the damage characteristics and depth is the governing parameter for damage to urban buildings (Dutta et al., 2003). Hence, Depth-damage functions are the standard urban flood damage assessment method for various building types (Gnan et al., 2022; Smith, 1994). However, in Nepal, the assessment and selection of investment alternatives for flood damage mitigation often require comprehensive economic and financial analyses, primarily due to the absence of systematic data on flood damages.

In Nepal, early flood warning systems are one of the most effective ways to minimize the loss of life and property (Bajracharya et al., 2017). The nation faces a critical challenge with its susceptibility to seasonal monsoon floods, necessitating urgent measures to mitigate the potential loss of life and property damage (Dewan & Extremes, 2015). This paper presents an output of a study conducted to assess the economic impacts of an extreme flood event in Gaur Municipality (21.53 sq. km), located on the right bank of the Bagmati River in central Terai of Nepal (Figure 1). While various factors influence flood damage, our analysis in this study, including flood depth, duration, building plinth height, number of stories, and building age, identifies flood depth as the primary determinant of the damage. Furthermore, flood simulation results from a hydrodynamic model, considering flood depth as a hazard indicator, were utilized to develop depth-damage functions assessing structural damage across various building types, subsequently applied to compute damage and generate flood loss maps for the municipality based on a 50-year return period flood event.

2. Study Area

The Bagmati River originates in the Mahabharat range of mountains about 16 km Northeast of Kathmandu, Nepal's capital city. As the river emerges from the hills, it enters the Terai region and flows as a divide between the Sarlahi and Rautahat districts. It drains out of Nepal across the Indian state of Bihar to join the Ganges. Its total length is 597 km, of which 195 km lie in Nepal and the remaining portion in India.

The river's floodplain comprises about half of the total area (2302 sq. km.) of the Rautahat and Sarlahi districts, comprising rural and urban settlements and agricultural land (Figure 1). Several settlements on both riverbanks in the study area are usually flooded during the rainy season. Flooding is mainly caused by the intense rainfall over its extensive catchment and generating high volumes of run-off that spills out of the riverbanks. The river's catchment area at Karmaiya and Indo-Nepal border are computed to be 2800 sq. km. and 3670 sq. km. respectively.

Gaur Municipality is located in the southernmost part of the Bagmati floodplain in Nepal. According to census 2021, it is spread across 21.53 sq. km., has 7235 households, and a population of 39,846 (https://censusnepal.cbs.gov.np/, accessed on June 20, 2024). Land use within the municipality can be mainly classified as agricultural, residential, commercial, water bodies and others. The municipality suffers from recurrent flooding owing to its relatively lower elevation and obstruction to gravity flow from north to south by a bund (insufficient drainage openings in the bund and channel capacity) running east-west immediately in the south of the municipality. In addition, runoff from surrounding areas during a heavy storm accumulates in low-lying areas of the municipality, increasing the duration of flooding and consequential damages.

Figure 1: Location of the study area

3. Data and Methods

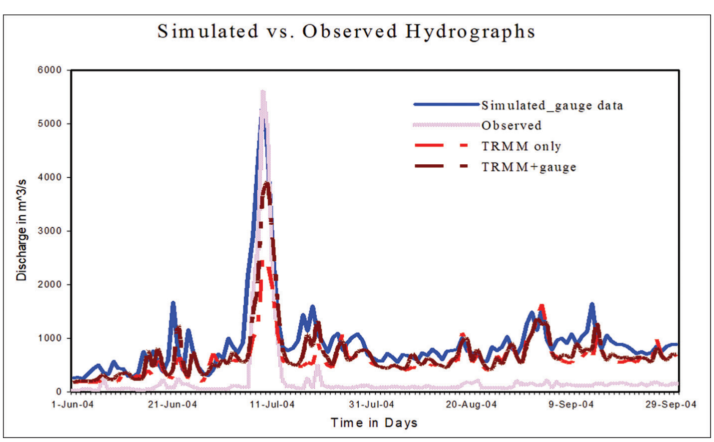
In this study, direct damage to residential and commercial buildings was considered. Vector data and orthophotos of the area were obtained from Nepal's Survey Department. River discharge data was obtained from the Department of Hydrology and Meteorology. Population data was obtained from Nepal's Central Bureau of Statistics. Data on flood damage was collected through a community-based survey.

The overall methodology integrates hydrologic/hydraulic modelling, vulnerability assessment of buildings, generation of depth damage functions and economic impact assessment. This study used the flood map produced by hydraulic modelling of a 50-year Bagmati river flood (11250 cumecs) event in a separate study (Kafle et al., 2007). The hydrologic model HEC-HMS, in combination with Geospatial Hydrologic Modeling Extension HEC-GeoHMS, was used to convert the precipitation excess to overland flow and channel runoff. The simulation spanned four months (June-September), encompassing the entirety of the 2004 rainy season. The predicted hydrograph was calibrated against the observed one, and the model parameters were manually optimized for good simulation.

Using rain gauge data, the predicted peak discharge was close to the observed value, and the smaller discharges followed the observed trend. The model framework developed in the previous study considered the spatial variation in the runoff response of the watershed by using curve numbers based on soil type, land use, and the spatial distribution of the rainfall in the watershed. The peak flow of the derived hydrograph was used as an input in the hydraulic model (HEC-RAS) for producing flood maps, forming the basis for inundation area extent and flood depths for this study.

3.1 Validation of model results

Validation of hydrodynamic model results is based on the comparison of modelled flood depths with observed depths and is shown in Figure 2. The results of hydrologic simulation are shown in Figure 3. Both the results are adopted from Kafle et al. (2007).



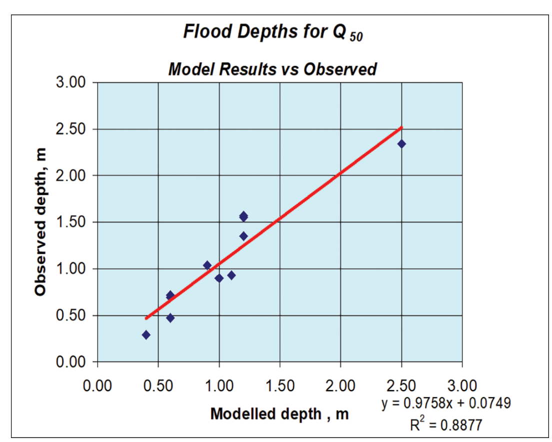


Figure 2: Observed and modelled flood depths **Figure 3:** Hydrologic Simulation Results

The normalized peak error (NPE), defined as follows was computed to be – 0.018.

$$NPE = (Q_{pmax} - Q_{omax})/Q_{omax}$$

Where Q_{pmax} is the predicted peak discharge and Q_{omax} is the observed peak discharge. The peak resembled well but the lower discharges need further refinement.

3.2 Generating building database

Buildings, classified into adobe, brick masonry (BM), and reinforced cement concrete (RCC), digitized on Orthophoto of 1999 combined with the surveyed data were utilized to construct a comprehensive building database. MS Excel and SPSS software were used to analyze the data. Table 1 gives a statistical summary of the building data.

Table 1: Summary of building data

S.N.	Variables	Unit	Min	Max.	Mean	Range
1	Building types	Adobe = 276, Brick Masonry (BM) = 188 and RCC frame = 26				
2	Building age	year	2	53	15.77	51
3	Building plinth area	sq. m	20	338.72	121.56	318.72
4	Number of stories	levels	1	3	1.11	2
5	Plinth height	m	0.1	2	0.35	1.9
6	Height of 1st floor	m	2	3.15	2.89	1.15
7	Present replacement value of building structure	NRs. ('000)	21.53	6458	632	436.87
8	Maximum flood height	m	0.1	3	0.9563	2.9
9	Flood duration	day	0.25	7	2.024	6.75
10	Cost of damage to building structure	NRs.	500	50000	8560	49500
11	Cost of damage to building contents	NRs.	200	50000	8505	49800
12	Cost of damage to outside facilities	NRs.	100	12000	2126.5	11900

Nepalese Rupees (1 USD = 70.00 NRs.) (exchange rate as per 2007)

Figure 4 shows the distribution of buildings in the study area.

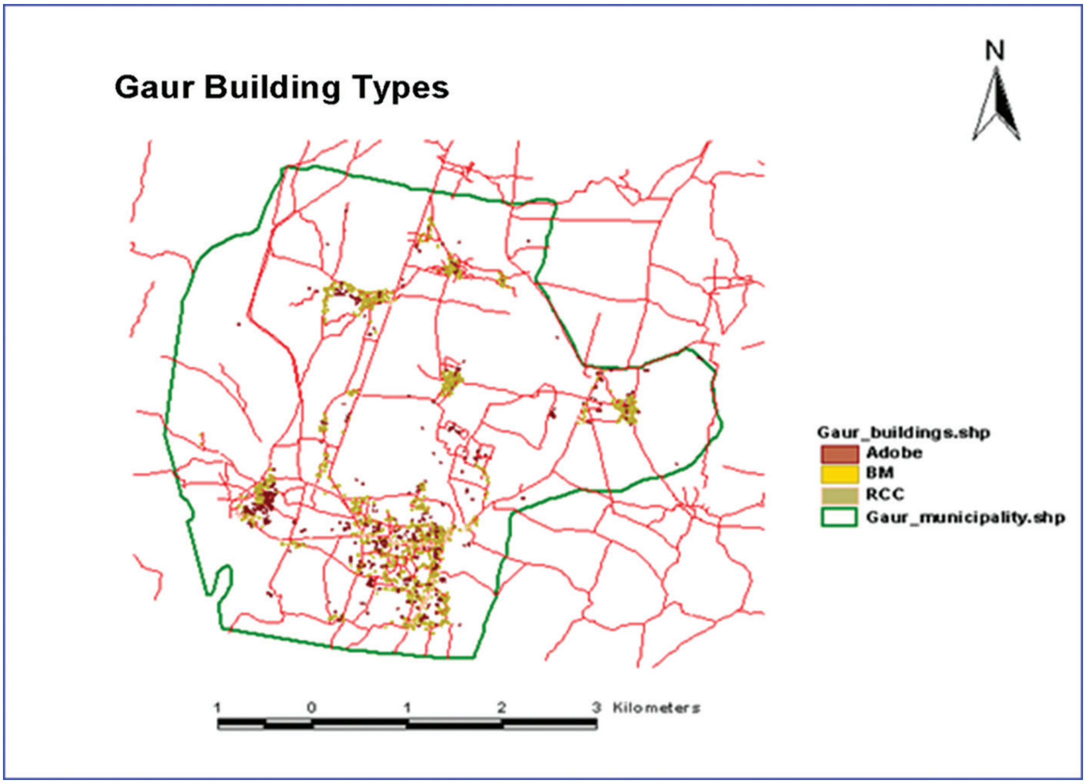


Figure 4: Distribution of building types in the study area

3.3 Community survey

Davis et al. (2013) have emphasized the need to integrate data from different sectors, e.g. social, technical, economic, and environmental, in assessing social vulnerability (Davis, 2013). In December 2006, a questionnaire survey was conducted on 490 flooding cases in 257 buildings, 6.5 percent of total buildings, of different types (20 RCC frame, 106 BM, and 131 Adobe) were sampled from various parts of the municipality to collect firsthand information on damages caused by floods in other years in the past to buildings and their contents. The survey consisted of interviewing residents of 257 households in the flood-prone area of Gaur Municipality to develop a database characterizing the building types, flood depth, flood duration, building age, plinth height, no. of stories and the damage caused to building structures, etc. The deterioration in monetary terms was estimated from the cost incurred in the repair/restoration of the damage. The survey was carried out with the help of engineers, junior engineers and supervisors of the Water Induced Disaster Prevention Office, Division No. 3, Bara, who were given prior orientation

3.4 Statistical analysis

Statistical analyses were carried out to generate a correlation matrix to identify the most sensitive parameters responsible for the damage. Regression analysis was performed to generate flood damage functions. The depth–damage curves were developed from data analysis on structural damage to residential and commercial buildings obtained through a questionnaire survey in the flood-affected areas of the municipality. Separate depth-damage curves were developed for different types of buildings based on the age of the buildings and flood duration.

3.5 Model integration

The flood events in the study area in 1993, 2000, 2002, and 2004 were used as the reference floods for the survey. Out of these, the 1993 flood was devastating, with a peak discharge of 16000 cumes and a return period of more than 100 years. The total loss due to this flood in terms of physical destruction was estimated to be Rs. 5 billion. It was estimated that the floods of 1993 retarded the country's development performance by at least two decades (Pradhan, 2007). The peak discharge of the 2004 event almost equalled a value corresponding to a 50-year return period in which flood depths in some parts of the municipality exceeded 3 meters, and the duration was more than three days. It caused inundation in about 72% of the municipality's total area (Kafle et al., 2007).

In conjunction with flood mapping, building inventory, and damage functions, this database was integrated into a GIS environment to create a flood loss map and evaluate the economic ramifications for Gaur Municipality. The methodological framework is depicted in Figure 5.

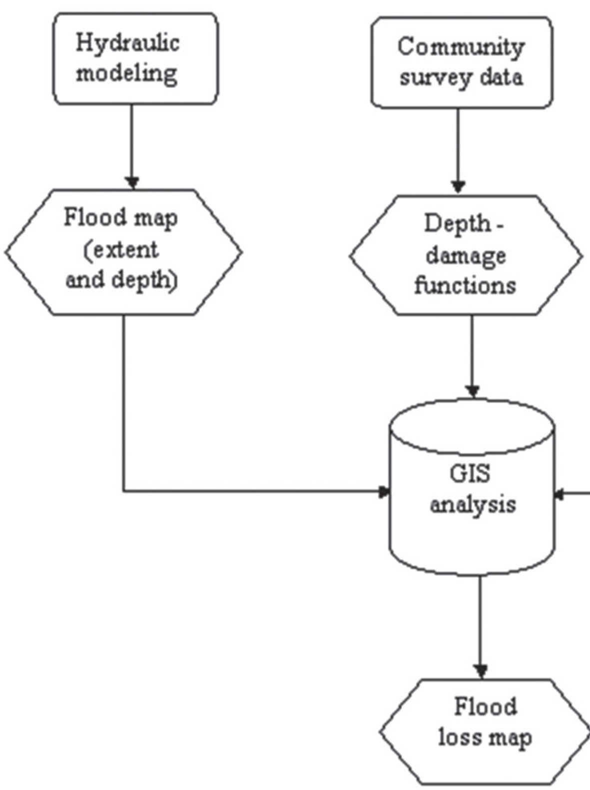


Figure 5: Methodological framework

4. Results and Discussion

4.1 Inundation area extent and flood depth

The inundation area extent and flood depths corresponding to a 50-year return period flood obtained from the hydrodynamic model formed the basis of flood depth in a given building location (Figure 6). The water depth inside the building was computed by deducting the plinth height.

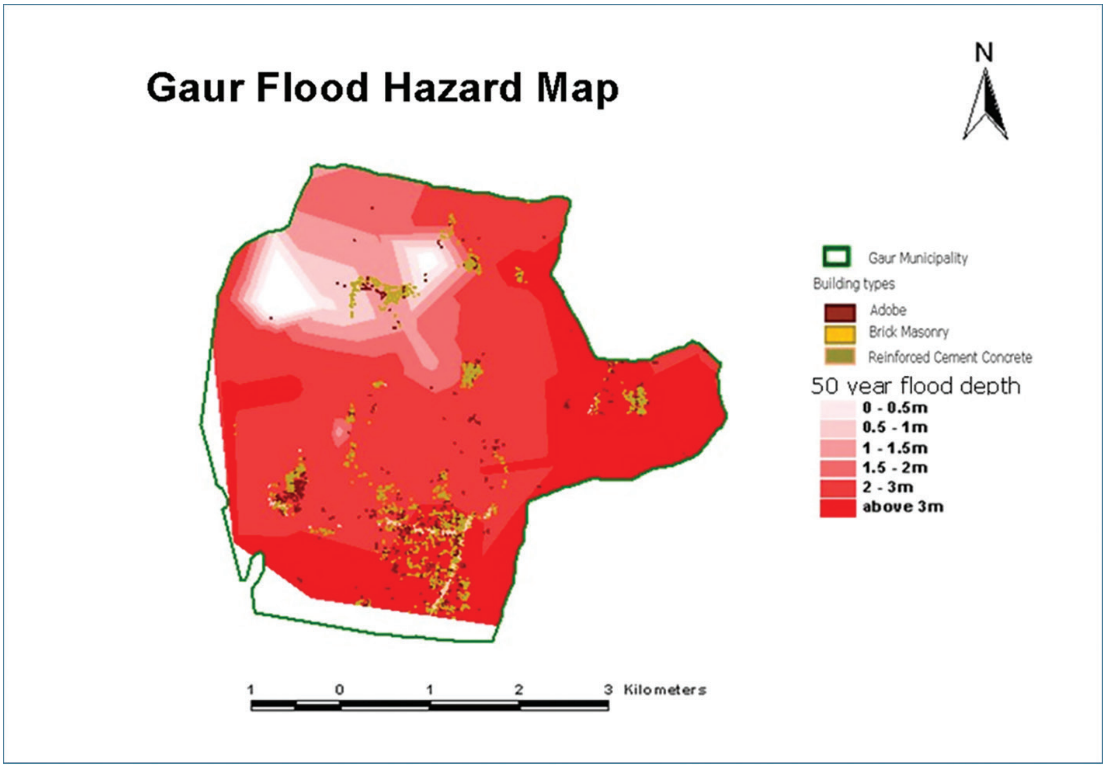


Figure 6: Gaur municipality flood depth map

The depth is found to be as high as 3 m. Considering the relatively inferior building materials, low height of roads and possibility to crop damage 1 m is considered as the critical depth beyond which the floodwater becomes more damaging. The municipality could refer to the flood depths in a given location for fixing plinth height to minimize submergence in extreme flood events. It could be inferred from the results that instead of constructing a single storied building with large plinth area, multiple storied building with reduced plinth area is desirable from the point of view of reducing damage, especially to the building contents.

4.2 Depth-damage functions

The depth damage data were analyzed for different scenarios, and best-fitted damage curves and functions were generated. The various damage functions are summarized in Table 2. The total damage within the municipality for a 50-year return period flood event was computed as NRs. 225 million. This shows the severity of the economic impact that a flood event with an annual exceedance probability of 2% might have on the municipality.

Table 2: Summary of flood depth - damage functions

S.N.	Building type	Flood duration (days)	Building age (years)	Depth - damage function	R^2
1	RCC frame	All data		y = 1.4687ln(x) +1.8713	0.73
2	BM	All data		y = 4.1053ln(x) +5.227	0.86
3	Adobe	All data		y = 15.161ln(x) +17.502	0.91
4	RCC frame	< 1		y = 1.2072ln(x) +1.6003	0.67
5	RCC frame	1 - 2		y = 1.5329ln(x) +2.0749	0.75
6	RCC frame	> 2		insufficient data	
7	BM	< 1		y = 3.139ln(x) +4.3717	0.70
8	BM	1 - 2		y = 4.7372ln(x) +6.0769	0.86
9	BM	> 2		y = 5.024ln(x) +6.5435	0.92
10	Adobe	< 1		y = 9.6035ln(x) + 9.9697	0.73
11	Adobe	1 - 2		y = 16.5832ln(x) +15.7870	0.89
12	Adobe	>2		y = 18.6550ln(x) + 18.2377	0.94
13	RCC frame		<= 10	y = 1.2782ln(x) + 1.7115	0.74
14	RCC frame		>10	y = 1.9398ln(x) + 2.5856	0.92
15	BM		<= 10	y = 2.6159ln(x) + 3.6630	0.77
16	BM		>10	y = 4.3259ln(x) + 5.5564	0.86
17	Adobe		<= 10	y = 17.8337ln(x) + 15.7129	0.87
18	Adobe		>10	y = 14.6778ln(x) + 12.9990	0.83
19	Crops damage			y = 21.766ln(x) + 62.646	0.33

y = percent damage, x = depth of flood (m)

The depth-damage curves for some analysis scenarios are given in Figures 7 to 10.

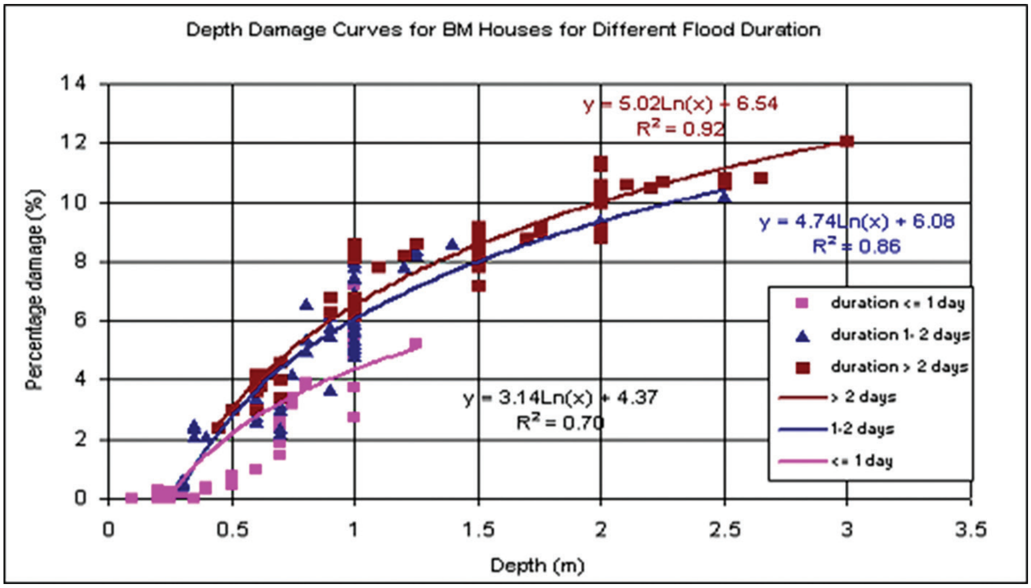


Figure 7: General depth-damage curves considering buildings of all ages and floods of all duration

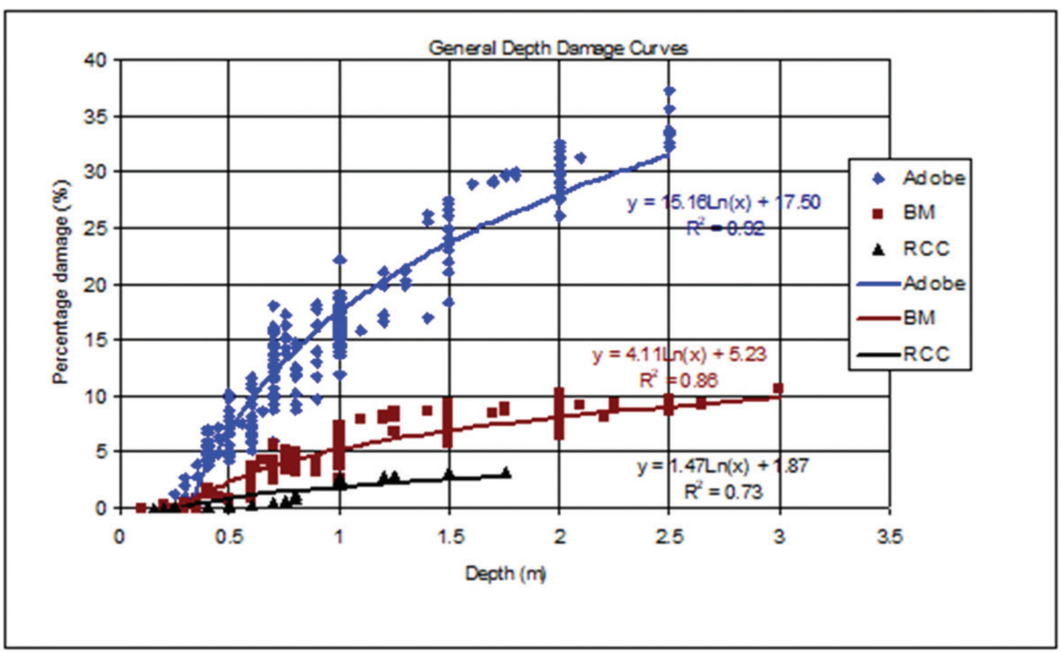


Figure 8: Depth-damage curves for brick masonry (BM) buildings

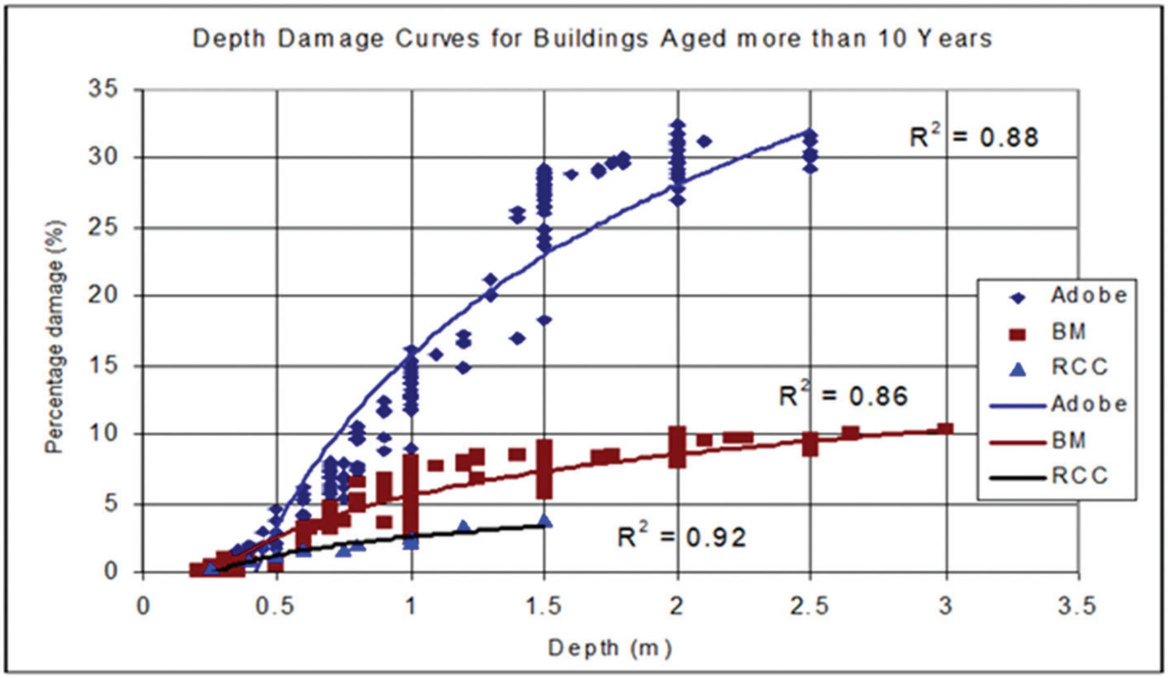


Figure 9: Depth-damage curves for buildings aged more than ten years

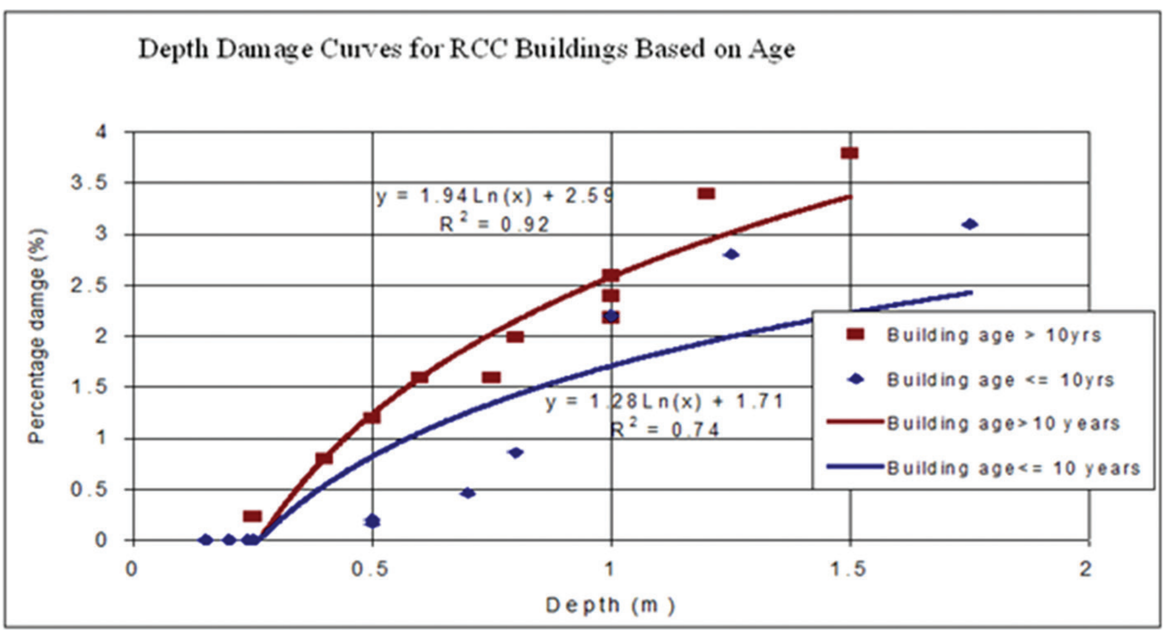


Figure 10: Depth-damage curves for RCC buildings based on age

The results indicate that in terms of percentage damage, RCC suffered the least and adobe the most for the same depth and duration of flood considering buildings of all ages and floods of all durations. Accordingly, the cost of repair for flood damage was found to be the lowest for RCC buildings as a fraction of the initial cost. Regarding the age of the building, newer buildings suffered less damage. Also, the longer the duration and greater the depth, the higher the damage. Hence maintaining local drains to reduce the depth and duration of flood is important. The total damage for each type of building was computed. The values were reclassified, and the number of houses falling under each class is shown in Table 3 in terms of replacement value.

Table 3: Distribution of houses by replacement value

Replacement Value (NRs)	Number of houses
0 – 5,000	739
5,000 – 15,000	1083
15,000 – 25,000	827
25,000 – 50,000	1222
50,000 – 100,000	1040
>100,000	474

From the above table, it can be deduced that 8.8% of the houses require more than NRs. 100,000 to restore the flood damages and for some 20% of the houses, such cost ranged from NRs. 50,000 to 100,000. Such information could be of use to the municipality for guiding investment in flood protection works.

4.3 Critical parameters for building vulnerability

The linear multiple regression model results carried out using a set of independent variables for each type of building to establish a relationship with structural damage are given below in equations (1) to (4).

For Adobe houses,

$$Y = -1.12 + 0.033X_1 - 0.1X_2 + 14.8X_3 + 0.52X_4 \quad (1)$$

$N = 276$, $R^2 = 0.923$

For BM houses,

$$Y = 1.3 - 0.003X_1 - 1X_2 + 5X_3 - 0.01X_4 - 8X_5 \quad (2)$$

$N = 188$, $R^2 = 0.763$

For RCC houses,

$$Y = 0.44 - 0.009X_1 - 0.144\, X_2 + 2.35X_3 - 0.22\, X_4 - 0.184\, X_5 \quad (3)$$

$N = 26$, $R^2 = 0.903$

Where,

Y = Percentage damage

X_1 = Age of building (year)

X_2 = Plinth height (m)

X_3 = Flood depth (m)

X_4 = Flood duration (days)

X_5 = No. of stories

Figure 11(a and b) show the scatter plots for regression standardized predicted values for Adobe and RCC buildings.

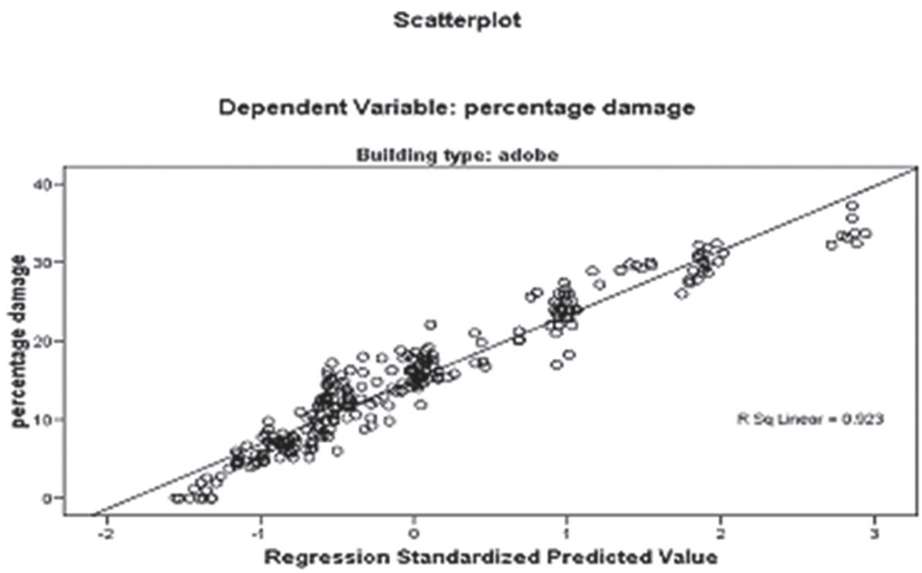


Figure 11-a: Generated structural damage functions - Adobe houses

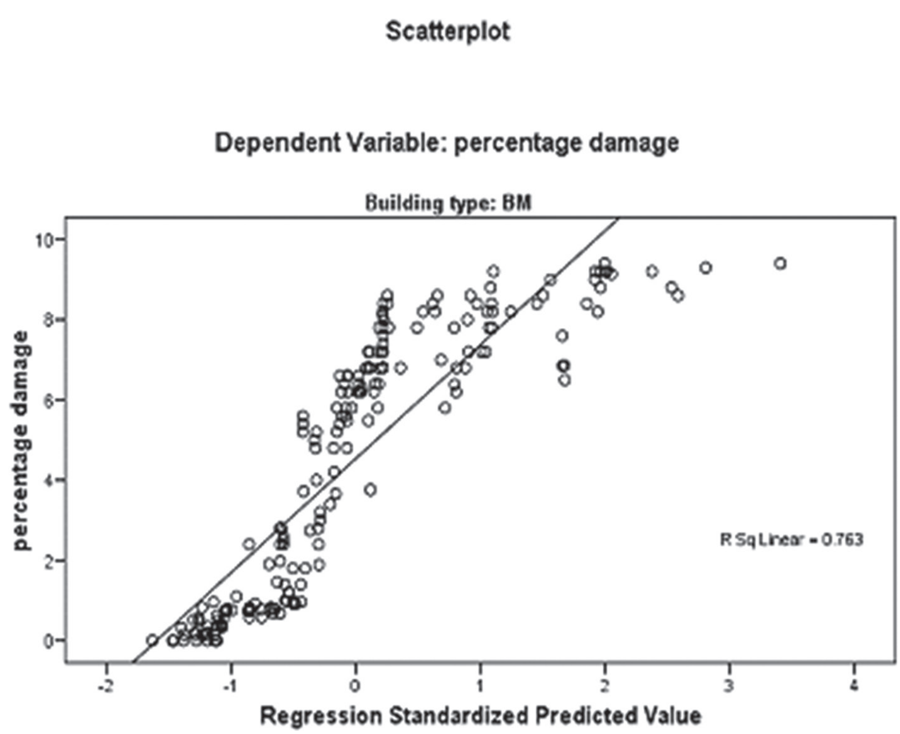


Figure 11- b: Generated structural damage functions - RCC buildings

Notable findings include a positive correlation between building age and damage costs to the structure, suggesting that older buildings may be more vulnerable. SPSS for descriptive statistics analysis was used to find the bivariate correlation of all types of houses for different variables: percentage damage, building age, plinth height, flood depth, flood duration and number of storeys of the houses surveyed. The heat map (Figure 12) shows the Pearson correlation coefficients between variables.

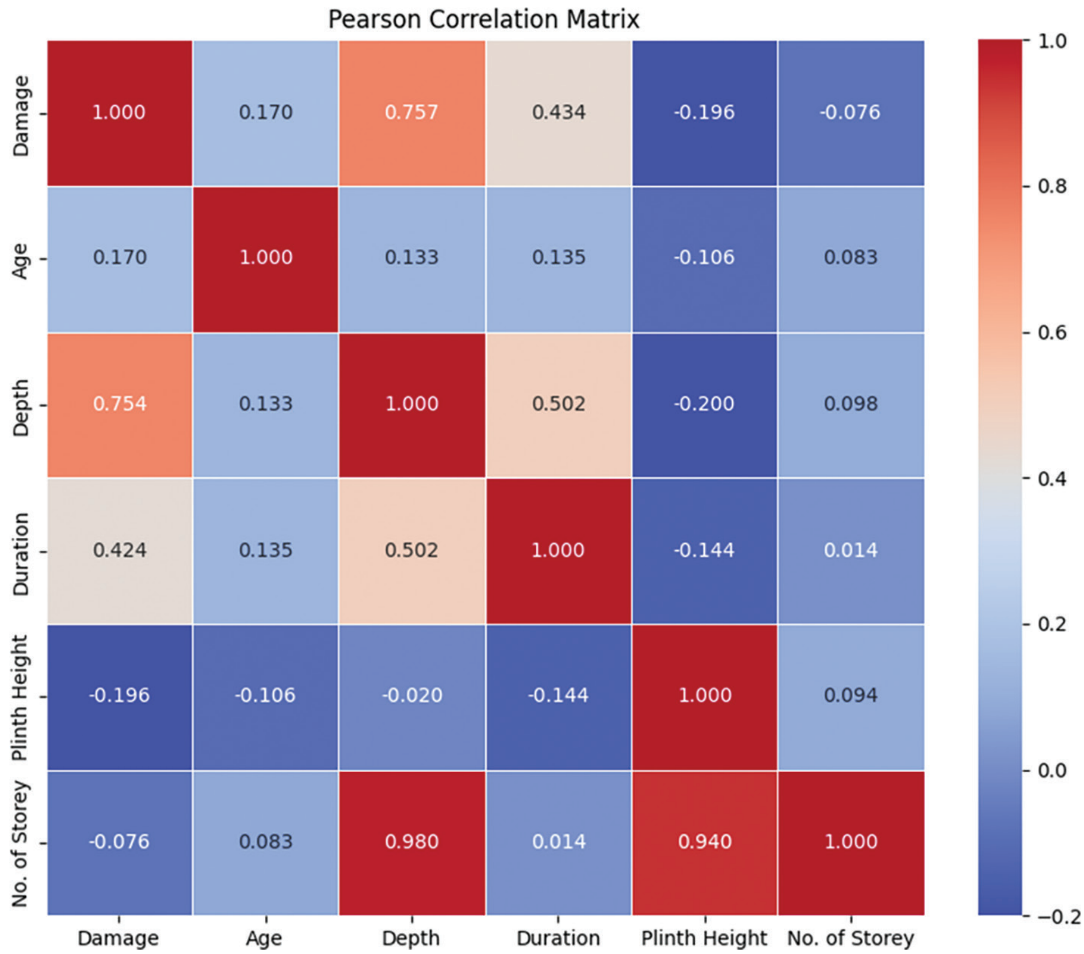


Figure 12: Pearson correlation matrix

The colors intensity represents the strength and direction of correlations, with warmer colors indicating positive correlations and cooler colours indicating negative correlations. The numeric values within each cell denote the correlation coefficient, ranging from -1 to 1. The matrix shows that the correlation coefficients of percentage damage with flood depth and duration are comparatively higher, at 0.75 and 0.42, respectively. At the same time, the correlation coefficient of percentage damage with building age, plinth height, and number of stories is relatively low. Thus, it can be concluded that flood depth and duration contribute most to structural building damage compared to other variables.

Positive correlations, such as the one between building age and damage costs, suggest potential vulnerabilities. Negative correlations, for instance, between plinth height and flood depth, indicate trade-offs or mitigating factors. The heat-map serves as a visual guide for identifying patterns and informing targeted interventions for building resilience.

4.4 Economic impact of flooding

The developed damage functions were used to estimate and generate flood loss maps. The study results showed that the municipality would have to bear the burden of substantial economic impacts due to potential extreme floods. The total structural damage to residential and commercial buildings alone was considered NRs. 225 million. The fact that this figure would rise, with time due to growth in urbanization and subsequent wealth accumulation, shows the severity of the economic impact of potential flooding within the municipality area and other municipalities in similar geographical settings. Figure 13 shows a flood loss map (distribution of structural damage to buildings within the municipality) corresponding to a 50-year return period Bagmati River flood.

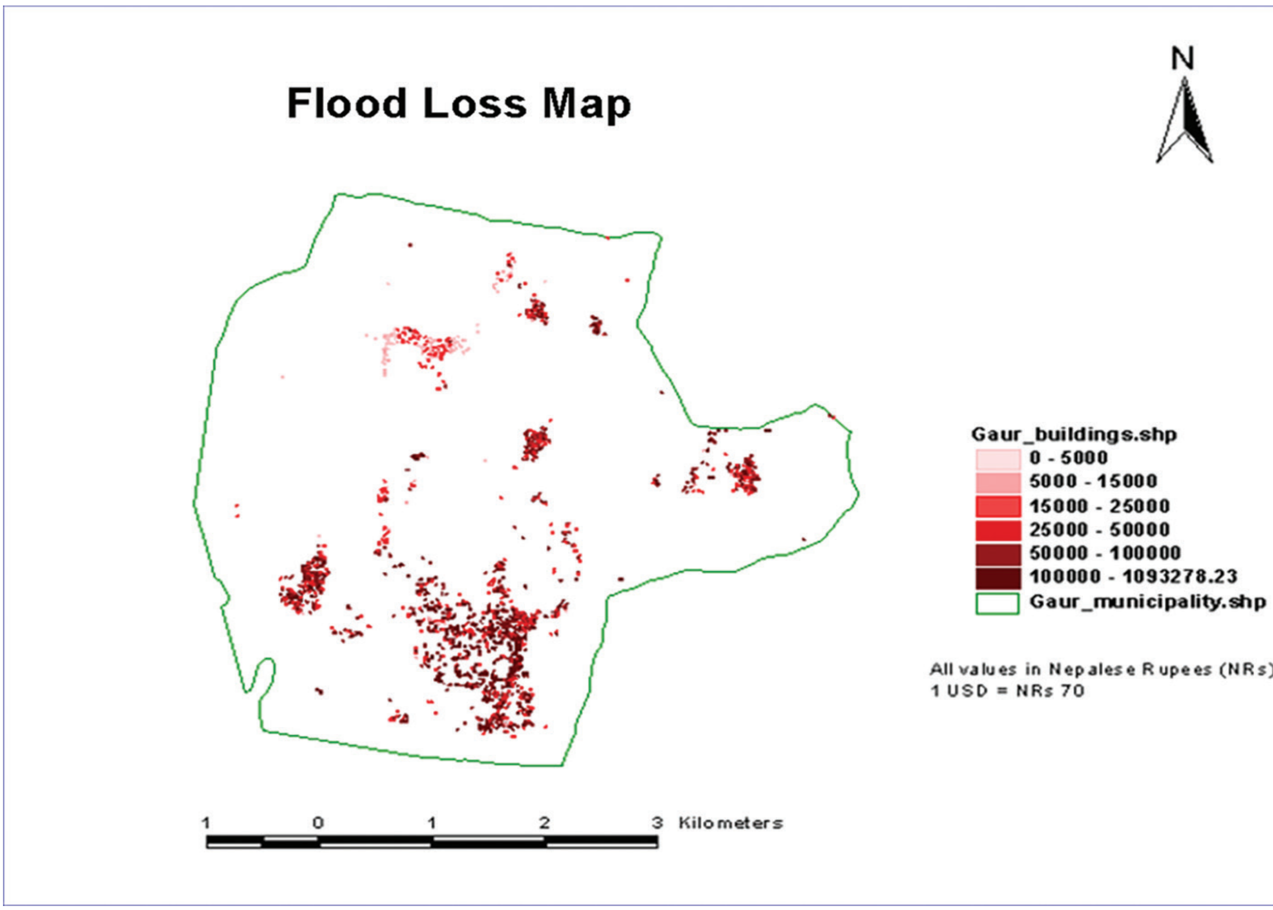


Figure 13: Flood loss map (Distribution of structural damage to buildings)

5. Conclusions

Depth-damage functions are the standard urban flood damage assessment method for buildings, central to flood damage estimation and serving as essential tools in quantifying the impact of floods on both lives and property. While flood depth and duration are notably sensitive factors affecting flood damage, their impact is also influenced by additional factors such as building age, plinth height, and the number of stories, further complicating flood damage assessment. The study gives the flexibility of selecting and applying appropriate damage functions for estimating flood damage. The generated functions for structural damage of buildings have R-square values from 0.67 to 0.94. The R-square value of 0.33 for crop damage could be attributed to people's uncertainty about damage in the context of crops. The developed flood damage functions, predicted damages, and the flood loss map showing the vulnerability of the different areas could help plan resilient urban development activities within the municipality and provide guidance for decision making in long-term investments in flood protection and drainage improvement measures.

Policymakers and urban planners can leverage the results to prioritize interventions based on identified correlations. The positive correlation between building age and damage costs underscores the need for proactive retrofitting strategies for older structures. Similarly, strong negative correlation between plinth height and damage suggests that plinth level of buildings be decided considering the potential flood depth in a given location, especially, in the low-lying areas of the municipality. It is expected that the findings of the study could contribute to the broader understanding of building vulnerabilities and can inform targeted interventions for enhancing disaster resilience.

While this study offers valuable insights of relationship within the dataset focusing on direct tangible damages, further research including intangible losses may make the study more comprehensive. Study using 2D hydrodynamic model may improve the accuracy of the findings. Future studies should consider alternative validation of the inundation area extent using satellite images capturing peak floods.

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Conflicts of Interest

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in authoring this article.

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