Article

Physical Flood Vulnerability Assessment using Geospatial Indicator-Based Approach and Participatory Analytical Hierarchy Process: A Case Study in Kota Bharu, Malaysia

Ismaila Usman Kaoje [1], Muhammad Zulkarnain Abdul Rahman [1,*], Nurul Hazrina Idris [1,2], Khamarrul Azahari Razak [3], Wan Nurul Mardiah Wan Mohd Rani [4], Tze Huey Tam [1] and Mohd Radhie Mohd Salleh [1]

1   Tropical Map Research Group, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia; ismail.kaoje@fubk.edu.ng (I.U.K.); nurulhazrina@utm.my (N.H.I.); tzehuey85@gmail.com (T.H.T.); mohdradhie.gis@gmail.com (M.R.M.S.)
2   Geoscience and Digital Earth Centre, Research Institute for Sustainability and Environment, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia
3   Disaster Preparedness and Prevention Center, Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Kuala Lumpur 54100, Malaysia; khamarrul.kl@utm.my
4   Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia, Kuala Lumpur 54100, Malaysia; wnurul.kl@utm.my
*   Correspondence: mdzulkarnain@utm.my

Abstract: The most devastating flood event in Kota Bharu was recorded in December 2014, which affected several properties worth millions of dollars and thousands of homes. Damage to physical properties, especially buildings, is identified as a significant contributor to flood disasters in Malaysia. Therefore, it is essential to address physical flood vulnerability by developing an integrated approach for modeling buildings' flood vulnerability to decrease the flood consequences. This study aims at developing a flood vulnerability assessment approach using an indicator-based model (IBM) for individual buildings in Kota Bahru, Kelantan, Malaysia. An intensive literature review and expert opinions were used to determine suitable indicators that contribute to the physical flood vulnerability of buildings. The indicators were grouped into three components, i.e., flood hazard intensity (I), building characteristics (C), and effect of the surrounding environment (E). The indicators were further refined based on expert opinions and Relative Importance Index (RII) analysis. Based on their contribution to the Malaysia local building flood vulnerability, priority weight is assigned by the experts to each of the selected indicators using the participatory Analytical Hierarchy Process (AHP). A spatial database of buildings in Kota Bharu is developed through field surveys and manually digitizing building footprints from satellite imageries. The identified indicators and their weight are added to each building footprint. The Weighted Linear Combination (WLC) aggregation method combined the weight of indicators into a vulnerability index and maps. The results of a physical flood vulnerability were validated using building damage information obtained through interviews with the community that experienced previous flood in the study area. The result showed that about 98% of the study area's buildings have either moderate or low vulnerability to flooding. The flood vulnerability map has an overall accuracy of 75.12% and 0.63 kappa statistics. In conclusion, the IBM approach has been used successfully to develop a physical flood vulnerability for buildings in Kota Bharu. The model contributes to support different structural and non-structural approaches in the flood mitigations process.

Keywords: flood; buildings; physical vulnerability; flood risk; indicator-based; index

1. Introduction

In recent decades, there has been a significant increase in the frequency, intensity, and magnitude of flood events in different parts of the world [1,2]. In a large floodplain

area, avoiding floods occurrence is challenging. Hence, communities within flood-prone areas are adapted to the floods by reducing its impacts [1]. One of the cost-effective ways to manage and adapt to floods are through a flood risk assessment. This could be conducted by analyzing the probability of flood occurrences (hazard) and its (vulnerability) potential consequences [3]. The flood depth and extent are the most important variables to assess flood probability [4,5]. On the other part, the vulnerability assesses the potential susceptibility consequences of the hazard to the exposed physical elements [6].

Physical flood vulnerability assessment usually refers to the assessment of damage as a result of flooding to physical structures (human shelter), mainly buildings [7]. The term damage used here refers to harm to the physical elements-at-risk, as well as the amount of resources needed to restore the affected elements to their original function. Understanding, quantifying, and analyzing the vulnerability of physical properties is essential for designing strategies and adopting an approach for its reduction [8]. Studies specifically in Malaysia have shown that death from flood-related disasters has decreased; however, the number and value of physical property losses due to flood disasters has significantly increased [9,10]. The study of Chan [11] has shown an increase in the annual expected flood damage (in terms of Malaysian ringgit). In 1982, the average annual value of expected flood damage is less than RM100 million (about $25 million), which increases to RM915 million (about $222 million) in 2010. Some of the notable floods in Malaysia are in 1996 with an estimated damage value of RM300 million ($72 million), 2006 with an estimated damage value of RM1.55 billion ($376 million), and the flood event of 2014 where about 300,000 people are affected with property and infrastructure losses estimated to about RM2.9 billion ($704 million) [12]. The majority of floods recorded in Malaysia are river floods that occur after prolonged precipitation over large basin areas [9]. Usually, river floods do not occur suddenly, affect vast areas, and can last for some days to weeks [13]. Currently, the development, management, and implementation of flood mitigation measures in Malaysia are under the Department of Irrigation and Drainage (DID) [14]. The DID flood mitigation strategy and policy consist mainly of structural measures (e.g., construction of dams and embankments to control flood flows), non-structural measures (i.e., flood risk assessment and mapping, land use planning and flood forecasting, and warning systems to mitigate flood impacts), and flood disaster relief and preparedness machinery [15]. Nevertheless, the study of Romali [6] highlighted the necessity of having a balance between structural flood measures and non-structural flood measures in order to have a successful long-term flood risk management strategy.

Furthermore, flood risk is an outcome of interactions between flood hazard, exposure, and the vulnerability of the exposed elements-at-risk. Within the concept of flood risk, hazard refers to the probability of the occurrence of a potentially damaging flood event [16]. Whether a hazard could lead to harm depend on the exposure and vulnerability of the element-at-risk to the hazard [17]. Exposure in this concept refers to the presence of elements-at-risk (e.g., people, buildings, services, infrastructure, or other properties) that could be adversely affected [18]. Vulnerability is the degree of harm expected under certain conditions of exposure, susceptibility, and resilience [19]. Susceptibility is the likelihood of dangerous events occurring based on local element conditions or as a result of its inherent characteristics' inability to withstand the hazard impact [20]. Meanwhile, resilience is the ability of an element-at-risk to anticipate, absorb or cope with, resist, and recover from the impact of a flood hazard [21]. The popular methods for assessing physical flood vulnerability are vulnerability curve, vulnerability matrices, and the indicator-based method [22], which are used appropriately in different vulnerability assessment approaches within the phases of the risk cycle [23]. The indicator-based methods have the strength of allowing significant factors (e.g., building material, construction type, number of floors, level of maintenance, ground floor material) that contribute to flood vulnerability to be considered during the vulnerability assessment [20]. The method is flexible, easy to use, and able to be understood by decision makers. Unlike the quantitative method usually expressed by the vulnerability curve functions, the indicator-based method does not require a significant

amount of field flood damage records and empirical studies that relate between flood hazard intensity and its corresponding building damages [17,23]. The primary practice of an indicator-based approach is the use of composite indicators. Vulnerability indicators are defined as variables that are operational representations of a characteristic or quality of the system able to provide information regarding the susceptibility, coping capacity, and resilience of a system to an impact of an albeit ill-defined event linked to a hazard of a natural origin [23]. Usually, the result of an indicator-based approach is index and indices representing a degree of vulnerability on a scale. An index represents reality using numbers or a ratio derived from a series of observations used as indicators [24]. To effectively implement an indicator-based approach, the priority weight of importance or vulnerability contribution of indicators and sub-indicators must be specified to create the final index [25]. There are different techniques for assigning the weight of indicators. Some are statistical models, such as data envelopment analysis (DEA), principal component analysis (PCA), and factor analysis (FA). Some are participatory methods such as conjoint analysis (CA), analytic hierarchy processes (AHP), and budget allocation processes (BAP) [21,26]. The participatory approach also allows the use of expert opinion to assign weights of indicators to reflect policy priorities or theoretical factors better. Stakeholders such as experts, citizens, and policymakers can be used to assign weights. Participatory methods are recommended when the basis for a national policy is known and clearly defined [27].

In 2008, the Malaysian Water Resources Council (MSAN) granted permission to the DID to develop flood risk maps in Malaysia for non-structural flood mitigation solutions [28]. Since then, flood hazard assessment and maps for most river basins have been completed [12,15]. However, flood vulnerability assessment and mapping are not well developed [14]. Detailed flood vulnerability maps of physical element-at-risk at a microscale are still not available. In addition, the development of a quantitative physical flood vulnerability model in Malaysia is always hampered by a lack of and unclear approach to field damage assessment [12]. Hence, the contribution of this study is to develop a framework for flood vulnerability modeling and mapping in Malaysia using an indicator-based approach. This is important as a starting point for a comprehensive flood risk assessment in Malaysia. This study will help local authority reduce flood vulnerability and risk by introducing suitable building structures that can cope with the flood. This is important since a flood usually is an act of nature, and in this scenario, we have to live with this hazard. Similarly, this study developed an indicator-based physical flood vulnerability in Kota Bharu, which considers local building characteristics, flood intensity, and the surrounding area. Previous studies show that flood intensity has not been considered in the indicator-based modeling [2,20]. Specifically, the objectives of this paper are as follows:

- To identify significant and suitable indicators for physical flood vulnerability of different buildings structures in an urban settlement of Kota Bharu, Malaysia.
- To develop a physical flood vulnerability model of buildings based on the indicator-based approach by assigning the weight of importance for the selected physical flood vulnerability indicators using the AHP approach.
- To produce a flood vulnerability map of the individual buildings in Kota Bharu by aggregating the flood vulnerability indicators and their weights into the flood vulnerability index.

2. Materials and Methods

2.1. Study Area

The study area is in Kota Bharu, Kelantan, which is situated in the northeastern part of Peninsular Malaysia (see Figure 1). The terrain is relatively flat (low-lying areas) representing depositional terrain and overlying unconsolidated alluvial, coastal, and marine sediments of variable thickness [29]. The entire district of Kota Bharu is situated in the Kelantan River Basin, representing typical floodplains and basins prone to annual monsoon/river floods in Malaysia [30]. During the 2014 flood disaster, it was reported that the homes of about 16,734 families were displaced [31].
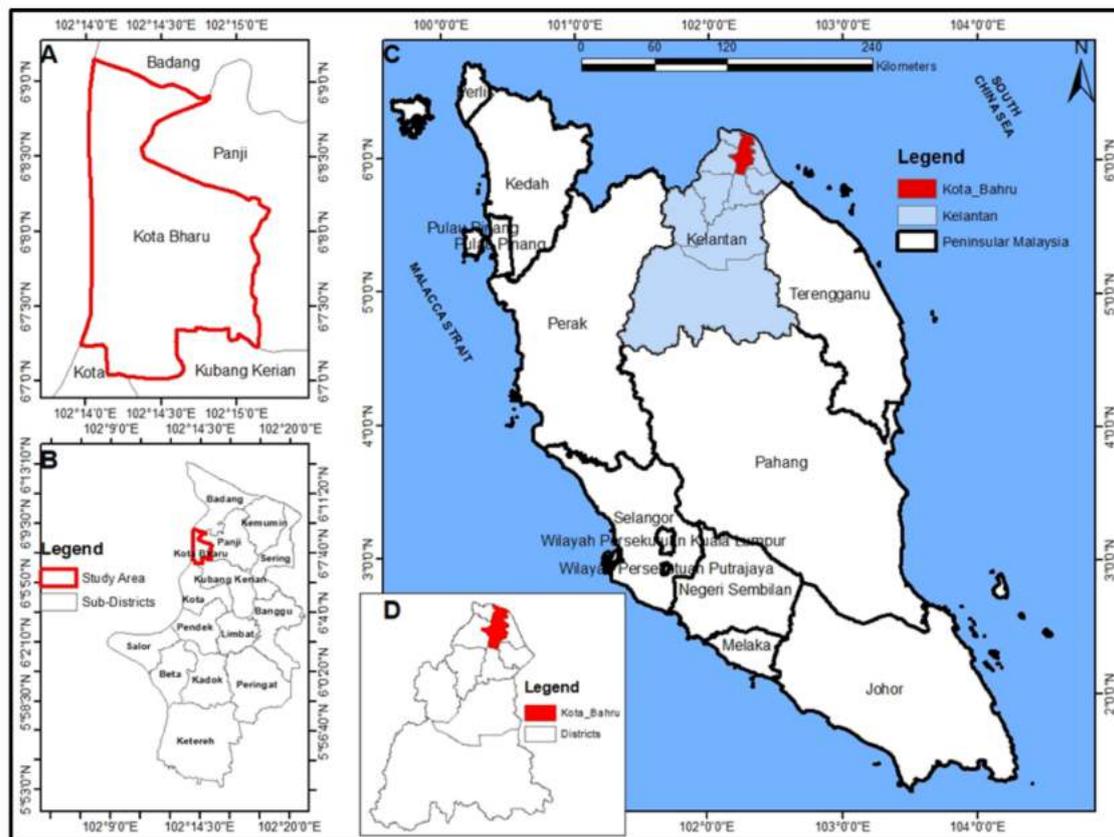
Figure 1. Location of the study area: (**A**) Kota Bharu city, (**B**) Kota Bharu District, (**C**) Peninsular Malaysia, and (**D**) Kelantan State.

2.2. Data Acquisition

WorldView-4 high-resolution satellite imagery taken in 2018 with a spatial resolution of 0.5 m is acquired for the purpose of extracting building footprints. For flood hazard simulation, several datasets are obtained from the Department of Irrigation and Drainage (DID). The obtained data are a Digital Terrain Model (DTM) with 3 m spatial resolution representing the floodplain terrain of Kota Bharu, river network geometry and cross-sections data for Kelantan River, detailed land-use for defining the Manning's n value, and hydrological data, which include hourly river flow discharge and hourly water level for the period of 1975 to 2015.

To validate flood vulnerability and hazard modelling, a field survey is conducted to collect previous flood records. The survey includes interviews to collect building damage information due to previous flood episodes. The survey is based on the stratified sampling strategy involving about 237 building samples from the 2014/2015 flood-affected areas. For validation of the flood hazard model, flood water depth marks are obtained from the field survey.

2.3. Hydrographs and Flood Hazard Modeling

In this study, the 1D-2D SOBEK flood hydrodynamic modeling is used to determine the flood extent and quantify flood hazard intensity. River discharge frequency is computed to define the probability of river flood occurrence. The maximum annual flow (m^3/s) of Kelantan River from 1975 to 2018 is used to determine the probability distribution (see Figure 2).
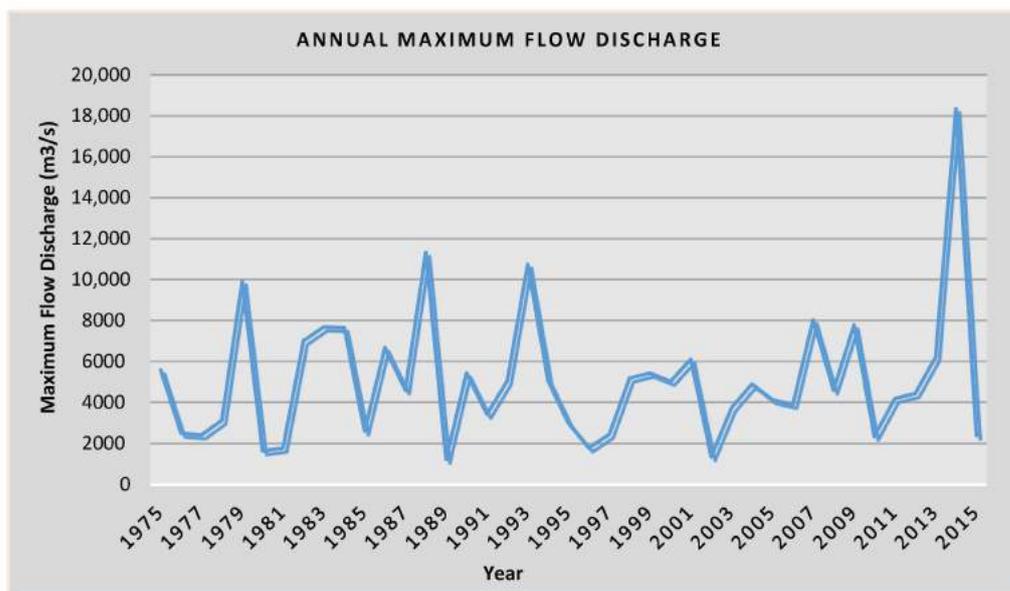
Figure 2. Maximum annual flow discharge of Sg. Kelantan from 1975 to 2015.

The selected probability distributions method used in this study is Log-Pearson III [32]. Flow discharge (m^3/s) is generated for the selected return period (see Figure 3). Peak flows corresponding to 2, 5, 10, 25, 50, and 100-year return periods are 4338 m^3/s, 7194 m^3/s, 9341 m^3/s, 12,314 m^3/s, 14,699 m^3/s, and 17,215 m^3/s, respectively. The 2014 flood event in Kota Bharu is classified as a 100-year flood event, and it is the maximum flood event ever recorded [9,30].
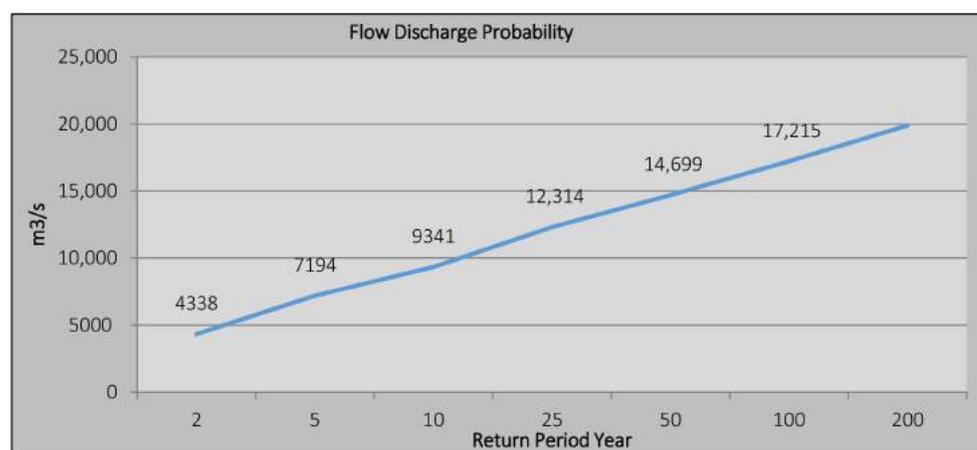

Figure 3. Flow discharge probability curve.

2.3.1. Defining Boundary Conditions, Model Schematization, and Flood Simulation

The DTM data acquired originally in 3 m spatial resolution were resampled to 90 m. This is necessary to reduce the size of simulation data and computation, which consequently reduce the simulation time. Extensive computation time is a significant limitation in SOBEK 2D hydrodynamic modeling. The river networks of the Kelantan River are necessary for the 1D flood simulation and used as the reference to digitize the river reach in the model schematization. Grid nodes are calculated at an interval of 200 m to define the reach direction from upstream to downstream. Similar to river networks, cross-sections are also necessary for characterizing the 1D river flow. For the flood simulation, 15 cross-sections are selected and inserted into the river network. The land-use and land-cover data are used to estimate Manning's *n* value by converting each land-use class into a raster pixel

with corresponding the Manning's *n* value. Flood modeling in SOBEK requires both inflow and outflow boundary conditions. The inflow boundary is set at the Kelantan River hydrological station located in the upstream area. The outflow boundary is set near the mouth of the Kelantan River (downstream), as shown in Figure 4. The inflow boundary condition is defined using per hour flow discharge (m^3/h), and the outflow boundary condition is defined using per hour water level data (m/h). The observed hydrological data records from 15th December 2014 to 1st January 2015 are used for inflow and outflow boundary conditions (see Figure 5).
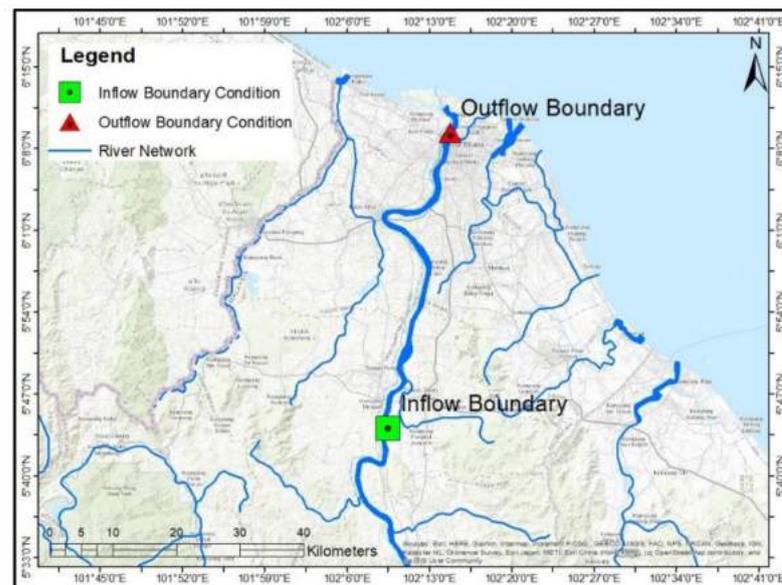

Figure 4. Location of inflow (upstream) and outflow (downstream) boundary conditions.
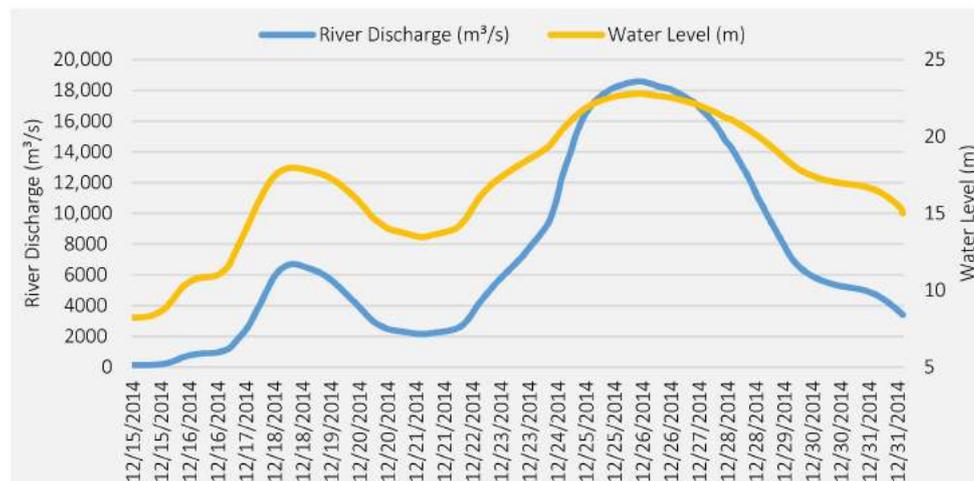
Figure 5. Input (Discharge) data for inlet boundary conditions–upstream and input (Water Level) data for outlet boundary conditions–downstream.

The SOBEK package consists of several modeling modules for river channel, including 1DFLOW and Overland Flow (2D). These models simulate the flood scenario of December 2014, where most of the Kota Bharu district is inundated by floodwater. The simulation model is set as unsteady calculation, in which water levels and discharge rates vary over time across the model area. The flood simulation results are generated for a 15-day period (17th December 2014 to 1st January 2015) at one-hour intervals covering the flood event

period. The output of the flood simulation is set to both hourly and maximum flood depth, flood level, and flood velocity. The flood calibration process is done by tuning the Manning's *n* value based on the differences between the observed and simulated flood level in the Kelantan River.

2.3.2. Post-Processing of Flood Modeling Results

The post-processing stage aims at producing spatial data that are ready for geographic information system (GIS) analysis to support flood exposure and vulnerability analysis. The water depth output is used to determine the flood extent. The maximum water depth of a 100-year return period flood is used in delineating the flood boundary in the study area. The flood extent map is used for flood exposure analysis, in which only the inundated buildings are selected for the flood vulnerability analysis. Flood depth, velocity, and duration (see Figure 6) will be used in the flood vulnerability analysis. Maximum flood depth and maximum flood velocity are used for the flood vulnerability analysis. Similar to most flood modeling packages, SOBEK does not provide direct information about flood duration. In this study, flood duration was derived from the post-processing of hourly flood depth. The raster files of flood depth are reclassified into a binary raster of 0 and 1. The values of 1 and 0 are assigned to inundated pixels (flooded area) and dry pixels (not flooded area). Finally, the raster files are summed up (using ArcGIS cell statistic tool) to generate the duration map.
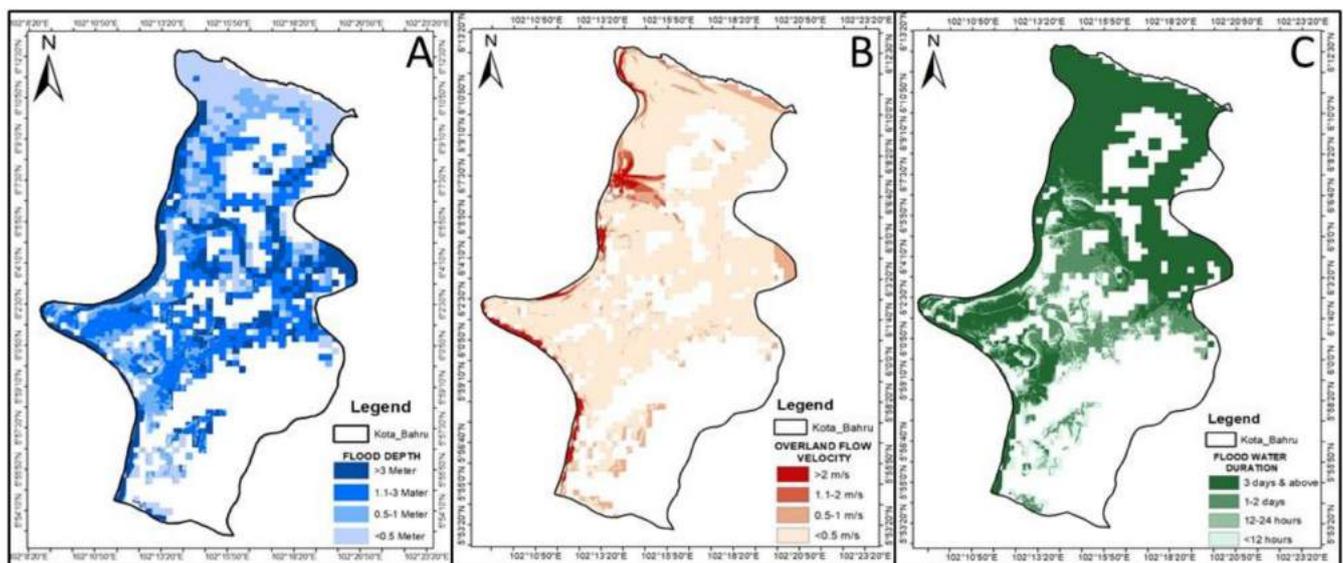

Figure 6. 100–year Kota Bharu simulated flood depth (**A**), flood velocity (**B**), and flood duration (**C**).

2.4. Flood Vulnerability Model

This study of flood vulnerability modeling employs the indicator-based method, which considers various indicators that directly impact the building damage due to flooding. The flood vulnerability modeling consists of four components, namely (1) identification and selection of flood vulnerability indicators, (2) assignment of weight for indicators and sub-indicators, (3) development of building vulnerability database and flood vulnerability modeling, and (4) validation of flood vulnerability results.

2.4.1. Identification and Selection of Flood Vulnerability Indicators

The flood vulnerability indicators and sub-indicators should consider flood and building characteristics in Malaysia, especially in Kota Bharu. The selection of relevant indicators went through the secondary data collection method (literature review), then empirical observation from the field study, and expert opinion survey. First, a range of potential

physical flood vulnerability indicators (see Table 1) are compiled and grouped into three clusters, i.e., flood hazard intensity (I), characteristics of buildings (C), and surrounding environment (E). Furthermore, an expert opinion survey form is designed containing all the potential indicators obtained from the literature review. A total of 31 experts are used for the selection of the final indicators. The experts are selected from different relevant specializations and organizations using a snowballing sampling approach. Among the respondents, 39% (12) are university professors/lecturers, 23% (7) are personnel of the Department of Irrigation Drainage (DID) Malaysia, 19% (6) are university post-graduate researchers, and 19% (6) are from other relevant organizations. The survey forms for the expert opinion survey are designed based on a closed-ended format. The experts assign a score of relevance to the indicators and sub-indicators based on their understanding, expertise, and experience on flood vulnerability in Malaysia. The respondents rated the indicators and sub-indicators on a 10-point scale from 1 to 10, using the scale of relevance, as shown in Table 1.

Table 1. Scale of importance and relevance of indicators and sub-indicators to the physical flood vulnerability.

Scale	1	2	3	4	5	6	7	8	9	10
Importance and relevance	Insignificant	V. Low	V. Low to Low	Low	Low to Mod.	Moderate	Mod. to High	High	H. to V. High	Very High

V. stands for very; Mod stands for moderate; H stands for high.

The return questionnaires forms were analyzed using the Relative Importance Index (RII) method to determine the suitability of each indicator and sub-indicator based on expert agreement. The formula adopted for RII is shown below (see Equation (1)).

$$RII = \frac{\sum w}{A \times N} (0 \leq RII \leq 10) \tag{1}$$

where w is the score as assigned by each respondent on a scale of 1 to 10. A is the highest score (10), and N is the total number of the respondents. Based on the RII of indicators, an RII weight of >0.50 is accepted, and indicators with an RII value below 0.50 are considered rejected [33], as shown in Table 2.

2.4.2. Assignment of Weight for Indicators and Sub-Indicators

After selecting indicators, the next stage is developing a model for the weighting and aggregation of the indicators into the vulnerability index. Indicators that determine the physical flood vulnerability of buildings have different levels of relevance in generating flood vulnerability. In this study, the Analytic Hierarchy Process (AHP) weighting approach is utilized to generate indicators' weight. The AHP method is a descriptive approach to support decision making developed by Thomas Satty in calculating the weight of factors from paired comparisons [34]. At first, a hierarchy of the decision problem is structured, as depicted in Figure 7. In this approach, the goal and vulnerability components are arranged in a hierarchical structure. The AHP model construction starts by defining the objectives, which is in this study to assign a physical flood vulnerability index score to buildings within the study area through prioritizing indicators. The hierarchical model is constructed with arrows going in one direction from top to bottom. Four sets of pairwise comparisons are carried out for this model: the components with respect to the goal and the indicators with respect to the vulnerability components. The paired comparison was conducted through an expert elicitation and questionnaire survey. A geometrical averaging method is used in aggregation of the respondent feedback.

Table 2. Expert opinion agreement on physical flood vulnerability indicators.

Indicators		(N = 31)			Decision
		Weighted Total ($\sum w$)	RII	Mean	
Characteristics of buildings (C),	Construction type and material	251	0.81	8.097	Selected
	Number of floors	218	0.70	7.032	Selected
	Presence of basement	82	0.26	2.645	Rejected
	Basement windows/opening	90	0.29	2.903	Rejected
	Height of opening from the ground	93	0.30	3.000	Rejected
	Age of building	64	0.21	2.065	Rejected
	Type/Use of building	39	0.17	1.696	Rejected
	Building size	98	0.38	3.769	Rejected
	Level of Maintenance/condition	113	0.36	3.645	Rejected
	Height of the building	92	0.30	2.968	Rejected
	Stilts/Elevated buildings	174	0.56	5.613	Selected
	Ground floor foundation material	205	0.66	6.613	Selected
Flood hazard intensity (I),	Flood water depth	302	0.97	9.742	Selected
	Flood duration	160	0.52	5.161	Selected
	Flood water Velocity	214	0.69	6.903	Selected
	Water sedimentation	42	0.14	1.355	Rejected
	Flood return period	98	0.32	3.161	Rejected
Surrounding environment (E)	Building distance from the coasts	116	0.37	3.742	Rejected
	Building row towards river	121	0.39	3.903	Rejected
	Building surrounding fence	104	0.34	3.355	Rejected
	Building surrounding vegetation	93	0.30	3.000	Rejected
	Distance from main river	219	0.71	7.065	Selected
	Terrain elevation	61	0.20	1.968	Rejected
	Drainage system	134	0.43	4.323	Rejected
	Existence of mitigation measures	128	0.40	4.000	Rejected
	Proximity to major road	212	0.68	6.839	Selected

The next step is the analysis of a pairwise comparison. The aggregated final pairwise comparison and model structure were inserted into Super-Decision software to manage the analysis effectively. After the pairwise comparison matrix, each matrix is normalized, and the principal right eigenvector (priority vector) of the matrix is computed by averaging across the rows of the normalized matrix. Lastly, to validate the AHP results, the consistency ratio (CR) is calculated using Equation (2) where CI is the Consistency Index and RI is the Random Index.

$$CR = CI/RI \tag{2}$$

$$CI = (\lambda\_max - n)/(n - 1) \tag{3}$$

The value of RI is related to the dimension of the matrix. It is usually extracted from the Random Consistency Index table. If the final consistency ratio exceeds this value, the evaluation procedure must be repeated to improve the model consistency [35]. In this study, the degree of consistency of all the pairwise comparisons are considered satisfactory, as shown in Table 3.
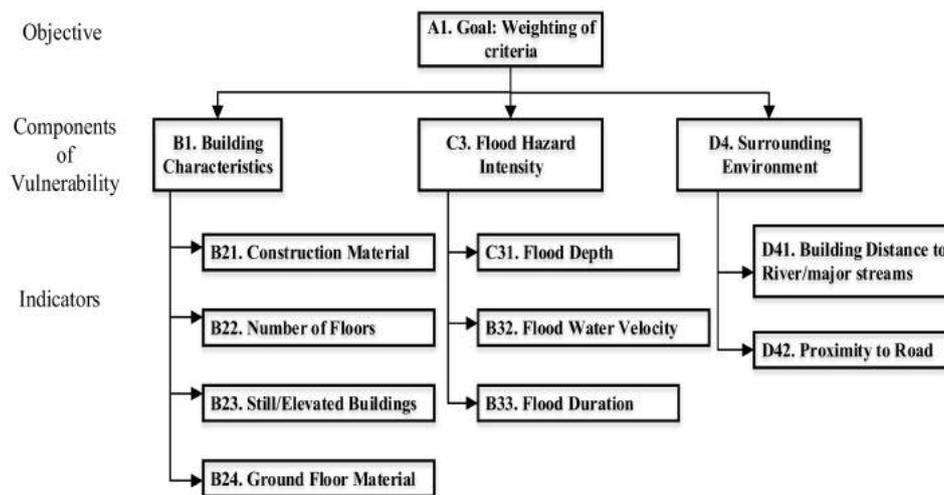
Figure 7. AHP hierarchical model of physical flood vulnerability indicators.

Table 3. Inconsistences index result of the AHP model.

Pairwise Comparison Cluster	Number of Items	Consistency Ratio (CR)	Random Index (RI)
Vulnerability components cluster	3	0.001	0.58
Building characteristics cluster	4	0.027	0.90
Flood hazard intensity cluster	3	0.036	0.58
Surrounding environment cluster	2	0	0

To aggregate the weights of flood vulnerability indicators into a flood vulnerability index of individual buildings, the AHP rating approach is used to rate the sub-indicator classes. It involves making paired comparisons of the criteria just above the alternatives, which are known as the covering criteria. The sub-indicator classes are assigned with intensities that vary in number and type. For example, these intensities can be high, medium, and low; or for a number of floors—single stories, two stories, three stories; or for flood depth, it can be <0.5 m, between 0.5 m and 1, and above 1 m. The classes are pairwise compared to obtain their priorities as to the importance. Then, they are put in ideal form by dividing with the largest value. Ratings are useful when the number of alternatives is very large to pairwise comparisons for each criterion. The ratings are of the assumption that very high is twice as high; likewise, high is twice the size of moderate, and it continues like that. The generated indicators weights calculated from AHP and the ratings of indicator classes are further integrated using the weighted linear combination method (WLC) in an ARCGIS environment for the computation of the flood vulnerability index of individual buildings. The following formula (Equation (4)) was used for the computation. Each indicator is multiplied by its indicator class's weight and the summation of all computed values is the final index value for each building. A scheme in Figure 8 demonstrates how the equations work. The index is proposed to be divided into five classes of expected vulnerability: very high (0.81 to 1), high (0.61 to 0.80), moderate (0.41 to 0.60), low (0.21 to 0.40), and very low (0 to 0.20), with each class vulnerability having a specific damage description.

$$F - VI = \sum_{1}^{m} w_m \times I_m \tag{4}$$

where $F{-}VI$ = flood vulnerability index, w_m = propriety weight of indicator, and I_m = indicator-class rating.
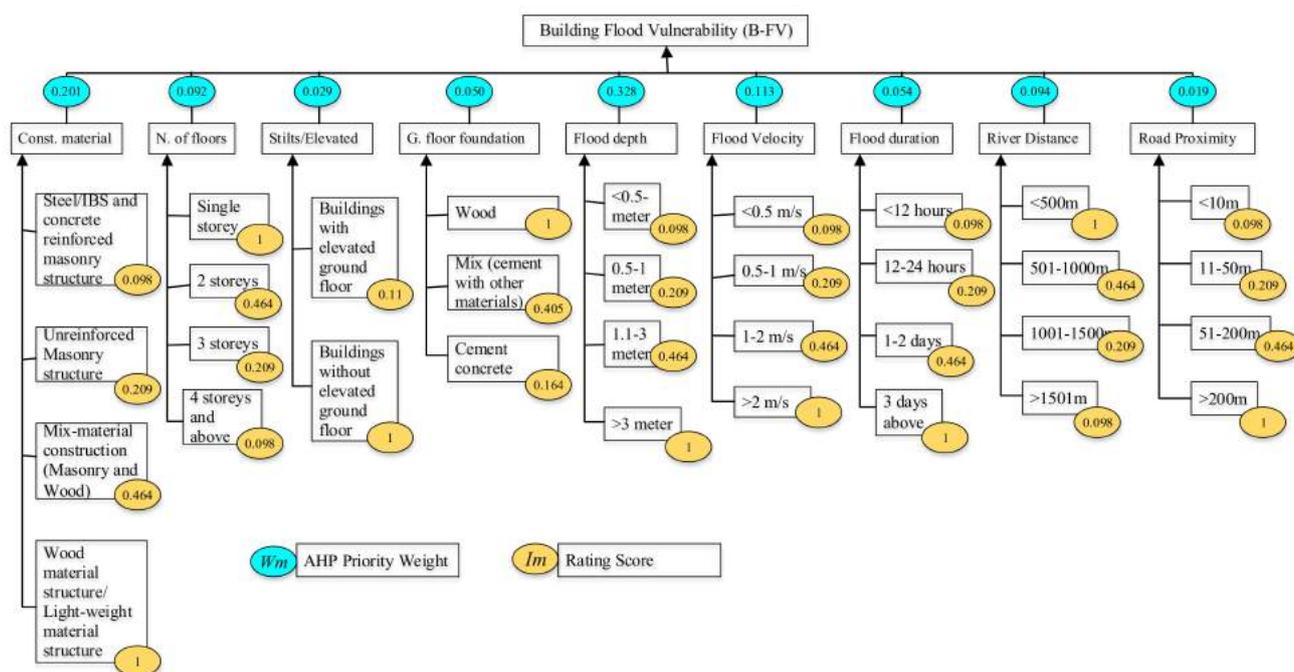
Figure 8. Aggregation model through Weighted Linear Combination.

2.5. Development of Building Vulnerability Database and Flood Vulnerability Modeling

Building footprints and their characteristics were extracted from a high-resolution world-view satellite imagery, land-use data, street-view from Google Earth Pro 7.3, and field survey. Satellite imagery was used for digitizing building footprints using the heads-up digitizing method. Due to complicated the building arrangements and locations in the study area, some building footprints were acquired through field visits. Each building's exact location was recorded using the ArcGIS Collector (version 20.2.2) application during the field survey. Based on the building footprints, a specific attribute database was developed for each indicator and sub-indicator. The indicator and sub-indicator values for each building were assigned based on the on-screen image interpretation and field visits. The on-screen method employs high-resolution satellite image and information obtained from Google Earth Pro in assigning indicators and sub-indicators to buildings. However, for assigning information regarding proximity to river and proximity to roads, a buffer tool analysis in ArcGIS 10.5 is used to measure buildings distances from the river and roads. Flood depth, flood velocity, and flood duration information were obtained from SOBEK flood hazard modeling (see Section 2.3).

2.6. Validation of Flood Vulnerability Model

The validation aims at comparing the estimated building damages and the building damage records obtained from the field survey or interviews. The field survey was done for selected individual buildings, and detailed interviews were done to complement the partial damage records due to the 2014 flood. At this stage, the past flood record data are also classified into five classes: very low vulnerability to floods, low vulnerability to floods, moderate vulnerable to floods, high vulnerability to floods, and very high vulnerability to floods. For the comparison purpose, a confusion matrix (Error Matrix) analysis is utilized to specify the overall and specific accuracies of the flood vulnerability modelling. The estimated building damages classes obtained through the vulnerability modelling are compared with the field data (reference data). From the confusion matrix analysis, the

commission error, omission error, producer accuracy, user accuracy, overall accuracy, and Kappa coefficient were derived using the following equations.

$$Overall\ Accuracy = \frac{\sum_{i=1}^{k} n_{ii}}{n} \qquad (5)$$

where n_{ii} represents the proportion of subjects in each category for which the two samples class agreed on the assignment. n is the total number of samples. Finally, the kappa coefficient is calculated. It is calculated using both the observed (total) accuracy and the random accuracy where $p_{(a)}$ is total accuracy, and $p_{(r)}$ is random accuracy.

$$Kappa = \frac{p_{(a)} - p_{(r)}}{1 - p_{(r)}} \qquad (6)$$

The kappa coefficient evaluates how well the generated flood vulnerability classification performed compared to the field damage record. A value of 0 to 1 indicates that the classification is significantly better than random with each value between 0 and 1 representing a certain degree of acceptance [36]. The values are interpreted into <0.20 as poor, 0.21–0.40 fair, 0.41–0.60 moderate, 0.61–0.80 substantial, and 0.81–1.00 almost perfect.

3. Result

Table 4 shows the priority weights of vulnerability components and indicators as obtained from the pairwise comparison. The table also depicts an ideal priority weight of the indicators' classes obtained from the AHP rating approach.

Accordingly, flood hazard intensity (I) is considered the most important with the priority weight of 0.52 (52%), which is followed by the building characteristics (C) 0.37 (37%) and lastly the characteristics of the surrounding environment (E) with the priority weight of 0.11 (11%). The total sum of the priority weight is 1.00 (100%), which is divided among the three components based on their pairwise comparison. The weight shows each component contribution in generating flood damage. Furthermore, the local weight highlights indicators relevant within each component, which is driven from the pairwise comparison. The local weight is multiplied by the component's priority weight to obtain the global weights of indicators. Global weights indicate that 'flood depth' (0.328) is the most relevant and vital factor among the nine physical flood vulnerability indicators; it is highest ranked and is followed by 'construction type and material' (0.2014) and 'flood velocity' (0.139): these are the three most important indicators. The fourth relevant indicator is 'distance to main streams and river' (0.094), followed by the 'number of floors' (0.092) and 'flood duration' (0.054). Others in order of ranking are 'ground floor foundation material' (0.050) and 'stilts/elevated building' (0.0287). The lowest-ranked vulnerability indicator is 'proximity to main road' (0.019).

From the selected list of flood vulnerability indicators, the actual circumstances that determine physical flood vulnerability are site-specific, hazard-dependent, and elements-at-risk dependent. Therefore, the collection of hazard information is necessary to define flood vulnerability indicators that are related to hazard intensity and also to determine the flood inundation extent for the identification of exposed buildings. In this study, flood depth, over-land water velocity, and flood duration are indicators that defined hazard intensity and exposure.

Footprints of affected buildings are the primary input for the flood vulnerability modeling developed in this study. Therefore, flood hazard maps are used to determine the exposure of affected buildings. As shown in Figure 9, the flood hazard map was overlaid on a buildings polygon to extract on exposed buildings. One of the strong arguments of this study is that for a building to be vulnerable to flood, it has to be exposed to the hazard [37].

Table 4. Priority weights of indicators and indicator classes rating.

Vulnerability Components	Indicators	Local Weight	Priority Weight	Indicator Classes	Rating
C (0.37)	Construction type and material	0.542	0.201	Steel/IBS and concrete reinforced masonry structure	0.098
				Unreinforced masonry structure	0.209
				Mix-material construction (masonry and wood)	0.464
				Wood material structure/lightweight material structure	1
	Number of floors	0.247	0.092	Single story	1
				2 stories	0.464
				3 stories	0.209
				4 stories and above	0.098
	Ground floor foundation material	0.134	0.050	Cement concrete	0.164
				Mix (cement with other materials)	0.405
				Wood	1.00
	Stilts/Elevated building	0.077	0.029	Buildings with elevated ground floor	0.11
				Buildings without elevated ground floor	1.00
I (0.52)	Flood water depth	0.637	0.328	<0.5 m	0.098
				0.5–1 m	0.209
				1.1–3 m	0.464
				>3 m	1.00
	Flood water velocity	0.258	0.133	<0.5 m/s	0.098
				0.5–1 m/s	0.209
				1.1–2 m/s	0.464
				>2 m/s	1.00
	Flood duration	0.105	0.054	<12 h	0.098
				12–24 h	0.209
				1–2 days	0.464
				3 days above	1.00
E (0.11)	Distance to main streams and river	0.833	0.094	<500 m	0.098
				501–1000 m	0.209
				1001–1500 m	0.464
				>1501 m	1.00
	Proximity to main road	0.167	0.019	<10 m	0.098
				11–50 m	0.209
				51–200 m	0.464
				>200 m	1.00

After identifying the exposed building structures, the vulnerability of the affected buildings is computed. Using the selected flood vulnerability indicators and developed weight for each indicator, the flood vulnerability index and map of the study location is generated. The buildings vulnerability Index (VI) 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. A total of 7780 building footprints located within the simulated 100-year flood inundated area of Kota Bharu city were successfully extracted for their vulnerability assessment. The generated flood physical vulnerability index (VI) as shown in Figure 10 was classified into five categories based on the proposed vulnerability classes: 0.00–0.20 (very low), 0.21–0.40 (low), 0.41–0.60 (medium), 0.61–0.80 (high), and 0.81–1.00

(very high). The proposed description of the vulnerability index classes (see Table 5) was determined from the field study-based 2014 flood record.
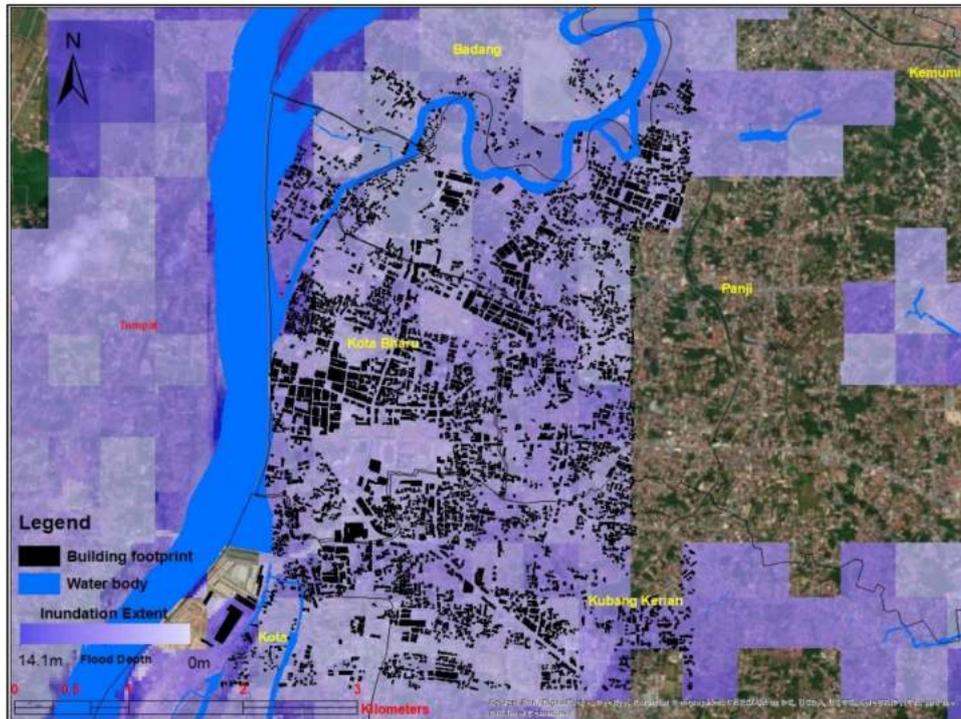

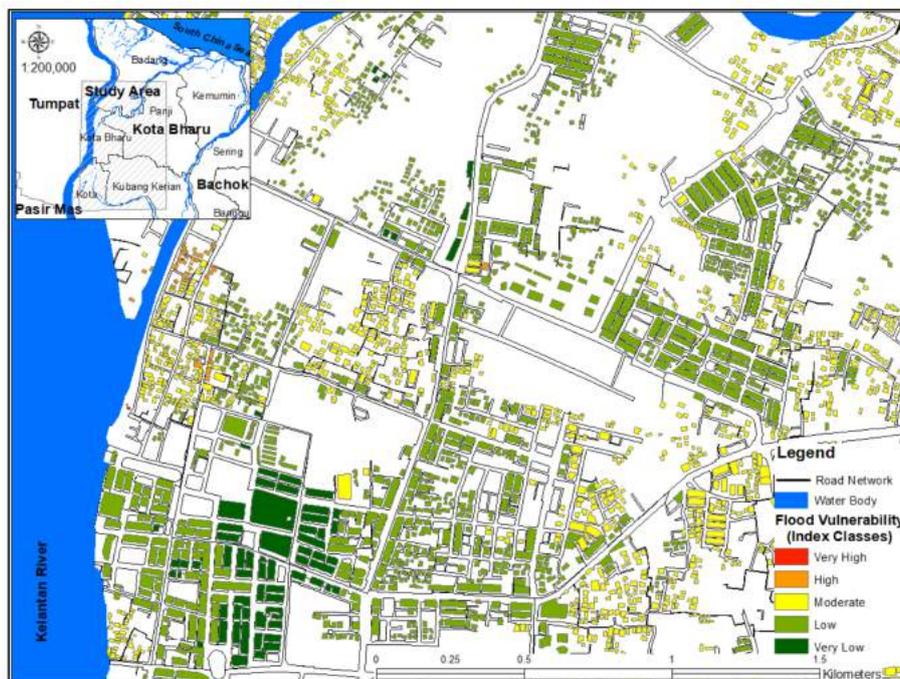**Figure 9.** Selecting of inundated buildings by location.

Figure 10. Spatial pattern of physical flood vulnerability index.

Table 5. Categorization of damage description.

Vulnerability Class	Index Value	Expected Damage Description
Very Low	0.00–0.20	Building comes into contact with flood water, but no damage or repair cost is reported.
Low	0.21–0.40	Building comes into contact with flood water but it was not evacuated before, during, and after flood. The reported lost is only related to wet furniture and home appliances.
Moderate	0.41–0.60	Furniture wet, broken windows and doors are reported. Some sections of the building were unusable during the flood event. The building returns to its full function after the flood with minor repairs.
High	0.61–0.80	Everything gets wet and some walls break. Major repair was conducted after the flood.
Very High	0.81–1.00	Building was completely damaged during the flood.

The frequency distribution of the VI classes is shown in Figure 11. The cross-tabulation analysis shows that most of Kota Bharu buildings have moderate and low vulnerability classification. The model statistics shows that the average flood vulnerability index value is 0.38889. This shows that in an extreme (100–year) flood occurrence, most of the buildings that will be flooded may not experience any structural damage. However, building contents and fittings may be affected (wet of furniture at ground floor). Therefore, evacuation for most of the buildings may not be necessary. As investigated, most buildings have either low (49.9%) or moderate (47%) physical flood vulnerability; this is because the majority of modern building structures are reinforced concrete structures. As a result of the way they are constructed, they tend to have high resilience to flooding. In addition, most buildings in Kota Bahru city (especially urban center) are more than one story. As the number of floors increases, the vulnerability decreases.
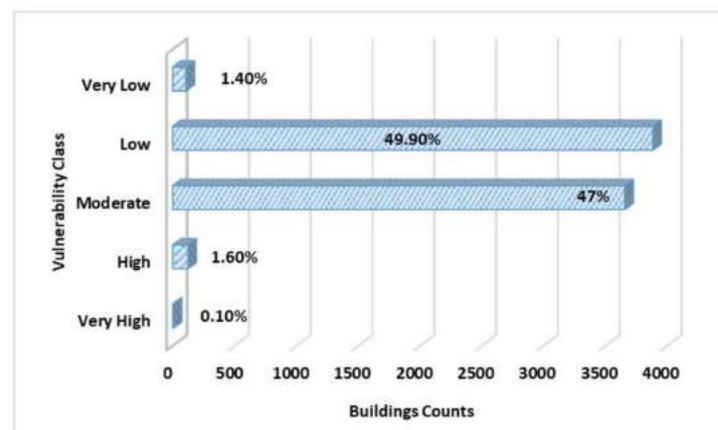
Figure 11. Frequency distribution of building flood vulnerability index classes.

Finally, the model output, which is the physical flood vulnerability index of buildings, was validated by relating the final index output with the 2014 flood damage description of buildings obtained from the field survey damage assessment. At this stage, the respondent descriptions of their property damage were used in validating the final flood vulnerability index developed in this study. Samples from 217 buildings were used for the validation. The description of buildings damage (from 2014 flooding) based on the respondents' interview are coded into five categories with each category representing a specific flood damage description, as shown in Table 5: very low = 1, low = 2, moderate = 3, high = 4, and very high = 5. The model output results and the presented survey result of the 2014 flood damage record were compared using Error Matrix (EM) accuracy assessment techniques.

The categorizations of damage descriptions from the field damage assessment are used as reference data in the confusion matrix analysis. The accuracy assessment analysis from the error matrix (EM) is shown in Table 6.

Table 6. Accuracy error matrix for flood index vulnerability classification.

| | | Reference Data | | | | | Total | Commission Error | User's Accuracy % |
		Very Low	Low	Moderate	High	Very High			
Model Classification	Very Low	7	2	0	0	0	9	22.22%	77.78%
	Low	17	81	1	0	0	99	18.18%	81.82%
	Moderate	2	15	52	0	0	69	24.64%	75.36%
	High	0	0	16	23	0	39	41.03%	58.97%
	Very High	0	0	0	1	0	1	100.00%	0.00%
	Total	26	98	69	24	0	217		
Omission Error		73.08%	17.35%	24.64%	4.17%	0.00%		Overall Class Accuracy	75.12%
Producer's Accuracy %		26.92%	82.65%	75.36%	95.83%	0.00%		Kappa Coefficient	0.63

The confusion matrix reveals that out of the 217 buildings surveyed, the classification of vulnerability was found to be correct at 163 sampling units. The Overall Accuracy of the flood vulnerability index classification is 75.12%. A higher percentage of Overall Accuracy implies better reliability. The model classifications depicted a positive relationship when compared with field damage reference data. Similarly, the Kappa Coefficient (k) shows a moderate relationship of 0.63, which means that the model accuracy is "Substantially Accepted". The User's Accuracy (%) and the Producer's Accuracy (%) of the vulnerability classes are computed from the confusion error matrix. The accuracy level is satisfactory and acceptable, except for the very high vulnerability class which as 0% accuracy for both User's and the Producer's Accuracy. This is because there are no buildings in this category among the surveyed buildings during the field study. Likewise, in the simulated flood vulnerability model, only a few buildings (1.40%) are in this category. At this stage, it is essential to discuss the possible sources of error that may affect the accuracy of the flood vulnerability model. Under or overestimation of the simulated flood hazard models affect the flood vulnerability modeling developed in this research. In this study, the simulated SOBEK flood model is validated by comparing the simulated flood depth with the observed visible flood watermarks of the 2014 flood event. From the comparison, the computed Mean Error (ME) is 0.31 m. The ME exhibits whether the simulated model measurements overestimate (positive ME) or underestimate (negative ME) the flood event. The error result shows that the simulated result overestimates the actual flood event based on the number of point samples used in this study.

4. Discussion

The study of [20,38] identified building walls' strength as one of the critical indicators that reduce flood vulnerability and vulnerability of natural hazard. The material and the construction type are significant in determining how fast water infiltrates buildings. Likewise, when the building is subject to immense hydrostatic and hydrodynamic pressure, structural damage may occur depending on the building construction type and material. Based on the construction types that are common in Malaysia, the building construction type and material are group into four major classes, which are (a) Steel/IBS and concrete reinforced masonry structure, (b) Unreinforced masonry structure (c) Mixed-material construction (masonry and wood) (d) Wood material structure/Lightweight material structure (see Figure 12). The purpose of classifying buildings into these groups as mentioned above is to categorize buildings based on their construction strength. According to available post flood field surveys [39–41], lightweight material and wood-constructed buildings have always suffered more serious structural damage. Masonry-constructed buildings are considered to have a moderate vulnerability to flooding, while reinforced concrete structures and steel/IBS structures are considered to be highly resistant to flood hazard.

Figure 12. Examples of different building construction type and materials in Kota Bharu, Kelantan.

Steel structure buildings are buildings constructed using steelwork to form the skeleton frames. In contrast, IBS buildings are types of buildings that are constructed under a well-supervised control environment. Reinforced concrete buildings are mostly constructed using reinforced cement concrete in which steel rods are embedded. Thus, reinforced concrete, steel, and IBS structures tend to have high resilience to flooding because of how they are constructed. Typically, Malaysia's urban masonry structures are made up of a single layer of cement bricks with reinforced concrete beams. They are considered to have a moderate vulnerability, but they can be affected under high intensity of flooding. It has been observed that in Kota Bharu, most of the modern urban buildings are masonry-constructed buildings. Most of the modern structures that came into contact with water during the 2014 flood event had a highly resistant their structural composition. Most of the damage that is experienced by such buildings is mostly on their fittings and internal properties. Unreinforced masonry structures are buildings where load-bearing walls and non-load-bearing walls are made of only cement bricks. Wood structure buildings are buildings constructed with wood or wooden parts, whether modern wooden construction or traditional wooden construction are both product of a more intricate fabrication process in which various wood strands, veneers, fibers, or other forms of wood are nail or glued together to construct a building. Both unreinforced masonry structures and wood buildings usually suffer serious consequences during flooding and thus are highly vulnerable to flood. Similar to wood structure buildings, buildings constructed with lightweight material are also very vulnerable to flood. In Kota Bharu suburban areas, it has been observed that many traditional buildings are constructed with wood material and others are constructed with both wood and masonry.

Furthermore, the level of flood damage is always associated with the type of building material and number of floors [7,14], suggesting that the number of stories is 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 buildings with more floors are expected to have more weight, which makes them difficult to be washed away by floodwater. It is always assumed that the higher the number of floors, the stronger the foundation and the ground floor. A 2006 post-flood survey study conducted in Java, Indonesia by [39] shows that single-story buildings collapsed when the water depth is higher than 2 m, while multi-story buildings were resistant to damage even when the water flow depth reached 4 m. Evidence from the field study shows that most single-story buildings that are completely inundated

by floodwater (during 2014 big yellow flood) were severely damaged, and some were completely destroyed. From the above observations, four indicator classes are selected based on the number of floors: single story, two stories, three-stories, and four-stories. Any building with four or more floors is strongly resilient to flood vulnerability due to the strength of the ground floor.

Another relevant indicator of flood vulnerability under building characteristics is the presence of stilts or an elevated ground floor. These are poles and pillars that are used to allow a building to stand at a distance above the ground. These buildings have their lowest elevated floor raised above ground level by foundation walls, shear walls, posts, piers, pilings, or columns (see illustration in Figure 13). Although there are many reasons for these types of building construction, elevated and stilts buildings have been used in Malaysia right from the olden days for the adaptation and mitigation of floods [42]. During flood events, elevated buildings allow water to pass under the buildings. It has been observed that in floodplain areas of Kota Bharu, especially along the river Kelantan, some traditional houses are built with stilts to mitigate floods. Unfortunately, modernization threatens this old practice and traditional lifestyle of flood mitigation. Elevated buildings are expected to reduce flood impact. Therefore, they have low flood vulnerability as compared to non-elevated buildings. Furthermore, information regarding ground floor material is also relevant for building flood vulnerability assessment. In the study area, the strength of the ground floor foundation material is broadly grouped into three different types of materials, which are cement concrete, mixed materials, and wood.

Figure 13. An illustration of elevated and non-elevated buildings.

Another important determinant of the flood vulnerability of buildings is hazard intensity. As earlier emphasized, a flood vulnerability assessment is hazard-dependent; the intensity characteristics of flood hazard are essential. The collection of information regarding flood hazard is necessary. Three flood hazard attributes (flood depth, flood duration, and flood velocity) are rated relevant as indicators that define hazard intensity. Therefore, hazard intensity is the function of flood depth, duration, and water velocity. Although flood hazard probability (return period) is not considered among the indicators, it is used as a boundary condition (flood extent) to run the vulnerability assessment. It determines the buildings that are exposed to the hazard. Therefore, only the vulnerability of buildings that are within the selected return period should be computed. In this study, the 100-year return period is used, which is the maximum flood that has ever been recorded

in the study area (Kota Bharu). The selected indicators and their intensity classes are presented below (see Table 7).

Table 7. Classification of indicators for flood hazard intensity.

Degree of Flood Intensity	Flood Depth (m)	Flood Velocity (m/s)	Flood Duration (hours/day)
Low	<0.5	<0.5	<12 h
Moderate	0.5–1	0.5–1	12–24 h
High	1.1–3	1–2	2 days
Very High	>3	>2	days above

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 be depends on their depth. The selected flood depth classes are supported by the study of [30]. It is expected that most buildings inundated with less than 0.5 m floodwaters will stay dry. As the water level increases to 1 m, the ground floor will be covered, affecting electric and other equipment. Therefore, evacuation may be necessary. At 1 to 3 m, it is expected that the single-story building and ground floor (except elevated buildings) will be inundated with floodwater. The inhabitants have to be evacuated or move to the upper floors. Any floodwater depth of more than 3 m is classified as a total disaster. Buildings less than two stories will be completely inundated with a very high possibility of collapsing. Flood velocity is another consideration: flooding can be damaging based on its depth–velocity functions. Flooding with high depth and low velocities may cause less damage because the water is motionless or calmer (it will not generate force to move the object). On the other hand, high velocities with low flood depths may result in severe damage and risks to human lives and properties. High velocities and high flood depths are expected to produce high flood damages. In most cases, low flood velocities and low flood depths do not cause much damage, and therefore, low damage is expected. The classes for flood velocity are selected based on the available information on the Urban Storm-water Management Manual for Malaysia [43]. Duration of flood inundation is also another critical indicator that determines flood hazard intensity. Extended flood durations tend to increase the damage of buildings and other structures. The longer the duration of the flood, the more damage it will cause to the building. This is mainly because the structures of many properties are made of porous solid materials, such as bricks, blocks, and concrete.

Furthermore, characteristics of the surrounding environment may reduce or increase the intensity of flooding on buildings and other elements-at-risk. Indicators regarding the surrounding environment are distance to water bodies, surrounding vegetation, surrounding fences, and artificial drainages. However, in this study, only the distance to major stream water bodies and proximity to main roads are rated high by the experts. This is because indicators considered for hazard intensity have already covered the surrounding environment's significance. However, the distance to main streams and rivers is considered. Since there is evidence from post-flood studies that most of the flood-affected areas in Kota Bharu are located close to main rivers [1,30,44], therefore, the distances of buildings from main streams and rivers should be considered as one of the indicators. The overflow of water bodies during the flood occurrence makes the adjacent area much more vulnerable and influences the water velocity as well. Likewise, proximity to the main road is also considered as a flood vulnerability indicator in this study. On the one hand, roads are a route, thoroughfare, or a way that has been built on land surfaces between places to allow the conveyance of people and motor vehicles. However, they also serve as drainage systems in urban areas by affecting the natural surface and subsurface drainage pattern of a watershed. In urban areas, major roads are mostly designed with an extra objective, which is removing excess rainwater from cities. Likewise, in Kota Bharu, it has been observed that most of the major roads and city roads serve as artificial drainage systems that aid

rainwater to drain out of the city. The drainage system of the roads is into two parts: "drainage" and "dewatering". Drainage refers to all the different infrastructural elements to keep the road structure dry, while dewatering covers the removal of rainwater from the surface of the road. Roads improve flood defenses by reducing the natural storage capacity of a landscape. In this study, proximity to roads is used as a factor that determines artificial drainage systems and artificial mitigation measures. The distance to major roads that are designed with artificial drainage plays a vital role in mitigating the effect of floods.

Furthermore, in this study, the expert survey's fundamental objective is to evaluate the physical flood vulnerability indicators that affect buildings in an urban setting. As mentioned in the methodology section, indicators for physical flood vulnerability have different level of contribution to flood damage. It is not easy to assign a suitable weight to the selected indicators. Indeed, assigning the weight of indicators is a very sensitive and controversial step in developing the vulnerability index [45,46]. In this study, a weighting (Analytic Hierarchy Process) approach that allows expert participation is utilized to assign the weight of importance to the indicators. The whole idea of the process is to obtain the final response through the consensus of participating experts. In this situation, the participating experts determined the indicators to be included in the vulnerability assessment and their weights of vulnerability contribution. The stakeholders' sense of ownership is likely to be improved through this approach, increasing the possibility that the results will be used.

5. Conclusions

This paper modeled the building vulnerability index using an indicator-based approach. It is a creative way to produce a flood vulnerability map, particularly at the details level. The model developed in this study is for non-monetary flood vulnerability assessment that provides a scale of flood vulnerability to element-at-risk. In anticipation of a flood disaster, the flood vulnerability index model developed in this study can be used to prevent significant losses.

Some of the disaster risk and vulnerability frameworks considered vulnerability to be independent of the magnitude of the hazard that was composed solely of susceptibility due to the element-at-risk characteristics. However, this study considers vulnerability to be a composition of both the inherent characteristics of elements-at-risk and hazard intensity. The benefit of a hazard-dependent vulnerability assessment is that it can be used to reduce the impact of floods by providing crucial information for strategy development and planning. One such piece of crucial information is to know the type of structural development that should or should not be allowed in an area with a certain probability of hazard intensity. Eliminating natural hazard is almost impossible and costly. Therefore, exposed communities must learn to live with it by developing adoption and copying capabilities, especially now that it has been proven that the magnitude and frequency of climate-related hazards are rising. The flood vulnerability modeling approach in this study can be utilized as a basis for decision making on flood proofing of buildings. Such a decision includes ensuring that all buildings within the flooding expected areas have a flood vulnerability index of less than a certain threshold. It can be achieved by replacing or renovating building structures that are highly susceptible to flood in the high hazard area.

The objective of national flood mapping in Malaysia is to have comprehensive flood risk models for future prediction, implementation of the mitigation project, and appropriate emergency response plans. Although this study is limited to a 100-year flood-return period, the basis for modeling flood vulnerability for the other flood-return period is provided. Likewise, the study explores the spatial distribution of flood vulnerability to urban buildings at risk, establishing a baseline to assess flood disaster risk. A high flood vulnerability to a building may be caused by a lack of drainage facilities, closeness to some natural drainage system or environmental settings, and its intrinsic characteristics. Evaluating these factors using the index model provides a simple answer to why some buildings are susceptible more than others.

References

1. Maruti, S.F.; Amerudin, S.; Kadir, W.H.W.W.; Yusof, Z.M. A hydrodynamic modelling of proposed dams in reducing flood hazard in Kelantan Catchment. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *140*, 012043. [CrossRef]
2. Ayala, D.; Wang, K.; Yan, Y.; Smith, H.; Massam, A.; Filipova, V.; Pereira, J.J. Flood vulnerability and risk assessment of urban traditional buildings in a heritage district of Kuala Lumpur, Malaysia. *Nat. Hazards Earth Syst. Sci.* **2020**, *20*, 2221–2241. [CrossRef]
3. Cai, S.; Fan, J.; Yang, W. Flooding Risk Assessment and Analysis Based on GIS and the TFN-AHP Method: A Case Study of Chongqing, China. *Atmosphere* **2021**, *12*, 623. [CrossRef]
4. Ahamad, M.S.; Ali, R.; Zakaria, N.A.; Ghani, A.A.; Chang, C.K. Flood loss assessment of the 2003 Muda River flood. In Proceedings of the 3rd International Conference on Managing Rivers in the 21st Century: Sustainable Solutions for Global Crisis of Flooding, Pollution and Water Scarcity, Penang, Malaysia, 6–9 December 2011; pp. 601–606.
5. Ernst, J.; Dewals, B.J.; Detrembleur, S.; Archambeau, P.; Erpicum, S.; Pirotton, M. Micro-scale flood risk analysis based on detailed 2D hydraulic modelling and high resolution geographic data. *Nat. Hazards* **2010**, *55*, 181–209. [CrossRef]
6. Romali, N.S.; Yusop, Z.; Sulaiman, M.; Ismail, Z. Flood Risk Assessment: A Review of Flood Damage Estimation Model for Malaysia. *J. Teknol.* **2018**, *80*. [CrossRef]
7. Custer, R.; Nishijima, K. Flood vulnerability assessment of residential buildings by explicit damage process modelling. *Nat. Hazards* **2015**, *78*, 461–496. [CrossRef]
8. Papathoma-Köhle, M. Vulnerability curves vs. vulnerability indicators: Application of an indicator-based methodology for debris-flow hazards. *Nat. Hazards Earth Syst. Sci.* **2016**, *16*, 1771–1790. [CrossRef]
9. Alias, N.E.; Mohamad, H.; Chin, W.Y.; Yusop, Z. Rainfall Analysis of the Kelantan Big Yellow Flood 2014. *J. Teknol.* **2016**, *78*, 83–90. [CrossRef]
10. Wahab, A.M.; Ludin, A.N. Flood vulnerability assessment using artificial neural networks in Muar Region, Johor Malaysia. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *169*, 012056. [CrossRef]
11. Chan, L. Challenges in Flood Disasters Management in Malaysia. Available online: https://www.iwra.org/member/congress/resource/1445_Chan_PS112007_Sidlaw_Tues.pdf (accessed on 25 April 2019).
12. Romali, N.S.; Yusop, Z. Flood damage and risk assessment for urban area in Malaysia. *Hydrol. Res.* **2021**, *52*, 142–159. [CrossRef]
13. Douben, N.; Ratnayake, R.M.W. Characteristic data on river floods and flooding; facts and figures. In *Floods, from Defence to Management*, 1st ed.; Alphen, J., Beek, E., Taal, M., Eds.; CRC Press: London, UK, 2006; pp. 19–35. ISBN 0-415-39119-9.
14. Romali, N.S. Flood Damage and Risk Assessment for Urban Area in Segamat. Ph.D. Thesis, Universiti Teknologi Malaysia, Johor Bahru, Malaysia, 2018.
15. DID. Flood Management Approaches Structural Measures Flood Relief Machinery and Organization. Available online: https://www.water.gov.my/index.php/pages/view/370 (accessed on 24 March 2021).
16. Len, N.L.S.; Bolong, N.; Roslee, R.; Tongkul, F.; Mirasa, A.K.; Lynn Ayog, J. Flood Vulnerability of Critical Infrastructures—Review. *Malays. J. Geosci.* **2018**, *2*, 34–37. [CrossRef]

17. Dall'Osso, F.; Dominey-Howes, D.; Tarbotton, C.; Summerhayes, S.; Withycombe, G. Revision and improvement of the PTVA-3 model for assessing tsunami building vulnerability using 'international expert judgment': Introducing the PTVA-4 model. *Nat. Hazards* **2016**, *83*, 1229–1256. [CrossRef]

18. Pörtner, H.-O.; Roberts, D.C.; Masson-Delmotte, V.; Zhai, P.; Tignor, M.; Poloczanska, E.; Mintenbeck, K.; Alegría, A.; Nicolai, M.; Okem, A.; et al. *Special Report on the Ocean and Cryosphere in a Changing Climate*; IPCC: Geneva, Switzerland, 2019.

19. UNESCO-IHE Institute for Water Education. Flood Vulnerability Indices (FVI). Available online: http://www.unesco-ihe-fvi.org/ (accessed on 25 March 2020).

20. Kappes, M.S.; Papathoma-Köhle, M.; Keiler, M. Assessing physical vulnerability for multi-hazards using an indicator-based methodology. *Appl. Geogr.* **2012**, *32*, 577–590. [CrossRef]

21. Connelly, A.; Carter, J.G.; Handley, J. State of the Art Report (4) Vulnerability Assessment. 2015. Available online: https://resin-cities.eu/fileadmin/user_upload/D1_1_SOTAVulnerability_UNIMAN_2015-11-30.pdf (accessed on 20 March 2020).

22. Nasiri, H.; Yusof, M.J.M.; Ali, T.A.M.; Hussein, M.K.B. District flood vulnerability index: Urban decision-making tool. *Int. J. Environ. Sci. Technol.* **2018**, *6*, 2249–2258. [CrossRef]

23. Papathoma-Köhle, M.; Gems, B.; Sturm, M.; Fuchs, S. Matrices, curves and indicators: A review of approaches to assess physical vulnerability to debris flows. *Earth Sci. Rev.* **2017**, *171*, 272–288. [CrossRef]

24. Nasiri, H.; Shahmohammadi-kalalagh, S. Flood Vulnerability Index as a Knowledge Base for Flood Risk Assessment in Urban Area. *J. Nov. Appl. Sci.* **2013**, *2*, 269–272.

25. Nazeer, M.; Bork, H. Flood Vulnerability Assessment through Different Methodological Approaches in the Context of North-West Khyber Pakhtunkhwa, Pakistan. *Sustainability* **2019**, *11*, 6695. [CrossRef]

26. Balica, S.; Wright, N.G. Reducing the complexity of the flood vulnerability index. *Environ. Hazards* **2010**, *9*, 321–339. [CrossRef]

27. JRC European Commission. *Handbook on Constructing Composite Indicators: Methodology and User Guide*; OECD: Paris, France, 2008.

28. Zakaria, S.F.; Rosli, M.; Ismail, M.; Saeed, B. The development of flood map in Malaysia. *AIP Conf. Proc.* **2017**, *1903*, 110006. [CrossRef]

29. Khan, M.M.; Shaari, A.A.B.; Nazaruddin, M.A.B.; Bin, D.A. Flood Impact Assessment in Kota Bharu, Malaysia: A Statistical Analysis. *World Appl. Sci. J.* **2014**, *32*, 626–634. [CrossRef]

30. Ghazali, N.H.M.; Osman, S. Flood Hazard Mapping in Malaysia: Case Study Sg. Kelantan river basin. *Cat. Hydrol. Anal. Flood Hazard Mapp.* **2019**, *1*, 1–30.

31. Irwan, Z.; Rahman, A.; Amin, M.; Farahiyah, W.; Kamarudin, W.; Muhammud, A. Pattern of Rainfall Distribution in Kuala Krai, Kelantan, Malaysia. *J. Appl. Environ. Biol. Sci.* **2017**, *7*, 1–7.

32. Chow, V.T.; Maidment, D.R.; Mays, L.W. *Applied Hydrology*; Mc Graw-Hill International Edition: New York, NY, USA, 1988.

33. Alizadeh, M.; Ngah, I.; Hashim, M.; Pradhan, B.; Pour, A. A Hybrid Analytic Network Process and Artificial Neural Network (ANP-ANN). Model for Urban Earthquake Vulnerability Assessment. *Remote Sens.* **2018**, *10*, 975. [CrossRef]

34. Saaty, T.L. The Analytic Hierarchy and Analytic Network Process for the Measurement of Intangible Criteria and for Decision-Making. In *Multiple Criteria Decision Analysis: State of the Art Survey*; Springer: New York, NY, USA, 2005; pp. 346–406.

35. Benítez, J.; Delgado-Galván, X.; Izquierdo, J.; Pérez-García, R. Improving consistency in AHP decision-making processes. *Appl. Math. Comput.* **2012**, *219*, 2432–2441. [CrossRef]

36. Altman, D. *Practical Statistics for Medical Research*; Chapman and Hall: London, UK, 1991. [CrossRef]

37. Grahn, T.; Nyberg, L. Assessment of pluvial flood exposure and vulnerability of residential areas. *Int. J. Disaster Risk Reduct.* **2017**, *21*, 367–375. [CrossRef]

38. De Ruiter, M.C.; Ward, P.J.; Daniell, J.E.; Aerts, J.E. Review Article: A comparison of flood and earthquake vulnerability assessment indicators. *Nat. Hazards Earth Syst. Sci.* **2017**, *17*, 1231–1251. [CrossRef]

39. Reese, S.; Cousins, W.J.; Power, W.L.; Palmer, N.G.; Tejakusuma, I.G.; Nugrahadi, S. Tsunami vulnerability of buildings and people in South Java–field observations after the July 2006 Java tsunami. *Nat. Hazards Earth Syst. Sci.* **2007**, *7*, 573–589. [CrossRef]

40. Dominey-Howes, D.; Papathoma, M. Validating a Tsunami Vulnerability Assessment Model (the PTVA Model) Using Field Data from the 2004 Indian Ocean Tsunami. *Nat. Hazards* **2007**, *40*, 113–136. [CrossRef]

41. Izquierdo, T.; Fritis, E.; Abad, M. Analysis and validation of the PTVA tsunami building vulnerability model using the 2015 Chile post-tsunami damage data in Coquimbo and La Serena cities. *Nat. Hazards Earth Syst. Sci.* **2018**, *18*, 1703–1716. [CrossRef]

42. Roosli, R.; Collins, A.E. Key Lessons and Guidelines for Post-Disaster Permanent Housing Provision in Kelantan, Malaysia. *Procedia Eng.* **2016**, *14*, 1209–1217. [CrossRef]

43. Department of Irrigation and Drainage. *Urban Stormwater Management Manual for Malaysia (Manual Saliran Mesra Alam Malaysia, MSMA)*; Publication of the Department Irrigation and Drainage Malaysia: Kuala Lumpur, Malaysia, 2001.

44. Rani, W.N.; Nifa, F.A.; Ismail, M.N.; Khalid, K.N. Planning for post disaster recovery: Lesson learnt from flood events in Kelantan Malaysia. *AIP Conf. Proc.* **2017**, *1891*, 020143. [CrossRef]

45. De Moel, H.; Jongman, B.; Kreibich, H.; Merz, B.; Penning-Rowsell, E.; Ward, P.J. Flood risk assessments at different spatial scales. *Mitig. Adapt. Strateg. Glob. Chang.* **2015**, *20*, 865–890. [CrossRef] [PubMed]

46. De Brito, M.M.; Evers, M.; Höllermann, B. Prioritization of flood vulnerability, coping capacity and exposure indicators through the Delphi technique: A case study in Taquari-Antas basin, Brazil. *Int. J. Disaster Risk Reduct.* **2017**, *24*, 119–128. [CrossRef]