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Synthetic flood damage function for direct damage estimation in Loei Town Municipality

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Abstract

The reflection between flood damage phenomena and flood characteristics in the flood-affected areas of Loei Town Municipality where flood damage issue is not deeply examined and documented, is desirable for a more accurate damage estimation. Therefore, based on the available empirical dataset collected during 2021-2023 floods, the site-specific flood damage functions and their curves were developed for assessing direct monetary damage to buildings. The replacement cost for household damaged contents was gathered through survey interview of 637 households, in which 75% and 25% of the entire dataset were randomly split for constructing and validating synthetic functions, respectively. The polynomial function was the best fitting method, rather than the other five damage functions (i.e., exponential, Fourier, Gaussian, Rational, and the Sum of Sines), as characterized by the highest R^2 values of 0.73, while relatively low values of MAE (0.17), MBE (-0.17), and RMSE (0.19) clearly indicated the validity of the synthetic damage function. All relevant data were then entered into the HEC-FIA software for damage estimation based on a structure-by-structure basis. The results revealed that the 2002 flood caused 199,330 USD in damage to Loei Town Municipality, which showed a reasonable agreement with the governmental relief budget (accounted for 56% of the 2002 total flood-relief budget of Loei Province). It is noteworthy that the findings gained from this study may be of assistance when assessing flood damage to buildings for the areas with flood-related data scarcity, in which the depth-damage function/curve developed herein could help pave the way towards more accurate flood damage estimation for risk assessment at local scale. Finally, this study could be technically beneficial for government and local authorities of Loei Town Municipality in making decisions in reducing flood damage and for residents living in flood-prone areas to achieve resilience after flood events.

Keywords: Flood damage, Depth-damage function, Replacement cost, Damage percentage, MATLAB, HEC-FIA

1. Introduction

Amongst the natural disasters and threats, there is no denying that the prevalence of floods and widespread devastation worldwide are of utmost concern. This can clearly be seen from the record between 2000 and 2019 released by the Emergency Events Database (EM-DAT) of the Centre for Research on the Epidemiology of Disasters (CRED) in 2020, who revealed that 3,254 occurrences out of 7,348 (44% of all occurrences worldwide) were related and dominated by floods. Meanwhile, widespread discussions on the increase in flood severity (both intensity and magnitude) and frequency of occurrence affecting human lives and their properties are also in progress and widely ongoing as documented by prior literature (e.g., [1-3], and many more). Based on the statistics of CRED, a notable increase is witnessed in the number of flood events from 1,389 in 1980-1999 to 3,254 events in 2000-2019 (increased by roughly 43%). Likewise, the Northeast of Thailand is also experiencing massive and worst floods frequently as noted by [4-7]. Similarly, as claimed by [8, 9], there are also growing flood risks in Loei Province, which is the fifth-largest province in Northeast Thailand, especially the economically and socially most important river basin in Loei Province like the Loei River Basin. This is partly due to the natural factor such as heavy rainfall, and partly because of manmade factors including deforestation, changes of land use, blockage of drainage by debris and vegetation, which were identified as contributors to flash floods and overflow from the Loei River. There is also the fact revealed by [9] that flood early warning system, emergency evacuation plan, and flood relief program are still inadequate in Loei Province, which can cause significant harm to people and assets, and these could also pose a threat to the resilience of affected populations. In fact, even different flood mitigation measures are in place in Loei Province, such as removing trash, sludge, vegetation, and other debris from watercourses and drainage channels, raising awareness about the consequences of deforestation and uncontrolled land use on flood risk, flood monitoring through sensor coverage in flood prone areas, flood and landslide risk

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assessment and mapping, etc., the vulnerability to flooding in Loei Province exacerbated by climate change will still be disruptive [10]. Nonetheless, there is evidence that continuing attempts are on their way to bridge the gap between climate-related matter and detailed urban flood modelling, as clearly seen from previous modelling efforts in Loei Province (i.e., [11, 12]). Yet, despite active researches seem to be in line with what local responsible agencies and concerned citizens/communities are increasingly expecting for, accurate flood modelling at high spatio-temporal resolutions and a better understanding of options for flood vulnerability mitigation remain a significant challenge for flood susceptible areas. Indeed, it appears that based on the current condition, little to no flood damage data is available, the determination of potential direct flood damage is therefore essential to strengthen flood management in current and future at-risk areas. Therefore, this work was set to tackle the aforementioned challenges by proposing the functions and curves that represent the direct flood damage in monetary terms corresponding to a given inundation depth for each building (structure), and compare the results with the estimated damage cost (economic loss) (where available). Eventually, the potential physical damage to exposed buildings in flood prone areas of Loei Town Municipality can be quantified, which is an important step toward a better understanding of possible flood risk exposure and the increasing threat from climate change and anthropogenic activities.

2. Data and methodology

2.1 Overview of the proposed methodology

To achieve the main objective as mentioned earlier, Figure 1 illustrates the overview of the research process with the key steps in the development of flood damage curves for Loei Town Municipality, as can be briefly described as follows.

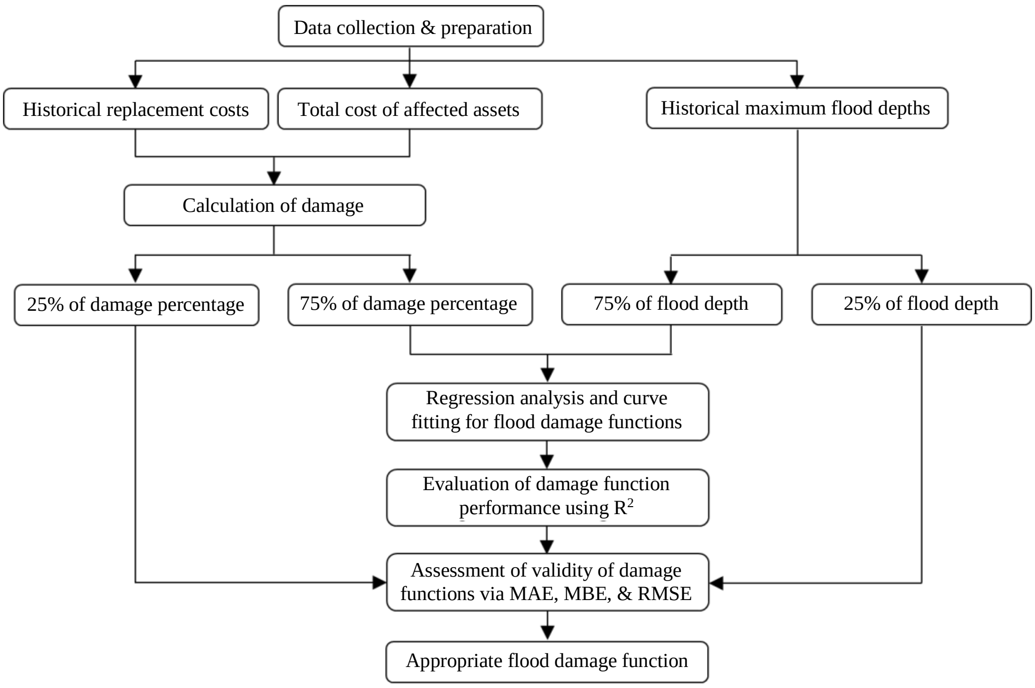

Figure 1 Flowchart illustrating a detailed framework for the development of depth-damage function for Loei Town Municipality.

As the starting point, to represent the relationship between hydraulic parameter (i.e., flood depth) and potential economic damage of exposed assets, the following information related to 1) a list of affected assets and its replacement cost subject to flood damage, 2) the estimated total value of affected assets, and 3) reported maximum flood depths for each flood event, are required. Then, the estimated damage percentage of each physical property, which represents the degree of damage indicated by the proportion of exposed assets expected to be damaged, was calculated as the ratio between the replacement cost and the estimated total value of affected assets. The aforementioned flood-related damage data used in this study were randomly separated into two datasets. The first dataset (hereafter referred to as the "full dataset" containing 75% of the full dataset) was used for regression analysis to derive flood damage function curves. The second dataset, termed the "validation dataset" containing the remaining 25%, was employed to evaluate predictive performance of developed flood damage function curves on independent data. Through the Curve Fitting Toolbox software operated in the MATLAB technical computing environment, regression analysis, and curve fitting were carried out to derive flood damage functions or curves, which represents the flood damage to the affected elements at risk as a function of flood depth. The regression damage function with a high correlation coefficient (R^2) value, which indicates a good correlation with damage functions developed on the basis of actual damage databases, was selected for reliable estimation of relative damages from different flood depths for Loei Town Municipality. The validity of the estimated flood damage costs was validated based on a one-to-one relationship between another 25% of the historical flood damage cost data and the flood damage costs derived from the newly developed flood damage function. The statistical error performance indicators, such as Mean Absolute Error (MAE), Mean Bias Error (MBE), and Root Mean Square Error (RMSE), were employed to evaluate this validation stage.

2.2 The study area

The study area, i.e., Loei Town Municipality, which is entirely located in Kut Pong Subdistrict, Mueang District, Loei Province, northeastern Thailand, covering the total area of 12.41 km^2 (see Figure 2 for details). According to the demographic information from

Loei Town Municipality [13], as of August 31, 2021, the Loei Town Municipality has the total population of 20,793 of which 10,390 are males and 10,403 are females, with a population density of 1,912 persons per square kilometer. The municipality itself is located in the central part of the province within the Loei River Basin, which is densely populated and is predominantly characterized by flat terrain surrounded by the mountain ranges, with an average elevation of about 270 m above mean sea level. The Loei and Man Rivers are its major rivers that flow through the municipality from south to north and west to north, respectively. Under a tropical savanna climate over Loei Province in 2022, as revealed by [14], the mean annual rainfall was recorded as 1,630.6 mm/year and spread over 132 rainy days, which was much higher than the year 2021 by approximately 113.8 mm. The highest daily rainfall event was 72.8 mm, which was experienced on 13 July 2022. The mean monthly temperatures range between 38.6 °C and 9.2 °C in April and January, respectively. Based on the Local Development Plan released in 2023 by Loei Town Municipality, the vast majority of the land within the municipality is categorized as agriculture (53.2% of the total municipality area), urban and built-up area (25.5% of the total municipality area), forest (19.3% of the total municipality area), and the water body is confined to a few small and scattered localities (2.0% of the total municipality area) (see Figure 2 for details).

In view of flood threat in the Loei River Basin where Loei Town Municipality is situated, during the past three decades, three severe flash flood events occurred in 2002, 2011, and 2017, which caused substantial economic damages, destruction and life losses [15]. As addressed by [12, 15], the Loei River Basin frequently and repeatedly experiences urban flash floods every year. This is due to the steep slope mountainous and forested terrain of the upstream area in combination with continuous heavy rain events, while the Loei River routes floods downstream more quickly through the downstream lowland urban and residential areas. Meanwhile, the inadequate capacity of drainage watercourses and canal blockages due to vegetation, trash, siltation, and debris, would also exacerbate the flood problems [10]. According to the statistics, the flood situations in Loei Province remain critical until now. Obviously, as revealed by [11], the 2002 tropical storm damaged a 101 km^2 wide area, exposed over 166,517 people, and caused 313 million Baht of damages, while 6,417 residents (2,289 households) in 44 subdistricts of 11 districts affected by the 2017 catastrophic flood as reported by [16]. This is in consistent with the information on one of the most destructive flood events occurred in 2022 disclosed by [17], and it resulted in substantial flood damage to 35,769 residents (13,284 households) in 70 subdistricts of 11 districts.

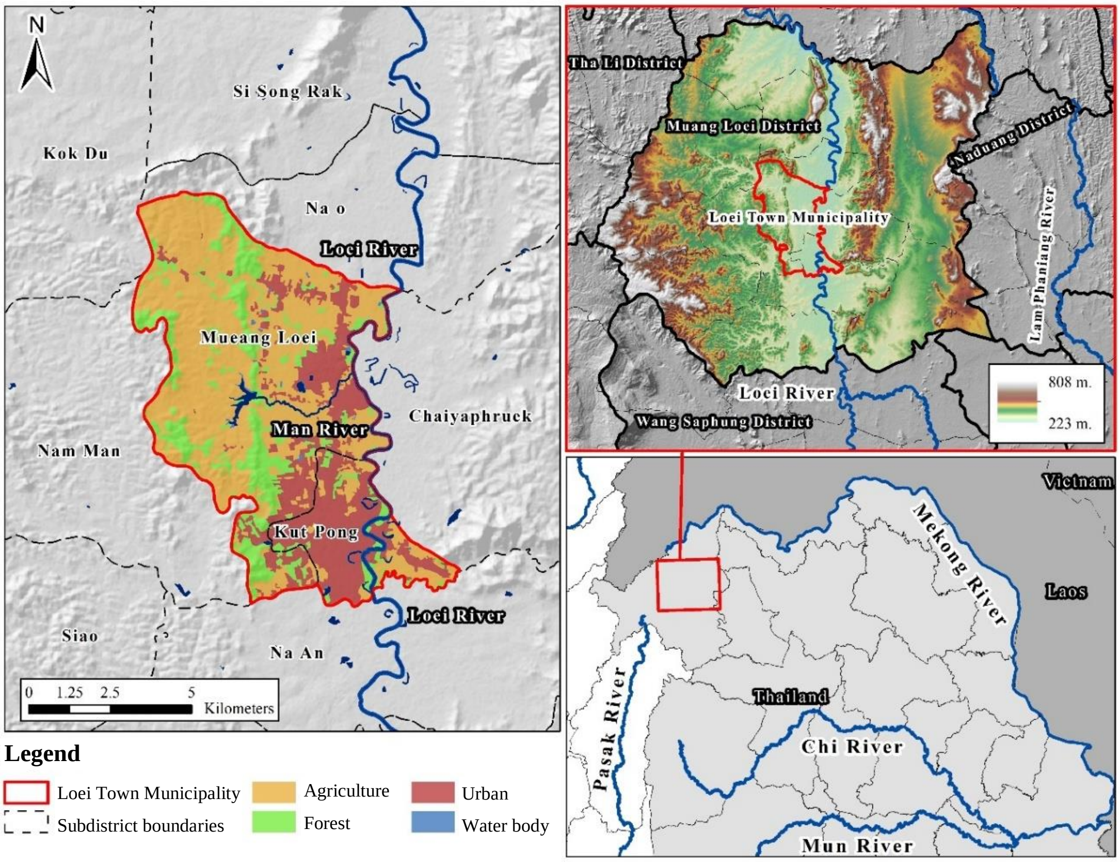

Figure 2 Geographical location, topography, and land use in the study area.

2.3 Data collection

In this study, the potential direct flood damage to exposed assets in Loei Town Municipality, which are in physical contact with floodwater, was concentrated in monetary terms. To compile the adequate flood damage assessment, the detailed and accurate information concerning flood characteristics such as inundation depth and damage costs would need to be gathered. However, due to the fact that reliable and detailed flood damage data surveyed by responsible government agencies in the framework of loss compensation usually cover only limited information, and are scarcely available. It was found that, as recorded in a per-household basis and face-to-face interviews by Subdivision of Disaster Prevention and Mitigation of Loei Town Municipality, only a one-off payment for repairing and replacing essential household items was available for the years 2021-2023. Therefore, this study relied on a comprehensive list of all available cost of repair and replacement for flood-damaged buildings with the same type of material and construction without deducting depreciation-related costs, consisting of 637 records extracted from three severe flood events for the time periods of 27 September 2021, 1-6 October 2022, and 9-11 October 2023. Each record represented some specific aid payments provided by the Loei Town Municipality to assist paying for flood damage (See Table 1 below for a detailed breakdown of flood-induced damage to residential buildings).

Table 1 Summary of flood damage to buildings from three major flood events occurred during 2021-2023

Event	Cost of repair/ replacement (USD)[1]	Flood depth (m)	Details of damage
Tropical storm Dianmu, 27 September 2021	1,050	0.5-1.0	12 households from 3 communities
Tropical storm Noru, 1-6 October 2022	39,814	0.3-2.0	569 households from 7 communities
Monsoon trough, 9-11 October 2023	3,659	1.0-2.0	56 households from 2 communities

Note: [1] Based on the exchange rate of 36.9506 Thai Baht = 1 USD set by the Bank of Thailand at the time of manuscript preparation in April 2024

2.4 Approaches for construction of flood damage functions

In the absence of comprehensive flood loss data, it is understandable that it would result in a lack of reference guidelines for compiling loss datasets after catastrophic flood events. Especially, when the continuous increase in flood damages is to be expected, there is really a growing need to assess vulnerability of exposed assets for future flood risk mitigation. To translate the intensity of flood hazard affecting assets into monetary losses, a site-specific flood damage function, which contains a set of damage curves describing how vulnerable the elements at risk/exposure are to the flood hazards, was often used.

Based on the literatures, there are two different approaches of data selection such as empirical (real) data and synthetic (hypothetical) data, which can be used for the derivation of detailed flood damage functions for different assets [18]. Firstly, the empirical approach is based on actual ex-post flood damage data or post-flood survey data on affected assets, type of each asset, flood characteristics, and degree of damage, collected from on-site inspections after flood events. Besides that, in case there is a lack of sufficient empirical data, the synthetic approach is considered viable for the synthesis of all data, including historical data. The relationship between the magnitude of a flood event and the resulting damage estimates can then be derived. The expected level of damage for certain flood situations can also be estimated by what-if hypothetical analysis and expert-based knowledge. However, it is important to consider the drawbacks of the latter approach that could result in bias in data interpretation or subjective results, and lead to a higher chance in producing uncertainty in damage quantification. Furthermore, the data are also hypothetically created and not all of them can depict real circumstances of flood events [18, 19].

Therefore, based on the abovementioned facts and documented evidence, the empirical approach was in favor as strongly supported by [20] who emphasized that the empirical method is the most common method, while the accuracy rate of implementing the real data is higher than the synthetic one as highlighted by [21]. This statement also agreed well with [22] who emphasized that the empirical flood damage functions derived from actual damage information, is better able to reflect variability within one category of asset and flood depth.

2.5 Damage percentage calculation

As emphasized by [18], much more attention is now devoted to flood hazard assessment process and outcomes, which is well recognized as a function of flood depth (the main determinant of direct damage), and is one of the main components of flood risk, for providing guidance on best practice in flood risk management. For Loei Town Municipality, the flood depth is then transformed to damage percentage for each object in order to estimate physical flood damage. In principle, the damage percentage is defined by dividing the replacement cost of flood damaged properties to the estimated total value of the building (see Equation 1) [23-26], and is plotted against the observed flood depth. In this respect, it is important to note that the actual flood damage data to properties collected after flood events are not available and it is hard to get such data through conventional sources. Therefore, the physical flood damage data were based on necessary expenses for the repair or replacement of damaged structural elements at the municipality level released by Subdivision of Disaster Prevention and Mitigation of Loei Town Municipality.

Regarding the estimated total value of the affected buildings, it was based on the estimation of the present marketable cost of dwellings designated by the Loei Provincial Capital Assessment Subcommittee in 2017, in the unit of value of the capital in Thai Baht per square meter. To identify the spatial distribution of buildings and structures on the ground, the outlines (polygon feature layer) with no information about the building and occupancy type, and basement floors and elevations, which was derived from high-resolution satellite imagery, was downloaded from Google Open Buildings website. Thereafter, the area of each building was then calculated to allow the total value estimation of the affected buildings to be appropriately carried out and stored at each individual structure.

$$\text{Damage percentage} = \frac{\text{Replacement cost of flood damaged buildings}}{\text{Estimated total value of the buildings}} \times 100\% \tag{1}$$

In detail, the values of damage percentage are allowed to vary between 0 and 1 (i.e., between 0 and 100%), while both costs of replacement of damaged household contents and the estimated total value of affected items should be considered within more or less the same time interval.

2.6 Establishment of flood damage function curves

To quantify the susceptibility of exposed assets in contact with floodwater, the fundamental element called “Flood damage function” or “Detailed synthetic depth-damage function, which is the relationship between hydrological impacts parameters (depth, velocity, duration, etc.), and the damage percentage for any object for a given flood condition, was used [27]. However, as stated by

[28-32], flood depth can solely be considered as a potential influencing parameter for describing the relationship between the magnitude of a flood event and the resulting damages.

In this study, the synthetic flood damage function was then derived based on detailed inventories of historical (actual) costs of partial structural repair and replacement collected from Subdivision of Disaster Prevention and Mitigation of Loei Town Municipality. To tailor the shape of the flood damage function curves with the insights into relationships between the damage percentage on the inundation depth in Loei Town Municipality, multiple sets of regression models were fit using MATLAB curve fitting toolbox, in which the independent/explanatory variable is flood depth (belongs on the x-axis) and the dependent/response variable is damage percentage (belongs on the y-axis). Thereafter, a curve/mathematical function, which gives the best fit to the series of data points with a continuous "S" shape and positive on the interval between 0 and 100%, was then chosen.

In detail, six types of regression models were tested to model the data, which are polynomial, exponential, Fourier, Gaussian, Rational, and the Sum of Sines functions. The functions can be considered as a significant indicator for flood damage developed for Loei Town Municipality if the regression fit with the correlation coefficient (R^2) is high enough as classified by four degrees of significance shown in Table 2 [33].

Table 2 Range of correlation coefficient values (R^2) and the corresponding levels of correlation

Correlation coefficient	Degree of correlation
0.3 – 0.5	Moderate
0.5 – 0.7	Significant
0.7 – 0.9	High
>0.9	Very high

2.7 Validation of flood damage function curves via benchmarking

It is worth mentioning that the validation process using site-specific data is highly recommended to ensure whether the developed flood damage function curves is reliable and is accurately able to reflect the fragility of properties to flood exposure. In this study, due to a lack of historical flood damage data, a total of 637 historical datasets were split into a 75% for building flood damage function curves (478 records) and a 25% for validating the developed curves (159 records). In detail, the developed flood damage function curves were verified based on the 25% of remaining datasets, in which the Mean Absolute Error (MAE), Mean Bias Error (MBE) and Root Mean Square Error (RMSE) were applied as the evaluation indices. The MAE was used to measure how close the estimated flood damage costs are to the validated data, where the value of zero represents perfect fit. In view of MBE statistic, it calculates the mean difference between estimated and actual values, where a positive value representing that the estimated values are larger than the validated values, a negative value indicating the opposite, and the desirable value is zero. The error estimation technique called "RMSE" was also used to measure how far estimated values are from validated values, where a low RMSE value indicates that the developed flood damage function curves make more accurate flood damage estimation and fit the validated data well, and a zero value indicates perfect match.

3. Results and discussion

3.1 Evaluation of synthetic flood damage functions

There seems to be no dispute that there is no such detailed damage information available for representing flood damages in Loei Town Municipality. Therefore, the appropriate flood damage function that details degrees of damage to assets over a range of flood depths, is highly indispensable. In fact, the damage function is used to store a set of damage curves, which are graphical representations that supplies damage estimation in a deterministic and quantitative way. For a better correlation between damage and flood depth, the regression analysis was carried out using the actual flood damage data from the records of Loei Town Municipality. The equations of the six regression curves, i.e., polynomial, exponential, Fourier, Gaussian, Rational, and the Sum of Sines functions, and the R^2 of the curve fitting to the smoothed dataset for all six functions, which was used to assess the performance of each function configuration, can be presented in Table 3. The high correlation coefficients (R^2) between damage level and flood depth (m) revealed that their correlation is strong with a similar trend in all regression functions. When looking at Figure 3, it is notable that the flood damage initiation point in flood damage functions was specified at a fixed flood depth of zero indicating no damage occurrence, while the percentages of damage increase with the flood depths. The maximum damage was approximately 3.8% when the flood depth was 2.0 meters, and the increase in damage was not seen at a constant rate. The damage percentage was observed to be quite low, which is reasonable since the cost of needed repair or replacement of the impacted dwelling structure is very low compared to the estimated total value of affected dwellings. This is due to a limited budget for repair/replacement, while the Loei Provincial Disaster Relief Committee would need to prioritize funding distribution for each destroyed dwelling according to the first level of eligibility screening conducted by Subdivision of Disaster Prevention and Mitigation of Loei Town Municipality. More importantly, all flood depth-damage curves still exhibited a reasonably acceptable correlation with the R^2 values of higher than 0.65 for all regression functions, though not as high as expected. This might be because of the limitation of small portions of replacement cost information that was taken over a short period of time (3 years). In addition, there were also no in situ measurements of flood depths available, whereas the information on variations in flood depths with respect to time and space were then not well described. As a result, the relatively constant depth information for each specific flood events were only collected from news and reports from different sources. Aside from those concerns, it is noticeable that there was a little difference in the highest three R^2 values. The polynomial is the best fitting function for a set of experimental data points, followed by Gaussian, and Rational functions, which were characterized by the statistical R^2 values of about 0.73, 0.72, and 0.72, respectively. In fact, the best three R^2 values were just slightly different from that of [34], which found out that the flood depth-damage curves with the R^2 of more than 0.76 are good enough and comparable with other studies. Hence, it can be said that the synthetic site-specific flood damage functions developed in this study are acceptable for indicating flood severity to buildings situated in Loei Town Municipality, and also for further studies related to flood damage assessment.

Table 3 Summary of flood damage functions and R^2 values of the regression analysis

Function type	Damage equation	R^2
Polynomial	$y = -0.6377x^3 + 1.9211x^2 + 0.6366x$	0.73
Exponential	$y = 1.1503e^{(0.6168x)} - e^{(-1.1361x)}$	0.66
Fourier	$y = 0.9333 - 0.9184\cos(1.2211x) + 2.0884\cos(2.4422x) - 0.7944\sin(2.4422x)$	0.70
Gaussian	$y = 3.8346e^{(-((x-1.9606)/1.1336)^\wedge 2)}$	0.72
Rational	$y = (2.2546x + 0.7954) / (x^2 - 3.263x + 3.9148)$	0.72
Sum of Sines	$y = 2\sin(0.042x + 1.5255) + 1.7727\sin(1.5555x + 4.6763)$	0.69

Note: y indicates the percentage of damage to assets corresponding to flood depth in Loei Town Municipality and x represents the flood depth expressed in meters.

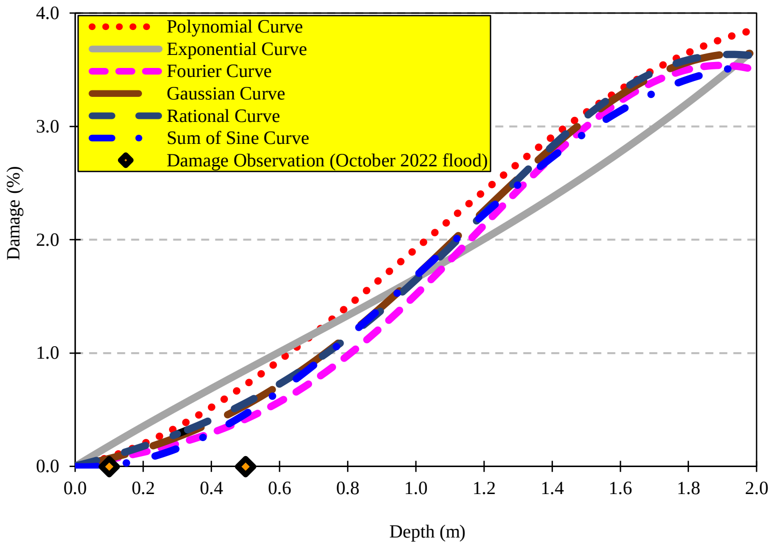

Figure 3 The empirically derived flood damage curves based on three flood events in Loei Town Municipality between the years 2021 and 2023.

3.2 Selection of flood damage function

It is crucial to highlight that the selection of the most realistic and appropriate flood damage function can significantly increase the correctness of flood damage estimation. For selecting the best flood damage function, due to a lack of real damage data, the remaining damage records of 159 samples (25% of historical datasets), which was partitioned from the total replacement cost data of 637 records, were used in which the precision of the derived function was tested by the Mean Absolute Error (MAE), Mean Bias Error (MBE) and Root Mean Square Error (RMSE) were applied as the statistical error performance indicators. Among all six proposed function types, the validity of the polynomial fit function was found to be the most reasonable representation of flood damage behavior in Loei Town Municipality, as seen from relatively low values of MAE (0.17%), MBE (-0.17%), RMSE (0.19%) (see Table 4 for details). This is consistent with the finding from [35] that, for the ex-post assessment of flood-induced damage for the urbanizing city like Bengaluru, India, the polynomial regression with high R^2, and low RMSE and MAE values was the preferred choice for developing flood damage curves for structural and content damages in residential and commercial settings. Based on the fact that the site-specific damage function that links the flood depth to the damage percentage was not existence before this date, the only available reported flood depths caused by the October 2022 rainfall event gathered from [36, 37] were then used to ensure whether the polynomial flood damage function can realistically be used to express the degree of vulnerability of exposures to flood depths. It was stated that the rain filled up rivers and led to flooding between 0.1-0.5 m throughout Charoenrat Road (in front of Loei Town Municipality and Loei Post Office, Loei Governor's Residence, Loei Technical College, Loei Vocational College intersection), Kok Muang Chi Community, and other city streets, while buildings were not affected. According to the above flood situation information, there was no flooding inside buildings along the aforesaid locations, which implied no significant damage with a zero-damage percentage (see the diamond-cut markers in Figure 3 for reference). Therefore, for the case of Loei Town Municipality, it can be strongly claimed that the polynomial damage function fits the data well, and it can capture a greater amount of the variability in flood damage placed upon assets (dependent variable y) in comparison to the other five types of damage functions.

Table 4 Error evaluation for flood-damage function

Function type	MAE	MBE	RMSE
Polynomial Regression	0.17	-0.17	0.19
Exponential Regression	0.25	0.25	0.29
Fourier Series Model	0.35	0.35	0.36
Gaussian Model	0.08	0.02	0.10
Rational Model	0.91	0.60	1.08
Sum of Sines Model	0.48	0.48	0.49

Note: The unit of MAE, MBE, and RMSE is percentage (%)

3.3 HEC-FIA Direct damage calculations

Referring to [38], it is likely that the upward trend in flood damages is expected to continue to rise in frequency and severity in the future, and this seems to be a topic of great interest and concern for the Loei Town Municipality. Therefore, to estimate economic losses to structures and their contents based on a structure-by-structure basis from specific flood events, the HEC-FIA (Flood Impact Analysis) software developed by the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center (CEIWR-HEC), which is a stand-alone, deterministic, event-based, and GIS-enabled software tool, was employed for the following reasons. Firstly, it is a no-cost public domain software available for free download. Secondly, it is suitable for the user's needs with the capability to quantify consequences with uncertainty. Thirdly, the software features the ability to analyze geo-referenced gridded data, displays plots and tabular reports, interfaces with Geographic Information Systems (GIS), and also includes a Graphical User Interface (GUI) that makes it easy to interactively view, enter, and edit data necessary for flood impact analysis. Last but not least, it is widely used with available reference materials (detailed technical report and user's manual) [39-41].

According to HEC-FIA modelling workflow indicated in Figure 4, the relevant data in digital map format, which were clustered into four different map layers such as watershed, geographic data, inundation data, and inventory, were imported in HEC-FIA for viewing and editing them in the map window. More explanations and details can be elaborated as follows. First, the watershed component was imported for describing a modelled physical state and providing a spatially correct representation of the study area, which consists of a terrain grid representing the ground elevation based on a 5-meter Digital Elevation Model (DEM). Second, with the geographic data component, the geographic locations and boundaries of flood impacted areas within the administrative border of Loei Town Municipality, which was used as the boundary data in HEC-FIA, can be identified for aggregation and reporting the entire simulated results. Third, the hydraulic input in the form of maximum inundation flood depth grid file with horizontal resolution of 5 meters obtained from the simulation results of HEC-RAS hydraulic model, was employed to estimate structural damage in HEC-FIA. Last, the inventory component, which includes inventory data representing geospatial points within the maximum inundation area, was taken into consideration for defining targeted damageable elements such as houses, household assets, etc. Regarding the structural damage identification and its severity estimation, the comprehensive estimated damage cost of flood-affected components of every affected element was based on a detailed list of expenses for materials needed for essential structural repair and replacement items without considering any damage to the surrounding areas, evaluated after severe flood events between 2021-2023 by Subdivision of Disaster Prevention and Mitigation of Loei Town Municipality.

Once all of the aforementioned data input components were defined, the last steps for the setup of HEC-FIA model were to create a new HEC-FIA alternative, time window, and simulations, by using the new model elements that have been created. In detail, the Alternative input includes different relevant data used for the computations that the HEC-FIA performs, e.g., target inundation configuration, impacted areas, structure inventory, a list of associated hydraulic events, consequences from a given flood hazard, computation settings, etc. After defining the specified alternative, the time window would then need to be created for setting the beginning and the end of the computation, time step, and warning issuance for each HEC-FIA simulation. Based on the combination of the detailed alternative, hydraulic event, and time window, each HEC-FIA simulation can then be defined. The simulation manager module in HEC-FIA is a combination of individual simulations, which links an alternative with an event and a time window. The same alternative can be added for multiple events, in which the events can be run in the same simulation group. Meanwhile, multiple alternatives can also be combined into the same event, the evaluation of damages can then be based on the changes in the study area identified in the alternative via either the watershed configuration or other changes in the alternative. Once a simulation is run in HEC-FIA by multiplying the flood depth in every grid cell with a weighted average of relative depth-damage functions and maximum damage values (see Equation 2), a file structure will be built to store the results from the system (note: the selected polynomial flood damage function describing the severity of damage in percentage at a given flood depth, which was developed based on 75% or 478 records of historical costs of repair and replacement, was imported into HEC-FIA for the estimation of direct losses for structures). The simulation damage results can then be viewed as a report, which will be generated and added to the list of reports.

$$D_i\ (\$) = d_i\ (\%) * v_i\ (\$) \tag{2}$$

where D_i is the direct damage, i is used to represent buildings or contents, d_i is damage percentage at a given flood depth, and v_i is the inventory value.

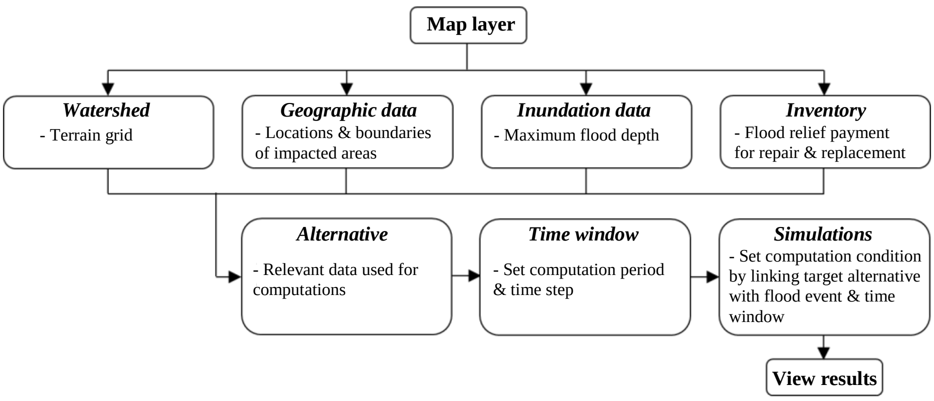

Figure 4 HEC-FIA modelling workflow for comprehensive flood impact assessment.

3.4 Comparison between estimated flood damage computed by synthetic function and recorded damage

For future flood damage assessment in Loei Town Municipality, it is apparent that the comparison between estimated and actual damage values in monetary terms deserves prioritization for consideration of whether the synthetic flood damage function is particularly suitable as the right evaluation tool for quantitatively calculating the potential flood damage cost to structure corresponding to different flood depths. However, this needs to be admitted by the fact that the growing damage cannot be quantified as accurately as expected, but rather with a reasonable and satisfactory rate of flood damage estimation.

To verify the reasonableness, reliability, and accuracy of the established damage function, the statistical flood damage data, which is specific to the locality reported by the Loei Town Municipality and reliable news media websites after the historical flood in 2002, was compared with the anticipated flood damage calculated from the polynomial damage function (note: only partial replacement/repair cost for affected dwellings situated at flood prone areas within Loei Town Municipality was available, the information-based minimal replacement/repair was then considered in this study for representing failure information of buildings).

It is remarkable to see a reasonable degree of agreement between the total cost of necessary replacement/repair for restoring dwellings in Loei Town Municipality to pre-flood condition of 199,330 USD (the exchange rate of 36.9506 Thai Baht per USD happened in April 2024), and the reported government reserve funds for emergency disaster relief in 2002 for the entire Loei Province of approximately 354,079 USD. This difference can be explained by the fact that the larger the flooded area, the more the quantity of affected dwellings increases. When considering the locations of flood damage, the dwellings within the Loei Town Municipality are subject to the worst effects from urban flood events as accounted for approximately 56% of the 2002 total disaster relief budget. Based on the 2002 flood damage information from online newspaper archives, there is a widespread distribution throughout the municipality, especially in a highly developed economic zone which was the largest spatial affectation, due to the influence of socio-economic and demographic development (see [42, 43]). This means that the derived flood damage function can be utilized for flood damage calculation in the Loei Town Municipality and its surroundings. Besides that, the above comparison is not just highly consistent with local statistical data, but it also confirms the accuracy of the input data sources.

4. Conclusion

It is widely acknowledged that the potential flood damage can be depicted and translated from the physical flood phenomenon into its economic impacts through a site-specific flood damage function. However, a thorough analysis of translation is not deeply examined in practice for future flood damage assessment at the case-study scale. Therefore, the development of depth-damage function for the estimation of direct monetary flood damage to buildings in Loei Town Municipality was the main objective of this study. The depth-damage functions for residential structures, which is the relationship between the flood depth (independent variable x) and damage percentage (dependent variable y), were derived based on empirical flood damage data from the historical flood events during 2021-2023 collected through interviews. The pre-processed data in terms of the cost to repair the flood-related damage to buildings was split into a 75% for deriving flood damage functions (478 records) and a 25% for validating the regression analysis results (159 records). It was found that the polynomial function with good fitting curve and highest R^2 value was the most efficient regression fit in describing variations in damage percentage to dwellings. To avoid concerns related to the reliability of flood damage function, the validity of the polynomial regression model was assessed using the statistical error performance indicators, and it was found to be the best fitted model and outperforms the other five models with a low Mean Absolute Error (MAE), a low Mean Bias Error (MBE), and a low Root Mean Square Error (RMSE). The total direct damage was then computed by multiplying the damage percentage with the replacement cost per building (all types) and summing the results. The HEC-FIA was run to translate the physical flood damage function into a direct monetary damage. The results revealed that the calculated damage was reasonably consistent with government records of loss and compensation from the 2002 flood event. Although the relatively poor availability of ex-post flood damage data may to some extent reflect the imperfection of flood damage assessment, the incorporation of a monetary damage and a specific characteristic of a flood event (i.e., flood depth) is still valuable for a structure-specific flood risk assessment. Certainly, the lack of well-documented actual/historical flood damage data is clearly a gap which needs to be closed in future research. To enhance a better performance of the developed flood damage function with some further refinement, the use of long-term flood damage data is highly recommended for considerable further study to reduce the uncertainty and improve accuracy of expected flood damage estimates. If the aforesaid recommendation is additionally implemented, the combination of robust research methodology together with the most comprehensive flood damage datasets will be very helpful for raising awareness about the potential flood damage that the communities living in the territory of Loei Town Municipality are currently facing and would expect to face in the future. Finally, a broader analysis of vulnerability and coping capacities of possible affected dwellings can be pinpointed for future research directions, while the synthetic approach used herein for creating flood damage functions and estimation for building damage can also be applied in other areas with scarce flood damage data.

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