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ASSESSMENT OF VULNERABILITY INDEX OF WATER RESOURCES TOWARDS CLIMATE VARIABILITY IN UPPER THE CITARUM WATERSHED, WEST JAVA, INDONESIA

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ABSTRACT: This study aimed to evaluate the vulnerability index of water resources towards the climate variability of the upper Citarum watershed in West Java Province. The vulnerability was estimated using the IPCC concept, where vulnerability is a function of exposure, sensitivity, and adaptive capacity. The criteria and indicators of exposure, sensitivity, and adaptive capacity were obtained via analysis of secondary data consisting of climate data, hydrological data, and the ability of the community to adapt to events of water resource vulnerability. The criteria and indicators were then scored and weighted according to their degree of interest; they were then presented spatially and overlaid to obtain the vulnerability maps. This study also predicted the rainfall intensity in Citarum Watershed until 2040. Rainfall is predicted to increase until 2040, especially in wet months (January-March); dry months are predicted to have no significant increase in rainfall. A vulnerability map was then prepared to show each watershed percentage with categories of high, medium, and low vulnerability levels. This review can be used for watershed management or other shareholders to construct a strategy, plans, and actions that overcome issues of water resource vulnerability.

Keywords: Dependable flow prediction, Rainfall prediction, Temperature prediction, Vulnerability index

1. INTRODUCTION

The Citarum River is the longest in West Java; it flows over ±297 km and is impounded by three reservoirs serving as the main source of electricity for Java and Bali. In addition to electricity, the Citarum River is the source of raw water (80%), Water Supply Company (6%), irrigation (86.70%), urban water sources (0.370%), and water suppliers for household and industrial activities (2%). Issues regarding raw water are critical for the drinking water supply system in terms of quality, quantity, and continuity. The Citarum River's high pollution level has been long recognized. High levels of pollution can reduce the quality of raw water for the people around the Citarum River. The Citarum River also experiences a decrease in terms of its quantity and continuity. In the last several years, a drinking water company that uses the Citarum River as its main source has reported drought [1-3].

Climate change can worsen these problems. The climate variability scenario estimates that the temperature will continue to increase between 1.30° C and 4.60° C in 2100, with a trend of 0.10°C - 0.40°C per year [4]. Such a temperature increase will be followed by an increase in evapotranspiration that directly affects the balance of the hydrological cycle and water availability.

A vulnerability evaluation is required to understand the extent of the risks or dangers of climate change's effects on water resources [5]. The vulnerability evaluation in this study used the concept of vulnerability from IPCC, where vulnerability is a condition in which natural and social systems are vulnerable to damage caused by climate change/variability as a function of exposure, sensitivity, and adaptive capacity.

About the vulnerability of water resources, exposure is the degree of natural vulnerability in the form of changes in watershed conditions, such as the analysis of trends in rainfall and land cover. Sensitivity is represented by water demand, while adaptive capacity is defined as the ability of a system to overcome the consequences of climate variability or adapt to climate variability, reduce the potential for damage, or take advantage of the conditions provided by the changing climate. Each of these components is defined using several variables and indicators, which are then quantified in the form of weights and scores to calculate the vulnerability index. The vulnerability index for each component is then overlaid (spatial approach) to produce a vulnerability map [4, 6].

Vulnerability is defined as a function of environmental exposure, sensitivity, and adaptive capacity, such as the concept of climate change suggested by the Intergovernmental Panel on Climate Change (IPCC). Environmental exposure is a degree of a system naturally vulnerable to climate variability as well as the negative impact of rainwater inundation. Sensitivity is the degree of an affected system, whether beneficial or adverse impact. Sensitivity refers to the attributes of a system, either from nature or by humans, which makes it more vulnerable or less susceptible to the environment. The combined effects of environmental exposure and sensitivity determine the potential impact. Adaptive capacity is defined as a system's ability to cope with the adverse effects of environmental degradation or adjust to climate variability, reduce potential damage, or take advantage of conditions provided by a changing climate [6, 7].

This research focused on the Upper Citarum watershed area, including a part of the sub-watershed as the analysis unit because the watershed approach is more holistic and can be used to evaluate the relationship between biophysical and social factors.

The results of the vulnerability evaluation can help understand the issues and factors that cause vulnerability. The results can help design and prioritize adaptation mitigation activities to avoid or decrease the effect of drinking water source scarcity due to climate change.

2. RESEARCH SIGNIFICANCE

The Citarum River is a water resource with uncertain quantity and continuity worsened by climate change. To understand the extent of the risks or dangers of climate change effects on water resources, a vulnerability evaluation is required. The vulnerability evaluation described here used the concept of vulnerability from IPCC, where vulnerability is a condition in which natural and social systems are vulnerable to damage caused by climate change/variability as a function of exposure, sensitivity, and adaptive capacity**.**

3. METHOD

This study used the concept of vulnerability from IPCC. Vulnerability criteria are exposure, sensitivity, and adaptive capacity.

3.1 Observation of Rainfall Changes (Trend)

The prediction of rainfall changes was made by using the data of *climate explorer* (KNMI). Rainfall data were from 10 rain stations in the upper Citarum Watershed (Figure 1). The availability of data was monthly rain from 1986 to 2013. The rainfall forecast data used the CIMP5 model from the climate explorer (KNMI) of the RCP 4.5 model (medium scenario). The RCP 4.5 data were in the form of modeling the average rainfall from 1986 to 2040 (data series from 1861 to 2100). The GCM output used was the spatial statistic of the multi-model means of CIMP5.

Fig. 1 The map of 10 rain station locations in Upper Citarum Watershed

This RCP data were then corrected with data from 10 rain stations in the Upper Citarum (1986 - 2013 RCP data were corrected against 1986 - 2013 observation station data). Since the RCP data were in the form of monthly average data, the existing observation station data was averaged first and then used as corrections to the RCP data.

3.2 Rainfall Analysis in Upper Citarum Watershed

The water resources observations helped analyze the discharge from the Upper Citarum Watershed. In general, the stages of the analysis were data collection, delineation of the catchment area, area, rainfall analysis, calculation of evapotranspiration, and dependable flow analysis.

3.2.1 The data collection

The data collection includes daily rainfall data, a map of the Digital Elevation Model (DEM) for the West Java area from the Shuttle Radar Topography Mission (SRTM), and climatology data (10 years of data) obtained from BMKG.

3.2.2 The analysis of polygon Thiessen rainfall

To determine the effect of the rain station, the Thiessen polygon method was used, while the reciprocal method was used to fill the empty/ unrecorded rain data.

$$P_x = \frac{\frac{P_A}{d_{XA}{}^2}+\frac{P_B}{d_{XB}{}^2}+\frac{P_C}{d_{XC}{}^2}}{\frac{1}{d_{XA}{}^2}+\frac{1}{d_{XB}{}^2}+\frac{1}{d_{XC}{}^2}} \quad (1)$$

where, P_A, P_B, P_C = rainfall data from the recorded station'sA, B, and C; DXA = distance between station X and reference station A; d_XB = distance between station X and reference station B; d_{XC} = distance between station X and reference station C. The average rainfall for the Thiessen

Polygon method was calculated using the following equation:

$$\boldsymbol{P} = \frac{\sum_{i-1}^{n} P_i A_i}{\sum_{i-1}^{n} A_i} \quad (2)$$

where, P_1, P_2, …, P_n = rainfall recorded in rain stations 1,2, ..., n (n: number of rain stations); A_1, A_2, …, A_n = width of polygon 1,2, …, n (n: number of rain stations).

3.3 Estimation of the Vulnerability Level of Water Resources to Climate Variability

The vulnerability level was measured with a spatial-based approach where the criteria and indicators of climate variability were arranged in a spatial form with the assistance of a geographic information system (GIS) to obtain a vulnerability map. The stages of preparing a vulnerability map are as follows:

1) Determination of criteria and indicators

Exposure criteria and indicators were obtained from several references, especially from National Development Planning Agency [8] regarding the road map of climate variability in Indonesia, as well as the Ministry of Environment [9] and Effendi [10] concerning the assessment of community vulnerability to watershed-based climate variability in Central Java. The results at this stage are several criteria and indicators that are all converted into spatial data (maps).

Estimation of criteria and indicators can be seen from each variable [8–11]. Exposure variables are viewed based on the criteria for changing land conditions. This criterion has 2 (two) indicators: rainfall and land closure. Sensitivity variables are viewed based on 2 (two) criteria: water demand and land dependence. Water demand is divided into 2 (two) indicators: population density and access to clean water. For the land dependence criteria, the indicator is the percentage of the community that depends on agriculture. For variable adaptive capacity, the criteria are based on human resource quality, community social economy, health facility, and water absorption area.

2) Weighting and scoring

The weighting and scoring of the criteria and indicators were performed based on literature studies/previous studies, expert opinion, and interviews with the community. Weights and scores were given based on the importance of these criteria and indicators to the vulnerability of water resources. The result at this stage is a score on each of the variables, criteria, and other indicators.

3) Determination of index and vulnerability map

The determination of the vulnerability index was done according to equation 8, which helps reduce the index of exposure and sensitivity by the index of adaptation capacity [11, 12]. This step was assisted by a raster calculator feature of ArcGIS 9.3 software. The result is presented in the form of a map of exposure, sensitivity, adaptive capacity, and vulnerability. The equation is as follows:

$$\boldsymbol{K} = \left(\left(\sum_{ie=1}^{n}(w_{ie} \times x_{ie}\right) + \left(\sum_{is=1}^{n}(w_{is} \times x_{is})\right)\right) - \left(\sum_{ie=1}^{n}(w_{iac} \times x_{iac})\right) \quad (3)$$

Here, K = index of vulnerability; W_{ie} = indicator weight of ei on exposure variable; X_{ie} = indicator score I on exposure variable; W_{is} = indicator weight of I on sensitivity variable; X_{is} = indicator score of II on sensitivity variable; W_{iac} = indicator weight of II on adaptive capacity; and X_{iac} = indicator score of I on adaptive capacity.

The value of the vulnerability index was then classified into 5 (five) levels/classes of vulnerability: high, slightly high, medium, slightly low, and low [12]. The determination of interval scales for the vulnerability class was calculated using Equation 4. The vulnerability level was analyzed descriptively per region based on the variables of exposure, level of sensitivity, and adaptive capacity. The results of the explanation of the vulnerability level in each region helped overview the vulnerability level of water resources to climate variability in the watershed. The formula for determining the interval class is as follows:

$$\boldsymbol{i} = \frac{R}{n} \quad (4)$$

Here, i = interval scale; R = difference of maximum and minimum score; and n = the number of evaluation classes formed.

To determine the accuracy of the vulnerability map to climate variability, an accuracy assessment was carried out by overlaying the vulnerability map with the disaster event maps. The assumption was that if an area has a high level of vulnerability, then disasters occur more frequently in that area.

4. RESULTS AND DISCUSSION

This study used the concept of vulnerability from IPCC. Vulnerability indicators are exposure, sensitivity, and adaptive capacity.

4.1 Rainfall in Upper Citarum Watershed Area

Rainfall patterns can be classified into three patterns: monsoon, equatorial, and local. The rainfall pattern in the Citarum watershed is classified as a monsoonal rainfall pattern because it has a graph in the shape of the letter "V", i.e., there is a clear difference between the rainy season and the dry season. The dry season is marked by minimum rain and occurs in June, July, and August or at the time of the east monsoon wind, which is when the sun is on the equinox. The west monsoon wind occurs (November-January) and is when maximum rainfall occurs [13].

The rainfall map in Figure 2 shows that the annual rainfall in the southern watershed is greater than in the northern part of the watershed; it is characterized by high rainfall with an intensity greater than 2500 mm. Figure 2 is a result of polygon Thiessen region rainfall methods.

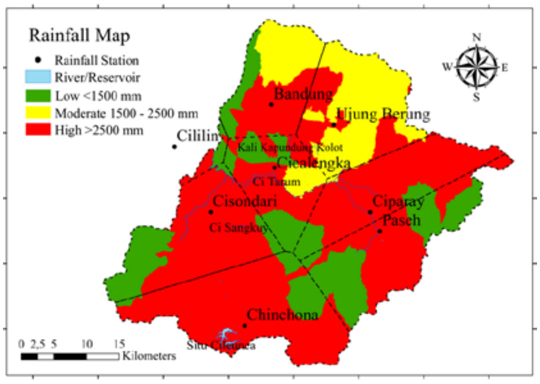

Fig. 2 Rainfall map in Upper Citarum Watershed.

4.2 Rainfall Prediction in Upper Citarum Watershed Area

Global climate change data are generally in the form of General Circulation Models (GCM). The GCM combines spatial and time series that are simulated in the form of a grid. Data from GCM results can stimulate climate predictions considering that GCM data can be prepared for both temporal and spatial models; it can even simulate predictions of climate change (Figure 3). GCM can provide information about climate shifts in the future. GCM generates data in the form of a low-resolution region plaque (2.5° or ±300 km), which represents the global climate condition but not on a regional or local scale.

GCM data were obtained from *Coupled Model Intercomparison Project* (CMIP) modeling, which has functions to:

1) Evaluate how realistically past models were simulated,
2) Provide predictions of future climate change on two-time scales: short term (up to 2035) and the long term (up to 2100 and above)
3) Capture some of the different factors that influence several models, including considering some inputs such as the effect of clouds and the carbon cycle.

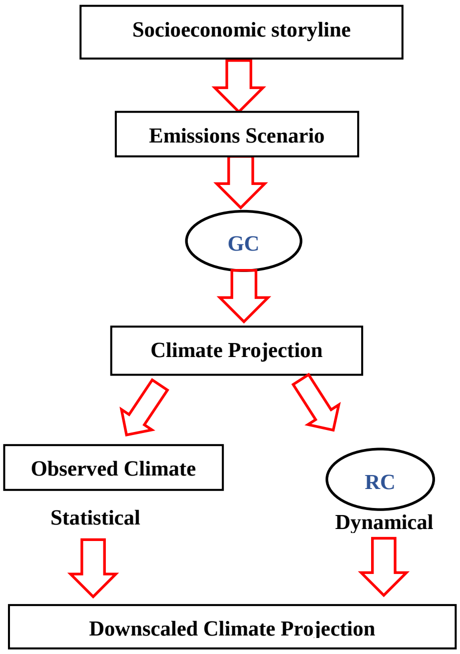

Fig. 3 Illustration of related components in the development of global climate prediction.

CMIP has several input scenarios for representative concentration pathways (RCP) that generate GCM data. The RCP scenario is modeled on an estimation of the high level of carbon dioxide (CO_2) emissions until 2100. The estimation of the level of carbon dioxide gas emissions is based on assumptions regarding economic activity, natural resources, population growth, and several other socioeconomic factors. The RCP scenario is divided into four types/levels: RCP 2.6 (aggressive mitigation strategy, gas emission level of 490 ppm); RCP 4.5 (medium-low, gas emission level 650 ppm); RCP 6 (medium-high, gas emission level 850 ppm); and RCP 8.5 (business, as usual, gas emission levels of 1370 ppm). The rainfall prediction carried out in this study is a rainfall prediction with RCP 4.5.

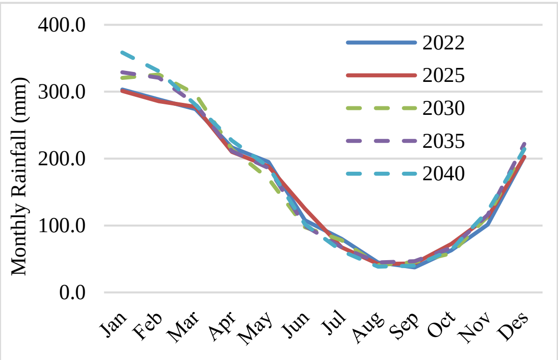

Fig. 4 The rainfall prediction in Upper Citarum Watershed, West Java

Rainfall prediction results show that there is an increase in rainfall, especially in the wet months (January - March). The dry months have no significant increase in rainfall (Figure 4). Figure 4 is the result of rainfall predictions up to 2040 as calculated by the Downscaled Climate Projection method. Therefore, it is necessary to watch out for the intensity of the rain, which has continued to increase. These incidents must be accommodated in all forms of development and regional planning.

Thus, there are at least two things that need to be considered based on the existing data: land use which is seen to have decreased, and predicted rainfall that increased along with climate change. These two things need to be considered in overcoming the threat of climate change in the Upper Citarum watershed, especially in extreme floods and drought.

4.3 Water Resource Vulnerability to Climate Changes

The mapping of the water resource exposure variable is the result of the overlaying rainfall map, land cover maps, and land criticality maps in the Upper Citarum watershed area. The results of a spatial study indicated that the highest level of exposure was scattered around the Bandung District and West Bandung District (5a). The high level of exposure can be caused by high rainfall and limited land cover in the region. Figure 5b shows that the highest level of sensitivity is in Bandung City; other regions are classified as moderate to low. Mapping the sensitivity of water resources to climate variability is affected by the level of water demand as represented by the level of population density and access to clean water as well as community dependence on agricultural land. The high population density in Bandung City made the region have a higher level of sensitivity than other regions.

The adaptive capacity of water resources was reviewed using criteria and indicators consisting of the quality of human resources, the community's socio-economy, health facilities, and water catchment areas. Figure 5c shows that almost all regions have a slightly high to a high level of adaptive capacity; only regions around Bandung City have a relatively low index. This is due to the high water-catchment areas in almost the entire Upper Citarum watershed—this makes it relatively high in adaptive capacity. After going through the weighting, scoring, and overlying stages, the combination of the variables of exposure, sensitivity, and adaptive capacity led to a vulnerability map (Figure 5d). Figure 5d shows that the areas with the highest vulnerability index are Bandung City and Cimahi City.

Figure 5a is obtained from the results of overlaying watershed condition change criteria divided into two indicators: rainfall and land closure. Rainfall indicators were divided into three categories. These categories are <1,500 mm with a score of 1 or low, category 1,500 mm–2,500 mm with a score of 3 or medium, and >2,500 mm with a score of 5 or high. Land closure indicators were categorized by a type of land cover—namely forest with a score of 1 or low, plantation with a score of 2 or slightly low, agriculture with a score of 3 or medium, savanna with a score of 4 or slightly high, and residential areas with a score of 5 or high.

Figure 5b is the result of overlaying indicators of population density, access to clean water, and agricultural land dependence. The population density indicator is divided into 3 (three) categories, these categories are <150 people/ha with a low score of 1, 151-200 people/ha with a score of 3 or medium, and 201-400 people/ha with a score of 5 or high. Access to clean water indicators is divided into 5 (five) categories. These categories are 0-20% with a score of 1 or low, 20-40% with a score of 2 or slightly low, 40-60% with a score of 3 or medium, 60-80% with a score of 4 or slightly high, and 80-100% with a score of 5 or high. Dependence on agricultural land was divided into five categories: 0-12.5% with a score of 1 or low, 12.5-25% with a score of 2 or slightly low, 25-37.5% with a score of 3 or medium, 37.5-50% with a score of 4 or slightly high, and >50% with a score of 5 or high.

Figure 5c is the result of overlays of literacy, the level of well-being of the population, health facilities, and water absorption areas. Indicators of human resource quality are literate and are divided into 3 (three) categories: <50% with a score of 1 or low, 50-70% with a score of 3 or medium, and >75% with a score of 5 or high. The criteria of community social economy are seen based on community well-being level indicators divided into 5 (five) categories: <60% with a score of 1 or low, 60-70% with a score of 2 or slightly low, 70-80% with a score of 3 or medium, 80-90% with a score of 4 or slightly high, and >90% with a score of 5 or high. Health facility criteria are divided into 3 (three) categories: not available with a score of 1 or low, available with a score of 3 or medium, and completely available with a score of 5 or high. Water absorption area criteria used indicators in the form of a percentage of water absorption region viewed based on 5 (five) categories: <20% with a score of 1 or low, 20-30% with a score of 2 or slightly low, 30-40% with a score of 3 or medium, 40-50% with a score of 4 or slightly high, and >50% with a score of 5 or high.

This study included rainfall and land cover in metrics of environmental exposure. The condition of land cover in an area is related to the amount of rain that falls; heavy rainfall can cause flooding [7].

The amount of rainfall in Indonesia is 1500 mm to 2500 mm per year. The Citarum watershed has a variety of land cover: forests, plantations, agriculture, savannas, and settlements dominated by plantation and residential areas. This is also by data from the Regional Development of West Java.

Sensitivity is seen based on population density, clean water needs, and land dependence. Population density is considered an important component in determining vulnerability because the state of the population itself is an important factor in predicting the extent of damage when exposed to environmental hazards [7]. The population density in the Upper Citarum Watershed is mostly between 150-200 people/ha. This is by the provisions in the Ministry of Public Works. Access to clean water is one of the sensitivity indicators related to the number of residents; this indicator assesses the vulnerability of water sources in watershed areas. Access to clean water in the Upper Citarum Watershed is still less than 50%.

The sensitivity of natural systems is divided into managed and unmanaged natural systems. Areas with a proportion of managed natural land cover are more sensitive because vegetation and crop yields are negatively influenced by environmental degradation. Unmanaged natural systems such as swamps and grasslands are affected by environmental degradation [7]. This can be seen based on the number of people who depend on agricultural land whose data were obtained from Indonesian statistical data. More than 50% of people in the Upper Citarum watershed still depend on agricultural activities.

Adaptive capacity can reduce the overall vulnerability. Adaptive capacity is divided into four criteria: the quality of human resources, socioeconomic communities, health facilities, and the percentage of the water catchment area. These four metrics are, in turn, further divided into several indicators. The quality of human resources is seen based on the ability to read data obtained from the central statistics agency. This assumes that people with good literacy skills can understand the rules regarding the environment.

The social condition of the community can impact the population's welfare; economic aspects are an important factor that affects adaptive capacity [7]. Health facilities in a region can reflect the welfare condition of the people in the region because not all areas have health facilities. More than 50% of people in the Upper Citarum watershed are literate; the community well-being level of people in the Upper Citarum watershed is 60-70%. The percentage of the water catchment area is used as an indicator of adaptive capacity because it has a relationship with water availability. Water availability can be observed based on discharge or runoff in watersheds.

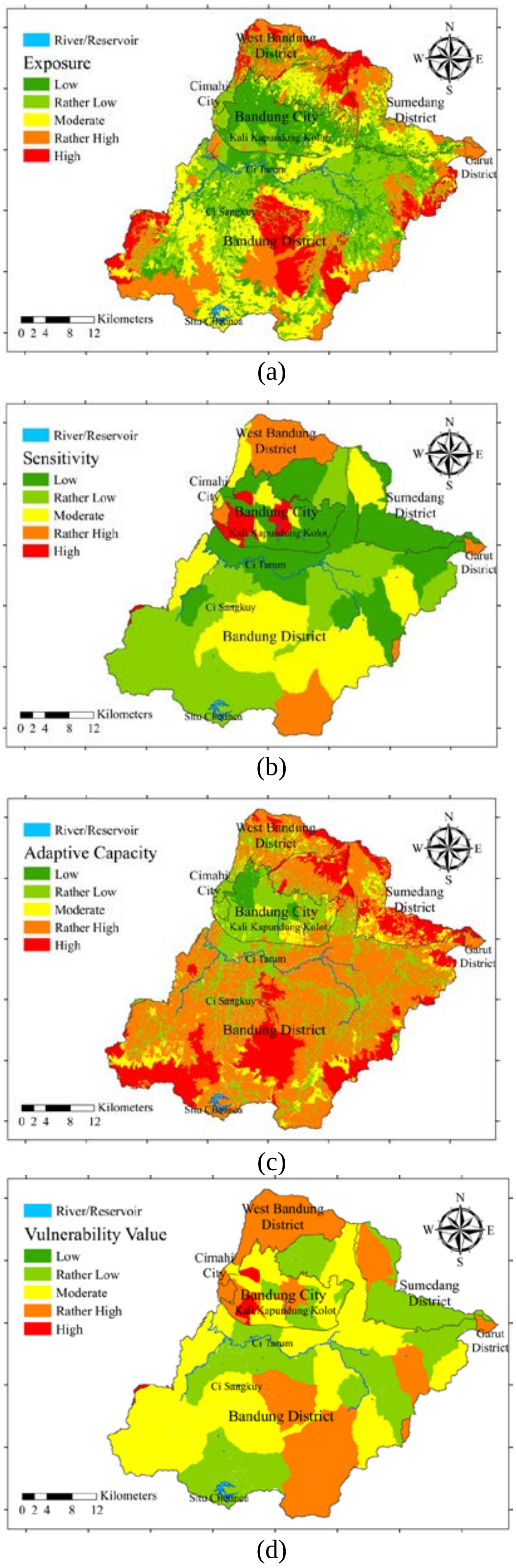

Fig. 5 Map of exposure level (a), sensitivity level (b), adaptive capacity (c), and vulnerability level (d) in the Upper Citarum Watershed.

The water discharge is high in the rainy season and low in the dry season [12]. The percentage of water infiltration can be seen based on the built-up area in a watershed area. The divisions are 5 (five) classes as having been done in previous studies [6, 12, 14]. A Strength-Weakness-Opportunity-Threat (SWOT) analysis was built based on the exposure, sensitivity, and adaptive capacity, especially in the Upper Citarum Watershed. This SWOT analysis is useful for local governments to take action in terms of technical and non-technical policies to adapt to vulnerability conditions that can happen. SWOT analysis can be seen in Table 1.

Table 1. SWOT analysis based on exposure, sensitivity, and adaptive capacity in Upper Citarum Watershed

Strength	Weakness
Intensity rainfall >2,000mm	More than 60% of land closure was covered by plantation and residential area
Literate capabilities >50%	Population density between 150-200 people/ha
Community well-being level: 60-70%	Access to clean water <50%
	Percentage of water absorption region <50%
Opportunities	Threats
There are technical and non-technical policies that support the sustainability of water resources	Increase in population due to births and migration
Opportunities	Threats
Construction of dams to provide water in the dry seasons	Increased land-use change to a residential area
Conservation behavior in the community can be improved through education facilities	The amount of infiltration capacity is decreasing
	Dependable flow in the river which is declining

5. CONCLUSIONS

Climatological data in the last few decades shows that climate variability has increased in the Citarum, Upper Citarum Watershed, West Java in terms of annual average air temperature in the downstream part of the watershed with decreased rainfall in the middle and downstream part of the watershed. Previous research results indicate that climate variability can have a significant effect on water quantity and quality. The combination of IPCC security concepts and the spatial approach used to evaluate the vulnerability level of water resources produces a water resource vulnerability map. This vulnerability map can display spatial vulnerability information as an effective and low-cost tool useful for policymakers concerned with strategies, plans, and actions in overcoming problems with climate variability in terms of water resources.

6. ACKNOWLEDGMENTS

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