Flood damage and risk assessment for urban area in Malaysia

Noor Suraya Romali and Zulkifli Yusop

ABSTRACT

In recent years, flood risk map has been widely accepted as a tool for flood mitigation. The risk of flooding is normally illustrated in terms of its hazard (flood inundation maps), while vulnerability emphasizes the consequences of flooding. In developing countries, published studies on flood vulnerability assessment are limited, especially on flood damage. This paper attempts to establish a flood damage and risk assessment framework for Segamat town in Johor, Malaysia. A combination of flood hazard (flood characteristics), exposure (value of exposed elements), and vulnerability (flood damage function curve) were used for estimating the flood damage. The flood depth and areal extent were obtained from flood modeling and mapping using HEC-HMS/RAS and Arc GIS, respectively. Expected annual damage (EAD) for residential areas (50,112 units) and commercial areas (9,318 premises) were RM12.59 million and RM2.96 million, respectively. The flood hazard map shows that Bandar Seberang area (46,184 properties) was the most affected by the 2011 flood. The flood damage map illustrates similar patterns, with Bandar Seberang suffering the highest damage. The damage distribution maps are useful for reducing future flood damage by identifying properties with high flood risk.

Key words | commercial, flood damage curve, flood damage map, Malaysia, residential

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HIGHLIGHTS

- In developing countries, literature on flood vulnerability assessment are limited especially on flood damage. Nowadays, vulnerability is considered as important as hazard.
- The paradigm shifts from the conventional to a risk-based approach focus more on generating flood risk map instead of flood hazard map. However, the type of maps that includes the consequences of flooding has yet to be satisfactorily developed by most of the developing countries including Malaysia which still depend on hazard maps, while a risk map that illustrated the risk of flooding in terms of monetary is rarely available.
- Hence an attempt have been made to develop flood damage map showing the impact of flooding in monetary term. The novelty of this research is the estimation of flood damage for an urban area in Malaysia using a site specific damage curve. As the study on flood vulnerability assessment are limited, these frameworks also serve as useful guidelines to initiate flood risk management practice in Malaysia, especially in producing a risk map showing the expected damage in monetary terms.

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INTRODUCTION

Flood has been accepted as the most common and damaging natural disaster in several parts of the world (Fijko *et al.* 2019; McGrath *et al.* 2019). Nowadays, the occurrence of flood is increasing worldwide due to extreme rainfall that is expected to occur more frequently as a consequence of the climate change phenomenon (De Silva & Kawasaki 2018; Lee & Choi 2018; Lee & Kim 2018). Flood causes great harm to people, major damage to properties and also impacts severely on socio-economic activities (Chang *et al.* 2008). Even worse, major floods often lead to the loss of human life and decrease the quality of human health (Jonkman *et al.* 2004). Globally, it is estimated that this natural disaster had taken about 100,000 lives and affected 1.4 billion people during the last decade of the 20th century (Jonkman *et al.* 2004). In Malaysia, flood occurs annually, affecting an approximate area of 29,800 km^2, involving more than 4.8 million people, and causing tremendous damage to properties (Asian Reduction Disaster Centre 2011).

Nowadays, the conventional flood control approach has shifted to a more risk-based approach in flood management to minimize the impact of flooding (De Moel & Aerts 2011; Ward *et al.* 2011; Velasco *et al.* 2015). In flood risk management, risk is defined as the combination of the physical characteristics of the flood event (the hazard) and its potential consequences (the vulnerability) (Apel *et al.* 2008; De Moel *et al.* 2009; Hudson *et al.* 2014). In Europe, the paradigm has shifted from the conventional to a risk-based approach focus, more about generating flood risk maps instead of flood hazard maps (De Moel *et al.* 2009; Velasco *et al.* 2015). The difference between these two is that flood hazard maps contain information about the probability or magnitude of an event, whereas flood risk maps contain additional information about the consequences, such as the economic damage and number of people affected (De Moel *et al.* 2009). Therefore, vulnerability is considered as important as hazard (Velasco *et al.* 2015). Furthermore, the identification of flood risk areas not only depends on the hazard characteristics (i.e., flood depth and flood extent), but is also influenced by the impact of the flooding (vulnerability). Knowledge of the flood hazard alone (extent and frequency) does not provide enough information for the public safety community to make informed decisions regarding potential social and economic losses (McGrath *et al.* 2015). Some areas with high inundation depth may experience low damage values, while some areas may have high damage although the flood level is lower. However, the type of maps that include the consequences of flooding has yet to be satisfactorily developed by most of the developing countries, including Malaysia, which still depend on hazard maps, while a risk map illustrating the risk of flooding in monetary terms is rarely available.

Flood damage is an important tool in the assessment of flood risk. Studies on flood damage assessment in developed countries can be tracked back to Penning-Rowsell & Chatterton (1979), Smith (1981), Appelbaum (1985), and McBean *et al.* (1989). In Malaysia thus far, the available damage estimation works are by KTA Tenaga Sdn. Bhd. (2003), Ahamad *et al.* (2011), and Tam *et al.* (2014). The studies in Malaysia and other developing countries have basically adopted the methodology from other developed countries, which may not reflect their own flood scenario and their socio-economic conditions. Data scarcity is a crucial issue in the assessment of flood damage in developing countries (Suriya *et al.* 2012; Craciun 2018). In Malaysia, the track of historical flood damage data is not well documented and is difficult to access. The missing information may affect the reliability of the damage estimates. It is compelling to produce a damage assessment framework that reflects our own local condition. Hence, with the aim to help Malaysia to switch from the conventional flood management practice to a more risk-based approach, it is compelling to carry out a study on flood risk, especially in the field of flood damage assessment. We outline the methodology of generating flood damage maps, especially in the assessment of flood damage. A flood damage map showing predicted damage in monetary terms is more appropriate nowadays as the expected damage for a certain flood-prone area can be incorporated in the flood risk management plan.

METHODOLOGY

Flood damage estimation is a research field that has not been studied in depth, especially in developing countries like Malaysia. Considering this as the starting point, the methodologies to assess flood risk in urban area are presented. The overall methodology used to assess flood risk and damage estimates is shown in Figure 1. The assessment considers flood hazard, exposure, and flood vulnerability as follows:

1. Hazard assessment which involved flood modeling to provide the flood extent (affected area and numbers of affected properties) and the information of flood parameters (flood depth) which is the input needed for the estimation of flood damage. Flood frequency analysis is performed to provide estimates of peak flow for selected flood event with average recurrence intervals (ARIs) of 10, 25, 50, 100, 200, and 1,000 years.
2. Exposure denotes the exposed elements that are vulnerable to risk as the effect of flooding. The exposure to different land use categories, residential and commercial, was assessed and unit property values used to quantify the exposed element in this study.
3. Vulnerability assessment involves the development of flood damage function curve which shows the relationship between the degree of damage to the corresponding flood parameters. It is referred to as damage factor in this study. The combination of flood

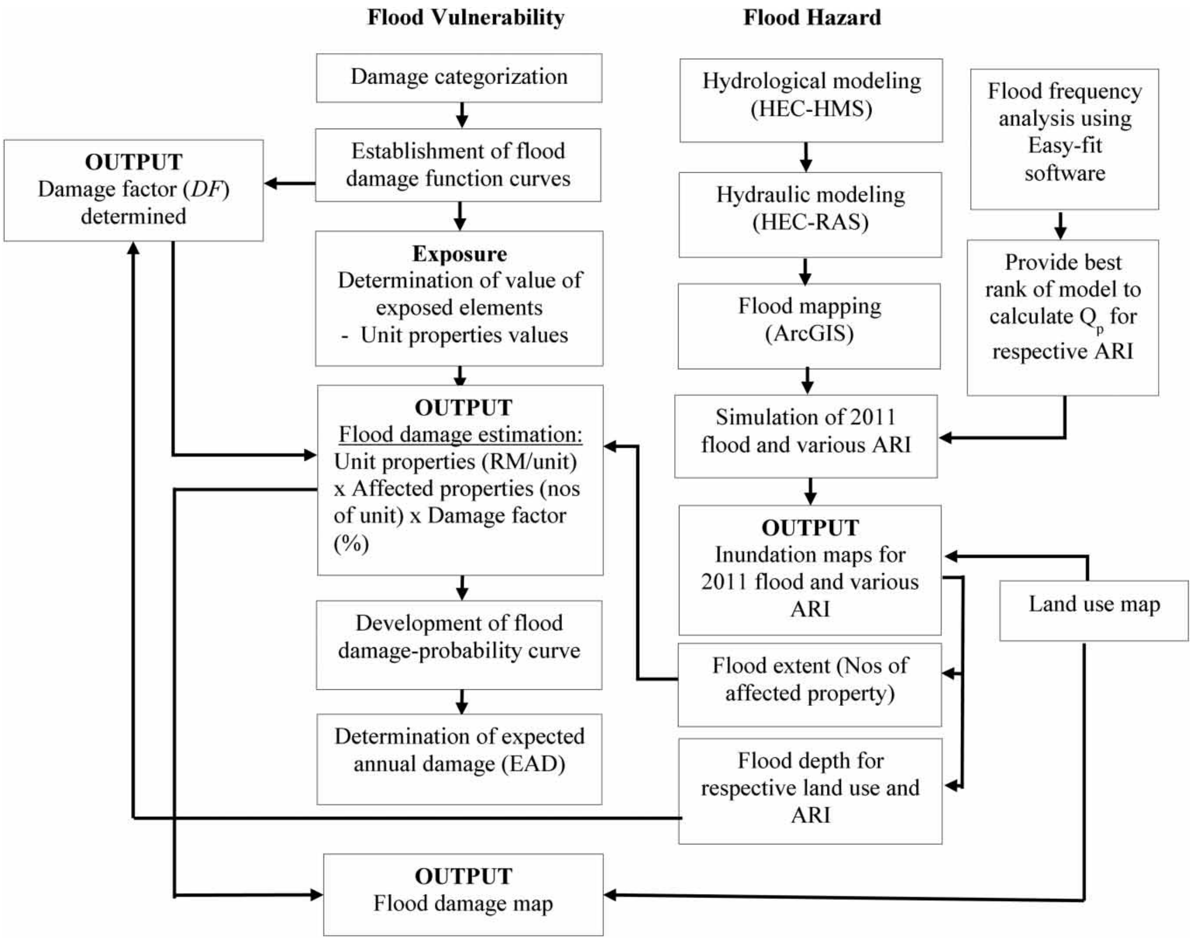


Figure 1 | Flowchart of flood damage and risk assessment framework.

hazard, exposure, and vulnerability was used to estimate flood damage, as shown in Equation (1):

$$\begin{aligned} \textit{Flood damage}\ (RM) = & \textit{Affected properties}\ (\textit{nos of units}) \\ & \times \textit{Unit property values}\ (RM/unit) \\ & \times \textit{Damage factor}\ (\%) \end{aligned} \quad (1)$$

Subsequently, the estimated flood damage is plotted against the respective ARI to produce the flood damage probability curve. Risk indicator, in terms of expected annual damage (EAD) is calculated as the sum of incremental probability of occurrence times the corresponding average damage for various flood sizes (Velasco *et al.* 2015). Then, the combination of land use map, inundation map, and estimated flood damage produces a flood damage map as the main outcome of this study.

The major part is to produce flood depth-damage curves, since there were no curves specially representing the flood damage in the studied area. The curves were developed for residential and commercial areas, where each category is composed of two curves for structural and content. The structural damage includes repair cost of the building, such as cleaning, re-painting, and changing the building materials. The content damage is related to damage inside the buildings, such as furniture, equipment, and business stocks.

The first step in developing the flood depth-damage curve was to gather relevant information. Due to data scarcity, a synthetic method was used which allows conversion of available data to a reliable estimate of flood damage (Smith 1981). The flood damage data were collected using a cross-sectional method by observing many parameters at the same point in time, without regard to time differences. A questionnaire survey to gain flood damage data was developed by considering various inputs, as suggested by McBean *et al.* (1989), Suriya *et al.* (2012), Penning-Rowsell & Chatterton (1979), and KTA Tenaga Sdn. Bhd. (2003). Finally, the flood damage function curves were developed as the plot of damage percentage versus selected flood parameters, according to the land use categories. The damage percentages were calculated using Equation (2):

$$\textit{Damage}\ (\%) = \frac{\textit{Overal replacement cost}}{\textit{Market value of properties}} \times 100 \quad (2)$$

STUDY AREA AND DATA

Description of study area

This study was carried out in Segamat town which is located in the Segamat River Basin (Figure 2). The total basin area is 685 km^2, of which, about 70% is hilly with elevation up to 1,000 m above sea level. Segamat town is frequently affected by large floods. It is a medium size town with an approximate area of 12,875 hectares and about 80,000 residents. The town center is divided into two, Bandar Atas and Bandar Seberang, as shown in Figure 2. Bandar Atas is the original town center while Bandar Seberang is the extension of the old city to the other side of the Segamat River. Several major floods have occurred in the last few decades, causing extensive damage and inconvenience to the local communities. The flood in December 2006 was possibly the worst in history with 100 years ARI or more (Shafie 2009). Other major floods were reported in the 1950s, 1984, and the most recent occurred in January 2011 (NAHRIM 2012).

Data

Flood hazard

For the purpose of hazard assessment, a digital elevation model (DEM) was used in order to set up 2D models for mapping the flood progression. DEM can represent a raster map (grid) or a triangular model network (TIN). The DEM was developed using Interferometric Synthetic Aperture Radar (ISFAR) data obtained from the Department of Irrigation and Drainage (DID) Malaysia. Frequency analyses for various ARIs up to 1,000 years were performed earlier in Romali & Yusop (2017). Based on the Kolmogorov–Smirnov (KS) test, the generalized Pareto was found to be the best distribution to fit the annual maximum flow data series. The annual maximum flow values estimated from frequency analysis for selected ARIs were subsequently used as input data for flood mapping in HEC-RAS model. Flood maps of 10, 25, 50, 100, 200, 500, and 1,000 year ARIs for the residential and commercial areas were developed. The results were then used in ArcGIS to prepare floodplain maps for different return periods. The detailed methodology of flood frequency analysis, verification of simulated hydrographs, and the flood

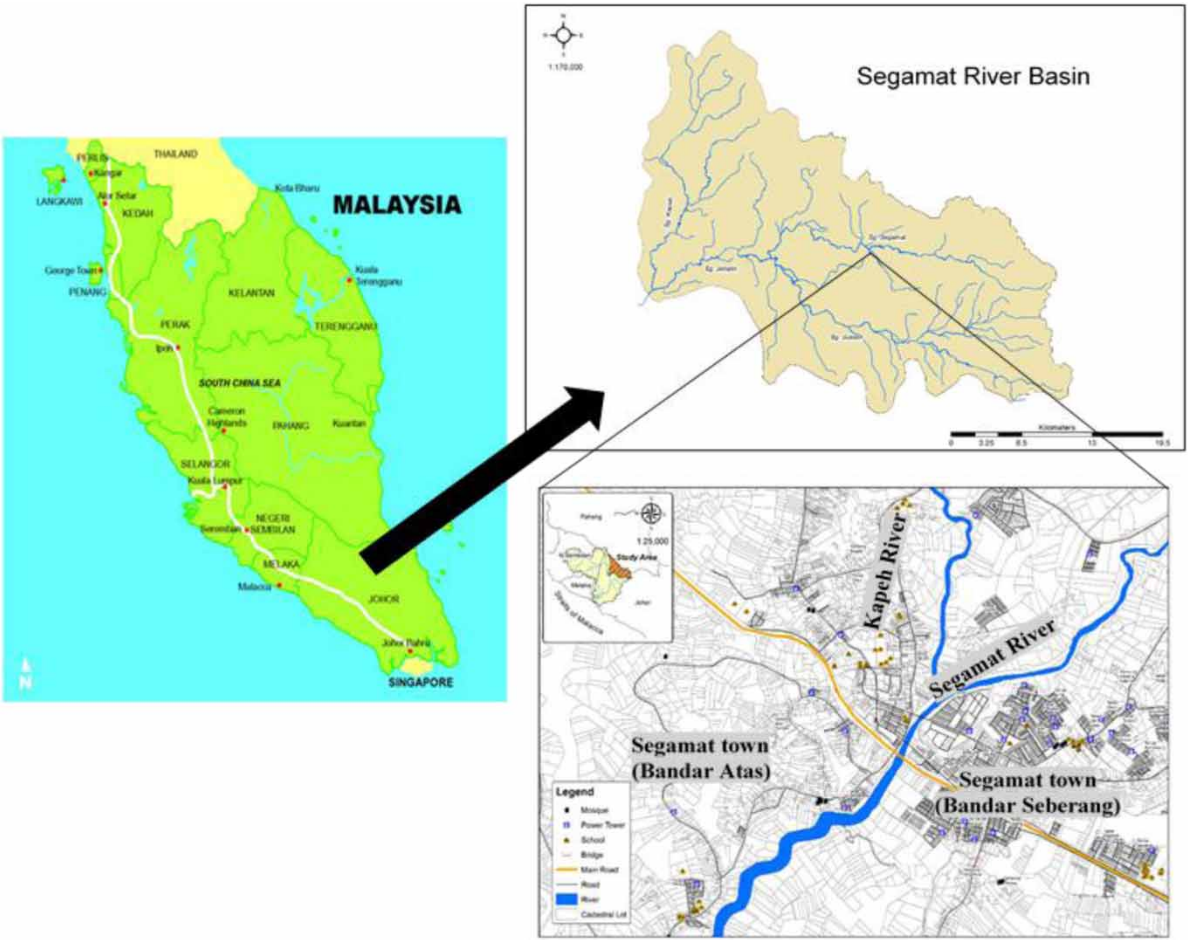


Figure 2 | Location of the study area: Segamat town.

inundation simulation can be found in earlier studies (Romali & Yusop 2017; Romali et al. 2018a, 2018b).

Exposure

Land use and individual building assets are used as the indicator for defining flood damage exposure in this study. Price of properties was obtained from Valuation and Property Services Department (JPPH) and District and Land Office of Segamat, while price of house contents (furniture, etc.) was collected through interview survey.

Flood vulnerability

The details and the source of data needed to develop the flood damage function curve are shown in Table 1. Using the damage factor obtained from the damage curves, the estimation of flood damage was obtained. The next analysis is to produce EAD, which is the mean damage for all flood sizes to occur in any year (Eleuterio 2012). It can be approximated from the area under the flood damage-probability curve (Ward *et al.* 2011; De Moel *et al.* 2014). To calculate EAD, several events of different return periods must be simulated. The number of data points (return period) used to plot the curve were selected based on previous studies. Merz & Thieken (2009) used seven data points, while Messner *et al.* (2007) suggested three and preferably six. Oliveri & Santoro (2000) used 50, 100, 300, 500, and 1,000-year return periods to develop a damage frequency curve for the city of Palermo in Italy, while Merz & Thieken (2009) used between 10 and 1,000 years' ARIs to produce risk curves for Cologne in Germany. In this study, we used 10, 25, 50, 100,

Table 1 | Input data required for depth-damage curve

Residential		Commercial	
Input data required	**Sources**	**Input data required**	**Sources**
Building and house content data	Data collection by valuation/ interview survey	Building, furniture, stock and equipment information	Data collection by valuation/ interview survey
Price (RM) per unit properties	District and Land Office of Segamat	Price (RM) per unit properties	District and Land Office of Segamat
House content value (RM)	Valuation and Property Services Department (JPPH) of Segamat	Content value (RM)	Valuation and Property Services Department (JPPH) of Segamat
Flood damage cost (structural and contents)		Flood damage cost (structural and contents)	
Flood water depth/ duration		Flood water depth/duration	

200, and 1,000-year return periods. The flood estimate for 1,000-year return period, although it may not be satisfactory, it is necessary in order to enclose as much as possible the area under the flood damage probability curve.

RESULTS

Flood hazard mapping

The results are presented for the 2011 flood and three selected return periods, i.e., for high probability, a return period of 10 years is used, 200 years for medium probability, and 1,000 years for low probability. The simulated flood depths for the 2011 flood and selected ARIs are shown in Figure 3. Almost 45% of Segamat town was affected by the 2011 flood and the flood depth at 66% of the flooded area was more than 1.2 meters. Most of the affected area was located at Bandar Seberang. The flood depth over the residential and commercial properties at the center of the crosstown area, i.e., Bandar Seberang, Jalan Sia Her Yam, Jalan Ros, and Jalan Genuang was up to 2 meters. Kampung Abdullah and Kampung Jawa were more severely affected with flood depth exceeding 3 meters.

The extent of flood hazard increases with the ARI. The simulation results for a 10-year flood indicate that only 7.43 km^2 (8.26%) of the Segamat town area was affected. On the other hand, the simulation of 200-year return periods shows that almost 40 km^2 of the area was flooded, which is five times larger than the simulated 10-year flood. The results also indicate that most of the areas inundated by the 200-year flood were also affected by the 2011 historical floods. The extent of the 2011 historical flood was almost similar to the simulated 200-year flood with the maximum flood depth of 5.87 and 5.49 meters, respectively, or different by about 6%. At 1,000-year ARIs, most areas of Bandar Seberang would be inundated with a flood depth more than 1.2 meters. The highest was near Taman Pawana with a flood depth of 7.34 meters. The detailed results of the flood inundation simulation and verification of simulated hydrographs with observation are not discussed in this paper. Those results were presented elsewhere (Romali *et al.* 2018a, 2018b).

Flood damage

The residential and commercial flood damage curves developed for both structural and contents are shown in Figure 4. According to the flood damage function model developed based on survey data conducted at the study area in Equation (3), the property's price has a significant effect on the value of structural residential flood damage. Hence, the structural curve was further classified into three sub-categories according to the property price, which are low price house (LPH), medium price house (MPH), and high price

(a)

(b)

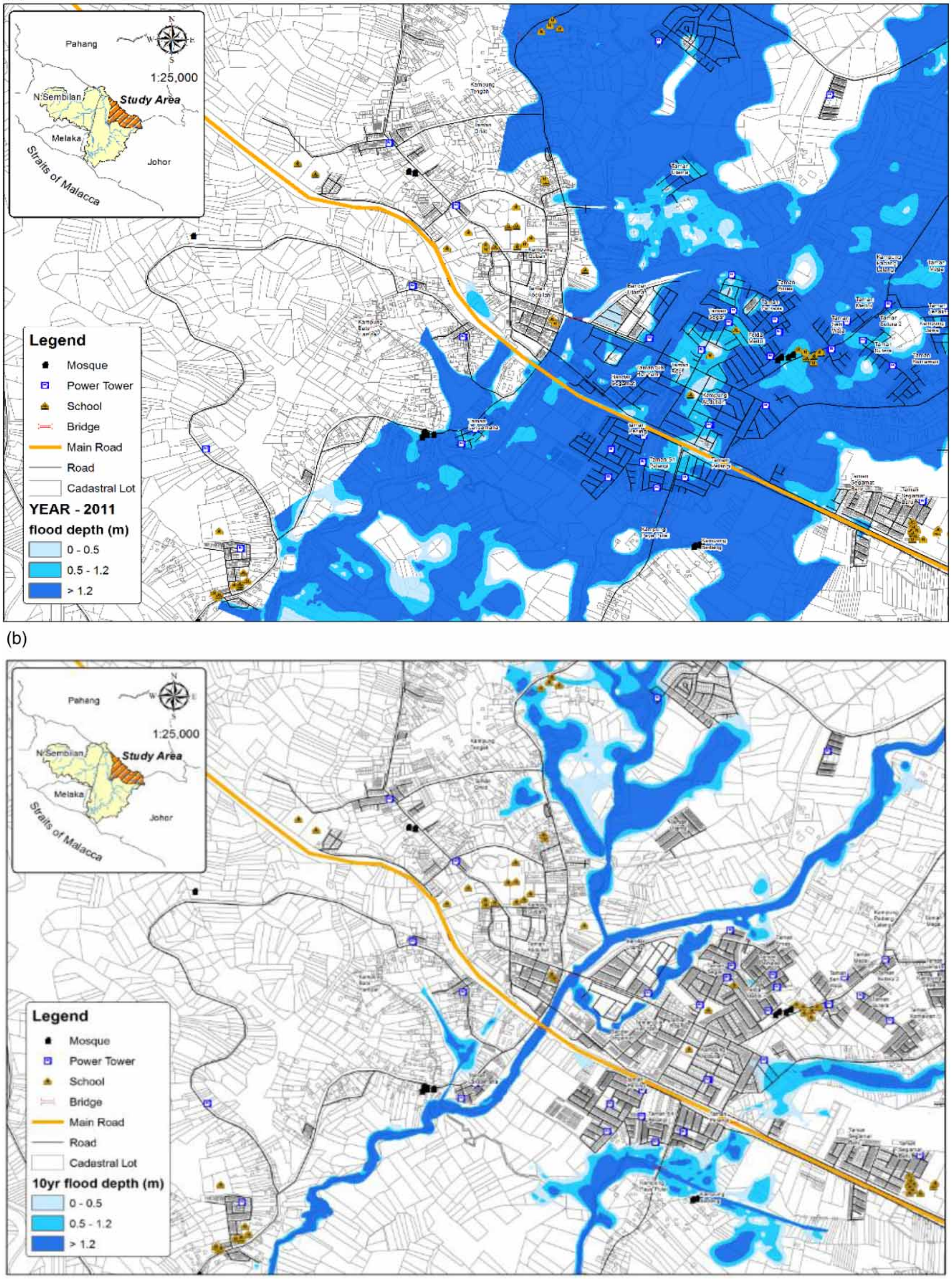


Figure 3 | Simulated inundated area for (a) 2011, (b) 10-year flood, (c) 200-year flood, and (d) 1,000-year flood. (*Continued*.)

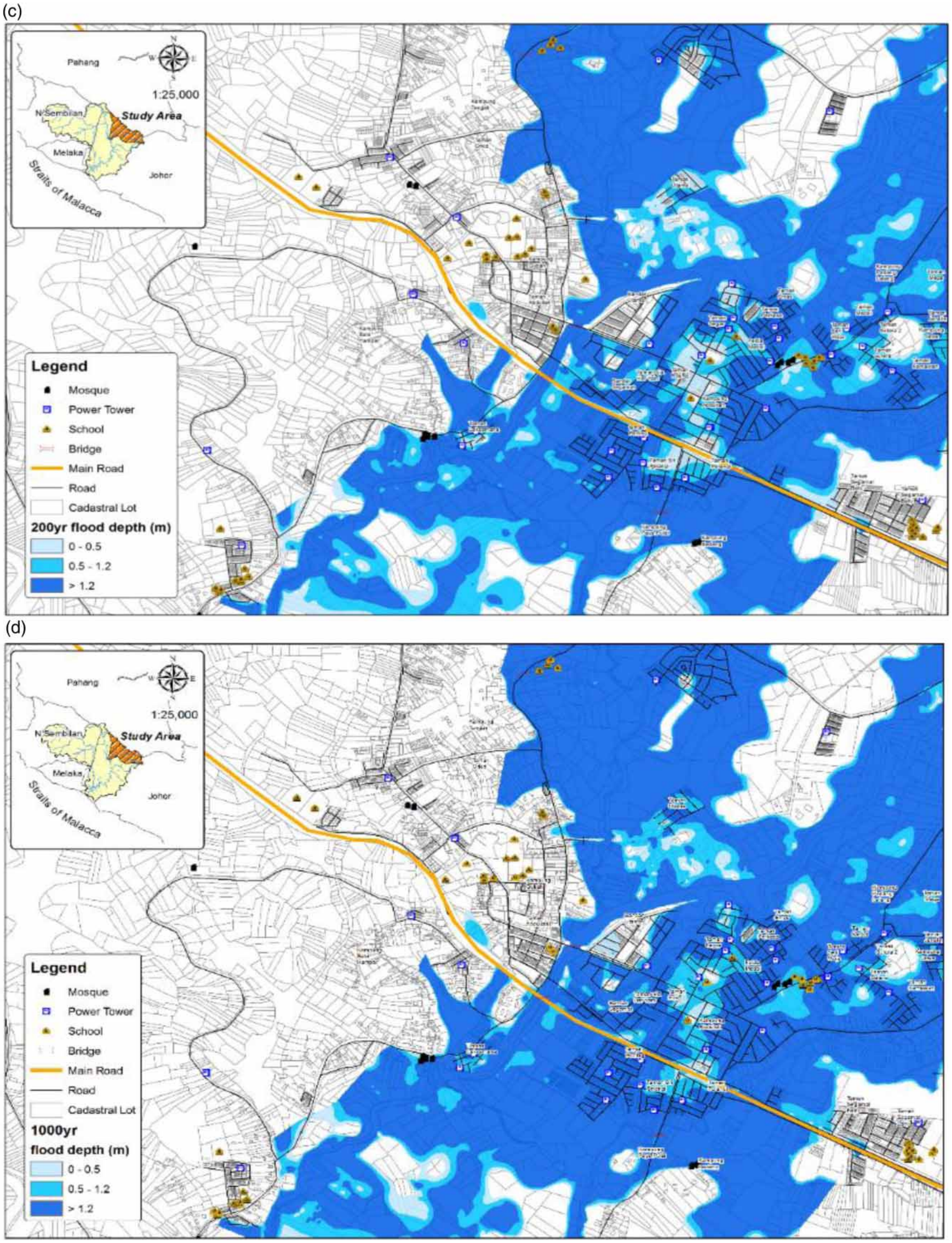


Figure 3 | Continued.

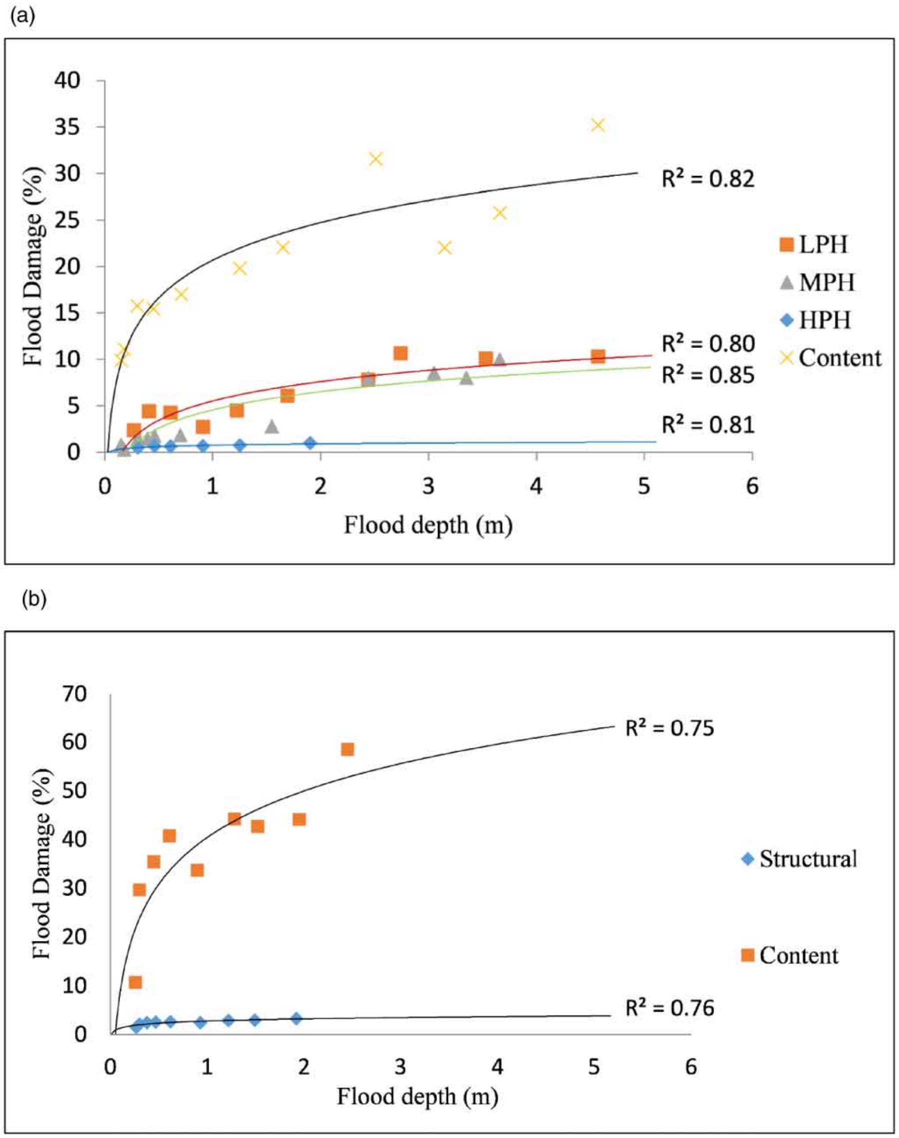


Figure 4 | Flood depth-damage curve for (a) residential and (b) commercial category.

house (HPH).

$$lnFlood_{RS} = 8.657 + 0.912(lnINCOME) - 1.307(lnPRICE) + \varepsilon_i \quad (3)$$

The estimate of flood damage was determined as the product of damage factor, numbers of affected properties, and unit property values for the respective damage categories. The estimated flood damage of the 2011 flood event for residential and commercial categories is presented in Table 2. The total estimated damage (structural plus content) for residential is approximately RM455 million, which is higher than the commercial damage (RM142 million). MPH sub-category is the most vulnerable to flood with total damages of RM328 million, followed by HPH of RM118 million, and the least for LPH category of RM9.7 million.

It can be observed from Table 3 that the total damage increases with the increasing value of ARI but decreases with the increasing value of probability. Studies by Oliveri & Santoro (2000), Ward *et al.* (2011), and Velasco *et al.* (2015) also found similar patterns in their probability–damage relationships where low probability event

Table 2 | Estimated damage for residential and commercial categories during the 2011 flood

		Estimated flood damage (RM)		
Category		**Structural**	**Content**	**Total**
Residential	LPH	6,814,866	2,880,956	9,695,823
	MPH	244,943,356	83,124,117	328,067,473
	HPH	42,498,718	75,580,046	118,078,764
	Total	294,256,941	161,585,119	455,842,060
Commercial		72,285,343	69,945,317	142,230,660
Total		366,542,284	231,530,436	598,072,720

contributed to a large value of damage. Similar to the damage pattern observed for the 2011 flood, the flood damage for various ARIs in the residential area was also the highest for the MPH sub-category, followed by HPH and LPH.

EAD is a risk indicator that receives wide interest as it helps to understand the potential impacts of an area due to flood (Velasco *et al.* 2015). The damage–probability curve for this study is presented in Figure 5 for both residential and commercial, respectively. The area under the curve represents EAD values of Segamat town, which are RM12.59 and RM2.96 million for the residential and commercial areas, respectively.

Flood damage maps

The spatial distribution of simulated damage to residential properties during the 2011 flood is illustrated in the flood

Table 3 | Estimates of flood damage for residential and commercial category for various ARIs

		Estimated flood damage (RM)					
		Residential			**Commercial**		
ARI (years)	**Probability Structural**	**Content**	**Total**	**Structural**	**Content**	**Total**	
10	0.100	6,321,889	5,784,626	12,106,516	737,411	727,959	1,465,370
25	0.040	38,042,107	32,287,233	70,329,339	3,257,141	2,734,058	5,991,198
50	0.020	106,324,646	68,808,438	175,133,084	20,534,195	19,181,515	39,715,710
100	0.010	299,155,841	164,584,979	463,740,820	71,697,363	69,945,317	141,642,679
200	0.005	311,429,053	173,721,787	485,150,840	76,724,888	74,390,967	151,115,855
500	0.002	365,910,554	189,089,248	554,999,802	81,390,232	80,411,900	161,802,132
1,000	0.001	386,183,093	198,045,930	584,229,023	87,862,457	86,898,846	174,761,303

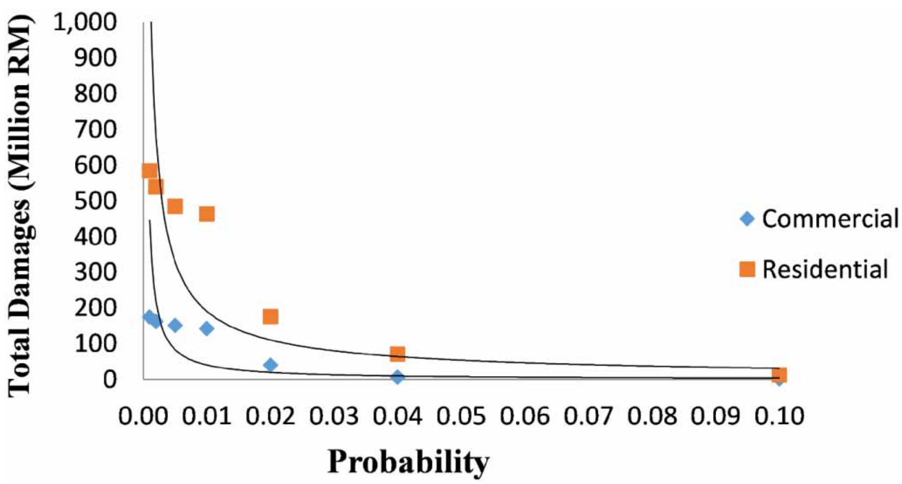


Figure 5 | Flood damage-probability curve for residential and commercial categories.

(a)

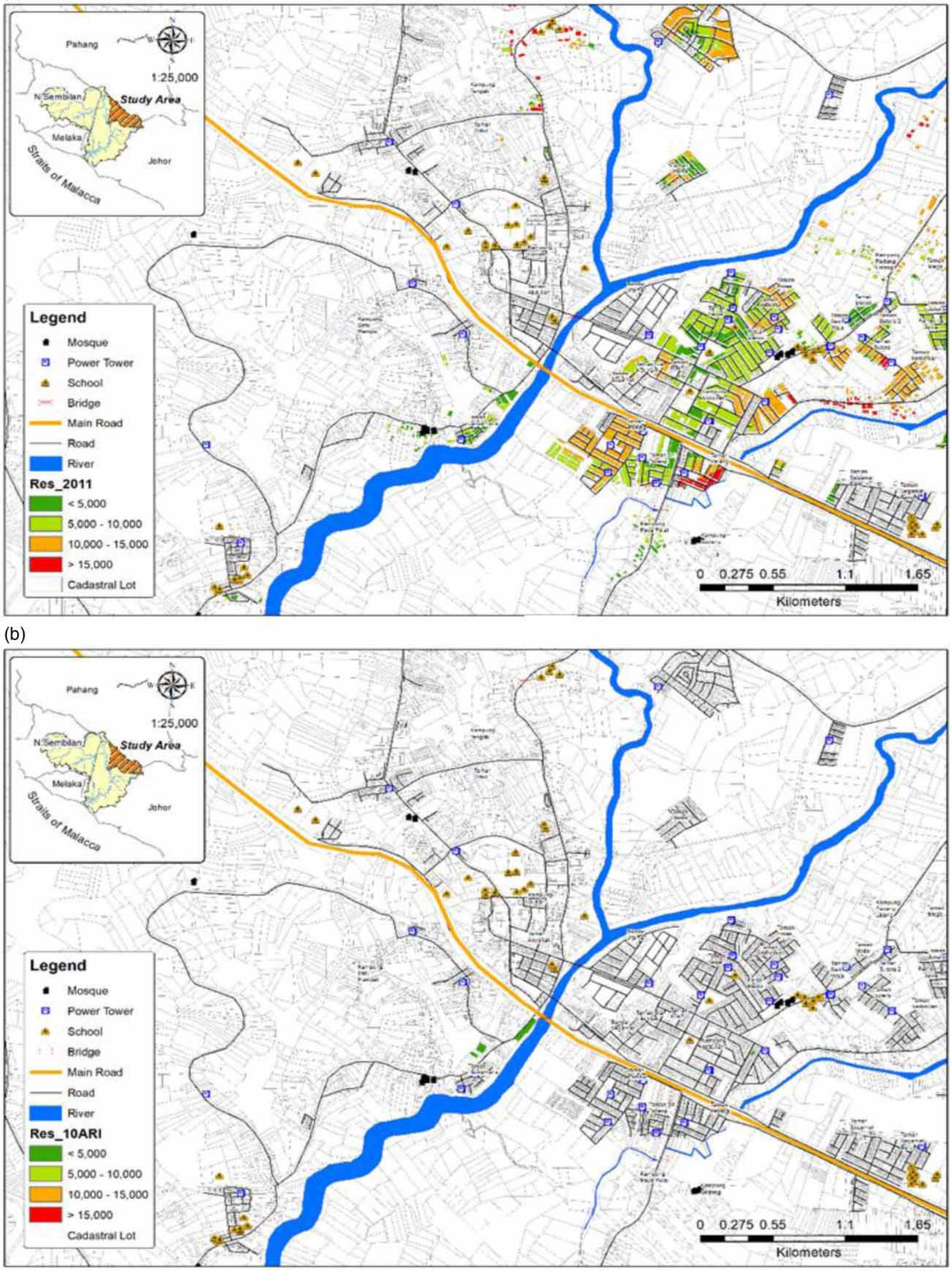
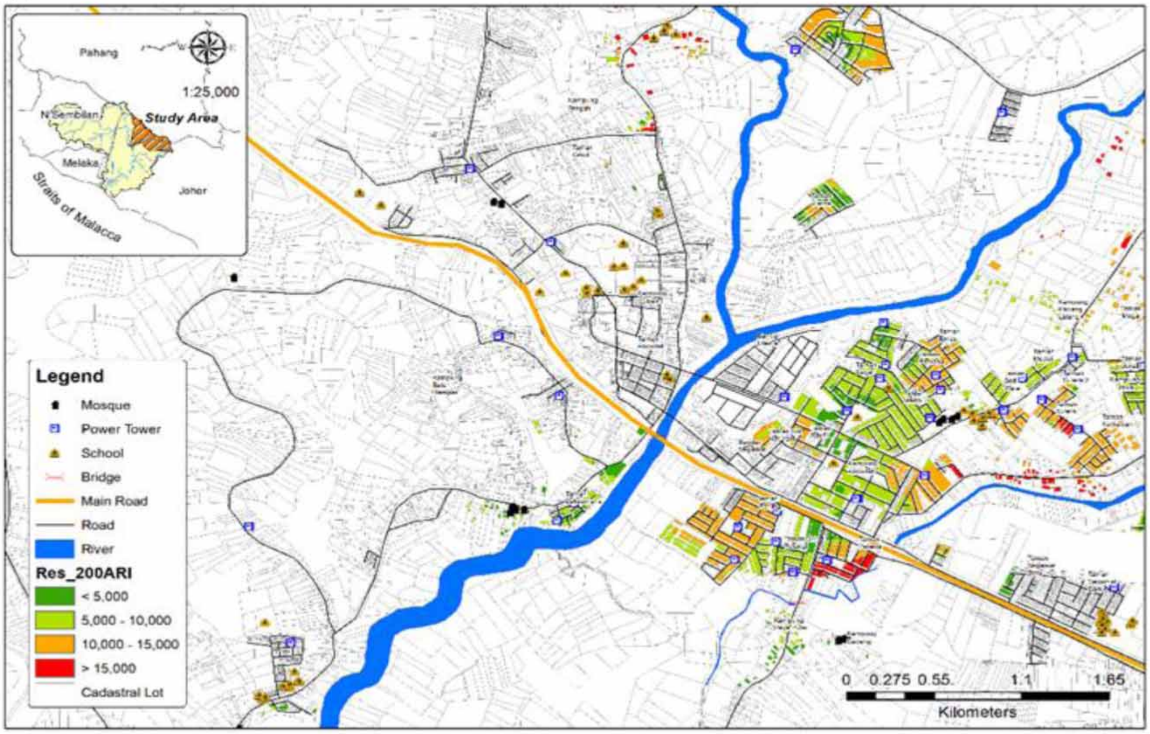


Figure 6 | Damage maps of the residential category for (a) 2011, (b) 10-year flood, (c) 200-year flood, and (d) 1,000-year flood. (*Continued*.)

(c)



(d)

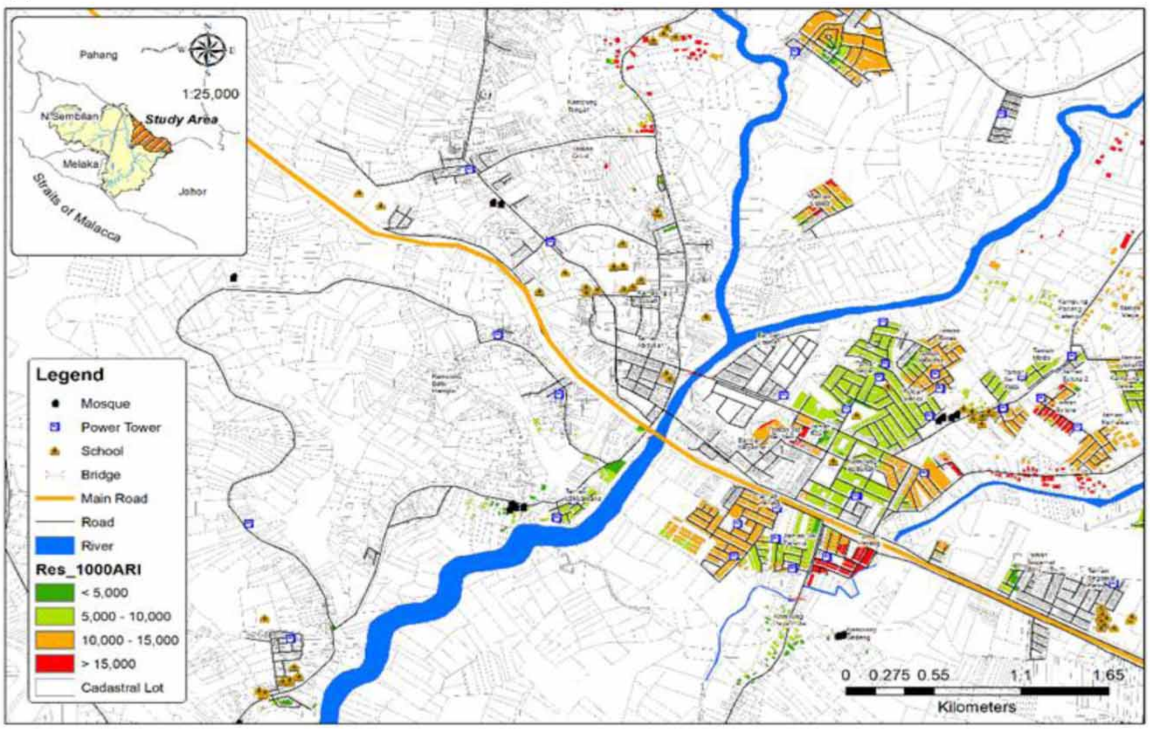


Figure 6 | Continued.

damage risk map in Figure 6(a). The highest property damage is observed at Bandar Seberang, especially in the densely populated town centers such as Taman Ros, Taman Segar, and Taman Sia Her Yam, ranging from RM5,000 to over RM15,000 per unit.

The properties with high values of damage (>RM15,000 per property) are mostly located in Taman Pelangi, Taman Sutera, and Kampung Tengah which are in the MPH sub-category. On the other hand, the high property price (HPH sub-category) such as at Taman Segamat Baru was less affected with damage, less than RM5,000 per property. A possible explanation for this is that the high price properties at Taman Segar, Taman Segamat Baru, and Taman Mida are located on higher ground or a less flood-prone area.

The distributed damage is low for 10-year flood, generally less than RM10,000 per unit. For 200-year flood, the damage increased more than RM15,000 per unit at Taman Pelangi and near Taman Kemawan. The simulated damage for a 200-year flood is not so different from the 100-year flood. The expected property damage at Bandar Atas (uptown) exceeds RM23 thousands per unit for the 1,000-year flood.

The damage for commercial properties during the 2011 flood at both Bandar Atas and Bandar Seberang exceeds RM15,000 per unit (Figure 7(a)). The less affected areas are Taman Pelangi and Taman Segamat Baru with damage of less than RM5,000 per property. For 10-year flood, the property damages range from less than RM5,000 to RM15,000 per property, as illustrated in Figure 7(b). The damage starts to increase to more than RM15,000 per property at 200-year ARI and as high as RM25,0000 at 1,000-year ARI.

Previous flood damage evaluation studies (e.g., Seifert *et al.* 2010; Vozinaki *et al.* 2015) found it is difficult to validate flood damage estimates due to the limited and incomplete historical damage data. This study also faced the same challenge, where absolute validation cannot be performed because the actual 2011 flood damage data are unavailable. Furthermore, the damage value needed is site specific for Segamat town only, but the data available are for the overall district of Segamat. To check the reliability of the damage estimation technique, OFAT (one factor at a time) approach is adopted where the influence of the components is manually varied in individual damage calculation. The sensitivity factor used to describe the level of sensitivity is determined as the ratio of the highest to the lowest damage estimates resulting from the variation of the components, while keeping the other components equal (De Moel & Aerts 2011).

The contribution of various components to the uncertainty in the final damage estimate and the sensitivity of the flood damage assessment are presented in Table 4. The estimates of residential damage for the 2011 flood using three variations of damage factors (DF1, DF2, and DF3) were compared. A separate calculation is performed using each different damage factor while keeping the other components unchanged. DF1 is the damage factor obtained from flood depth-damage curve developed in this study (Segamat curve), which resulted in a total residential damage of RM455 million. DF2 is based on DID guidelines that had been used by KTA Tenaga Sdn. Bhd. (2003) where a damage factor of 0.80, which is the ratio of actual damage to potential damage was applied in this analysis. DF3 is the damage factor based on JICA 1999, 2000 (DID 2003). The usage of DF2 and DF3 caused a large change in damage compared to the baseline situation (DF1) and are RM8.8 billion and RM2.16 billion, respectively.

DISCUSSION

The estimation of flood damage is a combination of hazard, vulnerability, and exposure. This study indicates that flood damage is mostly affected by hazard components, i.e., flood extent and magnitude. The area of residential properties (approximately 67,158 hectares) is larger than the commercial area (approximately 12,680 hectare), thus generates a higher number of flood-affected properties. As a result, the total estimated damage (structural plus content) for residential is approximately RM455 million, which is higher than the commercial damage (RM142 million), although the damage curve for the commercial category is higher, as shown in Figure 4. According to different residential categories, the estimated damage was RM328 million for MPH, RM118 million for HPH and RM9.7 million for LPH. The number of affected properties under the LPH sub-category is the least, i.e., 2,022 units, hence generated lower damage compared to HPH (16,105 units) and MPH (31,988 units). Besides the flood extent, the effect of flood

(a)

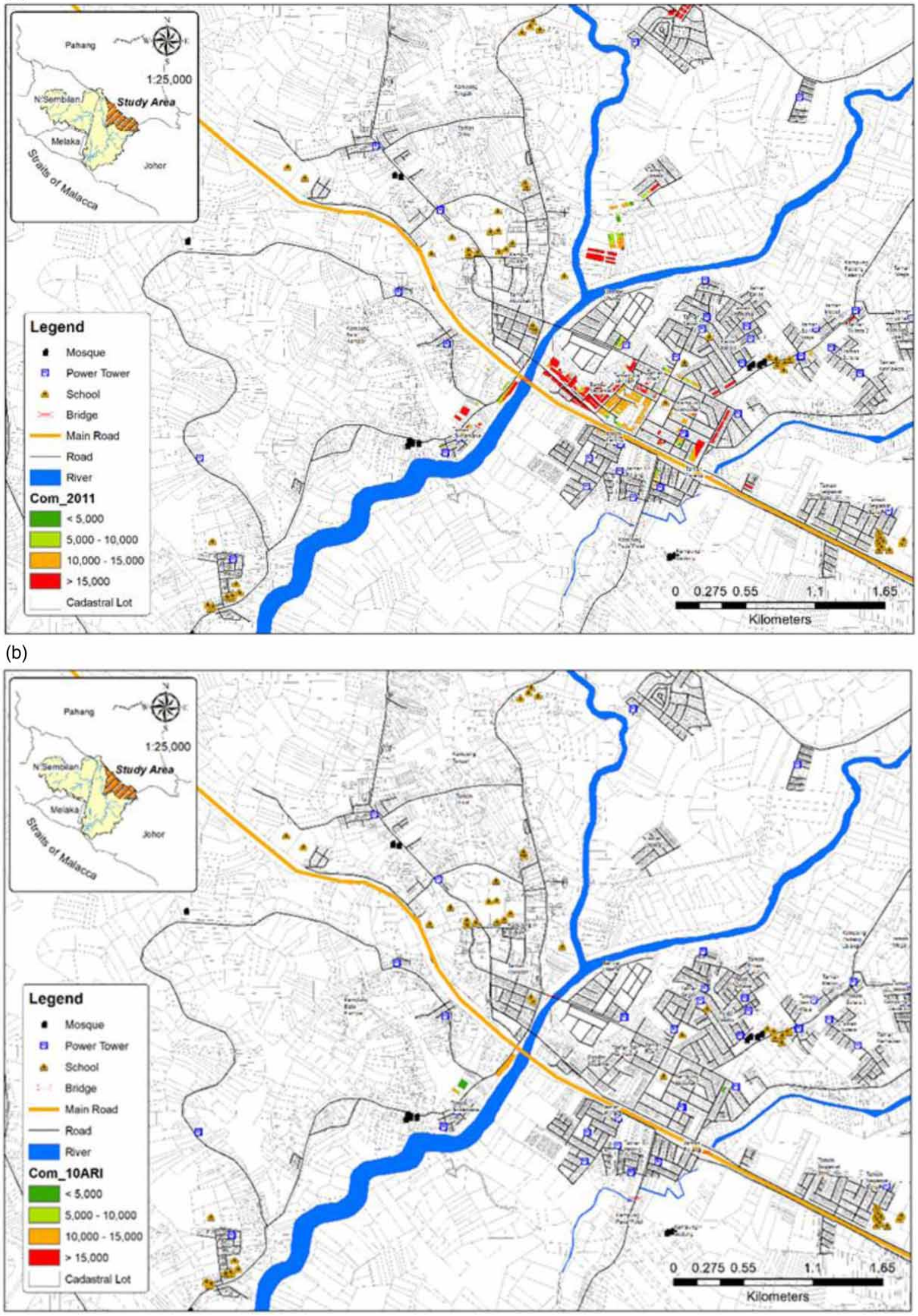


Figure 7 | Damage maps of the commercial category for (a) 2011, (b) 10-year flood, (c) 200-year flood, and (d) 1,000-year flood. (*Continued*.)

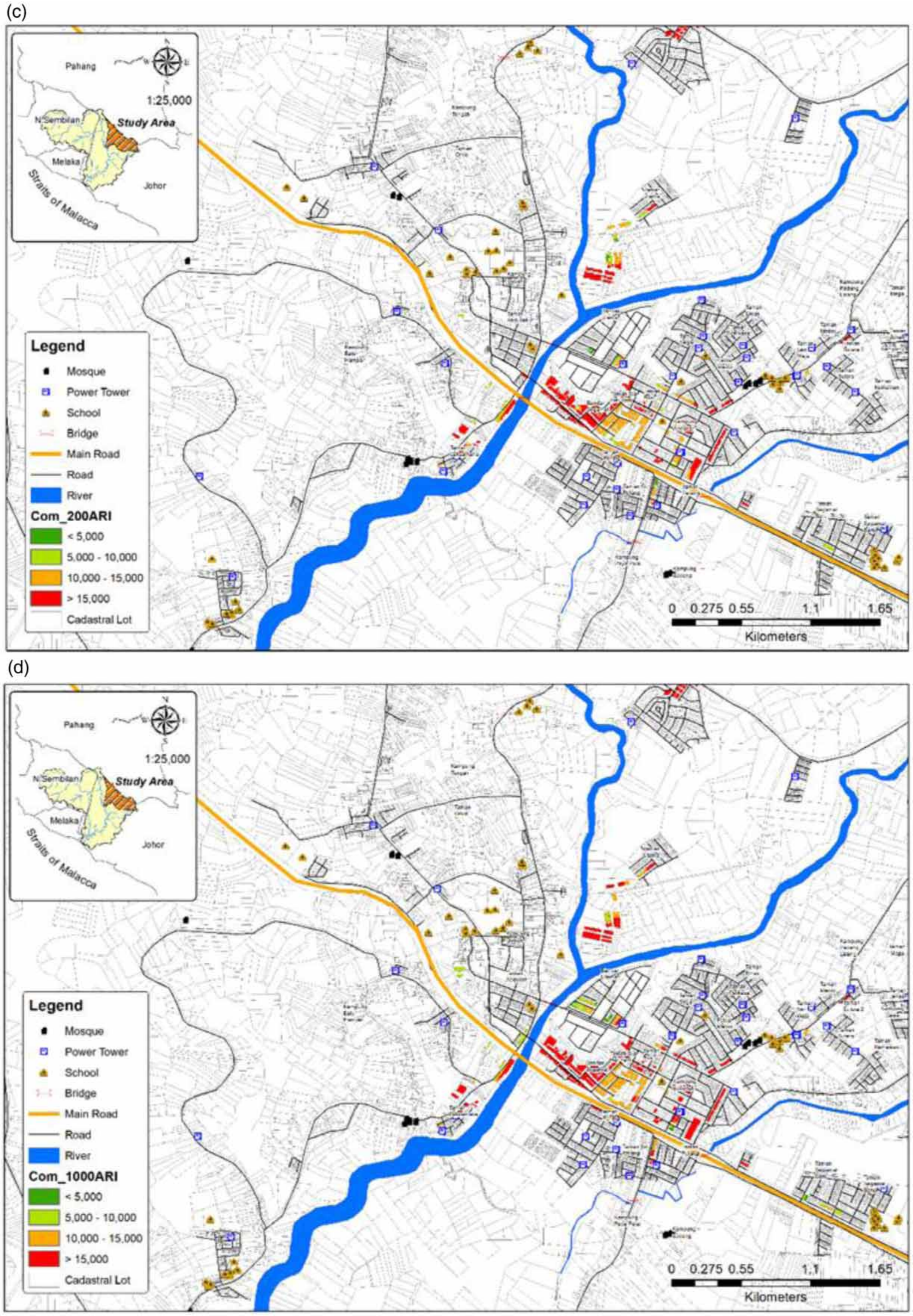


Figure 7 | Continued.

Table 4 | Sensitivity factor and damage estimates (RM) using variations of damage estimation components

Components		Flood damage (RM)	Sensitivity factor
Damage factor	DF 1	455,842,060	19.3
	DF 2	8,800,940,140	
	DF 3	2,158,923,978	
Inundation depth	ID 1	455,842,060	1.3
	ID 2	593,121,615	
Value of exposed elements	Average unit properties value	455,842,060	1.5
	Maximum properties value	697,043,080	

hazard to damage estimates is also attributed to flood depth where the MPH areas recorded the highest depth (5.87 m), followed by HPH (4.52 m) and LPH (3.71 m).

The effects of varying ARIs to flood risk can be observed in Table 3, where the flood damage increases as the return period used to estimate that risk increases. In Figure 5, it is interesting to see that the curve flattens off at return periods between 200 and 1,000 years. It is noted that at the maximum 1,000-year ARI, the damage for residential category is RM584 million, just 14% higher than the damage for 200-year ARI (RM485 million) and is only 5% higher compared to risk at 500-year ARI (RM555 million). This result is in agreement with Ward *et al.* (2011), who summarized that low return periods are responsible for a relatively large part of the total expected annual damage. The commercial risk increases abruptly from 25- to 50-year ARIs by a factor of 7, from RM6 to RM40 million annual damage. Figures 6 and 7 show no remarkable difference in the extent of damage for 200-year and 1,000-year ARIs. The maximum damage for both return periods is quite similar, i.e., RM23,654 and RM21,870 for 1,000- and 200-year ARIs, respectively. However, the maximum flood depth at 1,000-year ARI is higher (7.34 m) compared to the flood depth for 200-year ARI (5.59 m). The finding suggests that topography plays an important role in restricting the inundated area during large floods where additional increase in flood volume is translated into increase in depth rather than the areal coverage. As such, the damage is confined within the same residential and commercial areas. Another explanation for the relatively small increase in damage at higher ARIs is because the peak flow or annual maximum flow is not increasing in a linear form. Instead, peak flow tends to increase at smaller rates at higher ARIs, typically following a logarithmic function.

On the other hand, the value of damage factors has a more notable impact on the uncertainties of damage estimates with the highest sensitivity factor 19.3 (Table 4). For the inundation depth and value of exposed elements components, the uncertainties of the final damage estimates range from a factor of 1.3 to 1.5. These results seem to be consistent with others (De Moel & Aerts 2011; De Moel *et al.* 2012, 2014; Yu *et al.* 2013), who found that depth-damage curve is the most important source of uncertainties in damage estimates. The reliability of damage estimates in this study can be illustrated by these results of uncertainty and sensitivity analysis. The usage of non-site specific damage curve may result in an overestimation of flood damage. These components deserve prioritization in future flood damage works.

CONCLUSIONS

The distribution maps of damage are helpful for the management of flood risk where the information from the maps can be used to protect the area against flooding. The classification of flood risk area not only depends on the hazard characteristics, but is also influenced by the impact of the flooding (vulnerability). The information from the maps is useful to identify areas that are vulnerable to flood in monetary terms. For example, it is noted that some areas with high inundation depth on the hazard map (Figure 3(a)) register low damage values. During the 2011 flood, the damage is low (<RM5,000 per property) at Taman Segamat Baru although the flood depth was up to 2.5 meters. Hence, a map with reliable monetary damage information can assist the government, as well as private agencies, in improving flood management plans.

Overall, this study has successfully developed a framework to assess flood damage and risk for an urban area. The flood damage estimation framework combines the elements of hazard, exposure, and vulnerability. The main outputs of the study include a site-specific damage curve, flood inundation maps, flood damage estimates, flood damage–probability curve, expected annual damage (EAD), and flood damage risk map of Segamat town. The main findings of this study are summarized as follows:

1. The hydrological characteristics (flood hazard) affect the level of damage. The damage caused by the 2011 flood at Segamat town was RM594.2 million, of which, RM455.8 million was in the residential category or about three-fold higher than the commercial category (RM142.2 million). This is attributable to the affected residential area during the 2011 flood which is larger than the commercial area. This also explained the higher value of EAD for residential area (RM12.59 million) compared to commercial area (RM2.96 million).
2. A similar result is observed for different residential categories. The estimated damage was RM328 million for MPH, RM118 million for HPH, and RM9.7 million for LPH. The number of affected properties under the LPH sub-category is the least, i.e., 2,022 units, hence generating lower damage compared to HPH (16,105 units) and MPH (31,988 units). Beside the flood extent, the effect of flood hazard to damage estimates is also attributed to flood depth where the MPH areas recorded the highest depth (5.87 m), followed by HPH (4.52 m) and LPH (3.71 m).
3. The total damage is mainly associated with structural damage rather than content damage. For the residential area, the property structure contributed higher damage (RM294 million) than its content (RM162 million). For the commercial category, the damages were RM72 million for the structural and RM70 million for the contents.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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