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Spatial-Temporal Vulnerability and Risk Assessment Model for Urban Flood Scenario

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As urban areas grow both geographically and demographically, the flood hazard and risk has been increased in the sub-districts of Makassar region recently. Hence, planning the urban areas will require a spatial analysis of flood risk assessment scenario to ensure that the potential developments arising from urbanization are optimized to reduce damages by floods. This paper presents a spatial and temporal model analysis for flood vulnerability and risk assessment, with the aim to establish a risk index at sub-district scales for urban flood scenario in the Makassar region. Firstly, we develop the overall vulnerability assessment to floods based on the local framework analysis of the BNPB (The Indonesian National Board for Disaster Management) and the use of Geographic Information System (GIS) modeling approach. Using a GIS grid mesh model of 50 meter scales as the spatial treatment unit spatial-temporal 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. Secondly, GIS analysis conducts grid index modeling of flood hazard model by incorporating the measurement of floods in 2013, as a flood hazard scenario. Finally, by combining the spatial factors of flood hazard and flood vulnerabilities, a spatial and temporal risk assessment model has been simulated at sub-district scales to evaluate the potential impact to the social, physical, economic, and environmental aspects.

Keywords: Risk Assessment, Urban flooding, GIS, Spatial model

I. INTRODUCTION

Flooding is an environmental phenomenon that can pose a risk to the social, physical, economic and environmental aspects. In urban areas, floods are usually the consequence of extreme rainfall, which creates an excess of runoff (Parkinson, 2002; Zhou, 2014). It has been reported that in the last decade, urban floods have impacted most parts of the world including the Unite States,

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Europe, and Asia (Tingsanchali, 2012). The cause of flooding in cities varies according to geographical location, topography, land-use, and watershed condition (Haki et al., 2004). Cities located on the coast within an extensive coastal plain are subjected to flooding from inland and from the sea (Clark et al., 1998).

Since 1900, flooding in Indonesia is ranked as the second most frequent and fourth most economically damaging natural disaster, causing an estimated of 4,493 deaths, affecting 6.2 million people and resulting in US$ 2.4 billion in damages (Riyanti et al., 2017). As the largest city at the Eastern part of Indonesia, Makassar's economy is booming, which develops and demands more commodities. Despite this economic success, the rapid urbanization of the Makassar region and the changing land-uses are large. Alteration of the coast and its wetlands through the urban development disrupts the interrelation between ecological systems and flood control. This makes the Makassar region and its residents more at risk to floods, with weather patterns become more intense and seasonal changes harder to predict. Indeed, factors influencing flood risks differ from one area to another depending upon local environmental context and management strategies. Recently, the city government proposes to create urban development in the land that is now undeveloped, because it is subjected to regular flooding. It is the large area on downstream of Tallo River. Hence, planning the urban development in the Tallo River area will require a spatial analysis for flood risk assessment scenario to reduce damages by floods in future.

An environmental approach to flood hazards is based on the view that both social and physical environments influence the creation of flood hazards and disasters (Cannon 1994). Flood risk should be viewed as a widespread product of social, physical, economic and natural usually. Risk assessment is a complex spatial process aiming at evaluating the different aspects that can disrupt or destruct a system. For complex systems that comprises of many components over significant geographical areas, the understanding of all factors involved in a risk situation is particularly demanding. Therefore, this paper presents spatial and temporal analysis for flood vulnerability and risk assessment, with the aim to establish a risk index at sub-district scales for urban flood scenario in the Makassar region. Moreover, this study evaluates the vulnerability scores based on the framework analysis of BNPB (The Indonesian National Board for Disaster Management). This framework analysis helped assess the major available local factors involved in the vulnerability of urban flooding at sub-district scales, and to have a good representation of the spatial-temporal distribution information of areas that are vulnerable to urban flood by Geographic

Information System (GIS). A flood risk assessment index is established at sub-district scales to evaluate the potential impacts to social, physical, economic, and environmental aspects, which are subjected by the flood hazard scenario in 2013.

II. MATERIALS AND METHOD

A. Vulnerability index to flood

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). According to the Intergovernmental Panel on Climate Change (IPCC), vulnerability is defined as the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Concerning flood vulnerability, it refers to the state of susceptibility to harm from the exposure of flood hazards, and the ability of a unit of analysis to cope with, and recover from, such exposure. 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, and environmental contexts that impose challenges to research, as shown in Figure 1. The BNPB framework suitably 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.

B. Indicator of vulnerability

Societies are vulnerable to floods due to three main indicators: exposure, susceptibility and resilience (Balica & Wright, 2009). Exposure describes the extent to which an area that is subject to an assessment falls within the geographical range of a hazard event (Balica & Wright, 2010). 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). 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.

Therefore, every vulnerability factor represents a set of constituent indicators based on the characteristics of local areas.

C. Selection of relevant indicator variables

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): 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 (E5).

2. Susceptibility (S): it was calculated by considering the percentage of number of children (< 5 or > 65 years) (S1), percentage of gender per sub-district area (S2), and the number of building codes related to the structural value and importance (S3).

3. Resilience (R): It was measured by the disable peoples e.g. homeless for a given sub-districts (R1).

D. Development of vulnerability indicators

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 xj by the number of vulnerability items, i.e. the maximum vulnerability value is 1. The normalized composite vulnerability was then calculated based on the equation:

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

where,

Xj is the normalized value (ranging from 0 to 1) of the indicator j of a vulnerability component (E, S, R); xj is the value of the indicator j; Max(xj) and Min(xj) 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):

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

VIsocial is the composite indicator with (E, S, R) referring to the three components of vulnerability; Wj is the weight of the indicator j; and Xj is the normalized value of the indicator j.

For the physical, economic, and environmental components, the indicator analysis undergoes a similar process. Physical indicators used for physical vulnerability includes 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). The indicators used for economic vulnerability incorporates the area of productive land (e.g. paddy fields and garden field) and the land resource base of PDRB (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 indicators used for environmental vulnerability are land cover. Environmental vulnerability index is different for each type of threat, and it is obtained from the average weight of the land cover type. Overall flood vulnerability is the result of the product of social, economic, physical and environmental vulnerability components, with different weighting factors (BNPB 2012), in which the Analytical Hierarchy Process (AHP) is applied. 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.

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

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 (Figure 2). By taking the BNPB framework and GIS modeling approach, relevant vulnerability indicators in the Makassar region were analyzed using spatial-temporal analysis to create the overall vulnerability assessment index, as shown in figure 3. Vulnerability interpretation index is described in table 1.

E. Urban flood occurrence in 2013

In January 2013, large scale floods occurred and struck a lot of areas in 6 districts which a total flooded area is about 3,000ha. Number of total peoples affected by floods reaches 101,972 inhabitants, as recorded values by Indonesian Regional Disaster Management Agency (BPBD). At that time, flood survey and measurements were conducted by the coordination between the governments of the city of Makassar and the BPBD. Flood hazard map in the Makassar region in 2013 was published by the local government. Figure 5a shows the defined flood hazard map as for the urban flood scenario risk assessment analysis in the next section.

F. Development of flood risk assessment

I. Risk assessment index model

In most cases, risk term has been defined in relation to the purposes of different science in which disaster management methods were required. Despite a lot of definitions in literature, the concept of risk with regard to hazard and vulnerability seems to be the most accepted in flood risk management so it is significant to know that risk is completely a human subject (Ben, 2004). Preparation of the flood risk assessment index requires additional spatial analysis after obtaining the required indices (vulnerability and hazard). The flood risk assessment index provides an overview of the area related to the risk level of a flood disaster in an area. The analysis process should be implemented for all flood areas that exist in each sub-district. Determination of risk level is calculated by using vulnerability index and flood hazard index. The risk index level determination is calculated by using the matrix, as shown in table 2. Determination is calculated by linking the two index values in the matrix. The color of the grid cell represents the risk level of a flood disaster in that area.

G. Flood hazard index

The flood hazard index was structured based on two main components, namely the possibility of a threat and the magnitude of impacts recorded for the flood disaster. It can be said that this index is compiled based on data and historical records of events that have occurred in an area. In this study, historical records of flood events in 2013 are used as flood hazard scenario for risk assessment. This flood hazard maps were provided by the local government of the Makassar which coordinated with BPBD. In the preparation of flood hazard index map, flood areas and depths are mapped using the GIS tool. Classification index system can be implemented after all data on the study area is obtained from predefined data source. The data obtained are then divided into 4 threat classes (very low, low, medium, and high). The flood hazard index can be seen in figure 5b.

H. Risk assessment index

Indicators used for risk analysis will be selected based on availability and local context. To make the index comparable at least in dimensions, the risk index used in the analysis is converted to a value between 0 and 1, where 0 is the minimum value of the original indicator, and 1 is the maximum value. In the case of low numbers that are numerous indexes and vary in sometimes high number, therefore the index classification by logarithmic conversions will be performed instead of linear conversions. Table 3 shows the result of index classification model for risk assessment definition of the study area. Flood risk indexes are classified by 7 classes from very low, low, low to medium, medium, medium to high, high, and very high. In this case, the risk index is calculated based on the multiple of the indices.

For risk index mapping analysis, a combination of vector-based GIS layers and grids is used, where index grid data is mainly stored using a vector, where the risk index can be easily calculated in a grid matrix format. Finally flood risk assessment index map is calculated from hazard index (see in figure 5b) and vulnerability index (see in figure 3), as shown in figure 6.

III. RESULTS AND DISCUSSIONS

The results of the risk assessment index in social component are calculated. Using these spatial criteria, sub-districts of Antang, Tamalanrea, and Sudiang Raya in Manggala District stands out as the most risk in social aspects, mainly due to its high number of people living in flood prone areas. The buildings with a higher density are mostly located at sub-districts of Tamalanrea and Kapasa in Tamalanrea District, and Antang in Manggala District. The spatial distributions of the building such industrial buildings, educational buildings, hospital buildings are densely distributed in the Tamalanrea district. Therefore, higher risk indexes in physical component are located in the Tamalanrea District. For the calculation of risk index to the economical values, the indicator of agricultural sector was used. Paddy fields, which mostly represents the production of rice in the Makassar region in order to gain the productivity land in the areas. Concerning the spatial distribution of the paddy field throughout the Makassar region, area percentage of risk index is high in the sub-district of Antang, Pampang, Tamangapa in the Northern east of the Makassar region, and these sub-districts are more concentrated in the production of paddy in the Makassar region in 2012.

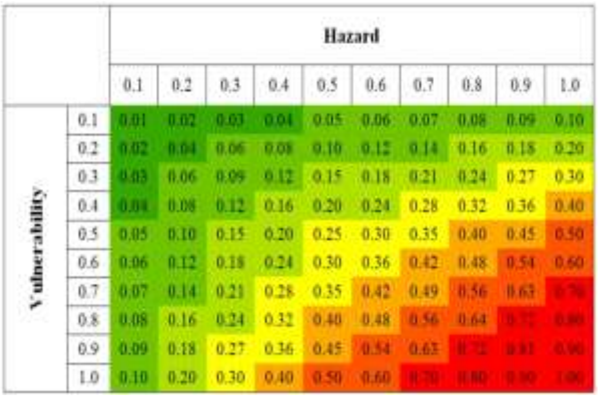
The environmental component shows the involvement of ecological systems in the flood risk management process. The environmental component is the result of the combination of three local indicators: natural forest, mangroves and shrubs. The vegetation cover at the sub-districts that are located in the west of the Makassar region appears very low. The most high risk index to the environment component is distributed in the sub-districts of Tamangapa, Tamalanrea Jaya, Panaikang and Pampang. Among these sub-districts, Tamangapa and Tamalanrea Jaya are potentially the higher environmental impacts, about 85 and 71 hectares areas, respectively. As a result of the composite vulnerability components (social, physical, economic, and environmental aspects) described above in the previous section, the sub-district presents the wide area with high risk index that are mostly located in Antang, and following by Sudiang Raya, Tamalanrea Jaya and Tamangapa (see in figure 7). Sub-districts of Tamalarea, Batua, and Panaikang are moderately high risk areas.

The Makassar region, including the coastline is vulnerable to flooding and this vulnerability can be exacerbated by changes in both the occurrence of severe rainfall events. Local conditions such as low-lying lands and slow surface water drainage increase the risk of flooding. As for the entire area of the Makassar region, only about 50% of the area of surface water runoff can be controlled by the urban drainage systems. The area mainly located in the Western part of Makassar, while the other Eastern part such as Districts of Biringkanaya, Tamalanrea, Manggala and Panakukkang are still experiencing problems due to the lack of systematic flood control, respectively. As a result, these areas are frequently flood disaster still occurs. Based on the Makassar Urban Spatial Planning of 2005-2015, the district of Panakukang, Rappocini and Manggala were developed under the plan of integrated residential areas. Districts of Tamalanrea and Biringkanaya were developed for an integrated airport, maritime and industry areas. However, these districts are facing the urge to change the function of the land into a residential area due to the high population growth, resulting in high flood prone of districts. Inadequately planned infrastructural development and urban development in the areas, for example, can also give rise to flood risk.

Table 1. Flood vulnerability interpretation (Balica et al., 2012)

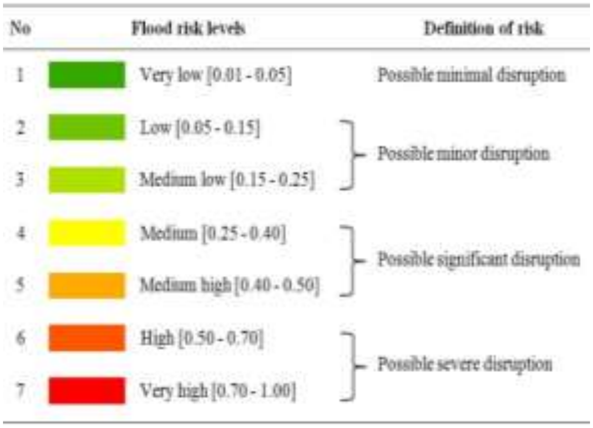
Index value	Description
< 0.01	Very small vulnerability to floods
0.01 - 0.25	Small vulnerability to floods
0.25 - 0.50	Vulnerability to floods
0.50 - 0.75	High vulnerability to floods
0.75 - 1	Very high vulnerability to floods

Table 2. Flood risk matrix model based BNPB for determining flood risk assessment index



		Hazard									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Vulnerability	0.1	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10
	0.2	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
	0.3	0.03	0.06	0.09	0.12	0.15	0.18	0.21	0.24	0.27	0.30
	0.4	0.04	0.08	0.12	0.16	0.20	0.24	0.28	0.32	0.36	0.40
	0.5	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
	0.6	0.06	0.12	0.18	0.24	0.30	0.36	0.42	0.48	0.54	0.60
	0.7	0.07	0.14	0.21	0.28	0.35	0.42	0.49	0.56	0.63	0.70
	0.8	0.08	0.16	0.24	0.32	0.40	0.48	0.56	0.64	0.72	0.80
	0.9	0.09	0.18	0.27	0.36	0.45	0.54	0.63	0.72	0.81	0.90
	1.0	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00

Table 3. Flood risk matrix model based BNPB for determining flood risk assessment index



No	Flood risk levels		Definition of risk
1	🟩	Very low [0.01 - 0.05]	Possible minimal disruption
2	🟩	Low [0.05 - 0.15]	Possible minor disruption
3	🟩	Medium low [0.15 - 0.25]	
4	🟨	Medium [0.25 - 0.40]	Possible significant disruption
5	🟧	Medium high [0.40 - 0.50]	
6	🟧	High [0.50 - 0.70]	Possible severe disruption
7	🟥	Very high [0.70 - 1.00]	

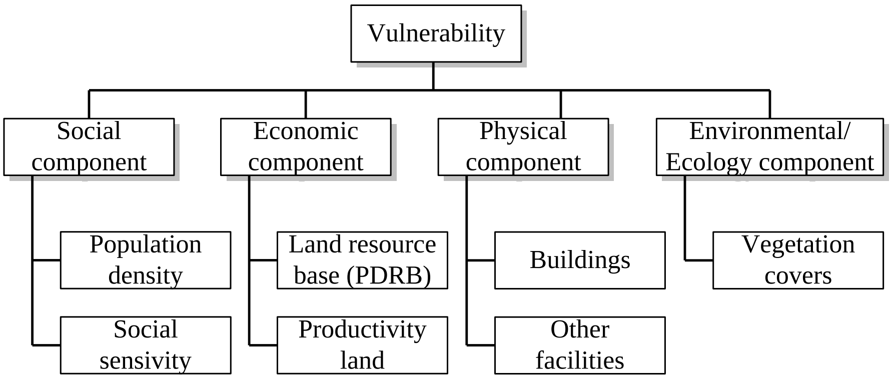
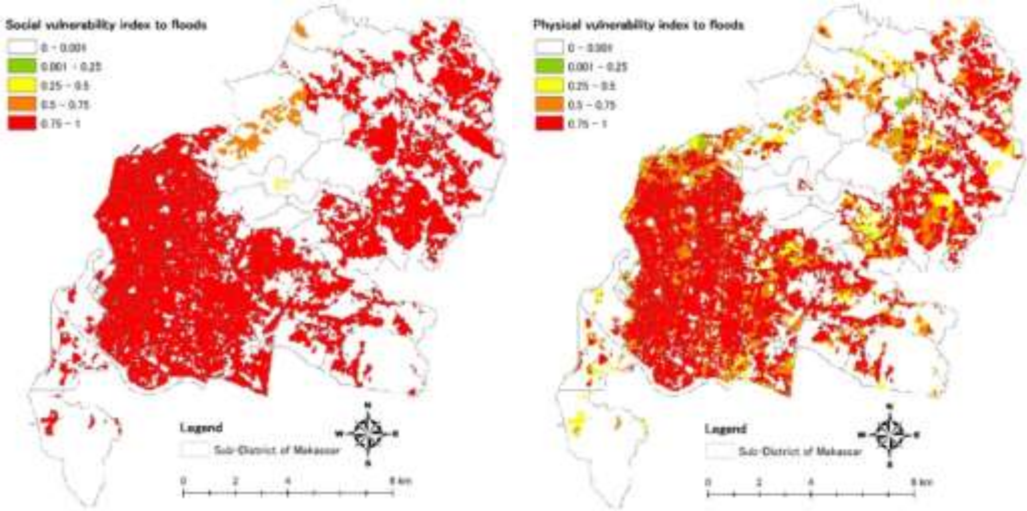
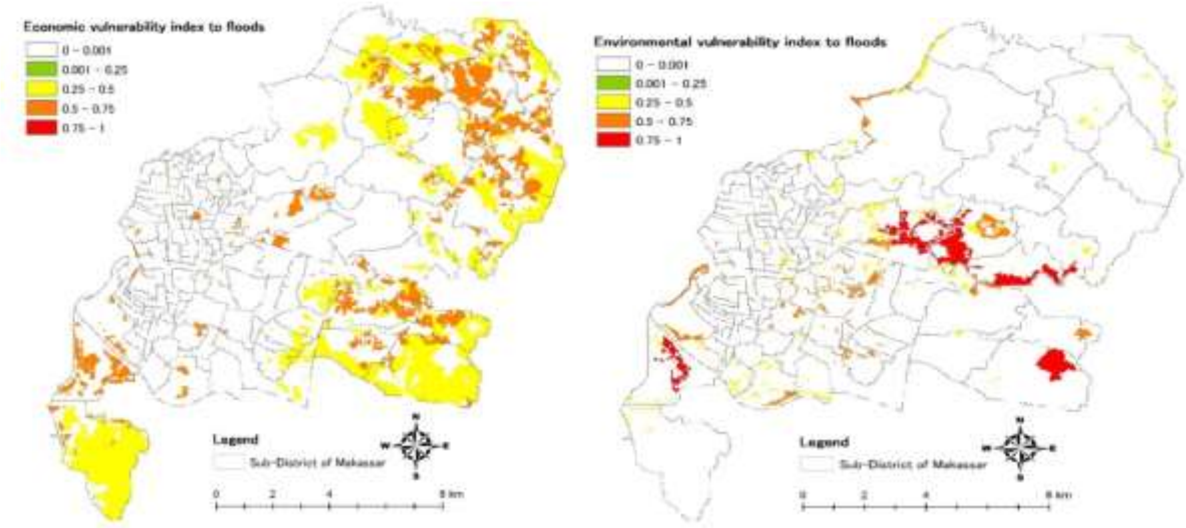


Figure 1. Indicator composition of local context for flood vulnerability based on BNPB framework



(a) Social vulnerability (b) Physical vulnerability



(c) Economic vulnerability

(d) Environmental vulnerability

Figure 2. Components of vulnerability index to flood

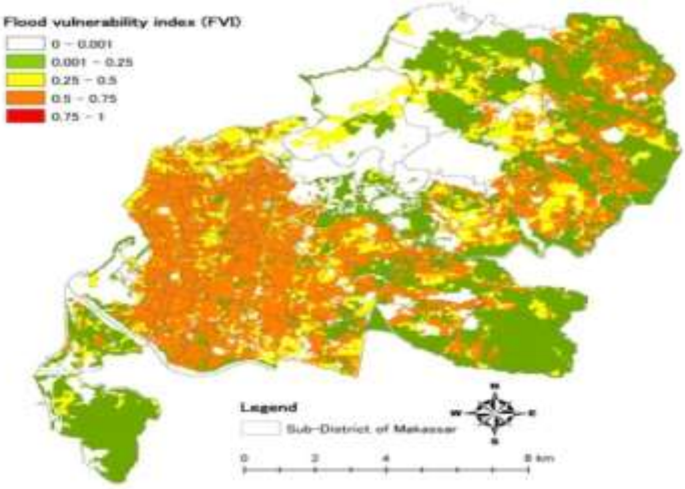


Figure 3. Overall vulnerability index to flood

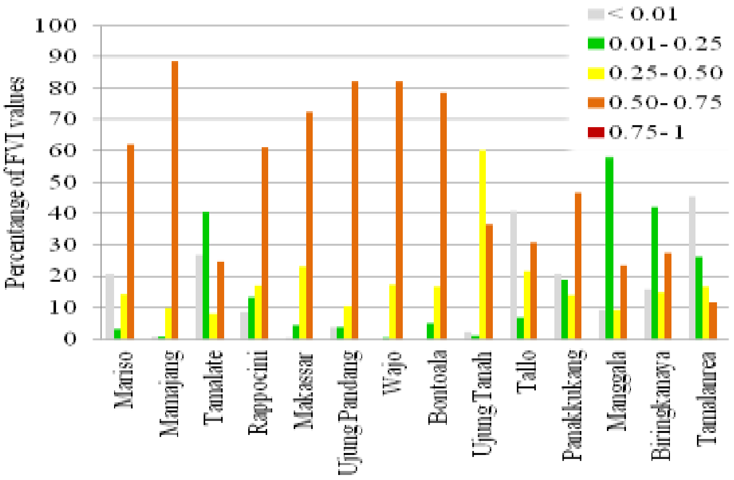
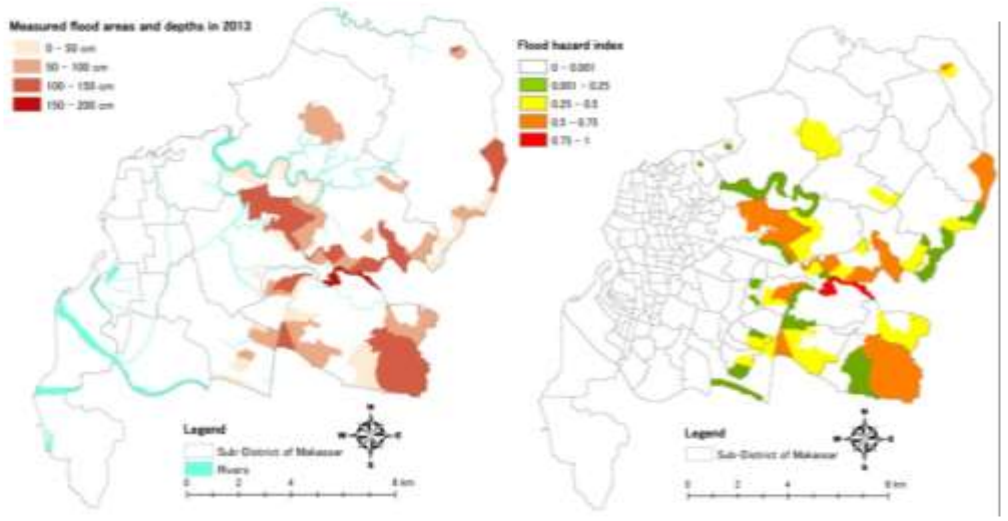


Figure 4. Comparative of the overall FVI at district levels



(a) Flood hazard map (b) Flood hazard index map

Figure 5. Map generalized from the predefined data by BPBD

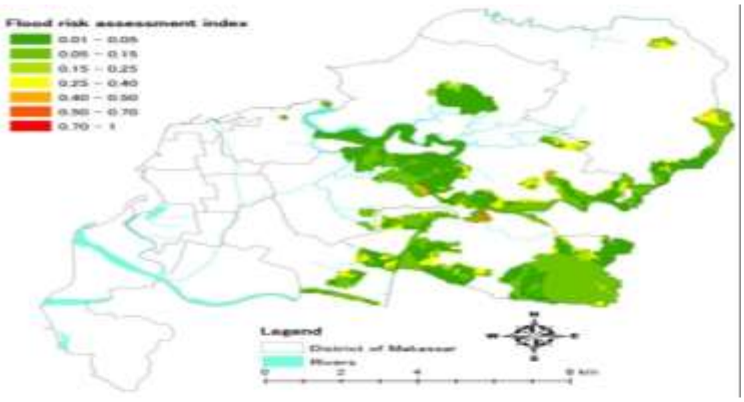


Figure 6. Flood risk assessment index map

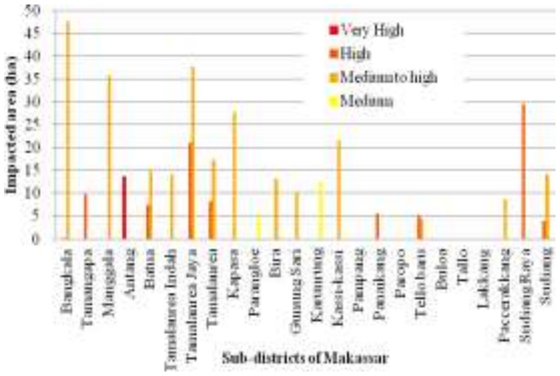


Figure 7. Comparative impacted area by risk index level at sub-district scales for overall vulnerability components

IV. SUMMARY

An assessment of flood vulnerability and risk index was conducted using a spatial-temporal model of GIS methodology. The vulnerability components to flood were assessed by incorporating the framework analysis of BNPB and using the available indicators at local context. The results revealed that many sub-districts are moderately vulnerable to urban floods in the Makassar region. Risk assessment index model was developed to calculate the spatial risk index level for each vulnerability components at sub-district scales. The potential impacts resulted from the urban flood scenario in 2013 on the vulnerability and risk index level was evaluated and compared at the sub-district levels. It is shown that the GIS spatial-temporal analysis has important tool and function to analysis each step of analysis for flood vulnerability and risk assessment index models.

V.ACKNOWLEDGMENT

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