AN INDICATOR-BASED APPROACH FOR MICRO-SCALE PHYSICAL FLOOD VULNERABILITY MAPPING

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ABSTRACT:

Map representation of vulnerability is a crucial step in evaluating flood impact and all vulnerability indicators that are the final product of risk assessment. So far, in flood risk assessment, this is probably the weakest link. Flood risk mapping suffers from inequality in the level of development in presenting the different components: where exposure and hazard modelling and mapping is well developed and advanced, while vulnerability analysis and mapping are underdeveloped. Therefore, the objective of this paper is to discuss a newly developed GIS-based approach on micro-scale flood vulnerability mapping of physical elements at risk using an indicator-based method. Micro-scale flood vulnerability is used to eliminate flood vulnerability in an area with a high probability of occurrences. The approach is suitable for cost-benefit analysis of structures protection measures. At micro-scale flood vulnerability mapping, it is more suitable to adopt indicator-based vulnerability assessment methods. Because it provides an opportunity for incorporating all the factors and characteristics of elements at risk that contribute to generating their flood vulnerability. Likewise, a considerable amount of studies argue that vulnerability assessment and its representation on maps should focus on the identification of variables that influence the vulnerability of an element at risk. Flood vulnerability mapping at micro-scale provides critical information for the decision-makers on why specific infrastructures are susceptible more than the others. Moreover, assessing and managing flood risk is crucial in order to reduce the loss and adapt to the combined effects of rapid urbanization and climate changes.

1. INTRODUCTION:

Vulnerability maps provide information on why certain regions, infrastructures or some specific element are susceptible more than the others (Jha & Gundimeda, 2019). Vulnerability mapping in relation to flood risk is still a challenge, especially when compared to other types of natural hazards (UNISDR, 2017). Vulnerability is among the three main components of flood risk, others are hazard and exposure (Lee Siew Len et al., 2018). Hazard is a component of risk which has the potential to cause harm to a vulnerable target. It refers to the probability of the occurrence of potentially damaging flood event (Schanze et al., 2006). Exposure is the predisposition of a system to be disrupted by a flood event due to its location in the same area of influence (UNESCO-IHE, 2012). It refers to the presence of people, livelihoods, environmental services and resources, infrastructure or economic, social or cultural assets in places that could be adversely affected (Romali et al., 2018). Vulnerability refers to the inability of the expose element to withstand the effects of hazards, in this case, flood (Ciurean et al., 2013). The interaction of flood risk components is depicted in Figure 1.

However, in comparison to other types of risk (earthquakes, landslide) assessment, flood risk assessment suffers from inequality in the level of development in assessing the different components: where exposure and hazard analysis and modelling is well developed and advanced while vulnerability analysis and mapping are underdeveloped (UNISDR, 2017; de Brito et al., 2017). Furthermore, vulnerability factors can be divided into four major category; physical vulnerability, social vulnerability, economic vulnerability and environmental vulnerability (Nasiri et al., 2013; Balica et al., 2009). Among which the interest of this paper is physical flood vulnerability.

There are three popular approaches in measuring flood vulnerability; vulnerability curves, vulnerability matrices, and indicator-based method (Nasiri et al., 2016). The matrix is a grid or table with the measure of likelihood on one side and consequences on the other, graded from low to high. It presents the possible damages on elements at risk, together with the corresponding intensity of the process (Papathoma-Köhle et al., 2017). Vulnerability curves relate the flood intensity with the corresponding degree of loss (de Ruiter et al., 2017). It is a curve associating the intensity of the hazard on X-axis and the damage response of element at risk on Y-axis (Nasiri et al., 2016). The two (Curve and Matrices) approaches are lacking the strength of summarizing complex and multidimensionality issues related to flood vulnerability (Papathoma-Köhle et al., 2017).

On the other hand, the strength of Indicator-based Method (IBM) to summarize the complexity and multidimensionality issues related to flood vulnerability makes it more suitable for identifying variables that influence the vulnerability of an element at risk (Balaca, 2013). The Indicator-based (IBM) evaluates the different factors (of vulnerability) at a different spatial scale (Mulok et al., 2019). It measures variables which are representations of a characteristic quality of an element at risk that make it able or unable to withstand the effects of a hostile environment, which can be easily represented on maps at micro-scale (Müller et al., 2011).

The indicators are represented into simple numbers which express reality, and this representation is known as vulnerability index, which is a measure of the exposure, susceptibility, coping capacity and resilience of the exposed elements (Mulok et al., 2019). The system of flood vulnerability index (FVI) can be used as an instrument to link a multi-disciplinary subject with a large number of components in a straight way and also can provide a useful review of vulnerability in different scales (Nasiri and Shahmohammadi-kalalagh, 2013). Accordingly, the objective of this paper is to discuss a newly developed GIS-based approach on micro-scale flood vulnerability mapping of the physical element at risk using an indicator-based method. Among the physical element at risk of flooding, building structures are the most critical element at risk, and their vulnerability modelling requires information from different sources (Papathoma-Köhle et al., 2017).

In order to develop a building flood vulnerability map, vulnerability needs to be modelled for individual buildings rather than in an aggregated manner (Custer & Nishijima, 2015). However, the stages of mapping flood vulnerability using IBM involve the selection of spatial scale, identification of element at risk, selection of vulnerability assessment method, carrying out vulnerability assessment, and representation of the vulnerability assessment into maps

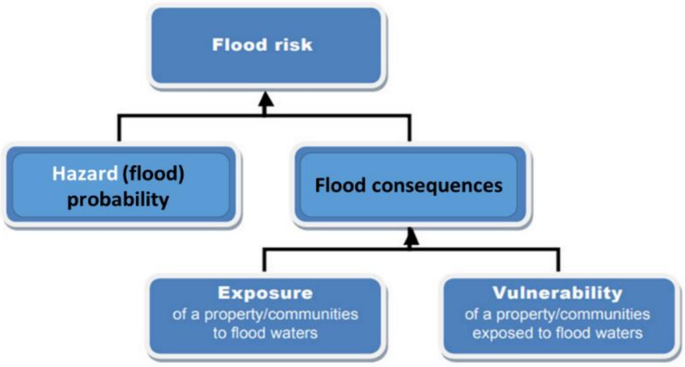

Figure 1. Components of flood risk (Modified from The State of Queensland, 2011)

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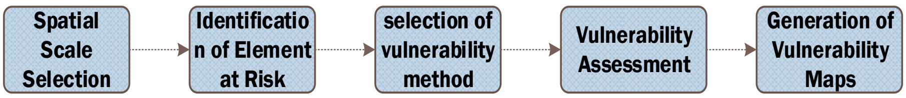

Figure 2. Processes involved in mapping flood vulnerability

2. SELECTION OF SPATIAL SCALE

Spatial scales are an important factor that determines the type of vulnerability measurement method when it comes to assessing flood vulnerability and their representation on maps (Balica et al., 2017). When it comes to Mapping flood risk and vulnerability, four different categories of scales used is identified by de Moel et al. (2015), as presented in table 1.

Table 1: Different spatial scales for flood risk and vulnerability

	Units	Description	Details	Map Use
Supra-National Scale	1:10,000,000 -above	The map may include entire globe or continent, encompassing a plethora of countries and river basins.	National, sub-continental and international boundary	For global and regional risk index, and monitoring global risk reduction progress.
Macro-scale	1:1,000,000-1:10,000,000	Representation of an entire country flood assessment.	State boundary, generalized roads and rivers	For rapid damage assessment, national planning, resource allocation.
Meso-scale	1:1,000,000–1:100,000	Relate to regional flood assessment, generally sub-national, referring to a particular province, watershed or large city.	Building density, road width and type, bridge by location, river channel width and depth	Land use and physical planning, early warning and public awareness, mitigation activities.
Micro-scale	1:100-1:100,000	Relates to a town, or specific river stretch, or single exposed elements assessment.	Individual buildings, walls, roads, Dam, bridges, culverts.	Flood mitigation to structures such as buildings, roads.

When selecting the cartographic scale at which a flood vulnerability is represented, it is significant to be familiar with the level of details expected in a map of a given scale. However, the focus of the paper is micro-scale flood vulnerability mapping. At micro-scale flood vulnerability mapping, it is more suitable to adopt indicator-based vulnerability assessment methods (Balica and Wright, 2009; Krellenberg and Welz, 2017; Müller et al., 2011).

3. INDICATOR-BASED FLOOD VULNERABILITY ASSESSMENT

Papathoma-Köhle et al., (2017) describe vulnerability indicators as variables which are operational representations of a characteristic regarding the exposure, 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, in this case, flooding. To developed flood vulnerability map using IBM at micro-scale, the required information needs to be specific in terms of the elements at risk (Kappes et al., 2012). Therefore, residential buildings are used in this review as an example of physical elements at risk. The indicators are represented into simple numbers which express reality, and this representation is known as vulnerability index (Balaca, 2013; de Brito et al., 2017; Müller et al., 2011; Yankson et al., 2017), which can be expressed on a scale from 0 (no damage) to 1 (total damage) (Nasiri et al., 2016).

To produced flood vulnerability map, the system of flood vulnerability index (FVI) can be used as an instrument to link a multi-disciplinary subject with a large number of components in a straight way (Nasiri and Shahmohammadi-kalalagh, 2013). A GIS database of elements at risk (building) structures is developed, and the generated index value can be assigned to each building individually (Custer and Nishijima, 2015). The processes involved in generating vulnerability index as identified by Papathoma-Köhle et al., (2017), includes the selection of relevant indicators, the identification of variables, their weighting and, finally, their aggregation in a vulnerability index.

At the micro-scale, there are multi-dimensional factors that influence the selection of vulnerability indicator. According to Yankson et al., (2017), selecting flood indicators can be based on two basic approaches: theory approach and data-driven approach. Widely accepted relevant indicators (element characteristics) are being presented in the literature (Fernandez et al., 2016; Papathoma-Köhle et al., 2017; Qasim et al., 2017). However, because the real conditions that determine flood vulnerability are site-specific, location dependent and hazard dependent, data-driven tools such as census, GIS, and remote sensing data as well as field surveys, expert interviews and flood depth and velocity modeling are useful to overcome limitations in the indicator selection process (Müller et al., 2011). Nevertheless, the indicators are characteristics of buildings at risk that constitute them susceptible to harm. For example, Fernandez et al., (2016), Stephenson et al., (2014) and Thouret et al., (2014) identified some these characteristics (Number of floors, Construction period, Building structure material, Level of maintenance). Likewise, the study Kappes et al., 2012 included (Height of lowest Opening, Basement, Protection measures, Building use, Building row towards river, Vulnerable population).

In addition, depth and velocity functions are recommended to be included as part of the flood vulnerability indicators by the study of Wright, 2016 and Mulok et al., 2019. This is because 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 objects). Similarly, high velocities with low flood depths may result in severe damage and risks to human lives and properties. However, high velocities and high flood depths produce high flood damages and thus is given a high hazard rating. Low flood velocities and low flood depths, in most cases, do not cause much damage and therefore is given a low damage rating.

The choice of indicators depends on the map use priorities. For example, the roof of a building may be important for the emergency planning maps because it enables vertical evacuation, however, when the focus is not the threat to life, but the economic loss, the height of the building, might be less important (Kappes et al., 2012). However, several literature has identified different indicators that are used in quantifying physical flood vulnerability, as summarized in Table 2, which are categories to into intensity, susceptibility, surrounding environment and people inside the building. Some factors are more important than others, which are based on user need or map purpose.

Table 2: Residential building vulnerability indicators.

Factors	**Source**	**Indicators**	**Sub-Indicators**	**Description/Contribution to flood**
Intensity	(Ahamad et al., 2011)	Flood water depth	<0.5m 0.5–1m 1-2m 2-5m >5m	It is expected that most element will stay dry with less than 0.5m flood water. At this level (0.5-1m); the ground floor will be covered which may saffect electricity. At 1-2M: The ground floor of the houses will be flooded and the inhabitants have either to be evacuated or move to the upper floor. At 2-5M: The first floor and often the roof will be covered by water. There is a high posibility of structures collapse. At >5 flood depth, all buildings lessthan 2 storeys will be completely inundated.
	(Yeganeh and Sabri, 2014)	Elevation (above the lowest point)	<5 m 5-10 >10	Topography affects the flood severity, flow size and direction. water remains in the lower area for a longer time
	(Wright, 2016)	Flood water Velocity	Depending on the situation	The motion energy could wash away element at risk and may result in huge damage (or building collapse).
Susceptibi	(Kappes et al., 2012)	Number of floors	1 2	Presence of second Storey or more offers the oppoturnity of vertical evacuation during an extreme flood event. It allow moving people and their

lity	(Papathoma-Köhle, 2016) (Papathoma-Köhle et al., 2017)		3 >3	belongings to a higher area (upper floors of multi-storey building) for evacuation or protection from flood water.
		Presence of basement	Yes No	Mostly basement are contructed below the land surface. So, even at very low flood-depth, the basement may be filed up water.
		Basement windows	Yes No	A basement with openings (light shafts) may easily be flooded and affected by debris, even under low intensities.
		Height of openings	h<1.5m h>1.5m	The lower the opening indicate higher chances of flood water reaching inside the building.
		Floor material		Some floor materials will raise the overall costs of reconstruction. For example, wooden floors often have to be entirely replaced whereas tiles may be used again after the material removal
	(Papathoma-Köhle et al., 2017)	Use of first floor	Stills	The use of the first floor is significant for human safety but also for content costs and the resilience of the building.
	(Fernandez et al., 2016)	Material of building	Concrete, Metal mixed wood	The type of building materials determine how they behave under water saturation, as well as in long period of time.
	(de Ruiter, et al, 2017)	Building types	Bungalow Apartment buildings Terrace/Flat Semi-detached Crude contruction	A single-family residence situated on a relatively small plot mostly owned by the occupants. A self-contained housing units that occupies only part of a building. A row houses or where a row of identical or mirror image houses share side walls. A single-family dwelling house built as one of a pair that share one common wall. A small single-story building of crude construction, serving mostly owned by relatively a poor people, or serving as a temporary house or shelter for migrants or even an indigene.
	(Stephensoet al., 2014)	Condition	Poor Good Excellent	Buildings in overall poorer condition, with less evidence of a continued programme of repair and maintenance, will be more vulnerable to inundation due to pre-existing fatigue in the structure and fabric.
Surrounding environment	(Papathoma-Köhle et al., 2017)	Building row towards river	First Second >Third	Other buildings may act as protection to other buildings as intensity of hazard may be reduce.
	(Qasim et al., 2017)	Houses built near coasts	<1000 m <2000 m <5000 m >5000m	People living very close to coastal areas may be more exposed to tidal floods.
	(Papathoma-Köhle, 2016)	Surrounding wall	Wall>1.5m Wall<1.5m No protection	Surrounding protection reduces the intensity or velocity of flood water on the building to a lesser degree. Also may act as protection to other buildings from floating object due to flooding.
		Distance from main stream and river	<500 m <1000 m <2000 m >2000m	Overflow of water during the flood occurrence makes the adjacent area much more vulnerable and influence the water velocity as well.
	(Papathoma-Köhle, 2016)	Surrounding vegetation	Vegetation (trees) Vegetation (bushes) No veg.	Surrounding vegetation may serve a protection against the moving object (or debris) due to the flood velocity or may reduce the velocity of flood water on the building to a lesser degree.
People inside the building	(Kappes et al., 2012)	Vulnerable population	Elderly Children Disabled people	This is a collection of information regarding the distribution and the characteristics of the population of the area, this kind of information is essential especially for emergency planners and the civil protection.
		Population density	No. of people inside the building.	
	(Qasim et al., 2017)	Income	Low income Medium income High income	More income to the people can have their houses in safer areas and they may also use flood resistant materials in house construction.

From the list of identified and selected indicators, flood vulnerability index is derived, which is based on the assignment of weights to indicators and sub-indicators. A weight quantifies the level of importance an indicator has on the vulnerability of the element at risk (Papathoma-Köhle, 2016). These weights may be obtained from existing sources or expert opinion (de Brito et al., 2017). After each indicator and sub-categories are given a value based on how they contribute to generating flood vulnerability. Numerous statistical formula can be applied, for example, Kappes et al., (2012) and Papathoma-Köhle, (2016) use a weighted linear combination method with the following equation (see equation 1), which is an analytical technique used in dealing with multi-criteria decision making (MCDM).

$$\mathrm{FVI} = \sum_{1}^{m} w_m \cdot I_m S_n \tag{1}$$

Where w represents the m different weights, I the m indicators and s the n scores of the indicators (Papathoma-Köhle, 2016). The final index gives a number from 0 to 1, signifying low to high vulnerability. In most cases, only exposed element vulnerability is computed, and non-exposed are given a value of 0 (meaning; no damage). Therefore, flood hazard modelling is recommended to determine the exposed element (Hadi et al., 2017). After the vulnerability computation manually or using GIS software, GIS can be used to develop a spatial database of the exposed element with their vulnerability value added as their attribute which makes it easier to be presented spatially. The use of GIS makes the database easy to update (Kappes et al., 2012). In summary, using the IBM approach, vulnerability level of elements at risk (such as buildings) can be presented in a single map, as depicted in figure 3. Where buildings with higher vulnerability to flooding are giving a higher vulnerability value, and such values can be represented on maps with visible colors.

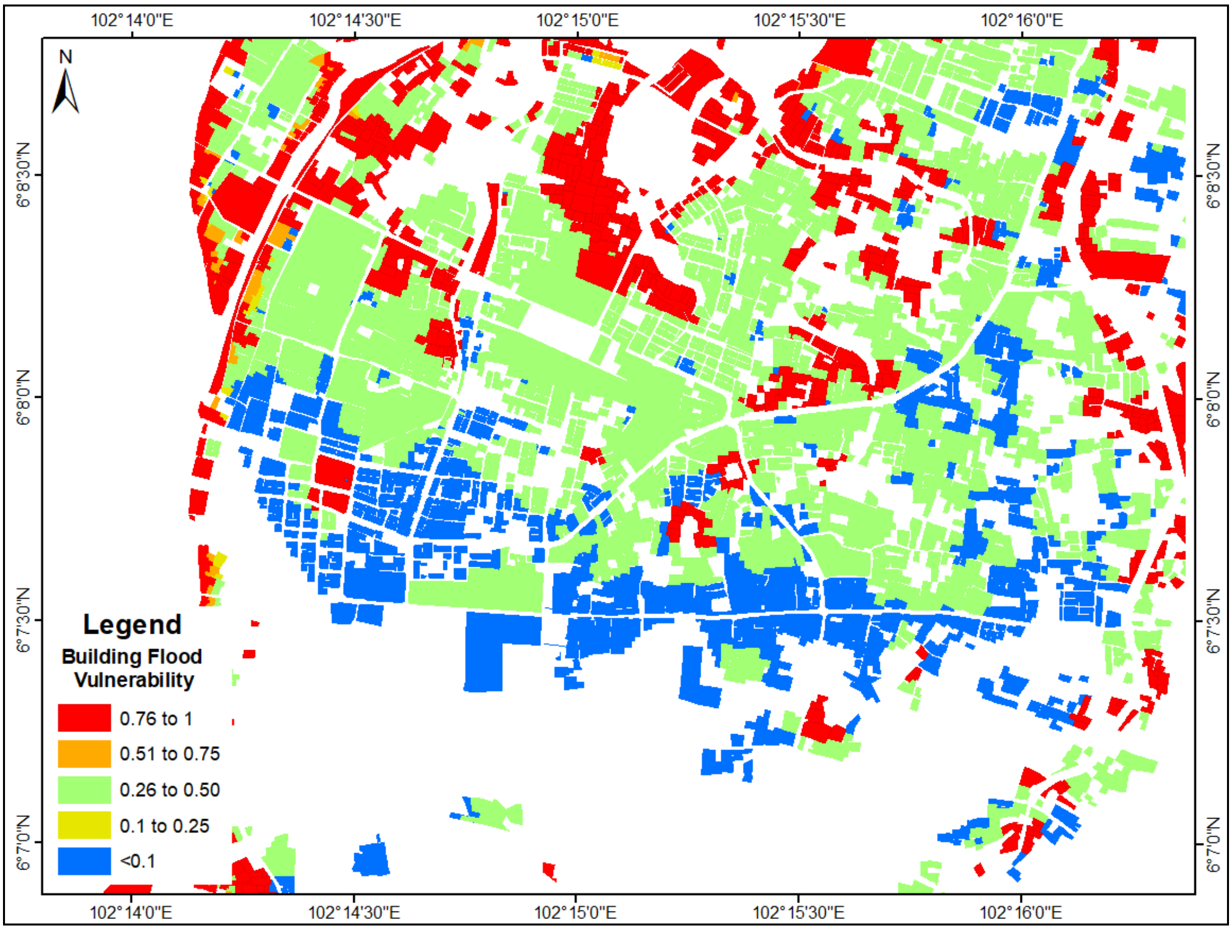

Figure 3: Example of micro-scale flood vulnerability map of some part Kota Bahru, produced using IBM (a preliminary study)

4. CONCLUSION

Flood vulnerability mapping highlights the sensitivity of flood to elements at risk by providing information on properties that are at high risk. It aids decision-makers to control the possible consequences of flood hazard and decide the accurate measures for mitigating flooding before it occurs. It is important to note that flood risk information or maps will not be complete without vulnerability information. Therefore, vulnerability assessment is strongly recommended when producing flood risk maps. However, this study shows that the geospatial flood vulnerability assessment of micro-element at risk (building, road, infrastructures) using IBM method is possible and can be more beneficial in mitigating flooding in an area with a high probability of occurrence. Likewise, the study highlighted that the approach provides information to different stakeholders in order to identify hotspots and focus their efforts in specific areas with critical element at risk.

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