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Development of the flood vulnerability index using a multi-element approach

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Abstract: The problem of flood vulnerability has been reviewed in several studies, however, the reviews focused exclusively either on the social or on the physical component of the problem. The components of flood vulnerability are interdependent and each of them makes an equally important contribution to the flood vulnerability index. This study identifies and evaluates the integrated flood vulnerability index (*FVI*) of an area by considering its multiple components (social, economic, and environmental). The Analytic Hierarchy Process (AHP) method was applied to evaluate the weight of each component. The evaluation was based on the judgements of experts working at local government policy-making agencies. The input data for the AHP were acquired through a questionnaire survey. Eleven indicators that delivered significant results were then selected. The *FVI* results show high flood vulnerability at the local scale. The *FVI* provides the basis for the identification of villages with high vulnerability indices. The results provide essential information about pluvial flood vulnerability at the local scale, about the area with the highest vulnerability index, and the most vulnerable villages. The results also show that the components that have a significant impact on the flood vulnerability index include environmental components (43.4%), social components (28.5%), and physical components (28.1%).

Keywords: analytical hierarchy process, fluvial flood, multi-element, vulnerability index

INTRODUCTION

In recent years, the vulnerability to floods has been increasing rapidly in many countries. The increase was due to the rise in the frequency and the scale of floods [KIM, GIM 2020]. Floods cause multidimensional damage, such as the loss of lives, damage to property, and damage to infrastructure. Floods result in an irrecoverable loss of land, destruction of valuable historical and cultural materials, and the loss of ecological resources [YANG, LIU 2020]. Therefore, dealing with the natural causes of flood vulnerability has been a more pragmatic solution than handling uncertain impacts of potential floodings [NASIRI *et al.* 2016].

There are interrelations between vulnerability, uncertainty about the future, exposure to flooding, and mutual responses between human beings and nature [IPCC 2014]. It is essential to explore the social, economic, and environmental aspects in the process of assessing the extent of the vulnerability parameters [IPPC 2014]. On the other hand, various geographical indicators related to distinct spatial patterns can be helpful in assessing the extent of social vulnerability [CUTTER 1996]. Nevertheless, we found only a few studies that reviewed and considered the vulnerability based on spatial units [MAINALI, PRICOPE 2017]. Other studies investigated social networks, social capital, and resource mobilisation in assessing vulnerability [JONES, FAAS 2016].

Therefore, it is necessary to further investigate the integration of the assessment of the above-mentioned aspects, mainly to identify vulnerable communities that need support in protecting their livelihoods. PARK and LEE [2019] have conducted a study on the flood vulnerability index on a global scale covering all parts of Java Island. However, a flood vulnerability index on a global scale may not be applicable to a particular location on a local scale because of different causes of vulnerability [MÜLLER *et al.* 2011]. Therefore, it is necessary to develop new vulnerability indicators suitable for local conditions and individual characteristics, such as the awareness of potential hazards and risks. Previous studies [MÜLLER *et al.* 2011] suggested that an analysis for the purposes of development of vulnerability indicators could be conducted through an extensive field survey on the awareness of hazards or perception of risks.

This research must incorporate relevant environmental, socio-economic, and physical components using GIS for a detailed local-scale assessment of practical flood vulnerability risk and the development of mitigation tools. Multi-criteria statistical techniques are the most effective, flexible, and widely used vulnerability assessment methods. Several studies have demonstrated the reliability of such techniques by conducting a composite environmental risk assessment at the local and regional levels. The research was conducted in a rural area in the vicinity of the estuary of the Welang River that is affected by periodic exposure to flooding.

STUDY AREA AND METHODS

STUDY AREA

Welang River crosses over the District of Pasuruan, the Province of Jawa Timur, Indonesia, and flows into the Madura Strait (Fig. 1). This river is 36 km long, with a watershed area of 518 km^2. Almost every year, flooding occurs on the river's estuary, with the floodwater depth ranging between 50 and 100 cm [DETIKNEWS 2020]. Historical records of the Welang River floodings show that floodwater spilt 3 km into adjacent areas. The flooding recurred at 20-year intervals.

The identification of historical flood zones was carried out based on the integration of oral testimonials (certain levels within a certain period) and the analysis of regional flood frequencies and inundation heights [DÍEZ-HERRERO *et al.* 2009]. According to the interview results, this flood inundated 12 villages in three subdistricts that are part of the city and the district of Pasuruan, located on the right and left banks of the Welang River (Fig. 1). Areas affected by flooding in Pasuruan districts that are located in the Kraton District include Kraton Village, Pulokerto, Sumare, Dompho, Tambaksari, Plingisan, and Tambakrejo, while those located in the Pohjentrek District include Sukorejo, Tidu, and Sungiwetan villages. Meanwhile, those located in the Gadingrejo District of Pasuruan City include Karangketug and Randusari villages.

The villages in the study area are situated between 0 m and more than 1.5 km away from the river. Soil types in the research area include alluvial (42.2%), Mediterranean (7.5%), and latosol (50.3%) soils. Land in the study area is primarily used for three purposes, namely housing (13.3%), rice fields (83.9%), and gardens (2.7%). This study area borders on the coast with an elevation between –2.24 m and 32.41 m a.s.l. The high tide reaches 2 m, causing backwater to reach Pulokerto, Semare, Kraton, and Tambakrejo villages.

The physical conditions in the villages in the study area are described as follows: the condition of sanitation facilities in ten villages is adequate, and in two villages (Tidu and Sungiwetan), it is still inadequate, considering that over 73% of the population uses Open Defecation (OD). The population density averaged 2,260 people per km^2, with the lowest being 499 people per km^2 in Tambaksari village, and the highest being 7,282 people per km^2 in Randusari village. The access to these villages by road is classified as very good; namely, 73.4% of the area of these villages are 250 m away from a road, and only two villages, namely Pulokerto and Semare, are located more than 1 km away from a road. The position of buildings in relation to the street level ranges between 0.5 m above the street level to 2.3 m below the street level.

METHODS

PROCEDURE

Several studies [KHAJEHEI *et al.* 2020] showed that flood vulnerability was related to the community's, resilience, and potential vulnerability to the area's hazards. Exposure is "the

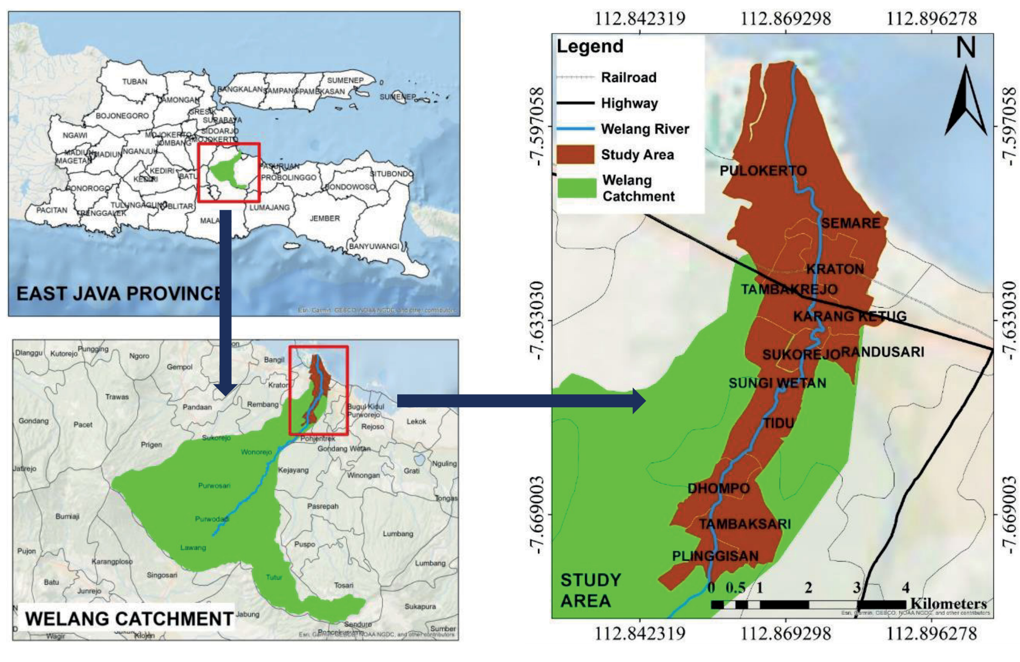

Fig. 1. Study area; source: own elaboration

predisposition of system disrupted by a flooding event due to its location in the same area of influence" [BALICA 2007]. Vulnerability can refer to properties and to vulnerable populations. Resilience is a system's capacity to suffer any perturbation, such as flooding, while maintaining significant levels of efficiency in its socio-economic, environmental, and physical components [BALICA *et al.* 2009].

According to MACKAY [2008], vulnerability to flooding is the extent to which all components (i.e., physical, environmental, economic, and social) are vulnerable and incapable of overcoming the negative impact of flooding. Therefore, this research will integrate the above-mentioned components into the flood vulnerability classes. These studies provide the basis for identifying the historical background and special conditions of the Welang River floodplain, which is essential for determining the area's flood vulnerability index. The flooding hazards, which are the critical factor determining an area's vulnerability, are assessed based on historical flooding records in the area.

The methodology applied to develop the flood vulnerability index is multi-criteria and GIS-based spatial overlays using three components of vulnerability: socio-economic, physical, and environmental. The steps of this study include the following:
– selecting the influencing indicators (AHP) and normalise the indicators in one element,
– assessing the score and normalisation for each indicator,
– calculating the flood vulnerability index (*FVI*),
– performing a reclassification of vulnerability.

SELECTION OF INDICATORS

The calculation of the flood vulnerability index for a village begins with categorising several components that affect the residents' vulnerability to the risk of flooding. This study acknowledges previous studies by identifying three components, namely socio-economic, environmental, and physical components that cover several indicators [BALICA 2007].

The socio-economic component describes the capacity, skills, and knowledge a household uses to assess current conditions and achieve social goals, depending on gender, level of education, vulnerable age, household size, the experience of flooding, and income. Socio-economic vulnerability data on vulnerable groups in the average village area come from the City and District Statistics of Pasuruan 2018. The calculation of socio-economic scores based on statistical information was then normalised based on each criterion's highest and lowest score.

The environmental component describes natural conditions that can affect the vulnerability of an area to flooding. This component's indicators include elevation, land use, soil type, proximity to rivers, and distance from the coastline. Environmental vulnerability data were presented using DEM SRTM 1 Arc-Second Global (30 m × 30 m resolution). This data was released in September 2014, and the data on soil types, river networks, and land use were obtained from the Rupa Bumi Indonesia. Each criterion map was converted to an appropriate projection coordinate system and converted to a raster.

Physical vulnerability describes the presence of man-made physical conditions that can affect an area's vulnerability to flooding. Physical vulnerability indicators include the state of sanitation facilities, the position of buildings in relation to the street level, access to the road, and building density. Physical vulnerability data were obtained from two sources, namely the City and District Statistics of Pasuruan 2018 and from the DEM SRTM 1 Arc-Second Global with a resolution of 30 m × 30 m.

The criteria weighting method for decision-making relies on the AHP method [SIDDAYAO *et al.* 2015]. Each indicator's weighting is based on the judgements of government agency experts responsible for handling water resources and disasters.

The criteria used to determine flood vulnerability classification for each indicator, adjusted for data available in the study area, and the results of field surveys, are shown in Table 1. The measurement of each indicator relies on a different scale, depending on its classification. It then normalises it to ensure objectivity, using a scale between 0 and 1, where 1 indicates the highest vulnerability and 0 indicates the lowest vulnerability. The final stage consists of the calculation of the flood vulnerability index (*FVI*).

Table 1. Indicator and the relationship between the indicator and vulnerability

Indicators	Indicator represents	Relationship between indicator and vulnerability	References	Correlation
Environmental component				
Elevation	Classification of elevation (m): (1) ≥6 (2) ≤3–6> (3) <0–3> (4) 0	The higher the elevation, the lower the vulnerability. More elevated areas are less vulnerable to the threat of inundation caused by rising sea levels and river overflows.	MURALI *et al.* [2013]	negative
Land use	Classification of land use: (1) barren land (2) vegetated land or open spaces (3) agriculture/fallow land (4) urban, environmentally sensitive regions	Areas with low vulnerability have low building density and are not barren.	MURALI *et al.* [2013]	negative
Type of soil	Classification of soil type: (1) latosol (high permeability) (2) mediterranean (moderate permeability) (3) alluvial (low permeability)	The lower the soil permeability, the more vulnerable the soil.	SANI *et al.* [2018]	negative

cont Tab. 1

Indicators	Indicator represents	Relationship between indicator and vulnerability	References	Correlation
Distance to the coastal line	Classification of distance to coastal lines in the form of buffers as long as (m): (1) ≥1000 (2) ≤500–1000> (3) ≤250–500> (4) <250	The closer to the coastline, the more vulnerable an area is to flooding because when the sea level is high, backwater occurs in the areas on either side of the river.	BAUČIĆ [2020]	negative
Distance to the river	Classification of distance to the river in the form of buffers as long as (m): (1) ≥1500 (2) ≤1000–1500 (3) ≤500–1000> (4) 0 and <500	The shorter the distance to the river, the more vulnerable an area will be.	MURALI *et al.* [2013]	negative
Socio-economic component				
Gender	Comparison of the vulnerability of women and men (0.75:0.25)	Women are more vulnerable than men, because recovery may be more difficult for women than for men.	CUTTER *et al.* [2003]; DEEPAK *et al.* [2020]	negative
Level of education	Persons educated below high school level are vulnerable	Education is related to socio-economic status. The lower the level of education, the lower the income, and the ability to understand flood recovery information.	MÜLLER *et al.* [2011]; CUTTER *et al.* [2003]	negative
Age	- Vulnerable age groups include children (under 14 years) and the elderly (over 65 years). - Persons aged between 15 to 64 years are classified as not vulnerable	There are two age groups vulnerable to flood disasters; children and the elderly are more susceptible.	DEEPAK *et al.* [2020]; KHAJEHEI *et al.* [2020]	negative
Household size	Fewer than 5 members/ more than 4 members	The larger the household size, the lower the social status and the higher the number of people affected, and the level of damage.	DEEPAK *et al.* [2020]	negative
Experience of flooding	People who are exposed to floods every year, once every 5–10 years, more than every 20 years	The more frequently a person has suffered from floodings, the more experienced the person becomes in dealing with floods, so the community's preparedness to mitigate it increases too.	MÜLLER *et al.* [2011]	positive
Family welfare	Prosperous family grouping: pre-prosperous families and prosperous family's groups I, II, III, and III+	Family welfare is closely related to income. The poorer households are, the more vulnerable they are to flooding.	UTOMO and SUPRIHARDJO [2012]	negative
Physical component				
Sanitation facilities	The existence of sanitation facilities is analogous to infrastructure vulnerability: Permanent Healthy Latrine (JPS), Semi-Permanent Healthy Latrine (JPSS), Sharing Open Defecation (OD).	The absence of facilities required to meet basic human needs, such as access to improved drinking water and sanitation, increases flood vulnerability.	NAZEER *et al.* [2019]	negative
Position of buildings in relation to the street level	Based on the integration of the land-use map and the DEM using GIS to obtain information about the buildings' location to the street level.	People living below the street level are more exposed to floods.	MÜLLER *et al.* [2011]	negative
Distance to the road	Classification of distance to the road in the form of buffers as long as (m): (1) 250 (2) 500 (3) 1000 (4) 2000	Access to the road network facilitates evacuation. The greater the distance to a road, the more vulnerable an area is.	MURALI *et al.* [2013]	positive
Building density	The building density is analogous to the population's density at that location, supported by statistical data (person per km^2).	Areas with a high population density are more vulnerable than ones with low population density, because the rescue process in these areas tends to be more complicated.	FERNANDEZ *et al.* [2016]	negative

Source: own elaboration based on literature.

DETERMINATION OF WEIGHTS FROM INDICATOR AND NORMALISATION USING ANALYTIC HIERARCHY PROCESS (AHP)

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making approach that allows for selecting the best alternatives through a subjective process based on personal preferences, that generates quantitative weights [SAATY 2001]. In several case studies, the weighting of flood vulnerability factors using the AHP method based on experts' judgements provided essential information about the vulnerability [MURALI *et al.* 2013]. Respondents were selected among experts working at three institutions responsible for flood disaster management in the study area, including the Ministry of Public Works and Public Housing, the Technical Unit for Water Resources Management, and the Regional Disaster Management Agency. Each institution selected ten people responsible for flood disaster management to fill out the questionnaire. The steps in the AHP method are as follows: (1) identifying the problem and specifying the solutions, followed by creating hierarchies, namely: the goal, the criteria, and the alternatives; (2) constructing a pairwise comparison matrix that uses scales [SAATY 2001]; (3) estimating the relative weight of each parameter; and (4) checking the consistency of the hierarchy, which is represented as a consistency ratio, of which the upper limit is set at 10%. If the ratio exceeds the limit, it is necessary to repeat the procedure. The consistency ratio (*CR*) is calculated on the basis of Equation (1). It is the ratio between the consistency index (*CI*) and the random index (*RI*).

$$CR = CI/RI \tag{1}$$

The consistency ratio in Equation (1) is calculated based on the matrix's maximum eigenvalue ($\lambda_{\max}$). The eigenvalue used is divided by the matrix order, as shown in Equation (2). Table 2 is a random index (*RI*), n is the number of parameters.

$$CI = (\lambda_{max} - n)/(n - 1) \tag{2}$$

ASSIGNING NORMALISED WEIGHTS TO VULNERABILITY COMPONENTS USING AHP NORMALISATION AND CORRELATION OF INDICATORS

The calculation of the vulnerability index according to each indicator using linear transformations in Equation (3) for the correlation of variables to positive and negative is expressed by Equation (4) [SALAZAR-BRIONES *et al.* 2020].

$$X_i = \frac{Z_i - Z_{\min}}{Z_{\max} - Z_{\min}} \tag{3}$$

$$X_i = 1 - \frac{Z_i - Z_{\min}}{Z_{\max} - Z_{\min}} \tag{4}$$

where: X_i represents the normalised value of a socio-economic, environmental or physical indicator at the location i, Z_i is the value of the variable for the exact location i, and $Z_{\max}$ and $Z_{\min}$ are the maximum and minimum values at all areas of these variables.

CALCULATION OF THE FLOOD VULNERABILITY INDEX (FVI)

The normalised weights derived from the AHP were used to calculate the vulnerability index for each component using Equation (5).

$$FVI_{SE,P,EV} = \sum_{i=1}^{n} W_{SEn,Pn,EVn} X_i \tag{5}$$

where: $FVI_{SE,P,EV}$ is the flood vulnerability index for each component; W_n is the weight of each indicator, of which the value ranges between 0 and 1.

Next, the composite vulnerability index that has been normalised is used to calculate the flood vulnerability index (*FVI*), which is the flood vulnerability index of all vulnerability indices divided by the number of influential components (m), as shown in Equation (6).

$$FVI = VI_{SE,P,EV}/m \tag{6}$$

The resulting *FVI* is then used to determine the vulnerability zone of the area. There are six vulnerability zones: very low vulnerability zone, low vulnerability zone, medium vulnerability zone, high vulnerability zone, and very high vulnerability zone. The division of the vulnerability zones into six classes is based on the following value ranges of the *FVI*: very low (0.00–0.01), low (0.01–0.25), medium (0.25–0.50), high (0.50–0.75), and very high (0.75–1.00) [BALICA *et al.* 2013].

RESULTS AND DISCUSSION

ASSIGNING NORMALISED WEIGHTS TO VULNERABILITY COMPONENTS USING AHP

In the present study, AHP was used to assign weights to the environmental, socio-economic, and physical components of vulnerability. The completed questionnaires were collected from experts working at three institutions: the Ministry of Public Works and Public Housing, the Technical Unit for Water Resources Management, and the Regional Disaster Management Agency. The geomean survey values were arranged in a pairwise comparison matrix for each component (Tab. 3, 4, and 5).

Next, the priority vector calculation, a normalised Eigen-vector from the matrix, was calculated and used as a weight in the objective hierarchy (Tab. 6, 7, and 8). Based on the AHP method, indicators for the environmental flood vulnerability (Tab. 6) with the highest weights include land use, distance to the coastal line, distance to the river, elevation, and soil type. Indicators for the socio-economic flood vulnerability in (Tab. 7) with the highest

Table 2. Values of the random index (*RI*)

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.48

Source: SAATY [2001].

Table 3. Comparison matrix for the environmental component

Matrix	Tidal range	Elevation	Distance to the river	Land use	Soil type
Distance to the coastal line	1.00	3.00	1.26	1.26	2.08
Elevation	0.33	1.00	0.33	0.33	1.26
Distance to the river	0.79	3.00	1.00	1.00	1.82
Land use	0.79	3.00	1.00	1.00	4.22
Soil type	0.48	0.79	0.55	0.24	1.00
Total	3.40	10.79	4.14	3.83	10.37

Source: own study.

Table 4. Comparison matrix for the socio-economic component

Matrix	Gender	Household size	Level of education	Experience of flooding	Age	Income
Gender	1.00	0.87	1.00	0.28	1.00	1.00
Household size	1.14	1.00	0.38	0.46	0.63	1.00
Level of education	1.00	2.62	1.00	3.00	1.82	0.79
Experience of flooding	3.63	2.15	0.33	1.00	2.92	1.96
Age	1.00	1.59	0.55	0.34	1.00	0.93
Income	1.00	1.00	1.26	0.51	1.08	1.00
Total	8.78	9.24	4.53	5.59	8.45	6.68

Source: own study.

Table 5. Comparison matrix for the physical component

Matrix	Position of the building in relation to the street level	Proximity of a road	Building density	Sanitation facilities
Position of the building in relation to the street level	1.00	0.57	2.08	2.71
Proximity of a road	1.75	1.00	1.00	1.44
Building density	0.48	1.00	1.00	0.79
Sanitation facilities	0.37	0.69	1.26	1.00
Total	3.60	3.27	5.34	5.95

Source: own study.

Table 6. Normalised matrix for the environmental component

Matrix	Tidal range	Elevation	Distance to the river	Land use	Soil type	Sum	Average
Distance to the coastal line	0.29	0.28	0.30	0.33	0.20	1.41	0.28
Elevation	0.10	0.09	0.08	0.09	0.12	0.48	0.10
Distance to the river	0.23	0.28	0.24	0.26	0.18	1.19	0.24
Land use	0.23	0.28	0.24	0.26	0.41	1.42	0.28
Soil type	0.14	0.07	0.13	0.06	0.10	0.51	0.10

Source: own study.

weights are the experience of flooding, level of education, income, gender, age, and household size. Indicators for the physical flood vulnerability (Tab. 7) with the highest weights include the position of the buildings in relation to the street level, the proximity of a road, the density of buildings, and sanitation facilities.

Table 9 shows the *CI*, *RI*, and *CR* values for each component. *CR* value (below 10%) indicates the reliability of each matrix. Finally, weights (*W*) derived using the AHP method and priority-based normalised ranks of each factor class (Tab. 6, 7, 8) were combined to prepare the vulnerability map for each cell/pixel in ArcGIS.

Table 7. Normalised matrix for the socio-economic component

Matrix	Gender	Household size	Level of education	Experience of flooding	Age	Income	Sum	Average
Gender	0.11	0.09	0.22	0.05	0.12	0.15	0.75	0.124
Household size	0.13	0.11	0.08	0.08	0.07	0.15	0.63	0.105
Level of education	0.11	0.28	0.22	0.54	0.22	0.12	1.49	0.248
Experience of flooding	0.41	0.23	0.07	0.18	0.35	0.29	1.54	0.256
Age	0.11	0.17	0.12	0.06	0.12	0.14	0.73	0.121
Income	0.11	0.11	0.28	0.09	0.13	0.15	0.87	0.145

Source: own study

Table 8. Normalised matrix for the physical component

Matrix	Position of the building in relation to the street level	Proximity of a road	Building density	Sanitation facilities	Sum	Average
Position of the building in relation to the street level	0.28	0.18	0.39	0.46	1.30	0.32
Proximity of a road	0.49	0.31	0.19	0.24	1.22	0.31
Building density	0.13	0.31	0.19	0.13	0.76	0.19
Sanitation facilities	0.10	0.21	0.24	0.17	0.72	0.18

Source: own study.

Table 9. Consistency ratio (*CR*) values for environmental, socio-economic, and physical components

CR	Value	Percentage (%)
Environmental	0.098	9.8%
Socio-economic	0.025	2.5%
Physical	0.092	9.2%

Source: own study.

ENVIRONMENTAL VULNERABILITY

The identification of the percentage area of the distribution of environmental vulnerability can be classified into four levels, namely very high (22%), high (43.4%), moderate (30.3%), and low (4.2%) (Fig. 2).

This research area is not evenly distributed in one village because it depends on the indicators that affect each region. Figure 2 shows that the high tide causes a very high vulnerability in the area near the coast. When the rainfall is high, the area near the sea will be calm. A high level of vulnerability is observed in most village locations. The distance from the river has a significant impact, and the river's lower elevation causes the area to be exposed to flooding. The existence of a stable embankment that can withstand air pressure becomes very important.

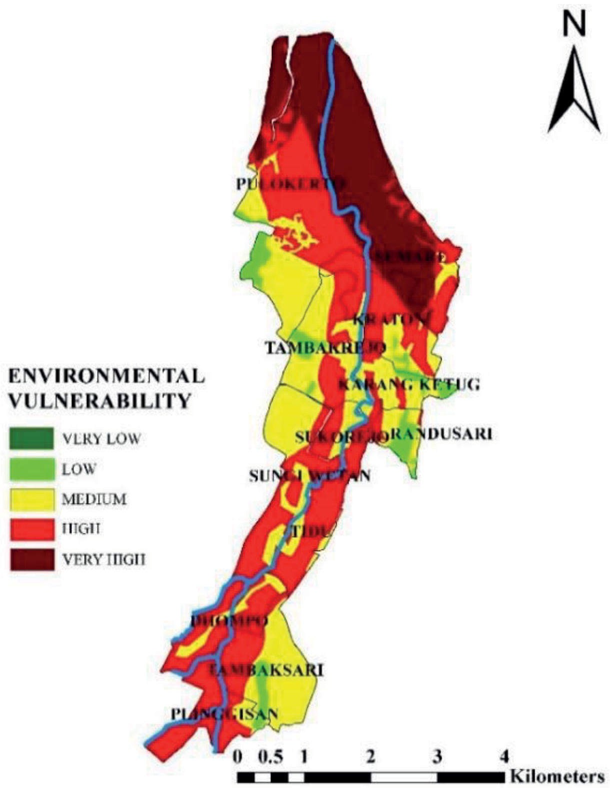

Fig. 2. Environmental vulnerability map; source: own study

SOCIO-ECONOMIC VULNERABILITY

The level of socio-economic vulnerability varies along administrative boundaries between villages. There are two levels of socio-economic vulnerability (Fig. 3), i.e., high (78%) and medium (22%). The average value of the socio-economic vulnerability index is high (0.53). The socio-economic vulnerability indices in eight villages, as presented in (Fig. 3), show a high-level vulnerability index, while four other villages have medium-level indices.

The values of socio-economic vulnerability indices depend on two indicators: education and awareness of the flood hazard.

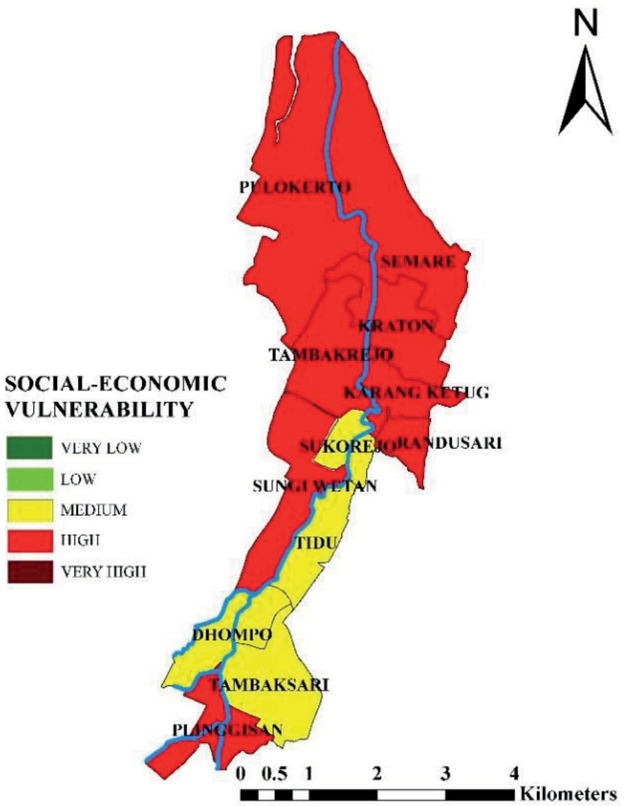

Fig. 3. Socio-economic vulnerability map; source: own study

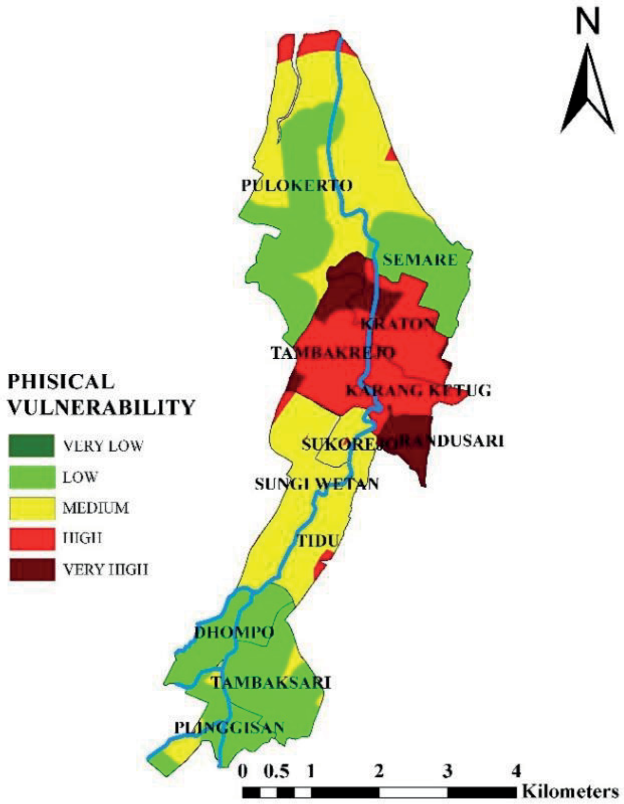

Fig. 4. Physical vulnerability map; source: own study

Both these indicators will affect common knowledge about flood mitigation.

The physical vulnerability indices for the five conditions are low (38%), medium (36.7%), high (19%), and very high (6.4%), as shown in (Fig. 4).

PHYSICAL VULNERABILITY

The four villages with high physical vulnerability are Randusari, Karangketug, Kraton, and Tambakrejo. The average value of physical vulnerability is 0.353, which fits in the low category. The indicator that has the strongest impact on the level of physical vulnerability is the position of buildings in relation to the street level, where lower land elevation implies higher vulnerability.

Moreover, more densely settled areas tend to be more vulnerable to flooding. It is due to the lesser absorption of floodwater. Three other indicators mitigate the level of physical vulnerability in the area. In most cases, adequate facilities, presence of a road within the distance of less than 250 m, and relatively low population density make it easy to evacuate an area. Only a small number of villages display an increased level of physical vulnerability; these include Tidu, Sungiwetan, Rabdusari, Pulokerto, and Semare.

FLOOD VULNERABILITY INDEX

In this study, we are looking at the extent of flood vulnerability in all study areas. The entire region has been classified into vulnerability levels which range from very low vulnerability to very high vulnerability. Therefore, the vulnerability was determined for each pixel/cell of the study area using GIS-based selective feature weights and normalised ranking of each criterion to visualise the large spatial variability of flooding across sites. The results showed that all components have a balanced weight. The integrated flood vulnerability (Fig. 5) shows that the three levels of the vulnerability index are high (51.6%), medium (47.7%), and low (0.7%).

The comparison of the indices for the three components identified for the eleven villages is shown in (Fig. 6). Based on the number and average value of the indicators that contribute to *FVI*, the socio-economic component of vulnerability has the highest position compared to the other two components of vulnerability. Environmental and physical components vary in vulnerability level from low to very high with a proportion below 50%. However, socio-economic components display a high level of vulnerability, and the proportion is still above 50%.

DISCUSSION

The integrated assessment of flood vulnerability of a flood hazard area by considering multiple elements based on GIS can produce a more detailed picture of vulnerability levels at a particular location, given the availability of environmental data and some physical data. The findings of previous studies, conducted simultaneously at a global scale by Kim and Gim [2020], indicate that socio-economic flood vulnerability contributes moderately. However, this study can describe the vulnerability level in more detail, namely, as moderate and high.

The flood vulnerability has offered a solution to the challenge of improving the adaptation to the floods in the estuary of Welang

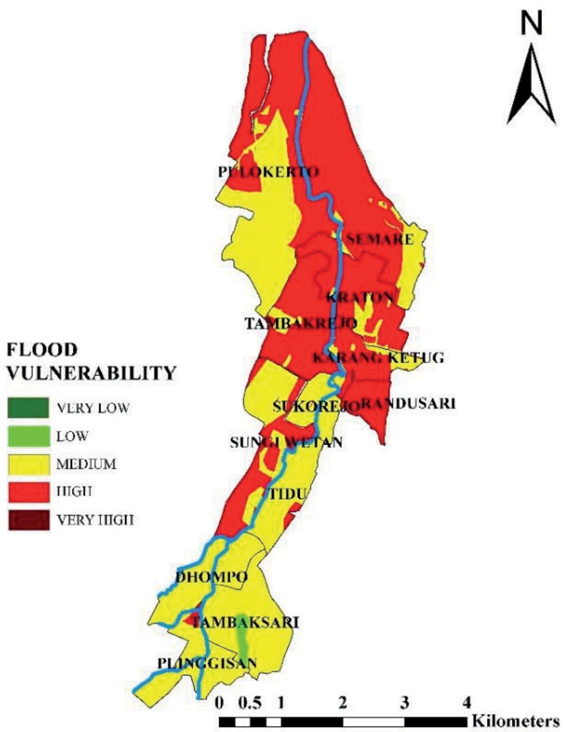

Fig. 5. Flood vulnerability map; source: own study

River, located on the north coast of Java island. Reduction in the vulnerability to floods cannot be achieved by addressing a single component only. Instead, it should be achieved by addressing all components that are directly or indirectly interdependent. It is crucial to address the environmental, socio-economic, and physical components, because they make the most significant contributions to flood vulnerability.

There are various factors that simultaneously contribute to high flood vulnerability. This study's findings help minimise the flood risk on the local scale and provide valuable information for decision-making institutions. Policymakers responsible for dealing with the floods need to prioritise reducing the flood vulnerability at the level of the environmental and physical components through careful spatial planning , as suggested by Park and Lee [2019]. The socio-economic vulnerability can be overcome by a cohesive management approach at all levels, to identify local capacity, to improve communication and awareness, and to increase preparedness, so that unexpected effects of the floodings can be reduced [Roder *et al.* 2017].

The limitation faced in this study is the availability of social and physical data (sanitation facilities), which is only based on regional statistical information, where the average value per village cannot describe the conditions of social and physical vulnerability with precision. For future research, this limitation can be overcome by surveying the social data and sanitation facilities directly for each household.

CONCLUSIONS

Among the components of high flood vulnerability, the socio-economic vulnerability (78.04%) has the highest significance, followed by environmental vulnerability (43.43%) and physical

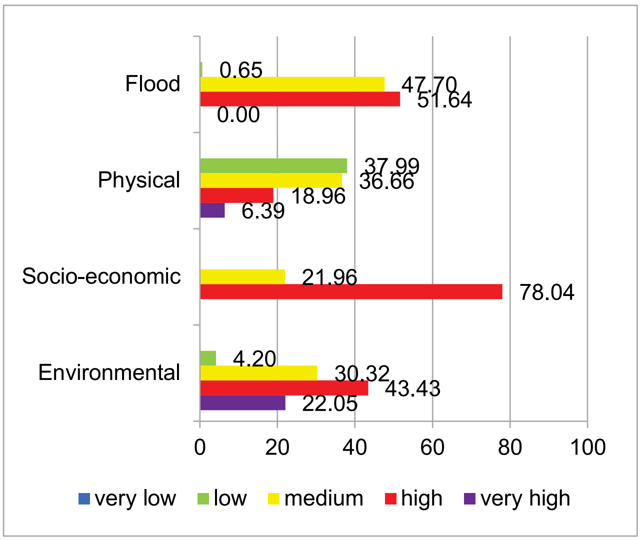

Fig. 6. Comparison of indices; source: own study

vulnerability (18.90%). The assessment of the level of flood vulnerability that integrates the analytic hierarchy process approach with GIS is an improvement on the current methodology and can describe vulnerability conditions. This approach would be even more effective if all the data could reflect the condition of the location in detail.

The results clearly show that low-lying areas and buildings positioned low in relation to the street level are mostly flood-prone due to the high probability of flood hazard and high population density. The capacity to minimise hazardous situations affecting nearly all villages in the northern coastal region, access to roads, and the use of a high proportion of lands as green spaces reduces vulnerability. Therefore, to minimise the risk of flooding, it is necessary to issue careful land-use plans with significant allocation for the provision of green spaces. In other words, the government must implement spatial policies to reduce the density of settlements, especially in areas with a high risk of flooding.

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