A GIS analysis approach for flood vulnerability and risk assessment index models at sub-district scale

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Abstract. This paper presents flood vulnerability and risk assessment index models, with the aim to establish a spatial risk index at sub-district scales for urban flood scenarios in the Makassar region. Firstly, the overall vulnerability assessment to floods based on the local framework analysis of the BNPB (The Indonesian National Board for Disaster Management) has been developed using Geographical Information System (GIS) analysis. These indicators were composed of various social, physical, economic, and environmental factors. Second, 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 flood risk assessment model has been simulated at sub-district scales to evaluate the potential impacts on social, physical, economic, and environmental aspects.

1. Introduction

As urban areas of Makassar region grow both geographically and demographically, the flood hazard and risk has been increased in the sub-districts, recently [1]. Flooding is an environmental phenomenon that can pose a risk to social, physical, economic and environmental effects. In urban areas, floods are usually the consequence of extreme rainfall, which creates an excess of runoff [2]. The causes of flooding in cities vary according to geographical location, topography, land-use, and watershed condition [3]. Cities located on the coast within an extensive coastal plain, which are subject to flooding from inland and from the sea [4]. 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. Flood risk should be viewed as a widespread product of a 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 comprise many components over significant geographical areas, the understanding of all factors involved in a risk situation is particularly demanding [5].

Therefore, this paper presents a 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 scenarios 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) [6]. This framework analysis helped assess the major available local factors involved in the vulnerability to 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 on social, physical, economic, and environmental aspects which subjected by the flood hazard scenario in 2013.
2. Characteristics of flood threat in the Makassar region
The Makassar region has topography with a slope of 0-2º (flat) and a slope of 3-15º (undulating) land with lowland stretching at an altitude between 0-40 meters above sea level. Due to topography conditions, many sub-districts of Makassar are regularly flood experiences during the rainy season, especially at the time of rain along with the rising tide. Generally, the topography is grouped into two parts. First, the west to the north is relatively low close to the coast. Second, the Eastern part is an area with hilly topography. The urban development of Makassar tends to lead to the Eastern part of the City. This is visible with the vigorous housing development in sub-districts. The Makassar region is covered by three watershed systems that are Tallo watershed, Manyikkoaya watershed, and Jeneberang watershed (figure 1). About 81% of the watershed area in Makassar is covered by Tallo watershed. About 11% and 8% of watershed areas are covered by Manyikkoaya and Jeneberang watershed. By the GIS hydro tool, watershed analysis has been conducted to identify the sub-catchment, stream network lines, and drainage points of Tallo, especially in the Makassar region. Figure 2 and 3 shows the simulation results of the hydrological model in GIS using the available Digital Elevation Model (DEM) data.

![Figure 1](image1.png)

**Figure 1.** Three watershed systems are covering the Makassar region.

![Figure 2](image2.png)

**Figure 2.** Catchment polygons created by DEM.

![Figure 3](image3.png)

**Figure 3.** Streamline networks.

2.1. Impacts of urban flood occurrence
Figure 4 shows the histogram of calculation elevation at catchments and flooded catchment areas (marked by arrow line). Moreover, the flooded area has a minimum slope at 0 degrees, maximum slope at 7.3 degrees and average slope at 1.8 degrees. Figure 5 shows the histogram of calculation slope at catchments and flooded catchment areas (marked by arrow line). The number of total peoples affected by these floods reaches 101,972 inhabitants, as recorded values by the Indonesian Regional Disaster Management Agency (BPBD). Numbers of impacted peoples located in the sub-districts of Kassi-Kassi, Panaikang Karunrun, and Tamalanrea Jaya are 10,961, 9,651, 9,532 and 8,735 inhabitants, respectively.

![Figure 4. Average elevation at flooded areas.](image1)

![Figure 5. The average slope at flooded areas.](image2)

Figure 6. Measured flood hazard.

Figure 7. Generalized flood hazard index map.

2.2. Establishment of flood hazard index map

Flood surveys and measurements were conducted by the coordination between the governments of the city of Makassar and the Indonesian Regional Disaster Management Agency (BPBD). The flood hazard map in the Makassar region in 2013 was already published (figure 6). In this study, historical records of flood events in 2013 are used as major flood hazard scenarios for risk assessment. The flood hazard index will be compiled based on data and historical records of events that have occurred in the Makassar region. The flood hazard index is structured based on two main components, namely the possibility of a threat (boundary flooded areas) and the magnitude of impacts (flood depths) recorded for the flood disaster. As measurement data in 2013 by the local government with BPBD, the established flood hazard map with the spatial information of flood depth and areas are used to construct the flood hazard index by GIS. Prior to the preparation of flood hazard index maps, flood areas and depths are analyzed using...
the GIS matrix tool. The matrix classification of the flood index system can be implemented after all spatial data on the study area is obtained from a predefined statistical data source.

The flood hazard index of the Makassar region represents a first attempt at providing a consistent, regional-wide spatial index of flood hazard. It was generated using a GIS and empirical approach that can easily be updated data by interpretation of higher resolution DEM and/or additional flood line maps. The hazard index used in the analysis is converted to a value between 0 and 1, where 0 is the minimum value of the hazard, and 1 is the maximum value. Furthermore, the data obtained are then divided into 4 threat classes (very low, low, medium, and high) to provide calculation easily for flood risk index analysis. The generated flood hazard index map by GIS is shown in figure 7.

3. Spatial analysis of flood vulnerability index

Vulnerability is considered as the extent of harm, which can be expected under certain conditions of exposure, susceptibility, and resilience [7]. While there is no universal definition, the definition varies so widely that, in an interdisciplinary context, the term becomes almost useless without further specification [8]. The concept of vulnerability is approached from different disciplines and professional fields such as academia, disaster management agencies, climate change community, and agencies [9].

Though many definitions exist, the concept of vulnerability in this study considers the local approach provided by the BNPB framework. By this approach, the vulnerability has specific spatial, socio-economic-demographic, environmental, and physical contexts that impose challenges to research on vulnerability to flooding [10], is shown in figure 8. The BNPB framework was developed to improve vulnerability assessment in Indonesia as part of risk evaluation and risk management in the context of disaster risk management in Indonesia. It is fulfilling a need for standards and guidance in estimating vulnerability as the critical component of risk at the local context.

3.1. 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.

- Exposure (E): it was measured by the number of people per sub-district area, differently exposed to floods 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, land resource base, productive land, and percentage of the vegetation cover.

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

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

3.2. 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%),

![Figure 8. Indicator composition of local context based BNPB framework.](Figure8.png)
percentage of gender (10%), and percentage of disability (10%). As for the practical implementation for each vulnerability component, the score was normalized by dividing the vulnerability value \( x_j \) 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:

\[
X_j = \frac{x_j - \text{Min}(x_j)}{\text{Max}(x_j) - \text{Min}(x_j)}
\]  

(1)

where,

\( X_j \) 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 \( j \); \( \text{Max}(x_j) \) and \( \text{Min}(x_j) \) 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):

\[
VI_{social} = \sum_{j=1}^{k} W_j X_j
\]  

(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 \( j \).

For physical, economic, environmental components, the indicator analysis is a similar process. Physical indicators used for physical vulnerability are building houses, public facilities, and critical facilities. Building cost is obtained by calculating the area of the polygon (square meter) and multiplied it by the unit price of each building code parameters [11]. The indicators used for economic vulnerability are 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. The environmental vulnerability index is different for each type of threat, and it is obtained from the average weight of the land cover type. The vulnerability interpretation index is described in table 1 [1].

| 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 1. Flood vulnerability interpretation.

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 follows.

\[
FVI = (VI_{social} \times 40\%) + (VI_{physical} \times 25\%) + (VI_{economic} \times 25\%) + (VI_{environmental} \times 10\%)
\]  

(3)

The study aggregated the local indicators to a single composite index that Tenable spatial vulnerability representation at sub-district levels. These indicators were composed of various social, physical, economic, and environmental factors (figure 9). 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.
4. Spatial analysis of flood risk index (FRI)
Flood risk assessment has two main components that are hazard and vulnerability. The hazard is a measure of the physical intensity of the threat at a particular location and the associated probabilities of these intensities. Hazard is location dependent. For example, flood hazard at a location near the coast and with flat land. Vulnerability is a measure of the damage that the danger can cause. The synthesis of data and the essential mapping of the spatial relationships between hazard phenomena and the elements at risk can benefit from the use of a GIS tool.

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 the 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. The preparation of the flood risk assessment index requires additional spatial analysis after obtaining the required indices (vulnerability...
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. The determination of the risk level is calculated by using a vulnerability index and flood hazard index. Determination is calculated by linking the two index values in the matrix. The matrix value is defined by the BNPB framework analysis. Indicators used for risk analysis will be selected based on availability and local context. 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 (table 2).

| 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] | Possible significant disruption |
| 4  | Medium [0.25 - 0.40]  | Possible severe disruption   |
| 5  | Medium high [0.40 - 0.50] |                           |
| 6  | High [0.50 - 0.70]   |                              |
| 7  | Very high [0.70 - 1.00] |                            |

Table 2. Specific flood risk classification model by local context.

| Potential impacts          | Very low | Low to Medium | Medium to High | Very High |
|----------------------------|----------|---------------|----------------|----------|
| Minimal disruption         |          |               |                |          |
| Generally no widespread impact, however, there may still be; |          |               |                |          |
| •Isolated and minor flooding of low-lying land and roads |          |               |                |          |
| •Little or no disruption to travel although wet road surfaces could lead to difficult driving conditions |          |               |                |          |
| Minor disruption           |          |               |                |          |
| •Localized flooding of land and roads |          |               |                |          |
| •Localized flooding could affect individual properties |          |               |                |          |
| •Localized disruption to key sites identified in flood plans (e.g., public utilities) |          |               |                |          |
| Significant disruption     |          |               |                |          |
| •Flooding affecting properties and parts of communities |          |               |                |          |
| •Damage to buildings is possible |          |               |                |          |
| •Disruption to infrastructure (e.g., utilities) |          |               |                |          |
| Severe disruption           |          |               |                |          |
| •Widespread flooding affecting a significant number of properties and communities |          |               |                |          |
| •Danger to life from fast flowing and / or deep water |          |               |                |          |
| •Widespread disruption or loss of infrastructure (e.g., utilities) |          |               |                |          |
| •Large scale evacuation may be required |          |               |                |          |
| •Severe disruption to travel networks. |          |               |                |          |

In the case of low numbers that are numerous indexes and vary in sometimes a high number, therefore the index classification by logarithmic conversions will be performed instead of linear conversions [2]. Table 4 shows the result of the index classification model for the risk assessment definition of the study area based on the BNPB framework. 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.

4.1. Analysis of flood risk to the social component

Five indicators, belonging to all factors of vulnerability, were used to determine the risk index levels. These were population, percentage of poverty, percentage of gender, percentage of ages and percentage of disabled peoples. Those indicators were statistically measured and spatially calculated in GIS. 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. A comparison of the impacted area at sub-district scales in the social aspect classified by the risk index level is shown in figure 10.

![Figure 10](image)

**Figure 10.** The impacted area by risk index level at sub-district scales for social component.

The spatial distributions of the building, such as industrial buildings, educational buildings, hospital buildings, are densely distributed in the Tamalanrea district. Therefore, higher risk indexes in the physical component are located in the Tamalanrea District. A comparison of the impacted area at sub-district scales in the physical aspect classified by the risk index level is presented in figure 11. It is shown that the sub-district of Tamalanrea has a high impacted area for the physical component. Following by the sub-district of Tamalanrea Jaya, Antang, Kapasa, and Batua, most of these areas are located in the Northeast part of the Makassar region, which moderately high impacted area from the flood risk.

4.2. Analysis of flood risk to the economic component

For the calculation of risk index to the economic values, the indicator of the agricultural sector was used. Concerning the spatial distribution of the paddy field throughout the Makassar region, the Area percentage of risk index is high in the sub-district of Antang, Pampang, Tamangapa in the Northeast of the Makassar region, and these sub-districts are more concentrated in the production of paddy in the Makassar region in 2012. A comparison of impacted areas at sub-district scales in the economic aspect is shown in figure 12.
4.3. Analysis of flood risk to the environmental component

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. 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 (figure 13).

Figure 11. The impacted area by risk index level at sub-district scales for the physical component.

Figure 12. The impacted area by risk index level at sub-district scales for the economic component.
5. Conclusion
Spatial analysis for flood vulnerability and risk assessment has been simulated in GIS. The flood hazard index has been established based on the historical flood hazard maps and measurement of flood occurrence in 2013. The overall vulnerability assessment to floods has been conducted based on the local framework analysis of the BNPB. A spatial matrix analysis has been performed. The study has been aggregated the local indicators to a single composite index that enables spatial vulnerability representation at sub-district levels. Furthermore, the determination of the risk level has been calculated by the matrix model from the variables of the vulnerability and flood index.

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