Assessment of Urban Vulnerability to Floods using GIS Based Modeling Approach

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ABSTRACT

Flooding is an environmental phenomenon that can pose a risk to social, physical, economic and environmental effects. In response to these flood risks coupled with high density population, the social and environmental implications of these floods affect a variety of vulnerability scores. Presenting a case study of the Makassar region, this paper develops the overall vulnerability assessment to floods using the framework analysis of the BNPB (The Indonesian National Board for Disaster Management) and Geographic Information System (GIS) modeling approach.Based on the grid mesh of 50 meter scales as the spatial treatment unit analysis, the study aggregated the local indicators to a single composite index that enable spatial vulnerability representation at sub-district levels. These indicators were composed from various social, physical, economic, and environmental factors. Overall flood vulnerability index (FVI) is assessed which areas are most vulnerable to flooding with regard to the system's components.

INTRODUCTION

Floods are recognized to be the most common and devastating type of natural disaster worldwide (Adetunji and Oyeleye, 2013). It has been reported that in the last decade, urban floods have impacted most parts of the world including the Unite State, Europe, and Asia (Tingsanchali, 2012). Recently, flooding occurs in the most developed countries (Adelekan, 2011). The causes of flooding in cities vary according to geographical location, topography, land-use, and watershed condition (Haki et. al., 2004).

Since 1900, flooding in Indonesia is ranked as the second most frequent and fourth most economically damaging natural disaster, causing an estimated 4,493 deaths, affecting 6.2 million people and resulting in US$ 2.4 billion in damages (Riyanti et. al., 2017). Cities located on the coast within an extensive coastal plain which are subject to flooding from inland and from the sea (Clark et. al., 1998). In response to flood risks, coupled with high density population, the social and environmental implications of these floods affect a variety of vulnerability scores. Hence, assessing vulnerability to flood hazards is an essential step towards effective risk reduction, as it helps identify local factors that contribute to the vulnerability and to measure their significance. Although flood hazards are natural phenomena, the vulnerability of an area to flooding is a combination of socio-economic and environmental factors that vary spatially from one place to another (Cutter et. al., 2003). There is therefore a need for a framework analysis and spatially processing method to assess flood vulnerability.

This paper aims to assess overall vulnerability to floods by providing a spatial analysis of the social, physical, economic, and environmental components of the Makassar region, Indonesia. Moreover, this study evaluates the vulnerability scoresbased on the framework analysis of BNPB (The Indonesian National Board for Disaster Management).

THE CONCEPT OF FLOOD VULNERABILITY

Theoretical framework

Vulnerability is considered as the extent of harm, which can be expected under certain conditions of exposure, susceptibility and resilience (Balica et al. 2009; Hufschmidt 2011; Fuchs et al. 2011). More specifically in the case of floods, a system is susceptible to floods due to exposure in conjunction with its capacity or incapacity to be resilient, to cope, recover or adapt to the extent. The concept of vulnerability is approached from different disciplines and professional fields such as academia, disaster management agencies, climate change community and agencies (Cannon, 1994). Though many definitions exist, the concept of vulnerability in this study considers the local context provided by BNPB framework. By this framework, flood vulnerability has specific social, physical, economic, environmental contexts that impose challenges to research. The BNPB framework was developed to improve vulnerability assessment in Indonesia. It is used as part of risk evaluation and risk management in the context of disaster risk reduction in Indonesia. It is accomplished as standards and guidance in estimating vulnerability as the critical component of risk at local context. The BNPB framework better fits the local context, since the data that are necessary for the framework are available and easily accessible in the study area. Indeed, in this paper, all the indicators considered, related to exposure, susceptibility and resilience, are covered by the BNPB framework. Following this framework, our methodology analysis involves statistical and spatial analysis, development of composite indicators using a GIS grid system.

Indicator of vulnerability

Societies are vulnerable to floods due to three main indicators: exposure, susceptibility and resilience (Balica and Wright, 2009). The vulnerability of any system (at any scale) is reflective of (or a function of) the exposure and susceptibility of that system to hazardous conditions and the resilience of the system to adapt and/or recover from the effects of those conditions (Smit and Wandel 2006).

Exposure describes the extent to which an area that is subject to an assessment falls within the geographical range of a hazard event (Balica and Wright, 2010). It was defined geographically in space as the social and material context, as represented by people, and ecosystem.

Susceptibility describes the predisposition of elements at risk to suffering harm resulting from the levels of fragility of settlements, disadvantageous conditions and relative weaknesses (Birkmann et. al., 2013).

Resilience is the capacity of any kind of system, community, society or environment, potentially exposed to hazards to adapt to any change, by resisting or modifying itself, in order to maintain or to achieve an acceptable level of functioning and structure (Pelling 2003). Lack of resilience describes the limitations of access to and the mobilization of resources and the incapacity of that system to respond by absorbing the impact (Depietri, 2013).

Understanding each concept and considering certain indicators may help to characterize the vulnerability of different systems. Every vulnerability factor represents a set of constituent indicators based on the characteristics of local areas.

DEVELOPMENT OF METHODOLOGY

Selection of relevant indicator variables

The first step in vulnerability assessment is to select appropriate indicators. The availability of data, the importance of certain indicators and the condition must be dimensionless for the purposes of comparison led to the formulation of the equations for each vulnerability component.

The method presented in this study uses the BNPB framework as a reference analysis to assess vulnerability. In this study, key factors of the BNPB framework analysis are defined as follows.

1. Exposure (E): In this study, it was measured by the number of people per sub-district area, differently exposed to flood due to their location. Exposure is calculated by considering the density of the population per sub-district area (E1), percentage of the population under poverty (E2), land resource base (E3), productive land (E4), and percentage of the vegetation cover (e.g. protected forest, natural forest, mangrove, shrubs) (E5).
2. Susceptibility (S): Children under 5 years and the elderly (above 65 years), and women are considered to be the groups most susceptible to harm in the case of flood events. Based on local context, susceptibility is calculated by considering the percentage of number of children less than 5 years or elderly above 65 years (S1), percentage of women per sub-district area (S2), and the number of building codes related to the structural value and importance (S3).
3. Resilience (R): Affected communities become more resilient to flood when they are able to recover from the hazard. The recovery process presumes the availability of sufficient means and risk transfer tools. It seems, therefore, that the disable peoples e.g. homeless, literacy rate, and handicap for lack of resilience for a given sub-districts (R1).

The explanation and references of each selected indicator are presented in **Table 1**.

Development of vulnerability indicators

Social vulnerability component

The indicators used for social vulnerability are population density, percentage of poverty, percentage of ages(5< and >65 years), percentage of gender, and percentage of disability. The index of social vulnerability is derived from the average of weight of population density (60%), and weight of social sensitivity (40%) consisting of percentage of poverty (10%), percentage of ages (10%), percentage of gender (10%), and percentage of disability (10%). As for the practical implementation for each vulnerability components, the score was normalized by dividing the vulnerability value x_j by the number of vulnerability items, i.e. the maximumvulnerability value is 1. The normalized composite vulnerabilitywas then calculated based on the equation:

$$Xj = \frac{x_j - \text{Min}\,(x_j)}{\text{Max}\,(x_j) - \text{Min}\,(x_j)} \qquad (1)$$

where,

Xj is the normalized value (ranging from 0 to 1) of the indicator j of a vulnerability component (E, S, R); x_j is the value of the indicator j; $Max(x_j)$ and $Min(x_j)$ are respectively the maximum and minimum values if the indicators j of the vulnerability component.

Thus, the normalized indicators were aggregated using the following equation, according to their respective social components ($E; S; R$):

$$VI_{social} = \sum_{j=1}^{k} W_j X_j \qquad (2)$$

VI_{social} is the composite indicator with (E, S, R) referring to the three components of vulnerability; W_j is the weight of the indicator j; and X_j is the normalized value of the indicator j.

Physical vulnerability component

The indicators used for physical vulnerability are building houses, public facilities, and critical facilities. Building cost is obtained by calculating the area of polygon (square meter), and multiplied it by the unit price of each building code parameters (PU, 2006). Index of physical vulnerability is obtained from the building (40%), public facilities (30%), and critical facilities (30%).

Economic vulnerability component

The indicators used for economic vulnerability are the area of productive land (e.g. paddy fields and garden field), and the land resource base ofPDRB (Gross Regional Domestic Product).The area of productive land can be obtained from land-use maps and the PDRB of statistical data at district or sub-district can be analyzed by statistical data. The index of economic vulnerability is derived from the weight of the area of productive land (60%), and weight of the land resource base (40%).

Environmental vulnerability component

The indicators used for environmental vulnerability are land cover (protected forests, natural forests, mangroves, and shrubs). Environmental vulnerability index is different for each type of threat, and it is obtained from the average weight of the land cover type. The index of environmental vulnerability is derived from the weight of the area of protected forest (40%), weight of the natural forest (40%), weight of the mangrove (10%), and the shrubs (10%).

The overall vulnerability to floods

Overall flood vulnerability is the result of the product of social, economic, physical and environmental vulnerability components, with different weighting factors.In semi-quantitative analysis, the lack of specific information about the sensitivity factor is compensated by the weight factor. The best weighting factors are obtained through the consent of expert opinions (BNPB, 2012). A methodology emerged into a consent is the Analytic Hierarchy Process (AHP). AHP is a measurement methodology by pair-wise comparison and relies on expert judgments to obtain priority scales. This is the scale that measures form relative. Comparisons are made using an absolute scoring scale, which represents how much one indicator dominates the other in relation to a particular flood disaster. Therefore; all the weighting factors used for vulnerability analysis are the result of the AHP process. The flood vulnerability index (FVI) is shown in the equation, as follow.

$$FVI = (\mathrm{VI}_{\mathrm{social}} \ \mathrm{x}\ 40\%) + (\mathrm{VI}_{\mathrm{physical}} \ \mathrm{x}\ 25\%) + (\mathrm{VI}_{\mathrm{economic}} \ \mathrm{x}\ 25\%) + (\mathrm{VI}_{\mathrm{environmental}} \ \mathrm{x}\ 10\%) \tag{3}$$

Total FVI of each sub-district area is calculated by four vulnerability components. This index value is described in **Table 2**.

FVI ASSESSMENT: A CASE STUDY

Makassar covers total area of nearly 177 km^2 which is divided into 15 districts and 153 sub-districts including in small islands. Data is collected from available local government, geospatial and satellite data, and observation of statistical databases. Using a grid mesh of 50 meter scales as the spatial treatment unit analysis, the study aggregated the local indicators to a single composite index that enable spatial vulnerability representation at sub-district levels. These indicators were composed from various social, physical, economic, and environmental factors. By taking the BNPB framework and GIS modeling approach, relevant vulnerability indicators in the Makassar region were developed and spatial-temporal analysis were used to create the GIS layers for vulnerability assessment.

Results and discussion

Social vulnerability

The results of the social component are shown in **Fig.1(a)**. Five indicators, belonging to all factorsof vulnerability, were used to determine the social vulnerability values. Using these criteria, some of sub-district stands out as the most vulnerable to floods, mainly due to its high number of people living in flood-prone areas. The social vulnerability map highlights five degrees of index which from very small to very high vulnerability to flood. Most of the sub-district has a social vulnerability to flooding that varies from high to very high. Most areas with very high social vulnerability are located in the Westand Centre part of the Makassar region.

Physical vulnerability

The results of the physical component are shown in **Fig.1(b)**. Three indicators are used to determine the physical vulnerability values. When examining the physical susceptibility, it can be seen that Makassar region is the most exposed to floods. This is mainly due to its high number of building with the high cost values. Physical vulnerability index is seen very low in the Northern-East part of Makassar region. Most of the Centre part of the Makassar region shows a high representation of physical vulnerability, significantly above more than half area of sub-districts. Medium to high physical vulnerability are more concentrated in the Southeast of the sub-district.

Economic vulnerability

Two indicators are used to determine the economic vulnerability values. They are productive land of agriculture (paddy field and garden field) and the land resource base (PDRB). The result of the economic component is shown in **Fig.1(c)**. It can be seen using these criteria that Makassar is the fairly vulnerable economically to floods.

Environmental vulnerability

As shown in **Fig.1(d)**, the most vulnerable environment is mangroves, having high environmental exposure, small storage capacity as well as being highly exposed to flood hazards. Shrubs and Mangroves area as having the higher environmental vulnerability, about 84 and 138 hectares areas, respectively, with smaller number of distribution areas. The forest has the lowest environmental vulnerability to floods; these areas are the least exposed from floods.

The environmental component is the result of the combination of three local indicators: natural forest, mangroves and shrubs. These sub-districts are mostly located in the Centre and South part of the Makassar region and have exposure ranging from medium to high and are sparsely distributed.

The overall of vulnerability to floods

Exposed to social, physical, economic and environmental factors, the Makassar region faces a moderate vulnerability to floods (**Fig.2**). Sub-districts of Mamajang, Ujung Pandang and Wajo are also highly vulnerable areas, largely because of the degree of exposure (both population density and environmental aspect). Sub-districts of Bontoala and Makassar are moderately high vulnerable areas, largely because area is physically vulnerable to floods, while Tamalate, Tallo, Manggala and Biringkanaya have equally low vulnerability, mostly because both have slightly less population and building than the other sub-districts, even though the environmental indicators are still significant. As aresult of the combination of the four compositeindicators of the vulnerability components, the highest vulnerability to flood affects almost at the Centre-West and the South-West. Comparative flood vulnerability index at sub-districts is shown in **Fig.3**. Generally, more than 50%of the sub-districts have a vulnerability index varying from moderate to high. The lowest vulnerabilitiesare sparsely distributed throughout the sub-district at the North-East and South-East (Sub-district of Ujung Tanah, Tallo, Panakukkang, Manggala, Biringkanaya, and Tamalanrea).

CONCLUSION

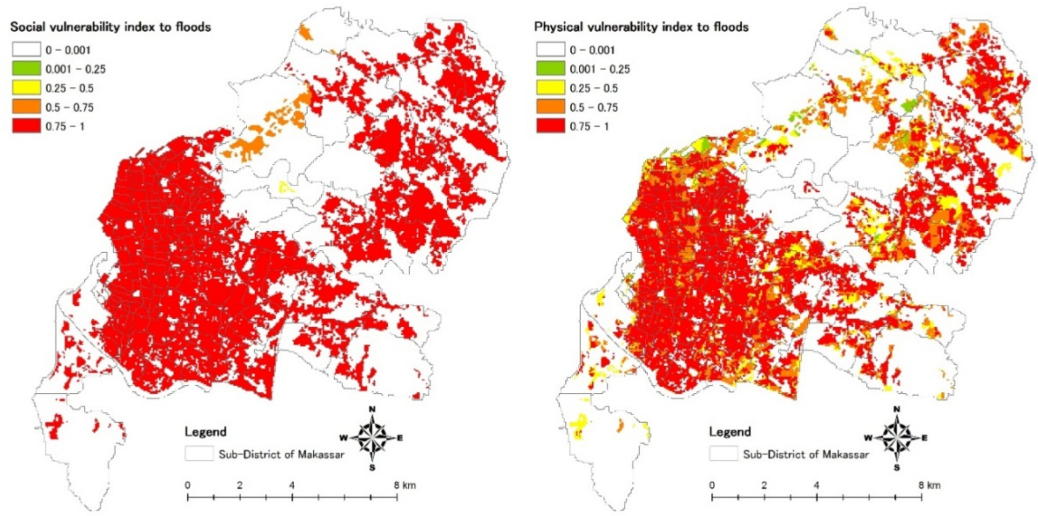
The flood vulnerability of the Makassar region has been assessed with local indicators using BNPB framework. Using grid 50 meter at sub-district scales as the spatial treatment unit, the study aggregated the local indicators to a single composite index that enable spatial vulnerability representation at sub-district level. These spatial indicators were composed of various social, physical, economic, and environmental factors. The results revealed that many sub-districts are moderately vulnerable to urban floods in the Makassar region. Exposure and susceptibility are factors that were identified to have high influence on vulnerability.

Table 1 List and explanations of each selected vulnerability indicator based on local context

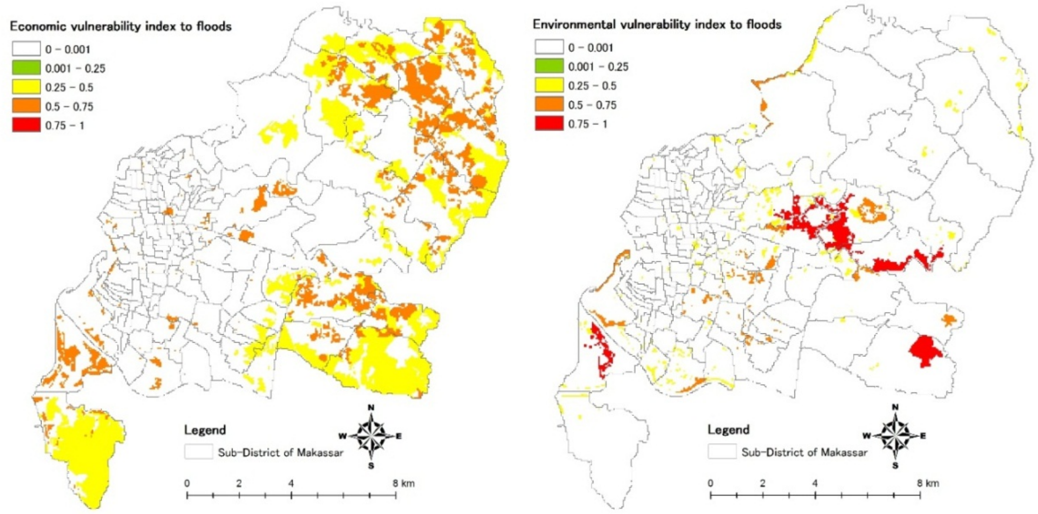
Factors	Code	Indicators	Explanations
Exposure	E1	Population density (inhabits/km^2)	The higher the population density, the higher the exposure (Kuhlicke et. al., 2011)
	E2	% of poverty	The higher the percentage of poverty, the higher the exposure (Kuhlicke et. al., 2011)
	E3	Productive land	The higher the productive land, the higher the exposure (BNBP, 2012)
	E4	Land resource base (PDRB)	The higher the land resource base, the higher the exposure (BNBP, 2012)
	E5	Vegetation covers (e.g. protected forest, natural forest, mangrove, shrub)	The higher the vegetation area, the higher the exposure (BNBP, 2012)
Susceptibility	S1	Percentage of children under 5 or elderly above 65	The young and the elderly people are vulnerable to natural hazard both because their physical condition (Haki et. al., 2004; Cutter et al., 2003)
	S2	% of gender (women)	Women are generally described as more vulnerable to natural hazards than men because of their stronger involvement in family life (Wisner, 2003)
	S3	Building codes (e.g. houses, public facilities, critical facilities)	Determines the physical fragility towards flood events and indicates the resistance to damage and also the social status (Clark et al., 1998)
Resilience	R1	% of disable peoples	The higher the disable peoples, the lower the capacity to understand early warning systems, and evacuation (Kuhlicke et. al., 2011)

Table 2 Flood vulnerability interpretation (Balica et. al., 2012)

Index value	Description
< 0.01	Very small vulnerability to floods
0.01 - 0.25	Small vulnerability to floods
0.25 - 0.50	Vulnerability to floods
0.50 - 0.75	High vulnerability to floods
0.75 - 1	Very high vulnerability to floods



(a) Social vulnerability (b)Physical vulnerability



(c) Economic vulnerability (d) Environmental vulnerability

Fig.1Components ofvulnerabilityindex to floods based on the BNPB framework and GIS model approach

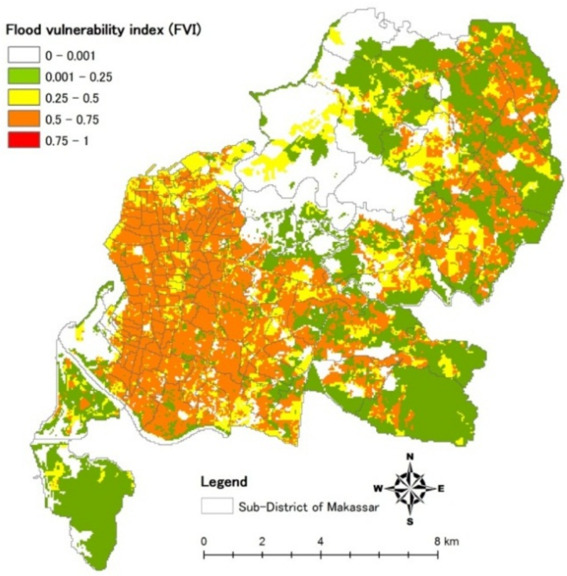


Fig.2Overall vulnerabilityindex to floods in the Makassar region

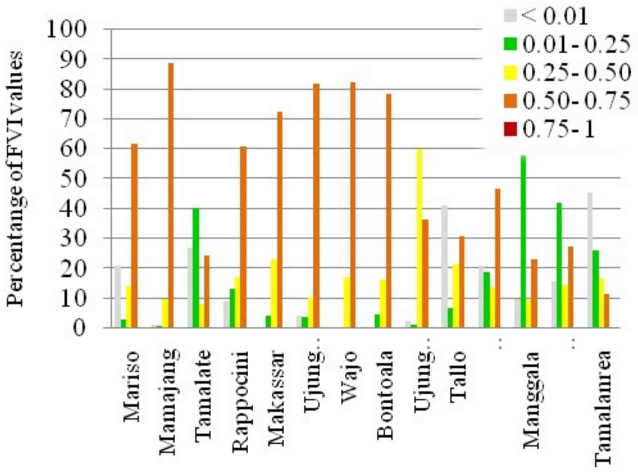


Fig.3Comparative flood vulnerabilityindex at sub-districts

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