Jurnal Kejuruteraan 37(5) 2025: 2159-2172
https://doi.org/10.17576/jkukm-2025-37(5)-11

Evaluating the Performance of Depth-Damage Curves in Flood Damage and Risk Analysis: A Case Study from Malaysia

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Received 18 June 2024, Received in revised form 13 February 2025
Accepted 13 March 2025, Available online 30 August 2025

ABSTRACT

Depth–damage curves (DDC) are widely used in flood risk analysis to represent the range of losses when exposed to a range of flood depth. However, variations in DDCs, whether from international, national, or combined sources, pose challenges for selecting the most accurate curve for local applications, particularly in developing regions. The availability of these varied functions enables scientists and practitioners to perform monetary flood risk evaluations, aiding better investment decisions. However, ensuring that these models are locally validated is crucial, as unverified models can lead to significant inaccuracies. This study aims to compare the performance of international damage curve (IDC), national dam age curve (NDC), and unified damage curve (UDC) in local flood-prone areas of Malaysia where the monetary damages for each models were analysed. Comparisons were made at a community scale, with verification against site-specific damage curves (SDC), which include uncertainty bounds that established using boxplot based on empirical data. Results show that the internationally derived DDC overestimates community-scale aggregated building-level damage by 30 times compared to the SDC, revealing a significant overestimation. Conversely, the aggregated damages using NDC and UDC fall within the SDC's uncertainty bounds. This demonstrates that integrating national data with international models significantly improves accuracy and reduces overestimation. Ignoring pre-treatment of IDC in flood risk studies could result in an alarming overestimation of damages. This study highlights the indispensable role of local data in ensuring accurate DDC representation and emphasizes the need for coordinated efforts in flood damage data collection and inventory management.

Keywords: Building-level damage; flood depth–damage function; flood risk; stage–damage

INTRODUCTION

Flood risk is generally understood as the combination of hazard, exposure, and vulnerability (Samuels & Gouldby 2005). Vulnerability refers to the susceptibility of people and assets to potential flood impacts (Kron 2009). In flood risk analysis, a deterministic damage curves or functions have been used to represent the potential susceptibility of elements at risk (Jongman et al. 2012; Pita 2021; Wing 2020). A depth-damage curve (DDC) links flood damage to flood depth, whilst developed either from empirical surveys, synthetic analysis, or combinations of them. Empirical surveys capture losses directly from individuals who have experienced flooding, making these curves potentially more accurate as they reflect real-world events (Gissing & Blong 2004).

However, collecting damage survey data is resource-intensive and often requires careful evaluation before finalizing a DDC. On the other hand, the synthetic method relies on expert judgment and often uses coarser inventory data, which may reduce its precision (Pistrika et al. 2014). Over the years, sophisticated and much computer extensive approach has been adopted to represent the damage curves, for example, using black forest method and multiple linear regression. Though the method reduces bias, the variance is much greater with multiple exogenous variables being included.

The concept of flood risk management has gained prominence over the past decade, becoming increasingly important in shaping climate change-related policies (European Commission 2007; Teng et al. 2015). Though risk-based analysis is well-adopted in flood management in many countries in the global north, not many countries in the global south fully adopted the method in flood management. Furthermore, sophisticated flood damage functions used to assess present and future flood risks could potentially undermine risk-based flood management due to a lack of sufficient data and resources needed to establish such functions. To account for data scarcity, hybrid approaches that utilize empirical and synthetic data are increasingly employed. This method has been applied in countries like the United States, Germany, and Japan, providing a more comprehensive understanding of flood impacts in areas with varying levels of development and data availability (Merz et al. 2009).

Empirically derived DDCs are especially important for flood mitigation projects, ensuring that investment decisions are grounded in actual flood losses faced by a country (Kabirzad et al. 2024). The impacts of climate change on flood damage have also prompted international efforts to focus on developing regional or national DDCs to better understand flood risk at local levels. However, due to limited access to national damage survey data, international DDCs are often based on synthetic information. For example, in Malaysia, flood damage assessments based on surveys and local interviews have been conducted by the government (BNM 2021; DID 2017; DID 2012b), and their application has been demonstrated in studies related to flood risk management for the country (Fatdillah et al. 2022; Rehan 2020; Rehan & Zakaria 2021).

Since empirically derived DDC is not fully accessible to the international research community, large-scale studies for climate change impact and adaptation have used global data to represent DDCs of a country or region (Huizinga 2017). DDCs formed by the international research community have paved the way for global-scale analysis of flood risk, but its validity is somewhat questionable due to the use of coarser information as compared to the national DDCs.

Few studies have examined the implications of global flood damage models on flood risk estimates but little is known about their effects in risk estimates in Malaysia. This study aims to evaluate the performance of global DDCs model against empirically derived DDC. It takes forward a national standard flood DDC (henceforth, refer as NDC) and internationally derived DDC (henceforth, refer as IDC) for Malaysia to explore their discrepancies. Furthermore, a unified DDCs (henceforth, refer as UDC) that combines information from the two sources was also evaluated to test the usefulness of flood damage curves integration in flood risk analysis. Comparisons were made alongside a site-specific derived function established from the present study that serves as validation to the tested DDC.

By investigating the effects of different forms of DDCs and how applications of it could be useful, this study suggests improvements on how international derived DDC should be cautiously used in large-scale studies involving countries with limited access to national data, which certainly have significant implications in international narrative and policies, as well as for local urban planning, insurance sectors, and disaster risk reduction strategies.

RESEARCH SIGNIFICANCE

The study investigates the DDCs that integrates information from global DDC and national DDC (henceforth, the integrated DDC is referred to as UDC). Validations were made against a site-specific derived function established from the present study. Evaluation was made qualitatively and quantitatively.

STUDY SITES

Malaysia is a tropical country in Southeast Asia that experiences heavy rainfall especially during monsoon seasons. Flooding has displaced thousands of people and caused significant damage to properties and infrastructure (Bell et al. 2020; Chen et al. 2022). The country's rapid urbanization, deforestation, and inadequate drainage systems have further exacerbated flood risks, particularly in densely populated, low-lying areas (Chan 1999; Foo & Tan 1986). Two study areas were selected for the implementation; The first study area is a residential area located in Kuala Lumpur and adjacent to the Toba River (referred to henceforth as Site 1). The second study area is in proximity to the Kelantan River (henceforth referred to as Site 2) and within several administrative boundaries of residential areas (i.e., Pak Nik Ya Village, Atas Paloh Village and Kubang Pasu Village in Kota Bharu District). Site 1 endured localized flood events (Fatdillah et al 2022), while Site 2 had a devastating flood event in December 2014 that affected several properties worth millions of dollars and thousands of homes (Usman Kaoje et al. 2021). Figure 1 shows the locations of the sites, and Figure 2(a) and 2(b) display examples of past flood events that impacted the area. Similarly, Sahdar et al. (2024) selected the Akelaka Watershed in North Maluku as a study area due to its vulnerability to significant flooding hazards.

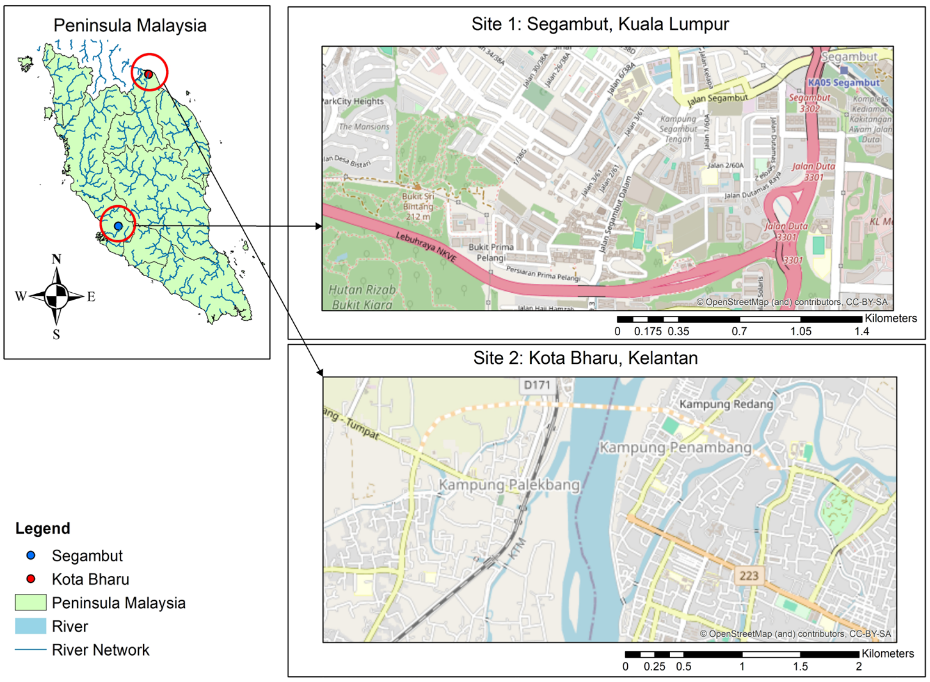


FIGURE 1. Street views of the study areas (retrieved from http://www.OpenStreetMap.org).

(a) (b)

FIGURE 2. (a) Flood event at Kelantan (DID 2017); (b) flood event at Segambut, Kuala Lumpur (DID 2020).

METHODOLOGY

STUDY APPROACH

The present study introduces four generic terms to represent the different sources of DDCs: IDC, NDC, UDC and site-specific damage curve (SDC). The focus is on impacts to residential buildings since this sector has been identified to be the highest in the rank to cause economic losses during floods (DID 2021). This is due to the higher concentration of population and assets in residential areas.

The IDC and NDC were prepared using off-the-shelf information, whereas the UDC was developed using information from the IDC and NDC. Meanwhile, the SDC was developed using surveyed empirical direct damage data that were duly processed to include uncertainty bounds apart from the best estimates. Figure 3 shows the components of and flows towards flood risk analysis.

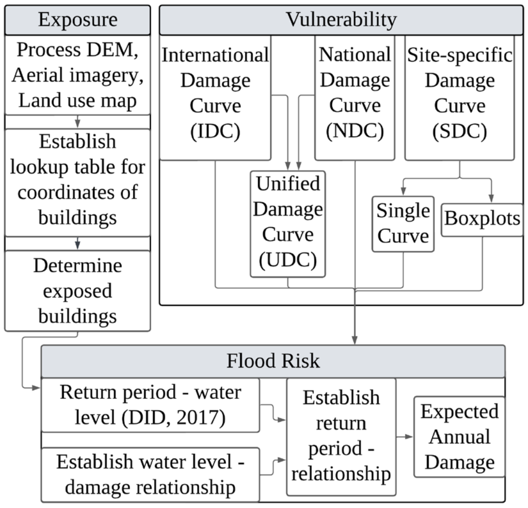


FIGURE 3. Flood risk analysis framework using DDCs of different representation.

FLOOD DAMAGE MODELS

Flood damage assessment is complex and influenced by regional rainfall, geography, flood control, and socio-economic conditions (Jin et al. 2022; Wang et al. 2020). The present study focuses on flood damage curves of economic losses governed by flood depths. Table 1 summarizes the damage curves used in this study and their differences in terms of cost base and model structure. For the analysis, the original data points from the respective curve were transformed into functions via regression. Excellent fits were found for the IDC considering the log function and the NDC considering a linear function. Meanwhile, the SDC was found to have a good fit with the power function and boxplots were used to establish the uncertainty range.

The functions can be discerned as either relative or absolute damage values. Relative functions are based on the ratio of the total replacement value to the total value of the flood affected property; however, the ratio of the repair cost to the market value of the affected building is also used (Pistrika et al. 2014). By contrast, absolute damage functions employ the absolute monetary amounts of the damage given flood characteristics (e.g., depth or duration). The NDC and SDC functions provide absolute values, but the IDC employs relative values that requires user to use a maximum damage value to convert relativity to absolute values.

INTERNATIONALLY DERIVED, NATIONAL STANDARD AND UNIFIED DEPTH–DAMAGE CURVES

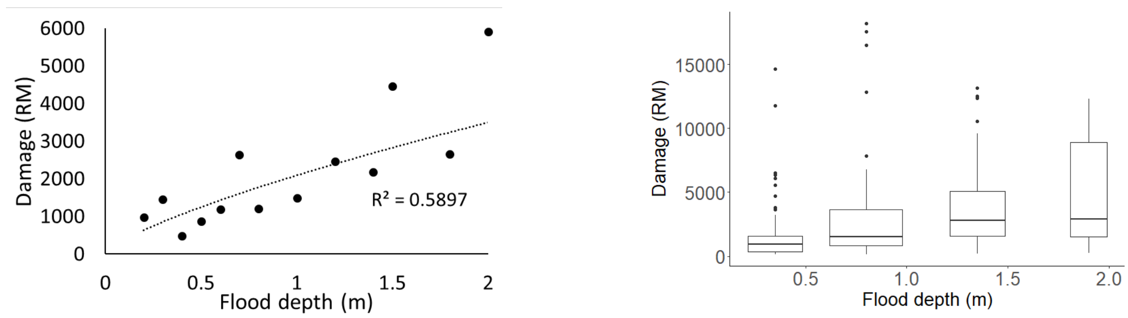
The Joint Research Centre (JRC) of the European Commission has made available continent-specific depth–damage datasets to support risk-based flood assessment in regions and countries with scarce damage information (Huizinga et al. 2017). JRC functions are available for Africa, Asia, Oceania, North America, South America and Central America continents among all. It has been widely used in flood risk-related studies, especially when local damage curve is not available (Albano et al. 2017; Jongman et al. 2012).

The JRC function applies a zero to one scale of flood damage corresponds to flood depths of up to 6 meters. The JRC proposed a maximum damage value at 6m flood depth as the multiplier of the fractions over the increment flood depth. The maximum damage value is unique for each country and is said to be determined from tests made on 'Maximum damages derived from the different national damage models identified in the literature review' and 'construction cost values from international surveys' (Huizinga et al. 2017). The loss values for residential buildings provided in the JRC report are given in three different alternatives, namely, building-based, land-use-based and object-based values. The maximum damage value for a residential building in Malaysia in the JRC report is given as €429/m^2 at the 2010 price. An assumption of 156 m^2 for the footprint size of an average residential building was made in this study considering that a grid cell of 625 m^2 consists of an average of four average-sized residential buildings (Fatdilah et al. 2022).

Efforts to establish damage functions for risk analysis in Malaysia over the past decade were evident from reports (DID 2003; DID 2012a). These studies attempted to collect as much evidence at their disposal at the time. The damage function published by DID (2012a) incorporates a nation-wide survey and more than 20 components of damage categories per building (e.g. internal, external, etc.). More than a thousand samples were collected from nationwide surveys that led to the establishment of a multiple regression function for residential building flood damage (DID 2012b).

TABLE 1. Depth–damage models used in the present study

Depth–damage model	Reference	Depth–damage function	
		Value/cost base	Model structure
IDC	Huizinga et al. (2017)	Maximum damage of construction cost from international survey versus global/national parameters, such as GDP, for Malaysia	The log curve shows a perfect fit on the datasets
NDC	DID (2012b)	Mean damage from absolute losses of historical floods (empirical data)	Linear regression
UDC	Not applicable	Harmonised information between NDC's damage value and IDC's damage factor	A log curve
SDC	Not applicable	Best fit value from absolute losses of historical floods (empirical data)	Two types: boxplot and best-fitted power function



(a) (b)

FIGURE 4. Depth–damage function derived from surveyed empirical data: (a) a best-fitted power function curve against the mean damage at each flood monetary direct damage (b) In the form of boxplots over across flood depth range

The present study adopts the function from DID (2012b) representing the NDC, where eq. (1) and (2) were made available from the source. The damage factor, F, used to calculate the monetary damage for a residential building, d_z. The explanatory variables are flood depth (z) in meters, flood duration (t) in days and residential-area strata state (s). Strata state, s, uses a binary classification, where 1 refers to an urban area and 0 refers to a rural area. The constant values (i.e., 0.93, 2.83 and 0.25) are mean values associated with the variables. The damage factor is multiplied by the average building damage (MYR 3,273.58) to calculate the monetary direct damage.

$$F = (z - 0.93) \times 0.32 + (t - 2.83) \times 0.08 + (s - 0.25) \times 0.33 + 1 \quad (1)$$

$$d_z = F \times 3273.58 \quad (2)$$

The UDC was derived using information from the NDC and IDC. The damage value of the NDC at flood depth 6 m was used alongside zero to one fraction provided by IDC over the range of flood depths. The new damage values from zero to 6m flood depths were then used to construct the UDC. This means the UDC's damage value at 6 m flood depth was discarded and substituted with that of NDC.

SITE-SPECIFIC EMPIRICAL DATA

The SDC was obtained from surveys of flood damage to residential buildings conducted in early 2020 at various locations in the west coast and east coast of Peninsular Malaysia that have experienced floods. These areas are constrained within Kota Bharu in the state of Kelantan, Segambut in the federal territory of Kuala Lumpur and Dengkil in the state of Selangor.

The way in which uncertainty range was established from the site-specific damage model is by using boxplots, which is a non-parametric method to establish uncertainty (Potter et al. 2010). The SDC provides a reference range for validation with other damage models by capturing the upper and lower limits of flood damages using boxplot analysis, allowing for a clear representation of variability within each depth category. The validation process evaluates how well the modeled damage estimates from the IDC, NDC, and UDC correspond to the observed damage patterns captured in the SDC. Because the SDC is derived directly from real-world flood damage survey data, it can be used to assess whether other models overestimate or underestimate flood damages.

Flood damages from the surveys were first arranged according to flood depths with 0.5 intervals between 0 to 2-meter depth. The number of samples are: 55 at 0–0.5 m flood depth, 76 at 0.5–1 m, 30 at 1–1.5 m and nine at 1.5–2 m. The boxplot for each division was formed with its lower and upper quartiles and median as given in Eq. 3 to 6, where n is the number of terms and th is the n(th) number.

$$\text{If } n \text{ is odd, } median = \left(\frac{n+1}{2}\right)^{th} \tag{3}$$

$$\text{If } n \text{ is even, } median = \frac{\left(\frac{n}{2}\right)^{th} + \left(\frac{n+1}{2}\right)^{th}}{2} \tag{4}$$

$$\text{Lower Quartile (Q1)} = \frac{1}{4}(n+1)^{th} \tag{5}$$

$$\text{Upper Quartile (Q3)} = \frac{3}{4}(n+1)^{th} \tag{6}$$

The resulting boxplots are shown in Figure 4(b). The outliers are scattered only at the upper range of the boxplot indicating the tendency of responses towards higher damage values from surveys. Nevertheless, the median of each boxplot shows inclination towards the lower quartile, indicating that the concentration of damage values from responses is dominated at the lower segment of the range and fewer people experiencing significant loss of assets from the population. The lack of samples at higher flood depths are apparent from the larger interquartile range of flood damage.

A power function was then fitted onto the (averaged) datapoints through a log domain function using the linear least square method for model fit. The power function provides a good fit to the data with R^2 value greater than 0.5 (Figure 4a). It is found that the best-fitted curve coincides with the median values of boxplots across the depth range, indicating a good representation of the power function to the datapoints. The curve also shows an exponential increase in damage, indicating an acceptable regression with a moderate effect from the size of the samples (Moore et al. 2013).

COMPARISON OF DEPTH–DAMAGE FUNCTIONS

The IDC, NDC, UDC and SDC are compared on the same graphical scale for flood depths up to 2 m from the damage threshold (Figure 5). The SDC used the single deterministic function power function for the comparison. All depth–damage relationships show an upward trend of damage against flood depths with IDC's damage values significantly outcasting the others (Figure 5a). The other types of depth–damage models are comparable, as shown in Figure 5b without IDC.

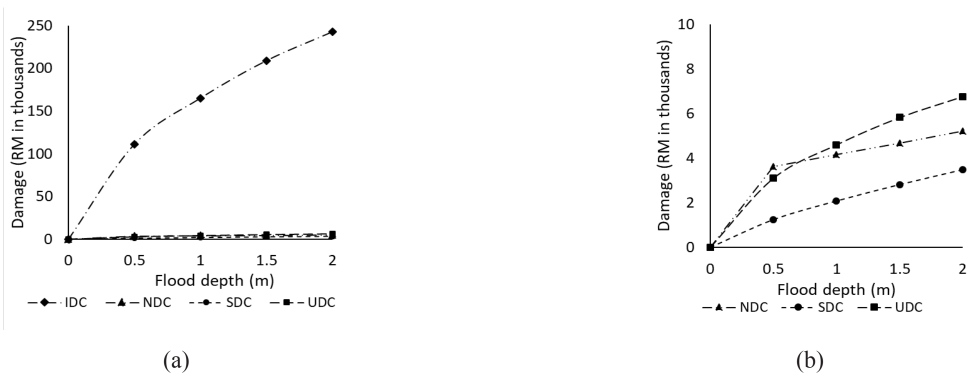


FIGURE 5. Comparison of depth–damage curves for IDC, NDC, UDC, and SDC for flood depths up to 2 m. (a) Includes IDC, demonstrating its significantly higher damage values compared to other models, while (b) excludes IDC to better highlight the relationships between NDC, UDC, and SDC.

With the new features introduced in UDC, flood damages were established and transformed from the overestimation of IDC and the linear depth-damage relationship of NDC. Leveraging information of IDC and NDC formed a curved shape depth–damage relationship UDC as compared to the original linear relationship of NDC. The NDC increases from zero to 0.5 m depth and coincides with UDC at approximately 0.7 m flood depth before their positions are swapped over the higher flood depths. It is also apparent that flood damage of NDC is higher than UDC across the higher flood depths, indicating that the fraction of IDC exerts a decreased transition of flood damage values across higher flood depths. Meanwhile, the SDC yields lower flood damage than the IDC, NDC, and UDC at all depths suggesting overestimations of the candidate curves.

The differences between the IDC, NDC, UDC, and SDC models, as summarized in Table 1, are primarily in their data sources, damage functions, and model structures: IDC relies on international construction cost and GDP-based data with a log curve fitting the dataset perfectly, potentially leading to overgeneralizations; while SDC, based on site-specific empirical surveys with a boxplot and power function model, provides the most localized and precise estimates, though it may overestimate or underestimate flood risks due to limited sample sizes and variability in survey data. A limited sample size may introduce bias, particularly at higher flood depths where fewer responses lead to a wider uncertainty range. However, the boxplot method helps address this limitation by capturing the spread of data, identifying outliers, and visually representing the interquartile range of damage values. This approach aids in filling the gaps caused by low sample sizes, ensuring a more reliable representation of flood damage trends; The NDC is derived from historical flood loss data using a linear regression model, which may overestimate flood damage and risk, particularly at lower flood depths**;** UDC harmonizes NDC's damage values with IDC's damage factors to create a hybrid log curve, addressing discrepancies but introducing potential inaccuracies from combining datasets.

FLOOD HAZARD, EXPOSURE AND VULNERABILITY

To simulate flood scenarios, this study adopted a static planar method of flood inundation to form layers of potential maximum flood levels. The dynamics of water flowing from the river to the land is neglected, and flood propagation is assumed to be governed by the terrain elevation. The layers of maximum inundation levels were carefully established using realistic scenarios of floods indicated in flood reports. Each layer was extended from where the river is to the adjacent land of the residential area to quantify the losses and relate it to the flood level (i.e., stage). The method has been applied in flood risk assessment studies because of its rapid analysis of flood inundation (Sulong & Romali 2022) and, thus, suitable for flood risk assessment. The method is applied in (Rehan 2018a; Rehan 2018b) to evaluate the cost-effectiveness of property-level measures. Additionally, the method was applied in Teng et al. (2015) across the Murrumbidgee region to rapidly generate inundation levels for large floodplains.

This study adopts damage calculations for sparsely located residential buildings. Eq. 7 shows how the total damages for a range of inundation levels are computed in this study (Rehan 2018a). Under the assumption that the individual buildings will be damaged once the maximum flood inundation level exceeds their ground floor elevation level, the function aggregates flood damages based on the ground elevations of residential buildings and the applied depth–damage relationship.

$$D_n = \sum_{i=0}^{n}\left(P_{g_{y=n-i}} D_{h_{z=i+1}}\right), i < n \quad (7)$$

The total aggregated damage is driven by the density of residential buildings (P) at each incremental ground elevation level (g) below the maximum inundation level (n) and the food depths (h) associated with the range of ground elevation levels of the residential buildings (y), i is the index of incremental elevation of buildings ground level as well as the incremental depth of damage by roof depth.

Prior to the computation of Eq. 7, a look-up table of the number of residential buildings residing on the adjacent land at different ground elevations was established from GIS analysis of the study area using Shuttle Radar Topography Mission (SRTM) DEM and OpenStreetMap (Esri 2020). This approach aligns with advancements highlighted by (Paulik et al. 2022; Yu & Wang 2022) who emphasize the integration of DDCs with GIS for comprehensive flood impact assessments considering diverse land uses and economic factors. As land use plays a critical role in shaping flooding patterns—urbanization, for instance, increases surface runoff and reduces infiltration (Feng et al. 2021)—understanding the distribution of urban and rural areas becomes essential. Accordingly, land use maps of the study areas were used to identify whether the study area lands are categorized as urban or rural areas (Florczyk et al. 2019). Selected sites of the study fall under the category of urban residential areas.

FLOOD RISK

This study conducted flood risk assessment at the microscale level, which is considered an effective approach for implementing targeted flood mitigation measures (Festa et al. 2022). To understand the implications of the damage curves to flood risk, the study adopted the analytical method for flood risk assessment. The risk is referred as the expected annual damage (EAD), which provides the expected losses over a yearly period given the probability of hazard and the potential economic damage (Rehan 2018a). Whilst there are unlimited debatable aspects of the risk component, the EAD in the present study was driven by the probability of extreme water levels and damages associated with it (Fatdillah et al. 2022) :

$$Risk = \sum_{i=1}^{N}(p_{i+1} - p_i)\frac{(D_{i+1}-D_i)}{2} \quad (8)$$

Where p is the probability of maximum water levels given their return periods, i is the flood event and Di is the flood damage of the i flood event.

RESULTS AND DISCUSSION

FLOOD HAZARD, EXPOSURE AND VULNERABILITY

To establish the layers of static inundation level, previous hydrological study by (DID 2017) on Kota Bharu area (Site 2) was referred. It was decided in this study that the buildings exposure to be included in the stage-damage relationship are limited to buildings that are located at the farthest 2 meters above the lowest ground of exposed buildings in the floodplain. Floods at 2 meters depth above the bank full level at the gauging station have been described as an event with 'high level of hazard' for this catchment (DID 2017) and thus in agreement with the specification.

The computation of stage-damage relationships was then conducted by interjecting the NDC, IDC, UDC and SDC, individually, into Eq. 7 alongside the look-up table of number of buildings and ground level. For the IDC, the building's exposure was characterised per unit land area determined by the DEM cell size overlaid with the land use map. Exposure for Segambut area (Site 1) was defined as buildings located at the highest 2 meters from the lowest ground of exposed buildings in the floodplain following the description for Site 2. This is to ensure the comparison is using the same reference point between the two sites. In terms of the building distributions, the sites exhibit unique distribution across the terrain. Figure 6 shows the number of residential houses at Sites 1 and 2 from the same spatial reference point. Site 1 consists of a total of 108 houses while Site 2 with 70 houses indicates a much denser building at Site 1. Furthermore, Site 1 has a greater exposure to flooding with more than half concentrated in the lower lying area while the opposite for Site 2.

The resulting stage–damage relationships were then compared in terms of absolute magnitude and percentage differences (Figure 7).

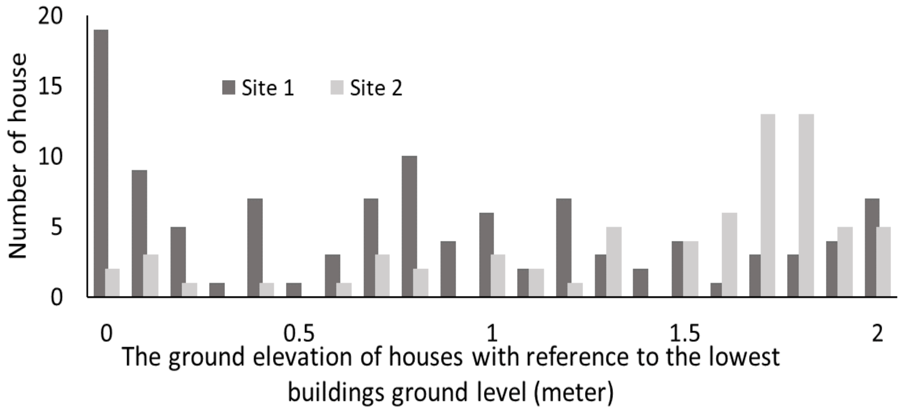


FIGURE 6. Comparison of the densities of residential properties at the riverine areas in Sites 1 and 2 with elevations corresponding to the ground level of buildings located nearest to the river as the reference level.

The curve derived from the IDC is significantly overestimated and, therefore, excluded from the figures for clarity. Their deviations from SDC were observed using the median values and upper and lower quartiles of boxplots. The largest deviation is coming from the IDC with approximately 30 times larger magnitude of damages as compared to the SDC. Whereas the percentage difference of NDC against the SDC generated curve shows a maximum of 2.5 larger estimated damage.

The overestimation of NDC was moderated by the scores of IDC's depth-damage relationship, which have resulted in the reduction of the overall damages of UDC. The UDC significantly reduces the overestimation observed in NDC by leveraging the ratio derived from IDC. For example, at the same flood depth, the damage value for NDC is RM24,000, while UDC reduces this to RM6,000. This indicates that UDC reduces the estimated damage by a factor of 4 or by 75% compared to NDC.

At both Sites 1 and 2, the deviance of IDC and to some extent NDC is decreased by the use of the UDC, where the UDC's stage-damage relationship is within the envelope of the SDC's uncertainty range. The overestimations of NDC are influenced by the NDC's linear depth-damage representation that yields overestimated damages at shallow flood. Nonetheless, the NDC curve converges to the SDC median at 6 m height due to the same damage value used (figure not shown). Meanwhile, the UDC's curves are within the upper and lower quartiles of Figures in the first row show the absolute damage in MYR. The second row shows the percentage difference, where the horizontal line of the x axis refers to the median values of site-specific damage.

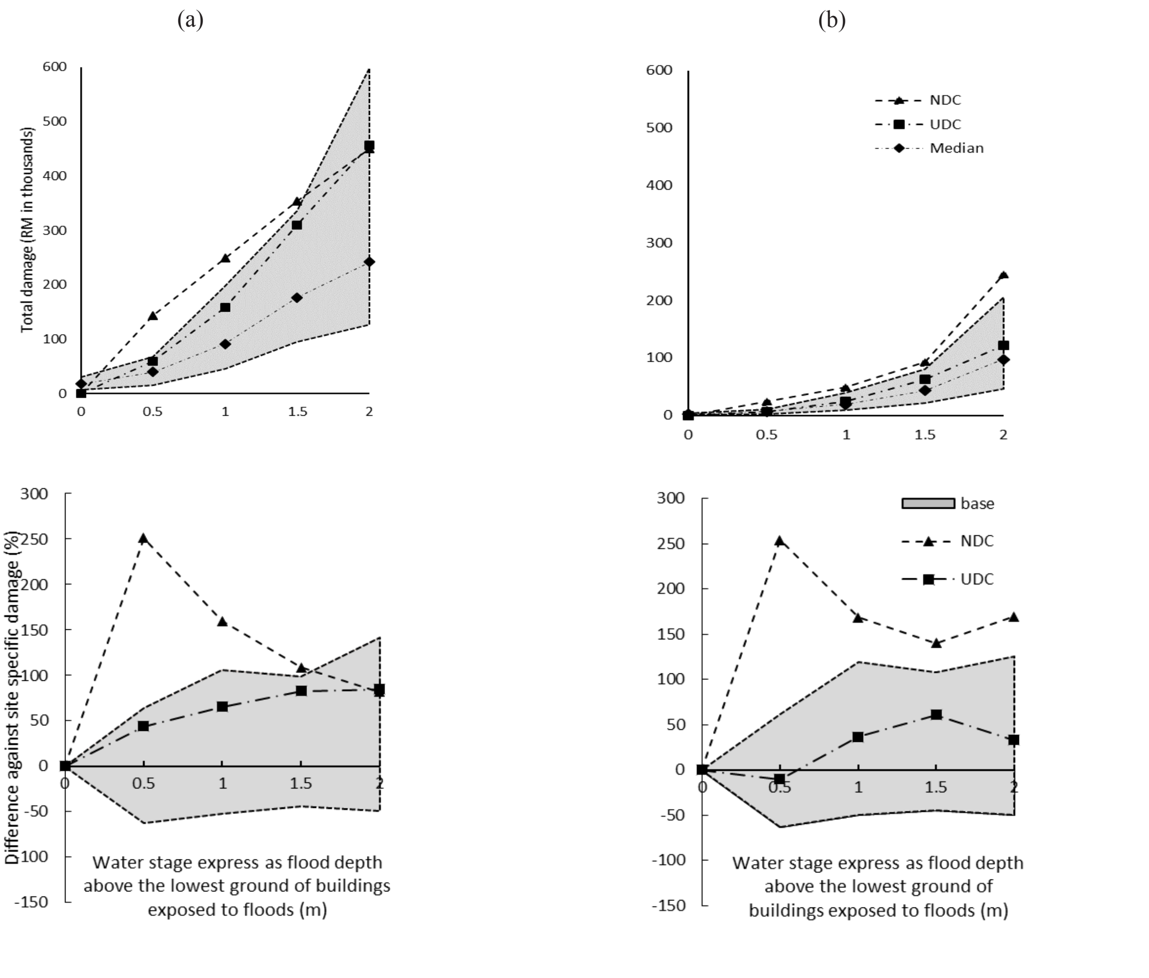


FIGURE 7. Stage–damage relationships using NDC and UDC against the site-specific uncertainty range, (a) Site 1: Segambut, and (b) Site 2: Kelantan. The gray space is the possible values under site-specific uncertainty range.

SDC's boxplots for both sites, highlighting the better performance of UDC as compared to NDC. Nonetheless, both UDC and NDC yield significantly lower aggregated flood damages as compared to the IDC. The smaller deviation of the NDC as opposed to IDC is expected since the NDC is driven by nationwide empirical information while IDC is not.

The effects of urban density and locations of buildings are apparent from the large difference of the stage-damage relations between Site 1 and Site 2. The disproportion signifies the influence of the greater density of buildings at the lower land area at Site 1, which pushed higher aggregated damage as compared to Site 2 at the higher inundation levels. The results indicate that both the functional form of a depth–damage relationship and the density of buildings govern the community-scale aggregated building-level damage. In terms of the percentage difference when compared to the median SDC between the two sites, the overestimation of NDC is somewhat higher when inundation is at the higher level. This is because of compounded losses by shallow flood depths over the higher number of buildings at Site 1 as opposed to Site 2.

FLOOD RISK

Flood risk was computed only for Kota Bharu study area (Site 2) because of the availability of secondary hazard information. The present study makes use of simulation results in (DID 2017), where magnitudes of water levels for 2, 5, 10, 20, 50, and 100-year return periods were extracted from longitudinal river sections corresponding to maximum water levels under the different return periods. Figure 8 presents the inundation maps for Site 2 under different flood scenarios based on hydrodynamic modeling.

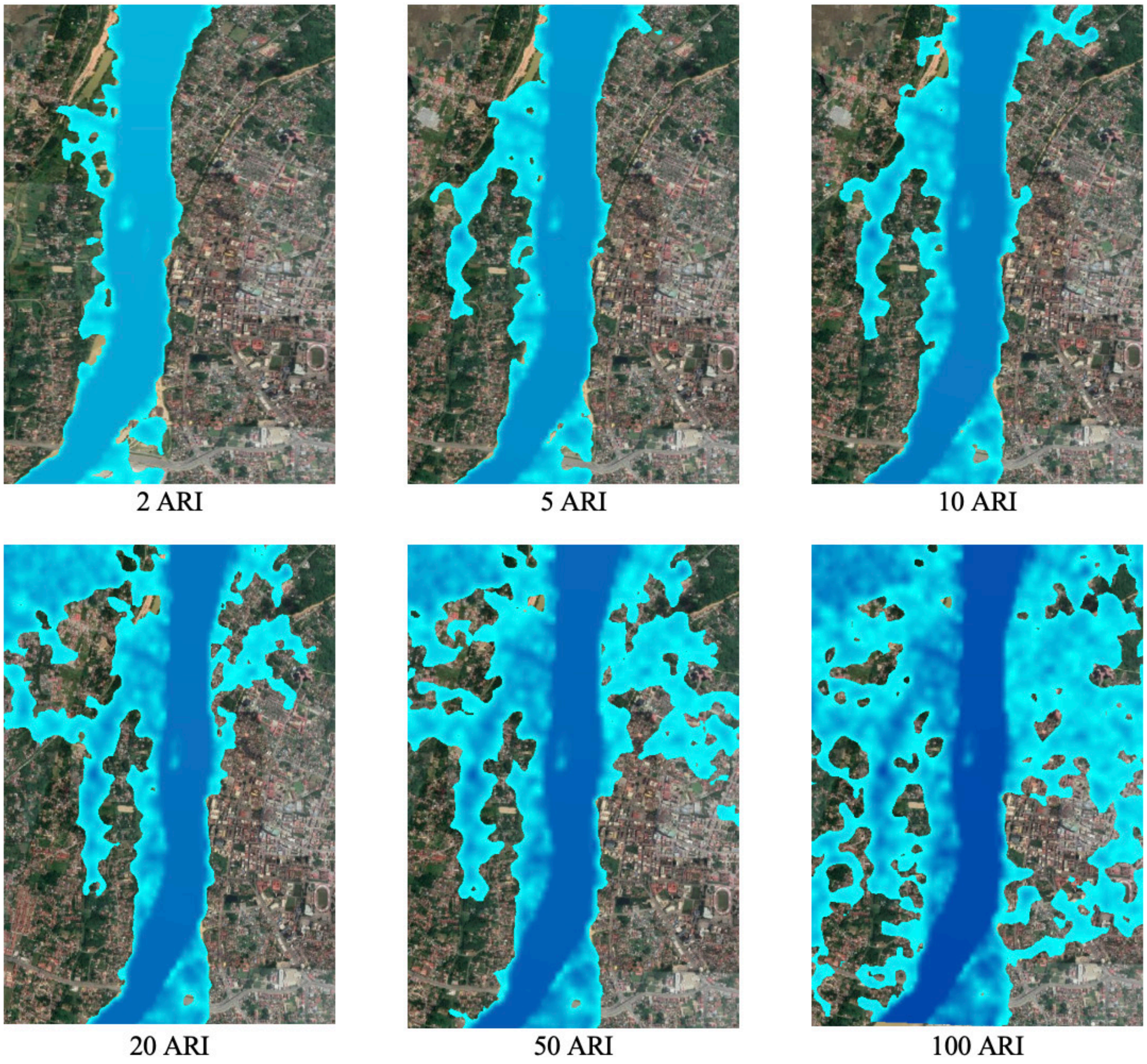


FIGURE 8. Inundation maps for Site 2 under different scenarios of hydrodynamic modeling.

The differences in flood risk governed by the different DDCs are shown in Figure 9. NDC and UDC exhibit similar deviations from the median risks for site-specific scenarios, with relative changes of 0.95 and 0.10, respectively, the IDC significantly overestimates losses, showing a relative change of 68 compared to the median. The UDC has successfully decreased the significant bias of the IDC in risk estimates.

The similarities between the magnitude of risk between NDC and UDC, on top of them being within the uncertainty range of the site-specific curve, suggest the minimum influence of discrepancies from the depth-damage curvature/linear shape as compared to the values of its 'maximum' flood damage on the magnitude of risk. Furthermore, the smaller discrepancies in risk estimates as compared to the stage-damage relationship are influenced by the integration of hazard's probability and the consequential damage.

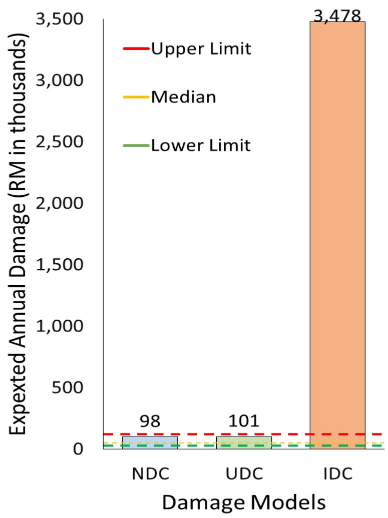


FIGURE 9. Comparison of Expected Annual Damage (EAD) between different depth-damage models.

This study demonstrates a parsimonious approach to addressing uncertainty in residential buildings' depth–damage function and how it propagates onto consequence estimates. In validation, the boxplots are proven to be useful when the expected values from the boxplots' depth–damage expected values converge with the deterministic power function's values at the community-scale aggregated building-level damage.

With some houses suffering less or more damage than the expected values, the uncertainty range propagated from the depth–damage to the community-scale aggregated building-level damage provides more information on flood management decision-making. The parsimonious boxplots approach to capture uncertainty eliminates the need for an underlying distribution. Notably, advancements in how the flood damage function is represented and how uncertainty is captured have included multiple variables and different complexities, for example, multiple linear regression, Bayesian networks, artificial neural networks and random forest (Mohor et al. 2021; Sulong & Romali 2022), yet univariate analysis remains a good compromise (Aribisala et al. 2022; Carisi et al. 2018) and is still widely used in the context of flood risk assessment. Despite the attractiveness of the complex models in addressing uncertainty, they need to be supported with sufficient and reliable data, which is often not the case.

This study explores the implications of DDC to risk estimates, focusing on (1) when curves representation over the flood depth range differs, and when (2) the magnitude of damage at the 'maximum' considered flood depth differs. It has been demonstrated in the present study that the model structure (i.e., curvature or linear form) of a depth–damage curve influences the estimates of residential community damages on aggregated building-level damage. Two DDCs on which one is curvature (UDC), and another is linear (NDC), but both with the same maximum damage, most likely yield preference on the one with the curvature shape. Nonetheless, the overestimation is minimized when the propagation is carried forward into the risk estimates due to the probability weighting effects. However, the smaller deviance in risk estimate is not the case for a DDCs that poses a significant difference in the maximum damage at the highest considered flood depth (e.g., IDC against UDC).

The JRC functions representing the IDC are governed by the information available at the global scale, whereas the NDC for Peninsular Malaysia and the SDC are based on empirical data. The IDC with a unit of land area that is subsequently converted into building-level damages, in contrast to the NDC and SDC that are directly derived for a building unit. Furthermore, the full construction costs used in the derivation of the IDC may lead to high values and overestimation of the estimated cost of flood damage. For countries where houses are primarily constructed with flood-resistant materials and not everything needs reconstruction when floods occur, the use of the full construction cost of buildings will inevitably overestimate the losses. The overestimation of flood damage aligns with international findings from Jongman (2012), which emphasize the significant discrepancies in the JRC damage model. In the broader context of climate adaptation and urban planning, such inaccuracies can lead to misguided policy decisions. Overestimated flood damages inflate flood risk projections, leading to potential misallocations in disaster response and infrastructure investment. A precise depth-damage function like the UDC supports sustainable urban planning by providing policymakers with reliable data for resilient infrastructure, flood mitigation, and land-use strategies, ensuring long-term resilience and economic sustainability amid increasing extreme weather events. Generally, the more local the model is governed by, the more preferred it is in terms of suitability for a detailed analysis of vulnerability and risk assessment in investment decisions at the national and state level. In the case where both can be improved, information can be leveraged from both types of functions to yield a better representation.

These findings emphasize the importance of localized DDC in flood risk assessment which can benefit other flood-prone regions or countries facing similar challenges. The use of UDC approach can also help countries with scarce empirical data better estimate flood damage and allocate resources more efficiently.

It is also found that the aggregated losses of a residential area at risk of flooding are uniquely shaped by the scattered locations of the buildings. Despite the same level of flood depth, two areas can have distinctly different vulnerability states because of the different degrees of exposure (e.g., the overall higher values of the community-scale aggregated building-level damage at Site 1 compared with that at Site 2 are influenced by the greater density of buildings in the lower-lying areas in Site 1). This highlights the importance of accounting for the uniqueness of the area in terms of exposure when it comes to evaluating flood consequences and risk at the building level (Löschner et al. 2016). This helps achieve an accurate and reliable analysis of the risk-based cost-effectiveness of measures, particularly at building level.

CONCLUSIONS

This study demonstrates the relative impacts of using established flood depth–damage relationships that are derived from global data, national data and leveraged information. The application of the function has been explored for community-scale aggregated building-level damage and flood risk estimates using real information. The considered depth–damage models were evaluated against a site-specific empirically derived function with upper and lower error bounds to represent uncertainty. On applying the methodology at two different sites, the results indicate that the international-led depth–damage model governed by synthetic information greatly overestimates aggregated flood damage and risk. Yet this can be reduced by leveraging information from national inventory to get a better representative function. It is also important to note that local flood damage survey information is valuable and indispensable. Therefore, effective data inventory and management are crucial to gain more evidence for a better representation of the damage curve.

The UDC developed in this study has significant practical applications for policymakers and stakeholders in flood risk management in Malaysia. By integrating insights from internationally derived (IDC) and national-level (NDC), the UDC provides a balanced approach to flood damage estimation, reducing the overestimation observed in NDC while maintaining localized relevance. This makes it a valuable tool for the policymakers that can leverage the UDC to standardize flood damage and risk assessments, improve insurance models, resource allocation in flood-prone areas and enhance urban planning strategies. Future research should expand its applicability to other asset types e.g. commercial, incorporate climate change projections, and refine its accuracy through additional empirical data.

ACKNOWLEDGEMENT

Funding This work is part of the project 'Flood Impact Across Scales' (FIAS), which is funded under the Newton Ungku Omar Fund 'Understanding of the Impacts of Hydrometeorological Hazards in Southeast Asia' by the Ministry of Higher Education of Malaysia (NEWTON/1/2018/WAB05/UPM/2). We appreciate the contribution of all FIAS project members that have provided comments on the early version of the paper. We would like to thank the Department of Irrigation and Drainage (DID) for sharing the hydrological data and reports, and PLANMalaysia for the land use information.

DECLARATION OF COMPETING INTEREST

None.

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