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ORIGINAL PAPER

District flood vulnerability index: urban decision-making tool

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Abstract

Flood vulnerability assessment as an essential part of the urban flood management is done by various methods by several researchers. In fact, the improvement in assessment methods is related to the necessity for enhanced decision-making procedures; for instance, economic or infrastructural investments in cities can be assigned in the best form. To achieve this aim, introducing indices for evaluating vulnerability and identifying more vulnerable zones and then doing relevant comparisons can be useful. District flood vulnerability index (DFVI) developed by the author uses 25 indicators in its calculation. Nevertheless, it is obvious that some of these indicators have no effect on the consequences. This paper presents the results of the analysis for the selection of the most significant indicators of the DFVI construction. This index is appropriate for urban district scaling (or: the urban district scale) and the various components of flood vulnerability (social, economic, environmental and physical). DFVI was made by analyzing the indicators' relevance and by studying the main indicators needed to depict reality of the urban district floods in an effective way. For this purpose, expert elicitation was done by Delphi and AHP method in two separate phases. Then, all these results were combined in order to construct DFVI equations. Finally, the index was implemented in Kuala Lumpur city's districts. This paper outlines which district of cities (in this case Kuala Lumpur) are most vulnerable to flood hazard with regard to the system's components, that is, social, physical, environmental and economic.

Keywords Vulnerability assessment · Flood vulnerability index · Fuzzy Delphi · AHP method · Urban district scale

Introduction

Flood hazards are expected to occur more severely and frequently because of the effects of climate change. As a result, many areas in the world are facing the serious threat of flood hazards. Unplanned or poorly planned urbanization, rapid conversion in land use, and fragile flood management are some of the factors contributing to adverse flood effects which would lead to escalating risks for the inhabitants (Nasiri et al. 2016). This paper argues flood vulnerability assessment as the vital part of urban flood management. During the International Decade of Natural Disaster Reduction (IDNDR) from 1990 to 1999, it was recognized that the earlier concept of "flood protection" was inappropriate (UNISDR 2009). There cannot be complete protection, which is inaccessible and cannot be sustained, due to very high costs and inherent unpredictability. Flood management has been suggested as a realistic alternative, because it is more applicable and this concept is now being increasingly accepted and practiced in environmental studies. Flood risk management encompasses a wide group of subjects and tasks extending from the forecasting the risk, their social implications to methods and tools to minimize risks and economic costs and loss of human lives to adequate and acceptable levels. Avoiding, decreasing or shifting the effects of flood for mitigation and adaptation is the primary objective of flood risk management (UNISDR 2009). Two approaches exist in facing flood: structural (flood protection) and non-structural measures. Structural measures involve expanding the infrastructure like levees, dams or river dikes that alter the river flow (Faisal et al. 1999). The basic principle

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requires storage, diversion and confinement of floods. Nonstructural measures involve numerous mitigation actions but do not include altering the river flow. They cover training, flood insurance, assessment methods, emergency services, land-use planning, construction codes, warning and forecasting, etc. (Ballesteros-Cánovas et al. 2013). The goal is to reduce loss of life and property, but it is inevitable, even structural measures could have useful consequences for a specific period; they also lead to potential threats as well because they rebuild natural processes but do not follow natural rules (Gao et al. 2007).

In flood risk management, flood risk is generally based on three factors: hazard, exposure and vulnerability (Roberts et al. 2009). Hazard is the extreme natural event including its frequency; exposure refers to the people, their environment and properties affected by flood; and vulnerability refers to the susceptibility of people and properties and the coping capacity to deal with flood impact (Kron 2009). In this regard, to decrease the impact of flood through flood management, the evaluation of flood risk constituents is unavoidable. Hence, evaluation of vulnerability is an important element of flood management and decreasing vulnerability is becoming more significant aspect of this kind of management, with population increasing in urban areas (Ahmad and Simonovic 2013). To achieve this aim, vulnerability assessment methods development is very appropriate (De Moel et al. 2012). There are diverse distinctions in the current methodologies for hazard vulnerability around the world. As regards to previous works with emphasizes on flood hazard, vulnerability assessment primary methods can be clustered into three groups (Huang et al. 2012).

Table 1 mentions these methods which are used by other researchers and describes the brief weaknesses and strengths of each group.

In the context of cities, urban planners have expanded urban management measures to tackling hazard impacts by simplifying the decision-making process and helping city authorities (Kang 2009).One of these measures is presenting new indexes for assessing vulnerability and recognizing more vulnerable regions.

Current paper presents attempts to decrease the scale of flood vulnerability index from large city to district scale of inner city, because different scales have dissimilar indicators which make them vulnerable to floods. This is desired for orienting future urban growth away from risk areas and promotes a resilient-district concept for which there is a need to recognize the most vulnerable areas of each city. The previous flood vulnerability indexes focus on large scale neglecting some of the factors which change the vulnerability of smaller spatial scales, such as urban districts. Accordingly, this study aims to develop flood vulnerability index with significant local factors and provides more comprehensive interpretation of these factors being suitable for district scale.

Theoretical framework

Urban systems can be vulnerable to floods because of three main aspects: exposure, susceptibility and resilience. As such, vulnerability of urban area reflects the exposure and susceptibility of the city to flooding and the resilience of that region to cope and recover from the impact of the flood. (Smit and Wandel 2006).

As mentioned, for assessing vulnerability of human systems, one of the simple methods is index construction. The index is a quantitative variable that would allow comparison of the disaster risk and its impacts between varied areas exposed to flood. (Birkmann 2007) Every index is conducted first by identifying the most suitable type of data to counting vulnerability and second recognizing available data at the spatial scale of study (Mclaughlin and Cooper 2010). The indexes let us to identify aims and provide strategies guidance to reduce vulnerability and to set more precise and quantitative targets for vulnerability decrease. (Balica 2007).

The flood vulnerability index is a method to assess flood vulnerability based on: river basin, sub-catchment, and urban area scales by categorizing different components that affect the susceptibility of the people who live in flood prone areas. The previous indexes identified four main social, economic, environmental and physical components which are specified by some indicators in (Balica 2007) research and Meteorological, Hydrogeological, Socioeconomic and Countermeasure Components in (Connor and Hiroki 2005) study.

Connor and Hiroki (2005) calculated this index for river basin system and stated that there are a lot of factors except precipitation and runoff, which influence a basin's flood vulnerability such as preparedness and resilience capacity. They suggested four key components in a river basin, which affect flood vulnerability; Meteorological Component (MC), Hydrogeological Component (HC), Socioeconomic Component (SC), and Countermeasure Component (CC). Balica (2007) extended this definition to sub-catchment and urban systems. She recognized another four components for these two scales: economic, environmental, social and physical components, which can be assessed by various indicators. Interaction between these components and the mentioned factors of the system (exposure, resilience and susceptibility) is the basis of flood vulnerability index methodology (Fig. 1). The social component ensures the vulnerability of an area to a flood in terms of social development. Physical components include physical condition, both natural and artificial, which affects flood vulnerability of a specific area. Environmental component consists of indicators which mention the environmental damages caused by flood hazard or

Table 1 Comparison vulnerability assessment methods. *Source*: Huang et al. (2012), Balica et al. (2013), Nasiri and Shahmohammadi-kalalagh (2013)

Method	Vulnerability index method	Disaster loss estimation	Modeling
Characteristics	Extensively used in flood vulnerability researches Covers all aspects of human system like social or economic aspect which neglected in other methods Be influenced by complicated indices and weighting of their subjective Can use other relative indicators in data shortage for special indicator Very simple for using by decision makers for comparing regions	Because of imprecise and randomly documented data, outcome should be treated caution Is based on actual damage survey Takes a lot of time and resource Not applicable for other regions(Specific site)	Unintelligible for public Low validity in data shortage condition Using these methods need some specific expertise which are sometime not very simple to learn

artificial interventions, which can raise the vulnerability of a particular area and finally economic components include economic issues such as income, economic activities, industries, agriculture and power production, which are affected by flooding (Balica 2007).

As regards to this theoretical framework, for introducing flood vulnerability index for Kuala Lumpur context, it is essential to identify the flood vulnerability components (physical, economic, environmental and social) and their indicators for Kuala Lumpur city and determine the most significant indicators which are appropriate for the district scale through expert opinions and regulate weights of selected indicators to define the index then at the end construct the district flood vulnerability index (DFVI) for Kuala Lumpur districts.

Malaysia case study

Malaysian cities are fortunate as they do not face hazards like earthquakes, but intensive floods happen regularly. Flash floods and monsoon floods are two kinds of floods that occur rather frequently in Malaysia. Table 2 displays

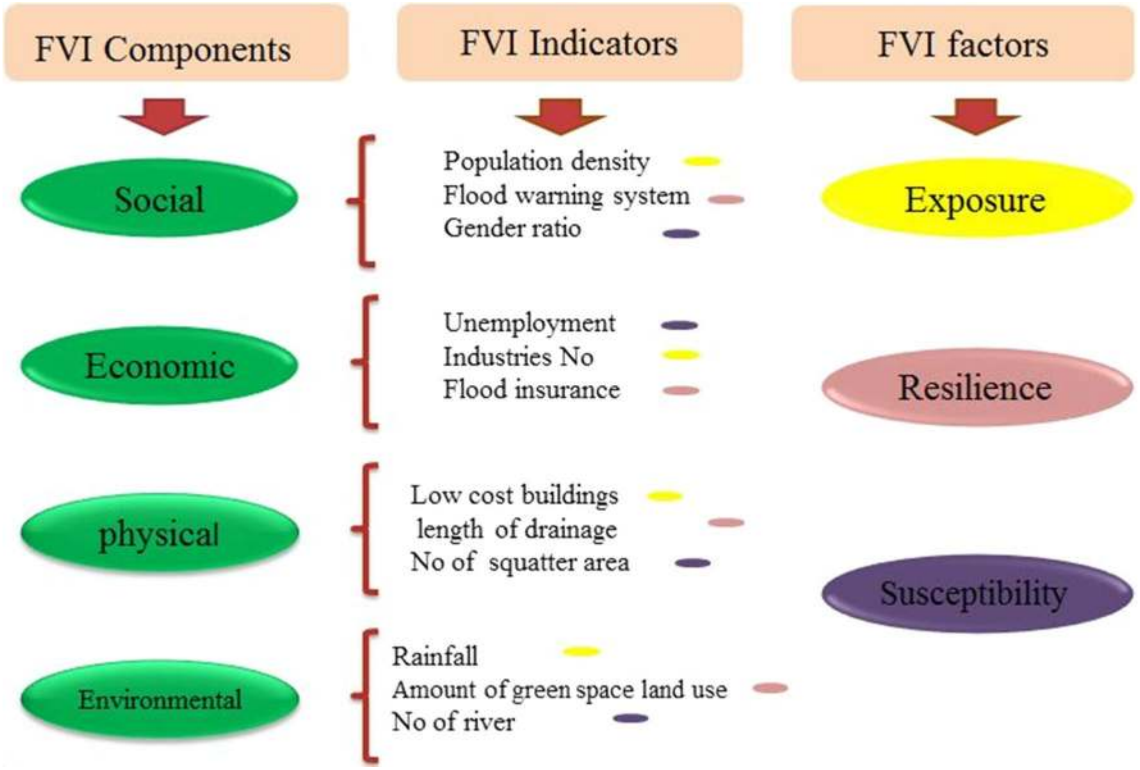

Fig. 1 Flood vulnerability index structure. *Source*: Author

Table 2 Most important floods in Malaysia

Date	No. of people affected in total	Cost of damage (000.US$)	Location
Jan 1967	140,000	25,600	Kelantan
26.12.1970	243,000	37,000	Kuala Lumpur
28.11.1986	250,000	11,500	Kelantan
2003	–	Unknown	Kedah, Kuala Lumpur
2006–2007	176,533	990,000	Johor, Malacca, Pahang, Negeri Sembilan, Shah Alam, Kuala Lumpur
28.12.2008	6000	21,000	Johor, Terengganu,
3.11.2010	50,000	8000	Kedah, Perlis,
28.1.2011	20,000	Unknown	Kajang, Kuala Lumpur (Jalan Tun Razak)
5.12.2013	37,000	Unknown	Pahang, Terengganu, Johor
15 Dec 2014 3 January 2015	More than 200,000	9.42 billion	Johor, Kedah, Kelantan, Pahang, Perak, Perlis, Sabah, Sarawak, Selangor and Terengganu

ADRC (2011), Guha-Sapir et al. (2014), Chan (2015), Abustan and Wahid (2008), Nasir (2015)

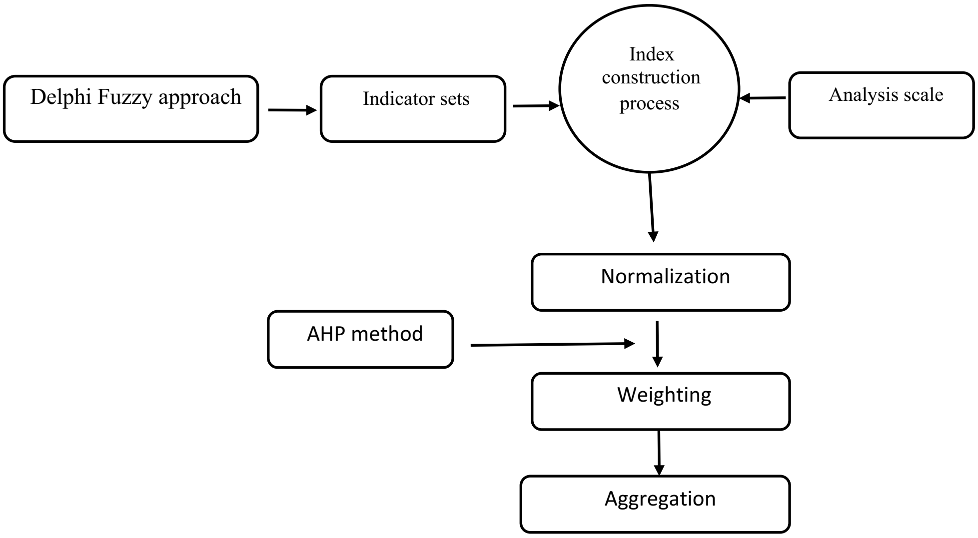

Fig. 2 DFVI construction flowchart. *Source*: Author

the most serious flood events in Malaysia between 1950 and 2015 which are arranged by number of people affected and extent of economic losses. But few studies have been done on introducing indexes on this area.

In fact, DFVI approach is one of the initial index methods for flood vulnerability assessment in urban district scale and the first structured effort to assess flood vulnerability with indexes in Malaysia. This will be more imperative when vulnerability assessment is a requirement of the European flood directive 2007/60/EC (Parliament and Committee 2007) for reducing natural hazard risk. In such a way, Kyoto 2005 manifesto (governments across the world obligate to proceed for reduce disaster risk and approved a guideline to decrease vulnerabilities to natural hazards, called the Hyogo Framework for Action (HFA)) has mentioned indicators-based approaches to different scales for observing disaster risk and vulnerability, and rise the capability of countries to manage risks (United Nations 2005; Balica et al. 2013). As a result, the indicators through the index can be a director to understanding the current and future state of an area in facing with natural hazards.

Materials and methods

For developing the new index, the model construction flowchart (Fig. 2) was beneficially used as an initial step. In the first step, a set of indicators from different sources was gathered. For screening more appropriate indicators for urban district scale, which will make a district vulnerable to floods, expert elicitation was done through Delphi Fuzzy method. With regard

Table 3 Defuzzification results of aggregated experts' values for all DFVI components

Components	Indicators	Opinions' mean	Crisp value	Result
Social	Population density	(0.57,0.82,0.93)	0.77	Approved
	Elderly population	(0.215, 0.42, 0.665)	0.433	Rejected
	Racial composition of district (Malay, Chinese, Indian)	(0.11, 0.23, 0.47)	0.27	Rejected
	Gender Ratio(male/female)	(0.125,0.29,0.525)	0.31	Rejected
	Flood hazard map existence in district	(0.49,0.72, 0.87)	0.69	Approved
	Warning system existence	(0.44,0.675,0.83)	0.64	Rejected
Physical	Proportion of low-cost buildings	0.535,0.78,0.91	0.74	Approved
	Length of drainage system	0.665,0.915, 0.98	0.85	Approved
	No. of cultural heritage	0.285,0.51,0.725	0.50	Rejected
	No. of Hospital/Clinic	0.395,0.64,0.805	0.613	Rejected
	No. of public transportation stations	0.195,0.355,0.575	0.375	Rejected
	No. of Squatter area	0.34,0.585,0.785	0.57	Rejected
Environmental	Amount of rainfall	0.69,0.94,0.985	0.87	Approved
	No. of River	0.65,0.895,0.955	0.83	Approved
	Amount of open land use in each district	0.53,0.78,0.92	0.74	Approved
	Temperature fluctuations	0.36,0.585,0.775	0.571	Rejected
	Runoff amount from rainfall regards to different land uses	0.51,0.755,0.915	0.72	Approved
	Average slope of district	0.41,0.65,0.825	0.62	Rejected
	No. of environmental protection zones	0.195,0.365,0.595	0.385	Rejected
Economic	No of industries unit	0.525,0.755,0.9	0.72	Accepted
	Unemployment rate	0.175,0.29,0.52	0.32	Rejected
	Be existent of flood insurance	0.315,0.55,0.755	0.54	Rejected
	Be existent of crisis management office in district	0.37,0.585,0.76	0.571	Rejected
	No. of commercial units	0.54,0.77,0.92	0.74	Accepted

Table 4 Final indicators for DFVI

No.	Abb.	Name	Units	FV factor	Definition
1	P_d	Population density	$\frac{\text{People}}{\text{km}^2}$	Exposure	There is an important exposure to flood if population is concentrated
2	F_m	Flood map existence	–	Resilience	If there is no F_m, then the value is 1, if yes, the value is 10 (Balica et al. 2013)
3	$L_{c \cdot b}$	Low-cost building	%	Exposure	The condition of low-cost buildings: (Shuid 2004) Poor quality of construction and material Space standards determined 60-65 m^2 High density of people (150 people per hectare Shortage of car parking space Affordability for House (RM):below RM85,000
4	D_l	Drainage length	km	Resilience	More drainage, less vulnerability
5	R_a	Rainfall amount	$^{\text{m}}/_{\text{year}}$	Exposure	Higher rainfall, higher vulnerability
6	R	River No.	Number	Susceptibility	More river, higher vulnerability
7		Open space land use	Hec.	Resilience	Open space increase leads to low vulnerability
8	S_t	Runoff amount	$\frac{\text{m}^3}{\text{s}}$	Exposure	Runoff rate used for this item which refers to Runoff coefficient data and the area of each type of land use in each district (Dingman 2002; Wong 1970)
9	I	Industries	Sq^2	Susceptibility	The higher number, higher vulnerability
10	C	Commercial units	Hec	Susceptibility	The higher amount of commercial land use, higher vulnerability

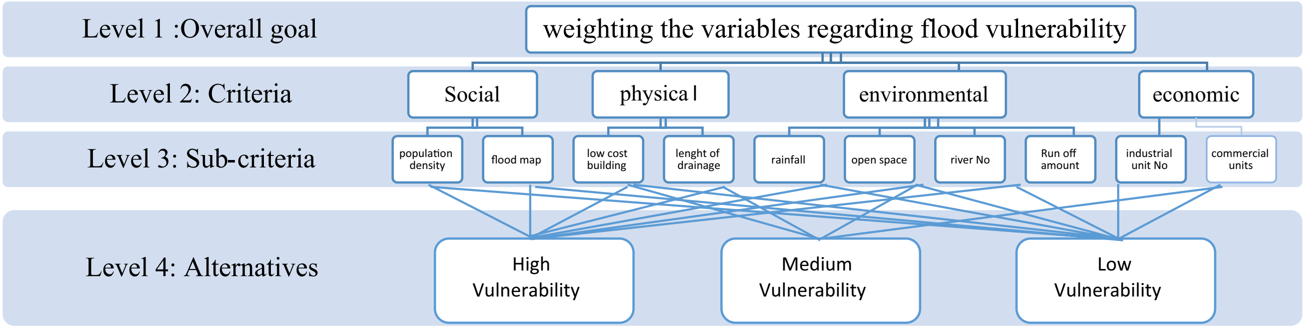

Fig. 3 A hierarchy for flood vulnerability indicators weight decision. *Source*: Author

to respondents' time limitations and with respect to accomplishing one round Delphi survey, which is assumed sufficient for screening the variables, researcher decided to choose this method for extraction of experts' opinion.

Five point Likert scale questionnaires' results which filled out by Kuala Lumpur urban planning and urban flood experts were accumulated in fuzzy pattern. Considerable discussion and consultation has been devoted to the identification of the variables used in the calculation of the DFVI. The primary indicator set which are more suitable for district scale is mentioned in results section.

Results and discussion

Recent section is divided into some steps: first is the screening the different indicators of an urban district which will make it vulnerable to floods through Delphi Fuzzy method. Second part presents the indicator weighing achieved by AHP methodology. For running the AHP method in the DFVI construction process, expert choice software is employed. At that moment, index construction was completed. It is followed by implementation of the constructed index in case studies and comparison of the indices in six strategic zones of Kuala Lumpur, aggregating the indicators in terms of vulnerability index. The acceptance and rejection of variables are also matters of threshold value that are determined by the researcher. The threshold is determined as 0.7 for this research. Those variables which show a real score higher than the threshold value after defuzzification were taken, and the rest discarded.

The final indicators for DFVI which gained from Delphi survey are presented in Tables 3, 4.

The next step in index construction is determining the weight of each indicator for using in index equation. By using the analytic hierarchy process (AHP) pairwise comparison process, weights or priorities are derived from a set of judgments. Once the model is built, the next phase is to evaluate the elements by making pairwise comparison hierarchy tree. This pairwise tree in this study can be divided into four parts as shown in Fig. 3:

- goal (weighting DFVI's indicators),
- criteria (social, physical, environmental and economic)
- sub-criteria (population density, flood map existence, low-cost building, length of drainage, rainfall, runoff amount, river number, open space land use, number of industrial units and commercial units)
- alternatives (high vulnerability zone, medium vulnerability zone and low vulnerability zone)

The final normalized weights for selected indicators are presented in Table 5.

After weights have been assigned to each component of index between diverse ways in which variables can be combined to form an index, we follow the composite index approach, as used in the construction of the Human Development Index and social vulnerability index and most of environmental issues. Index aggregation was done with regard to two equations.

First: Additive aggregation is implemented in the index as a weighted linear combination of normalized indicators

$$y = \sum_{i=1}^{n} W_i X_i \tag{1}$$

Second: Flood vulnerability equation (Connor and Hiroki 2005; Balica and Wright 2010) respects to exposure, susceptibility and resilience components

$$FV = \frac{E \times S}{R} \tag{2}$$

where E shows all the indicators in exposure factor, S contains all the indicators in susceptibility factor and R covers the resilience indicators.

With merging these two equations, Eq. (3) is achieved

$$\text{DFVID} = \frac{\sum_{E=1}^{n} X_E \cdot W_E \times \sum_{s=1}^{n} X_S \cdot W_S}{\sum_{R=1}^{n} X_R \cdot W_R} \tag{3}$$

Table 5 Final assigned normalized weights to DFVI variables

Indicator	Population density	Flood map existence	Low-cost building	Drainage length	Rainfall	River No.	Open space	Runoff amount	Industries No.	Commercial units
Weight	0.165	0.143	0.203	1.00	0.782	0.219	0.154	0.774	0.076	0.090

where, X_E: District vulnerability indicators in exposure factor, W_E: Weight of Exposure factor indicators, X_S: District vulnerability indicators in susceptibility factor, W_S: Weight of susceptibility factor indicators, X_R: District vulnerability indicators in resilience factor, W_R: Weight of resilience factor indicators.

According to assigned weights to each of the district indicators which are attained in previous part (Table 5), subsequently final indexes are achieved

District social flood vulnerability

$$\mathrm{DFVIsocial} = \left[\frac{0.165P_D}{0.143\mathrm{flood}_{\mathrm{map}}}\right] \tag{4}$$

District physical flood vulnerability

$$\mathrm{DFVI}_{\mathrm{physical}} = \left[\frac{0.203L_{C.B}}{1 * D_L}\right] \tag{5}$$

District environmental flood vulnerability

$$\mathrm{DFVI}_{\mathrm{Environmental}} = \left[\frac{0.782\mathrm{Rainfall} + 0.774\mathrm{Runoff}{*}0.219R}{0.154\mathrm{O}_{\mathrm{LU}}}\right] \tag{6}$$

District economic flood vulnerability

$$\mathrm{DFVI}_{\mathrm{Economic}} = [0.076\mathrm{I} + 0.090C] \tag{7}$$

$$\begin{aligned}\mathrm{Overall}_{\mathrm{DFVI}} = &\mathrm{DFVI}_{\mathrm{Social}} + \mathrm{DFVI}_{\mathrm{physical}} + \mathrm{DFVI}_{\mathrm{Environmental}} \\ &+ \mathrm{DFVI}_{\mathrm{Economic}}\end{aligned} \tag{8}$$

Pilot implementation of DFVI at Kula Lumpur districts

The implementation of flood vulnerability index is done within the context of a particular place. For this research, the test bed for the analysis is the Kuala Lumpur city due to the devastation this area suffered from flooding. Kuala Lumpur as the federal capital is most inhabited city in Malaysia. Population data reveal nearly 1.6 million people resided within the 243 km^2 area. Kuala Lumpur is distinct within the boundaries of the Federal Territory of Kuala Lumpur. It is a district within the state of Selangor, on the central west coast of Peninsular Malaysia (DBKL 2004). Kuala Lumpur megacity has been divided into six strategic zones for city plan 2020 whose boundaries support with major roads, rails and river corridors. These strategic zones can be used as this research required scale because they are the most suitable small scale inner the Kuala Lumpur with more available data for running the vulnerability index model. This division includes the following areas (Fig. 4).

Alongside the DFVI values for each district, normalized results are presented for further comparison and also

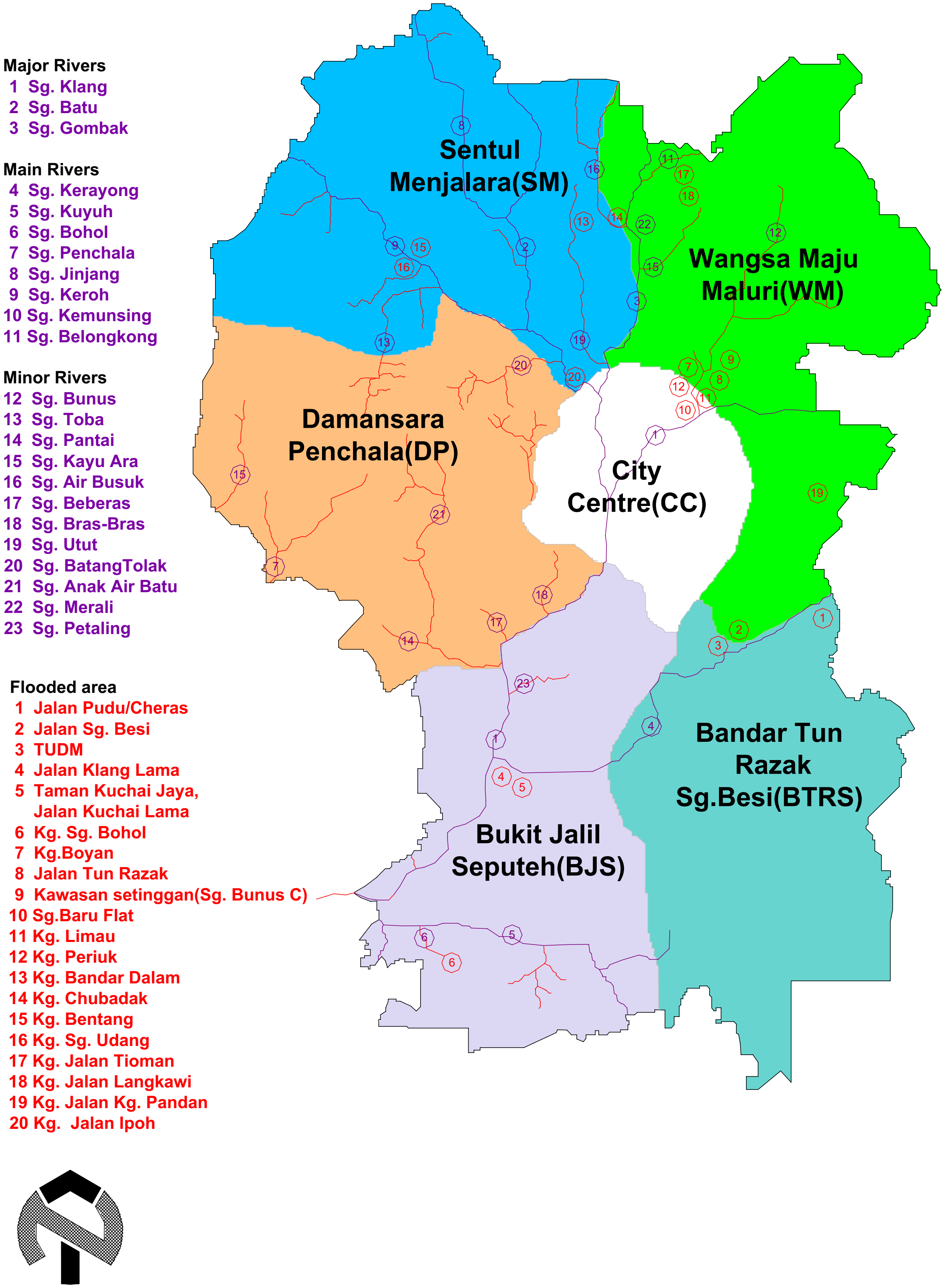

Fig. 4 Strategic zones of Kuala Lumpur with rivers and flooded area. *Source*: DBKL 2004

Table 6 Final district flood vulnerability index in Kuala Lumpur context

District	Wangsa Maju	Sentul	Damansara	City Center	Bukit Jalil	Bandar Tun-Razak
Overall DFVI	4.79	3.94	3.682	4.76	2.73	2.43
Normalized DFVI	1	0.822	0.768	0.99	0.56	0.50

serve the purpose of easier interpretation (Table 6). Figure 5 shows these values in graphical form.

Conclusion

The application of the district flood vulnerability index could offer a unique attitude to the assessment of vulnerability to floods in a more precise and local manner. Media and policy-makers consider rising attention at composite indexes as an attractive tool to draw the community's caution and help by concentrating on policy debates. In this regard, DFVI construction method has been presented. The district-based DFVI offered comparative information on many characteristics of vulnerability and flood risk. Nevertheless, this method also increased challenging questions about the selection and aggregation of the indicators. Some of the chosen and combined indicators were found to be redundant to a certain extent. Moreover, some indicators were found to be very context-specific and thus need to be selected with precaution when applying them for other societies and scales. For example, indicators such as "rainfall amount" or "river number" could be different in district of tropical mega cities (e.g., Kuala Lumpur), but in other geographical regions no meaningful difference between city districts' rainfall amount was noticed. For instance, the rainfall amount does not provide meaningful insights when comparing districts of the same city in dry semiarid climate. Consequently, alternative indicators will be needed. In other words, modifications are required in the index method in order to ensure that the approach evaluates the context, such as the differences between districts in different climatic regions. In conclusion, DFVI approach was found a suitable scheme which enables an interesting composing of indicators for physical, environmental, social and also economic vulnerability on the local level.

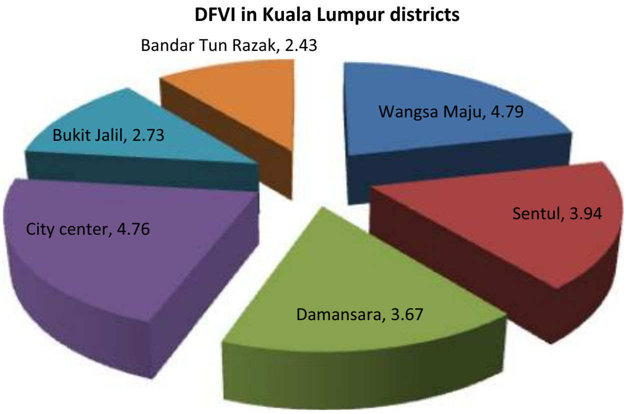

Fig. 5 Flood vulnerability index for each district of Kuala Lumpur

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