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An Indicator-Based Approach for Micro-Scale Assessment of Physical Flood Vulnerability of Individual Buildings

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ABSTRACT

The current trends of floods event in many countries are alarming. Hence, managing flood and the associated risk are crucial in order to reduce the loss and to be well prepared for the combined impact of urbanization and climate changes. The best approach to manage flood activities is a risk-based approach, where the vulnerability of elements at risk is reduced to a minimum. There is a significant number of studies that use an indicator-based approach for flood vulnerability assessment with focus on the macro-scale. However, this paper assesses physical flood vulnerability of buildings at micro-scale using an indicator-based method in Kota Bharu, Malaysia. The region is one of the most flood affected regions in Malaysia. Micro-scale vulnerability assessment considers damages for individual buildings at risk, rather than in aggraded manner. In this study, the methodology adopted involve the use of 1D-2D SOBEK flood modelling, the selection and weightage of indicators, development of spatial based building index and, production of building vulnerability maps. The findings demonstrate the physical pattern of flood vulnerability of buildings at a micro-scale. The approach can assist in flood management planning and risk mitigation at a local scale.

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1. Introduction

Globally, flooding is the most destructive event in terms of collective and expected annual loss (Najibi and Devineni, 2018). In recent years, a risk-based approach has been proven to be beneficial in managing flood-related problems (Romali *et al.*, 2018). The term risk in a natural disaster is defined as "the combination of the probability of hazard occurrences and its (vulnerability) potential consequences" (Ayala *et al.*, 2020). Flood hazard is the context of this study. Therefore, flood risk is a measure of the statistical probability of flooding combined with its adverse consequences (DID, 2015). A risk is considered to be the elements of hazard, exposure and vulnerability, where the combination of these provides a better estimate of expected damages related to flood risk (Nasiri *et al.*, 2016). Similarly, flood risk is analyzed through the main components of risk: hazard, exposure, and vulnerability. In comparison to other types of natural hazard, "flood risk assessment" suffers inequality in the level of development among the three components, where hazard and exposure studies and assessments are more developed and advanced while vulnerability assessment and analysis are inadequately developed (UNISDR, 2017). Similarly, in Malaysia, most of the flood risk studies are on flood hazard modelling with little or no information on vulnerability level (Wahab and Muhamad Ludin, 2018; Zakaria *et al.*, 2017).

In day-to-day use of language, the term "vulnerability" is understood as the inability of elements to endure the effects of hazard or hostile environments (Ciurean *et al.*, 2013). Within disaster research, the concept of vulnerability keeps on developing from time to time. Likewise, there are various attempts to define and explain the meaning of "vulnerability" (Balica *et al.*, 2013; Liew *et al.*, 2019; Nasiri *et al.*, 2016). It is understood that the definition of vulnerability depends on the goal and nature of the scientific study to be conducted. Although, there is an agreement between the disaster risk management researchers' that "vulnerability is the root cause of disasters" (Ibrahim, 2017), however, in this study, the adopted vulnerability definition is that of UNESCO-IHE (2012) where "vulnerability is the extent of harm", which will occur under certain conditions of hazard, exposure and susceptibility. Figure 1 shows how the three mentioned factors of vulnerability interact with each other.

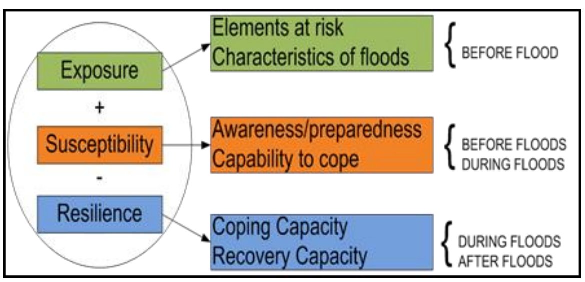

Figure 1 Vulnerability components (UNESCO-IHE 2012)

Likewise, there are several vulnerability assessment approaches (methods) which are different in their vulnerability description, methodology and theoretical framework (Nasiri *et al.*, 2016). However, the three most common approaches used in assessing flood vulnerability by most studies are vulnerability matrices, vulnerability curves, and, vulnerability indicator-based method, with each having some strength and weaknesses (Papathoma-Köhle *et al.*, 2017). The strength of Indicator-Based Method (IBM) to summarize the complexity and multidimensionality issues to gauge the level of vulnerability makes it more suitable for assessing the variables that influence the flood vulnerability of an element at risk. In Malaysia, significant number of studies use indicator-based approach for flood vulnerability assessment (Liew *et al.*, 2019; Hadi *et al.*, 2017; Ibrahim 2017; Lee *et al.*, 2018; Nasiri *et al.*, 2018). However, these studies focus more on macro-scale approaches and less on micro-scale approaches. Therefore, there is a need to develop an indicator-based method to address flood vulnerability at a micro-scale, especially when considering the primary goal of national flood risk assessments and mapping in Malaysia is an effort towards providing the country's non-structural solutions to support the structural measures (Zakaria *et al.*, 2017).

Recently, there are attempts to study the physical vulnerability of buildings to flood (Mazzorana *et al.*, 2014). Also, significant number of studies have argued that flood vulnerability assessment studies should focus on the identification and evaluation of variables that influence the vulnerability of specific element at risk (Liew *et al.*, 2019; Papathoma-Köhle, 2016; Connelly *et al.*, 2015). Unlike social vulnerability, assessing the physical vulnerability of all kind of hazard using Indicator-Base Method (IBM) is only in its infancy stage (Papathoma-Köhle *et al.*, 2017). Indicator-based assessment is used to evaluate different factors of vulnerability as variables, namely exposure factors, susceptibility characteristics and resilience characteristics (Mulok *et al.*, 2019); where "exposure" is seen as the predisposition of a system to be disrupted by a hazard because of its location in an area of hazard influence. Susceptibility is the likelihood or probability of harmed at times of hazardous floods. Resilience is the ability of an element to return to its normal capacity after being affected by flooding or the capacity of an element to survive a disaster by maintaining a significant level of strength of its physical components (UNESCO-IHE 2012).

Mostly the result from indicator-based vulnerability assessment produces vulnerability index, in this case, Flood Vulnerability Index and Flood Vulnerability Maps, which involves sequential stages, including the selection of indicators, their normalization, weighting and aggregation to a final index. However, the objective of this paper is to assess the physical flood vulnerability of buildings, using an indicator-based vulnerability method in Bandar Kota Bharu sub-district. The result is useful in flood management planning and risk mitigation. From the previous record, most of the events of the extreme floods recorded in Malaysia are in the east coast of the Malaysian peninsular (Alias *et al.*, 2016), mostly on the present-day state of Kelantan with Kota Bharu as one of the most affected areas.

The Indicator-based Method (IBM) measures indicators (variables) which represent characteristic of an element at risk that makes it unable to withstand the effects of a hazard, such as flooding (Müller *et al.*, 2011). The result is indices that can be represented on maps, and the representation is known as the vulnerability index. Among the physical structures at risk of floods, buildings are the most critical element at risk, and their vulnerability assessment and mapping require data and information from many sources (Papathoma-Köhle *et al.*, 2017). In order to represent the flood vulnerability of buildings on the map, flood vulnerability needs to be assessed and modelled for each building rather than in an aggregated manner (Custer and Nishijima, 2015). In Malaysia, there are limited researches on flood risk and vulnerability assessment at micro-scale. However, the objective of this paper is to introduce and demonstrate the practical approach for micro-scale flood vulnerability assessment of buildings using an indicator-based method. In December 2014 the Kota Bharu is affected by an extreme flood event resulting in several losses of life and properties. To prepare and prevent the future occurrences of such disasters, it becomes necessary to develop models and approaches for assessing flood vulnerability that can reduce flood consequences.

2. Description of the Study Area

The study area is Bandar Kota Bharu, located in Kelantan State of Malaysia. The city is located in the north-eastern region of Peninsular Malaysia. The district of Kota Bharu covers an area of approximately 409 km², with a total population of 314,964 in 2010

(Hua, 2015). It is located at latitudes 4°40'N to 6°12'N and longitudes 101°20'E to 102°20'E. Kota Bharu consists of seventeen sub-districts (Bandar Kota Bharu, Kadok, Limbat, Salor, Badang, Kemumin, Panji, Kota Bharu, Sering, Kota, Kubang Kerian, Banggu, Pendek, Pendek, Peringat, Beta and Ketereh) as depicted in Figure 2. Bandar Kota Bharu serves as the royal seat and the state capital of Kelantan. About 90% of Kota Bharu relief is between 2 to 10 meters above sea level, with relatively flat surfaces of overlying unconsolidated alluvial and depositional terrain of marine sediments. The entire Kota Bharu is situated in the Kelantan River Basin, which represents typical floodplains and basins that are prone to annual monsoon floods in Malaysia (Khan *et al*., 2014). Kelantan River constitutes the primary hydrological pattern of Kota Bharu, which contributed to shaping its terrain with many minor streams flowing into Kelantan River. According to Khan *et al*., (2014), the geographical characteristics of Khota Bharu, unplanned urbanization and proximity to the South China Sea make it is extremely vulnerable to monsoon floods every year. The unprecedented flooding of December 2014/January 2015 triggered by monsoon rains, has been described as one of the worst natural floods in the history of Kelantan with Kota Bharu and Kuala Krai as the most affected districts (Alias *et al*., 2016)

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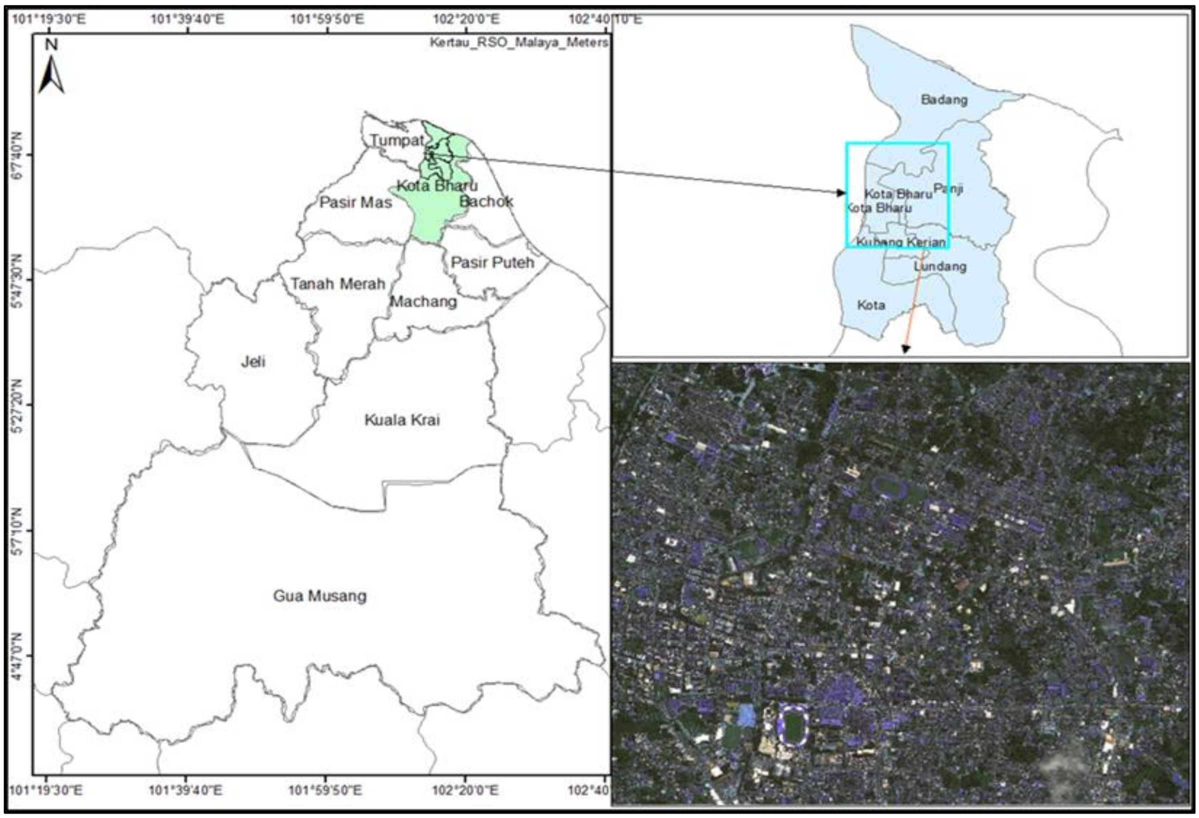

Figure 2 Location map of the study area in Kota Bharu

3. Methodology

The flow of methodology for assessing physical flood vulnerability of buildings is shown in Figure 3. The methodology involved 3 main stages which include 1-2D SOBEK flood modelling, selection and weighting of indicators, and building flood vulnerability computation and mapping.

3.1 1D-2D SOBEK Flood Modelling

Flood vulnerability is site-specific and hazards dependent (de Brito *et al*., 2017). Therefore, the first step adopted in this study is 1-2D SOBEK flood modelling for the mapping of flood hazard. It involves data collection, pre-processing of data, model schematization, flood simulation and generation of flood depth maps. It is important to establish the fact that for a building to be vulnerable to flood hazard, it has to be exposed to the hazard (Grahn and Nyberg, 2017). Therefore, flood hazard assessment and modelling are significant in order to define the level of flood exposure and vulnerability indicators that are related to hazard intensity such as flood depth, inundation, velocity and duration.

3.1.1 Data Acquisition

The required data for SOBEK flood modelling are Digital Terrain Model (DTM), hydrographs of inflow and outflow boundaries, land-use/land-cover information, stream network geometry and river cross-sections. The DTM data is acquired from LiDAR, which have 3-meter spatial resolution and is obtained from geoinformatics department, UTM. For the hydrographs, hydrological data is

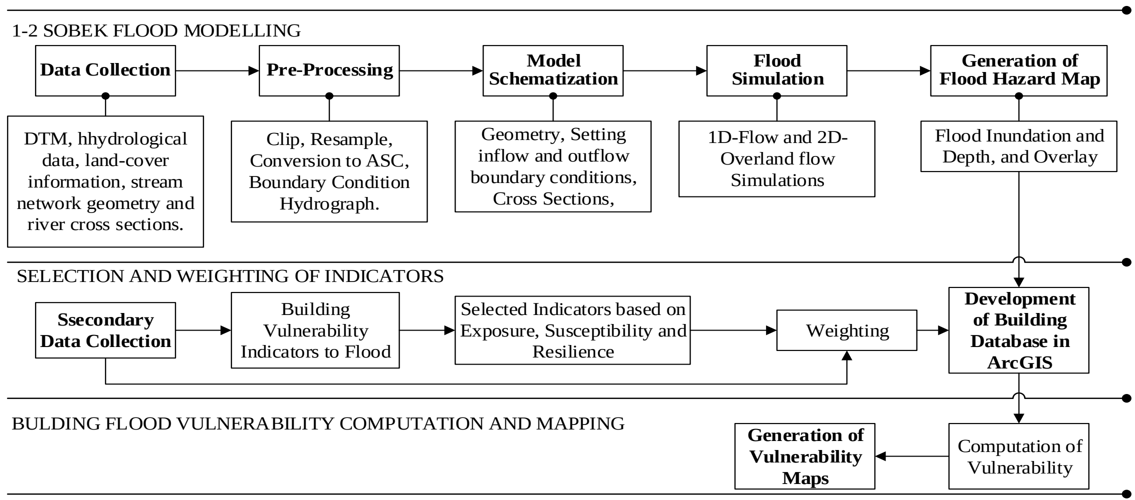

Figure 3 Flowchart of Methodology

obtained from the DID Sg. Kelantan hydrological station. The data consist of an hourly water level and streamflow discharge from 1 December 2014 to 1 January 2015. Furthermore, in order to conduct a realistic flood simulation, a detailed land-use map in shapefile ArcGIS format is used to estimate Manning's n value for input into SOBEK. For the computation of 1D model stream network, geometry and cross-sections are used as input.

3.1.2 Pre-Processing

The 3 meter LiDAR DTM is resampled to 90 meters spatial resolution for the input into the model schematization. This is necessary in order to reduce the simulation time. Extensive computation time is a major limitation in SOBEK 2D hydrodynamic modelling (Vanderkimpen *et al*., 2008). Likewise, the land-use map is converted into raster Manning's file, and the

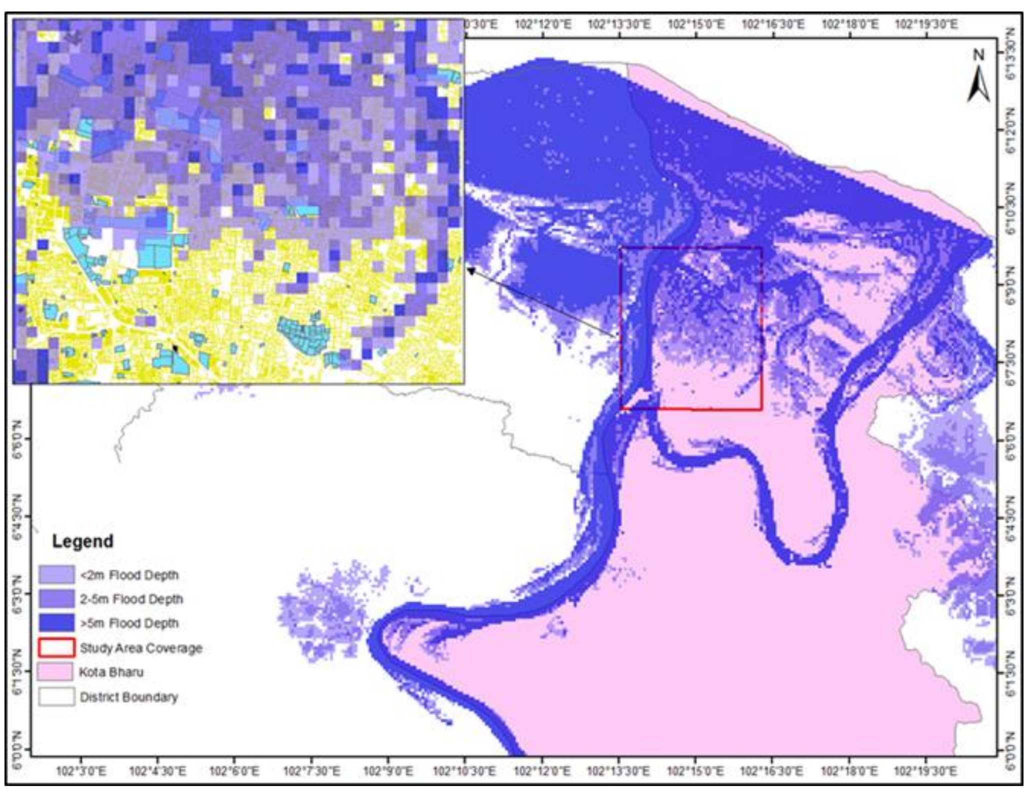

Figure 4 Generated flood inundation and depth map

spatial resolution of the DTM is used. The Manning's value used in this study for land-use classes is depicted in Table 1.

Table 1 Manning's *n* value of land-use (Maruti *et al*., 2018)

Land-Used Class	Manning's *n*
Water Bodies	0.033
Forest	0.3
Rubber	0.15
Paddy	0.2
Oil Palm	0.25
Built-up Area	0.8
Others Agriculture	0.2
Cleared Land	0.01

3.1.3 Model Schematization

This stage allows geometric data to be inserted into SOBEK using a network editor interface called NETTER. For the inflow and outflow boundary conditions. The hourly discharge hydrograph is selected for the upstream condition while the water level is selected for the downstream condition. The selected targeted to capture and simulated the December 2014 flood event in Kota Bharu, since the data is captured in real-time. Similarly, at this stage, both the DTM and Manning's raster files are inserted in SOBEK. Likewise, Sg. Kelantan geometry is digitized, and the cross-sections are added to the river network.

3.1.4 Flood Simulation and Generation of Flood Hazard Map

Using the model schematization, 1Dflow and overland flow are simulated. It simulated flood scenario in December 2014, where most of the Kota Bharu district is inundated by floodwater. This study mainly focuses on Kota Bharu urban center, but the entire Kota Bharu district is covered making the model a near real-life scenario. From the simulated results, the vital parameter of interest (i.e. flood inundation depth) is extracted. Therefore, the obtained model output is the floodwater inundation depth. The model output is exported into ArcGIS (see Figure 4) for further analysis.

Figure 5 Extraction of element-at-risk from satellite imagery using heads-up digitizing

The result is used to define buildings flood exposure of buildings in this study area.

3.2 Selection and Weighting of Indicators

The procedure used in identifying flood vulnerability indicators of buildings and their weight beins with the secondary data collection method; review of relevant literature is carried out in the scope of this research. A range of widely-accepted physical vulnerability indicators that are relevant to building flood vulnerability assessment are compiled together with their weight. However, due to the study limitations, this research selected the following indicators (it considered sufficient) as identified in Table 2 to demonstrate the vulnerability mapping capacity using IBM. The indicators are selected based on the three components of vulnerability; exposure, susceptibility and resilience. Each of the selected indicators are classified into different categories, with each category having a different vulnerability value. However, information on flood insurance and flood warning system are not sufficient therefore they are given 0 weight.

Table 2 Building indicators for flood vulnerability

Indicators	Score	Categories	Weight	Weight
Exposure:				
Floodwater depth	**0.3**	>3m 1.1-3m 0.5-1m <0.5m	1 0.75 0.5 0.25	(Ghazali and Osman, 2019)
Proximity to river	**0.1**	<20m 20-40m 40-80m >80m	1 0.75 0.5 0.25	(Kappes *et al.*, 2012)
Susceptibility				
Building materials	**0.3**	Wood Mix-material Unreinforced Reinforced	1 0.75 0.5 0.25	(Usman Kaoje et al, 2020)
Number of storeys	**0.3**	1 storey 2 storeys 3 storey >3 storey	1 0.75 0.5 0.25	(Ayala et al., 2020)
Resilience				
Insurance	**0.0**	Yes No	0 1	(Balaca, 2013)
Warning System	**0.0**	Yes No	0 1	(Balaca, 2013)

3.3 Development of Kota Bharu Building Footprint Database

Buildings footprints (polygons database) were derived from satellite data (world-view satellite imagery), land-use data, and street-view from google earth pro. First, the satellite imagery was used to manually digitize buildings footprint using the heads-up Digitizing method (see Figure 5). It involves visualizing the satellite imagery on a computer screen and then traces the points, lines and polygons using digitizing tools. Likewise, some building footprint were acquired during the field study using the ArcGIS Collector application at the same time, also their attribute. At this stage, each of the building footprints was assigned a feature number to maintain consistency during further processing. Google earth-pro is used in assigning building attribute (number of floors and construction material) to buildings that are not covered during the field study. The digitized polygon's projection was converted into a WGS-1984, a format recognized by the google earth pro application. Then they were directly imported into the application for the identification of their attribute (indicator category). Each building can be directly viewed using a street-view. From their building characteristics, information that is selected as indicators are assigned to each building. At this stage, weight of indicator categories are entered into the database. For proximity to river, a buffer tool in ArcGIS is used to measure buildings distances from the river. For floodwater depth, information obtained from flood modelling (see Section 3.1) was used.

3.4 Building Flood Vulnerability Computation and Mapping

From the final weight of indicators, an index value is assigned to each building using a flood vulnerability index equation adopted from the study of Kappes *et al.*, (2012). The approach uses a weighted linear combination method, an analytical method used in handling Multi-Criteria Decision Making (MCDM). Each indicator is assigned a weight based on its importance. The higher the score, the more significant an indicator is to the analysis. The computation is done by using Equation 1:

$$F - VI = \sum_{1}^{m} w_m * I_m \quad \text{(Eq 1)}$$

Where, $F - VI$ = flood vulnerability index, w_m = propriety score of indicator, I_m = indicator-category weight. The vulnerability index constructed here shows that buildings considered with high vulnerability will suffer more damage during flood occurrence. The building vulnerability is computed according to the model shown in Figure 6. The model is based on Papathoma Tsunami Vulnerability Assessment (PTVA) model (Dall'Osso et al., 2016; Papathoma-Kohle et al., 2019; Kappes *et al.*, 2012)

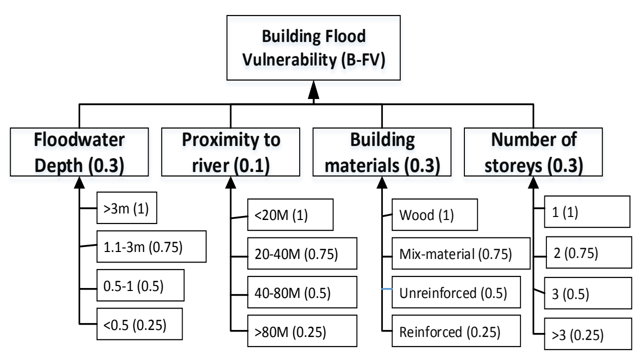

Figure 6 The vulnerability index computation model

4. Result and Discussion

The choice of variables used in the vulnerability analysis and their classification is very important (Ibrahim, 2017). In this study,

Table 3 Description of building flood vulnerability indicators

Indicators	Categories	Description
Exposure:		
Flood water depth.	>3m 1.1-3m 0.5-1 <0.5	At less than 0.5m flood depth, buildings are expected to stay dry during flooding. At flood depth of 0.5-1m; the ground floor is expected to be covered which may affect buildings, but less damage is expected. At 1-2m: The ground floor of buildings can be flooded and the people have to be evacuated or move to the other floors. Flood depth at 2-5m: the single storey buildings and the first floor of other buildings will be covered by flood water. At this stage, there is a high possibility of building collapse. At more than 5m flood depth, buildings with less than two storeys will be completely inundated by flood water and they have to be evacuation.
Proximity to river.	<20m. 20-40m. 40-80m. >80m.	The distance to a river can determine whether the building will be undercut by a fast eroding stream that can lead to collapse of buildings.
Susceptibility		
Building materials.	Wood/Light weight Mix-material construction Unreinforced masonry Reinforced masonry.	Different types of building materials behave differently under flood water saturation. Therefore, different level of vulnerability. It is expected that metal and concrete building are more resilient to flooding than wood constructed buildings and buildings constructed with mix-materials of both wood and concrete.
Number of storeys.	1 storey 2 storeys 3 storey >3 storey	More than one storey building offers vertical evacuation opportunity during flood disaster. It allows people and their properties to be move to upper floors of the building and also for evacuation.
Resilience		
Flood insurance.	Yes. No.	Flood insurance is used for flood recovery after flood event and it covers a dwelling for losses sustained by water damage from flood.
Warning System.	Yes. No.	Availability of flood warning service, whereby those at risk can be provided with a reliable information on what and when to expect flooding so they can be adequately prepared.

building vulnerability indicators are selected based on their significance in causing flooding in the study area. The sub-categories of flood depth indicator are extracted from the SOBEK flood modelling. Among the exposure indicators, flood depth is the most significant (Ouma and Tateishi, 2014). Furthermore, the study of Kappes *et al*. (2012) highlighted the significance of the influence of building surrounding to flood vulnerability, which may play an important role by offering protection from a range of hazards. However, Table 3 described the behaviours of the building indicators for flood vulnerability.

4.1 Spatial Distribution of Flood Vulnerability Indicators in Kota Bharu

As depicted in Figure 7, each indicator's spatial pattern is shown separately—map "A" of Figure 7 depicted buildings exposure to flood depth. Flood depth is an essential indicator among all the selected indicators. Without the impact of water depth, no damage is generated. An indication of how damaging floodwaters can depend on their depth. Map "B" represent buildings proximity to a river where flood is originated. Overflow of water bodies during the flood occurrence makes the adjacent area much more vulnerable and influences the water velocity as well (Maruti et al., 2018). Map "C" represent the spatial distribution of buildings based on their construction material and type. Lastly, map "D" shows the spatial distribution of buildings based on their number of floors. Custer and Nishijima (2015) suggest that the number of storeys are among the most vital indicators for building flood vulnerability. Likewise, if we acknowledge building structures as engineering structures. The foundation strength is a direct function of building weight, and building with more floors is expected to have more weight, making it difficult to wash away by floodwater.

4.2 Composite map Based on Integration of all indicators

Furthermore, a composite index map is necessary, where the collection of all indicators is combined to represent the overall flood vulnerability. Figure 8 shows the aggregated vulnerability results in a map with vulnerability values assigned to each building block based on vulnerability designations modified from Balica et al. (2013). The description of the rank designation of the vulnerability index is depicted in Table 4. The vulnerability map is derived using the vulnerability indicators after Figure 7. Since the 2014 flood event is a 100-year flood event (Alias et al., 2016), the simulated flood hazard map is also considered a 100-year hazard model. During a flood event, buildings with higher vulnerability rating are expected to suffer more damage. As a result, they should be evacuated when high intensity (100-year) flooding is forecasted. The flood damage description assignment to the vulnerability index is probably difficult in the index-based flood vulnerability assessment. However, since the primary purpose of the flood vulnerability index is to assess flood vulnerability index value to buildings in relation to vulnerability indicators, the generated index value of between 0 and 1 is divided into five using an equal distance, and the assigned index classes (Very Low, Low, Moderately, High, Very High) are based on standardized vulnerability indices (Balica et al., 2013).

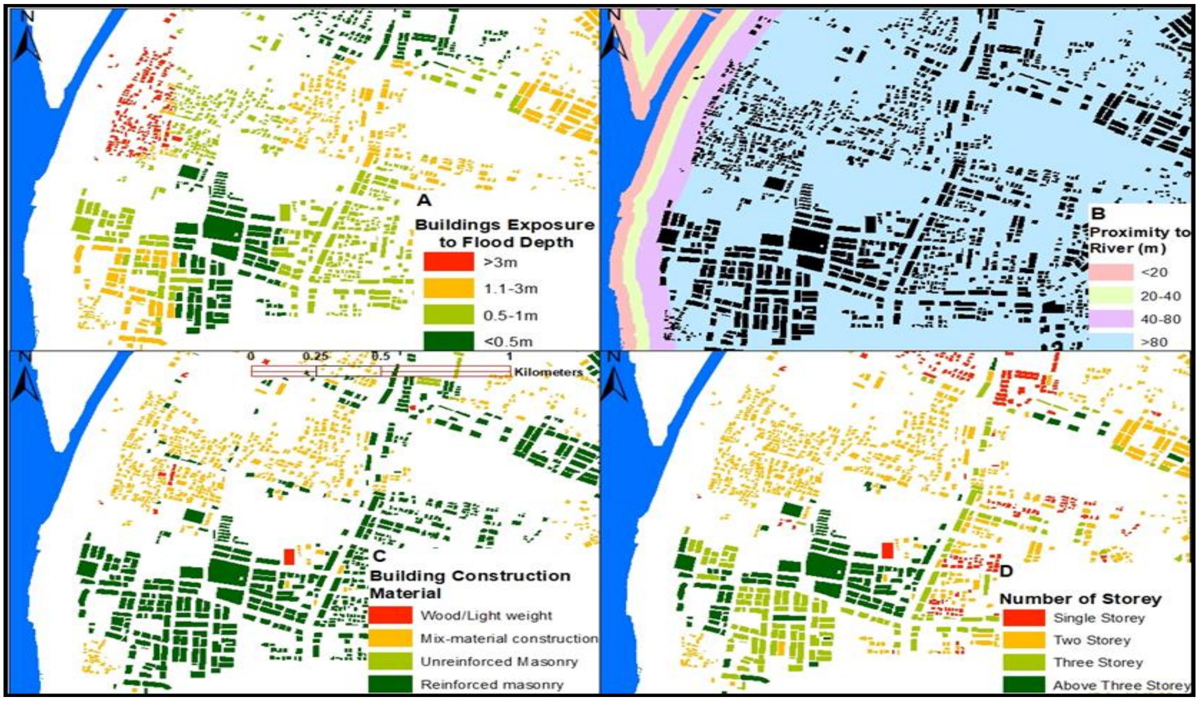

Figure 7 Spatial representation of building according to indicators categories (A) Flood depth, (B) Proximity to river, (C) building construction materials, (D) Number of floors

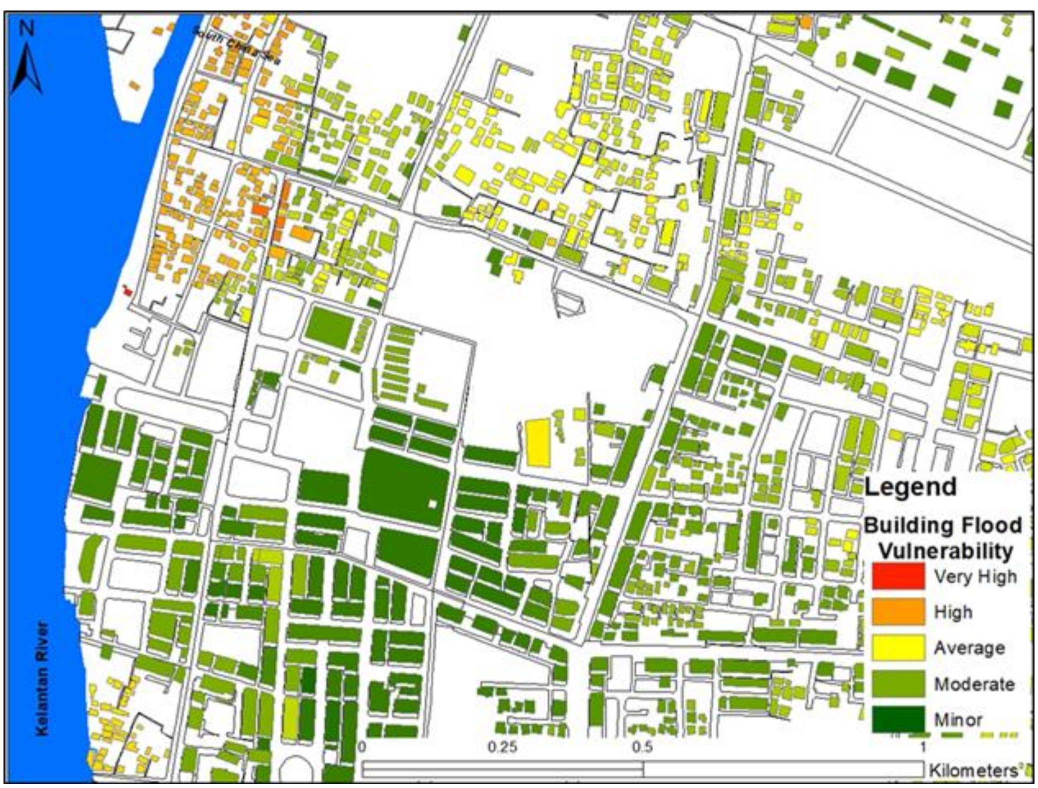

Figure 8 Spatial distribution of flood vulnerability in Kota Bharu

Table 4 Flood Vulnerability Designations (Modified from Balica *et al*., 2013)

Designation	Index Value	Description
Minor Vulnerability	0.00 – 0.20	Minimal vulnerability to floods, no property will be damaged, elements recover fast.
Moderate vulnerability	0.21 - 0.40	The element is vulnerable to flood, but the recovery process is fast due to the high resilience measures, damage to the infrastructure is minimal. If a flood occurs, the damages are not high, so small vulnerability.
Average Vulnerability	0.41 - 0.60	The element is vulnerable to floods, small amount of damage may be observing, the element can recover after flood water drains with a minimal damage. Average resilience measures.
High Vulnerability	0.61 - 0.80	The element is vulnerable to floods, significant amount of damage may be observing and properties may be lost, recovery process is slow, low resilience.
Very high vulnerability	0.81 - 1	The element is very vulnerable to floods, and it can experience total collapse or wash away by the floodwater.

5. Conclusion

This paper adopted the UNESCO-IHE definition of vulnerability. It carried out a flood vulnerability assessment of Bandar Kota Bharu buildings using the Papathoma-Kohle framework for physical vulnerability assessment. The study mapped the spatial distribution of flood vulnerability to explore the vulnerability of buildings. The flood vulnerability index of buildings presented in this study provides a scale of criticalities for individual buildings that will be severely affected at the occurrence of 100-year flood events. There is a difference between flood event and flood disaster. Small flood event occurrences in Kota Bharu is like an annual event. For an event to be seen as a disaster, it has to overpower the local coping capacities. Flooding at a 100-year event is seen as a great disaster and can cause widespread devastation. In anticipation of a flood disaster, the flood vulnerability index model can be utilized to prevent significant losses. Likewise, the current study demonstrates the ability of the indicator-based method (IBM) approach to identify individual infrastructures at high risk based on their vulnerability category. It also demonstrated the integration of the IBM approach with GIS by giving a clear visualization of building spatial vulnerability. This approach can help decision-makers in disaster management to make informed decisions, for instance, developing a spatial database for identifying buildings that need to be evacuated during flood disaster or in anticipation of high magnitude flooding. Such as in this study, buildings identified within the class of very-high vulnerable to floods can experience total collapse or wash away by the floodwater. As such, in planning flood evacuation, they require more attention. For future research, it is recommended to consider other necessary indicators that is location dependent as to empower the ability of spatial model in modelling vulnerability aspect.

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