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FLOOD CHARACTERISTICS IN THE LOWER CITARUM RIVER, INDONESIA AND THEIR POSSIBLE MANAGEMENT PRACTICES

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ABSTRACT: Citarum River is the third longest river in Java. It is classified as a nationally strategic river area since it is essential for the national economy. However, annual flooding occurs upstream and downstream of the river. Lower Citarum River (LCR) often experiences flooding due to the high flow release of the reservoir and the contribution from the other basins. The most significant recent extreme flow was in 2021, with 1,141 m³/s flow, which inundated parts of many regencies, posing a significant risk to property, economic disruption, and human health. Even though floods in the LCR occur frequently, studies regarding the characteristics of floods there are still limited. Floodway scenarios simulated using HEC-RAS 1D-2D with SWE-ELM solver regarding flood characteristics in LCR and involving selected potential management to predict its performance, impacts, or behavior under specific conditions. The scenarios considered were floodway 30 m, floodway 60 m, flood estate, and combination scenario, along with evaluating benefits and costs. The benefit calculation evaluates the economic loss of a single flood event and, thus, the benefit if the flood is avoided by implementing the evaluated construction. The floodway 30 m scenario had the best benefit-cost ratio (0.87). This scenario reduced the flood inundation from 13,602 ha to 6,527 ha, and economic loss decreased from 16.8 million USD to 5.9 million USD. However, other scenarios with 1.5 times higher construction costs show lower economic losses (thus higher benefits) but a lower benefit-cost ratio. The benefit of the measure grows as more flood events occur.

Keywords: Citarum River, Flood, Flood Management, Shallow Water Equations, Floodways

1. INTRODUCTION

Citarum River (Fig.1) is West Java, Indonesia's longest and largest river. It serves 25 million people with energy, water, agriculture, fisheries, industry, and sewage needs [1]. The river greatly impacts the lives of the people in West Java, Jakarta Metropolitan Area, and Indonesia in general (for food and energy supply). For its importance, Citarum is classified as a nationally strategic river basin. Despite its importance, the river basin experiences recurring floods, drought, soil erosion, landslides, water contamination, and dam technical failures. Lower Citarum River (LCR), i.e., the area downstream to the Jatiluhur reservoir (Fig.1), often experiences flooding due to the high flow release of the reservoir and the contribution from the other basins. The largest extreme flows were recorded in 2010 and 2021, with 1,600 and 1,141 m³/s flows, respectively. However, the 2010 flood's value was not well recorded with such value as an estimated flow [1]. Such flood events inundated parts of Karawang and Purwakarta regencies, with both events posing a significant risk to property, economic disruption, and human health. In 2021, more than 9,000 families were affected, and 1,000 were displaced. The observed flood height ranged from 100 to 250 cm. A thorough survey recorded breach locations along the LCR where the levee breached or overtopped, causing river overflows to the agricultural and urbanized areas. A study regarding flooding characteristics in the lower Citarum River is of high urgency [1].

Although floods in LCR are significantly disruptive, studies on flood characteristics and potential management solutions are still in the early growing stage. On the other hand, the Upper Citarum River (UCR) has had numerous previous studies conducted. Some of the most recent studies analyzed the flood characteristics and modeling in the UCR [2–4]. In another study, a research project collaborated with the local community to install several automatic weather stations and water level recorders in various watershed parts. The project also enhanced the already in-practice community-based flood early warning. Other studies in the UCR focus on the strained groundwater supply, which has ties to the increasing risk of flooding. The case then further aggravated with no signs of development slowing down and continuous land conversion [5,6].

Handayani et al. [7] studied the historical textile industry in the Majalaya area, which is also a part of the UCR, concerning the Citarum watershed. The industry particularly blossomed due to the abundance of water and workforce in the UCR. Alam et al. [8] studied microplastic distribution in rivers in the Majalaya area. Microplastic particles were discovered and sorted by size and shape using a binocular microscope. The particles were found both suspended in water as well as in the sediments. Safarina et al. [9] quantified river capacity metrics in the UCR tributaries, calculating the ratio between discharge load and its capacity. The study showed that most of the rivers in the UCR have more than one ratio, with some classified as severely damaged. Rohmat [3,10] also worked in the Majalaya region and studied areas vulnerable to yearly flooding. As Majalaya is a vital component of the economy of the Bandung Metropolitan Area, the study intended to recreate the devastating flood that occurred on February 22, 2018, damaging a significant amount of property and the surrounding area.

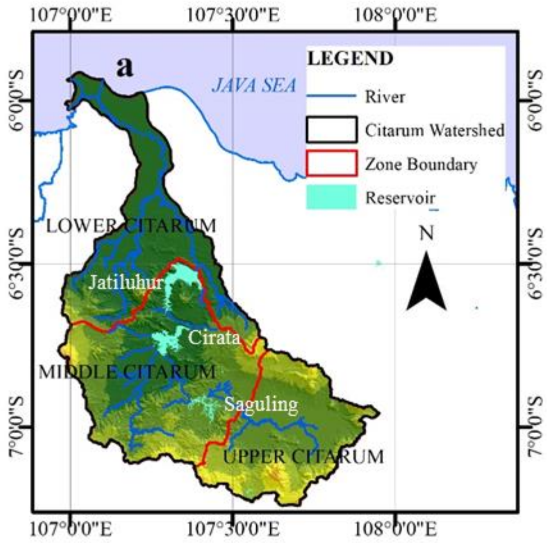

Fig.1 Map of Citarum River and the management zones: UCR, MCR, and LCR

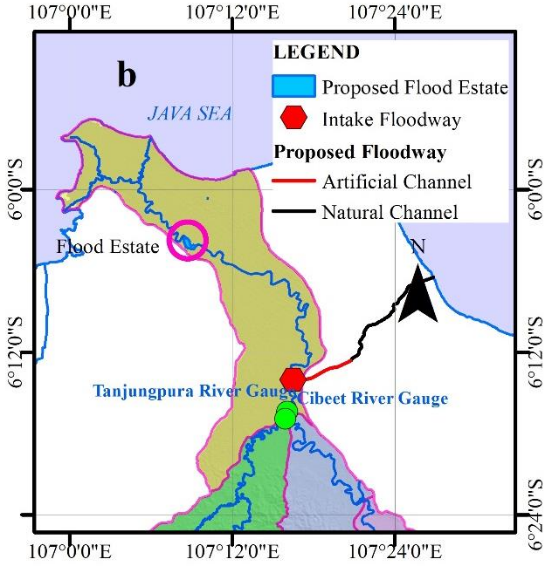

Fig.2 Focused map of LCR showing its tributaries, river gauges, and the location of the proposed flood management measures.

The prior study used surveyed topographic terrain data for flood modeling using HEC-HMS and HEC-RAS, as well as gauged and satellite observations of precipitation, stream flow records, Indonesian National DEM (DEMNAS), Light Detection and Ranging (LiDAR), and other methods. The crowdsourced flood extent of a recent major flood event recorded by the neighborhood was contrasted with the flood extent predicted by flood models. The limitations of modeling, changes in flow characteristics brought on by trash clogging, and the quality of crowdsourced flood records were all noted as reasons for the discrepancies between the simulated and actual flood extent [11]. Based on the flood simulation, the paper suggested three measures to reduce the risk of flooding: boosting river conveyance, building a sizable retention basin, and designating a floodway. It also suggested potential directions for further research.

Such information indicates that the subject of the Citarum flood is a growing topic. As shown by such references, previous studies focused more on hydrology [12], river management, and the related topics in the UCR [13]. Although flood events in the LCR locus exist and significantly disrupt the region's economy [1], the studies are yet to be published. Based on that, this study presents a case study regarding flood characteristics in LCR and the review of selected potential management measures using a numerical hydraulic model to evaluate the flood characteristics. This paper identifies the Citarum River with the LCR as its main focus (Fig.2), then continues with the data used in this study, e.g., flow observation records, river geometry, and the DEM. This study uses the HEC-RAS model [14–16] with 1D-2D modeling selected and the shallow water equation approach. Six management scenarios (existing condition, floodway 30 m, floodway 60 m, flood estate, floodway 30 m + flood estate, and floodway 60 m + flood estate) are assessed both hydraulically and economically. The scenarios are then compared to assess the relative preference.

2. RESEARCH SIGNIFICANCE

Citarum is a strategic river on Java Island that irrigates extensive paddy plantation areas, providing electricity, fisheries, tourism, and Indonesian cities' raw water source. Specifically, LCR is home to 5.7 million people which is also the center of the industrial area of West Java [17,18]. The threat of flooding will cause substantial economic losses to the industrial sector, e.g., long-term reduced investor confidence in economic development in the region. The flood impact could disrupt the investment climate and hinder economic growth for West Java and Indonesia since most of Indonesia's industrial activities are concentrated in this region.

3. STUDY AREA: CITARUM RIVER BASIN

Citarum River stretches 297 km from its upstream area at Cisanti Lake to the estuary at Muara Gembong. Its watershed has a total area of 6,621 km². Geographically, the Citarum River Basin is located at 106.85°E–107.85°E and 7.32°S–6.40°S. Citarum River has three cascade reservoirs: Saguling, Cirata, and Jatiluhur (Fig.1). The two dams upstream (Saguling and Cirata) are single-purpose dams for hydropower generation. Meanwhile, Jatiluhur was built for irrigation, raw water supply, hydropower, flood control, and recreation.

For management purposes, the river is divided into three zones: UCR, Middle Citarum River (MCR), and LCR parts. The UCR stretches from the mountains to the inlet of Saguling Reservoir. MCR from the Saguling reservoir to the outlet of the Jatiluhur reservoir, including the Cirata reservoir (Fig.1). The LCR starts from the outlet of the Jatiluhur reservoir to the Muara Gembong estuary in Bekasi Regency. The three large reservoirs in the MCR supply West Java and Jakarta's municipal raw water, irrigation needs, and regulate floods [19]. The dams in the MCR also provide hydropower generation connected to the nationally strategic Java-Madura-Bali power grid [20]. The topographical features of the three regions are different [21–23]. The UCR area looks like a giant basin whose morphology is surrounded by mountainous and hilly areas. The elevations range from 2,900 m.asl (meters above sea level) in the headwaters to 625 m.asl in the Saguling reservoir. The elevation of the MCR varies between 250–2,400 m.asl, with varying morphology from plains, mild hills, steep hills, and volcanic morphology [24]. The LCR part is dominated by plains with elevations between 0–800 m.asl, starting from the tailrace of Jatiluhur reservoir to the estuary at Muara Gembong, primarily in the Karawang and Bekasi regencies [25,26]. LCR is a flat area (slope <8%) and is a transportation hub in the western part of Java Island and is very close to various education and health facilities. It makes LCR an area with the potential for fast regional development due to easy access and availability of facilities.

The average temperature ranges from 27°C and humidity between 76–84%. So far, the lowest temperature was recorded at 9°C in the mountain peak and the highest at 34°C in the coastal area. In the upper reaches of the river in the highlands/mountains, the average minimum air temperature was 15°C recorded in the upstream region. Relative humidity ranges from 80–92%, with an average annual evaporation rate of about 1,640 mm. The climatic conditions of the Citarum River Basin, like most areas in West Java, have a tropical monsoon climate with relatively constant temperature and humidity throughout the year. The tropical monsoon climate is characterized by two seasons: rainy and dry. The rainy season occurs in October–March, and the dry season occurs in June–September [27]. The other months are a period of transition. Classification of land use in the Citarum watershed includes forest, gardens/plantations, industry, settlements, irrigated rice fields, rainfed rice fields, dry fields, shrubs, vacant ponds, salt ponds, and mangroves [27,28]. Based on image analysis conducted in the status study of the Citarum watershed, the largest land use in the Citarum watershed is irrigated rice fields by 25%, followed by settlements by 15%. Regarding the soil, the latosol soil type dominates most of the Citarum River Basin; this is fertile soil suitable for agriculture and plantations.

The water potential in the Citarum watershed is 13 billion m³/year. Only 7.5 billion m³/year, or 57.9% of the water potential, has been utilized [29]. The remaining 5.45 billion m³/year, or 42.1%, has not been utilized. The Citarum River area has three large reservoirs as a water supply for raw water, irrigation, and power generation. The three reservoirs are Saguling Reservoir, Cirata Reservoir, and Jatiluhur Reservoir, located in one flow of the Citarum River and four districts, i.e., Cianjur, West Bandung, Purwakarta, and Karawang. The problems faced by several reservoirs in the Citarum River area include a significant increase in sedimentation in recent years. Then, the proliferation of floating net cages increases reservoir water pollution due to excessive fish feed [30–32].

The specific location of this study is the Citarum River after the confluence with the Cibeet Tributary. Although the LCR ranges from Jatiluhur's tailrace to the estuary, the flood was observed after the Citarum-Cibeet confluence. Right downstream of the confluence, a stream gauge with daily data reporting exists and is used as the upstream boundary condition of the modeling.

4. MATERIALS AND METHOD

Fig.3 presents the general steps of the analysis, starting with data collection. Then, the water system analysis of the LCR as the study object started from the end of Jatiluhur Reservoir. Since the reservoir's data used is only the released flow, the reservoir operations were not within the scope of this study. The records from important water structures downstream of the reservoir were incorporated, and calculation data based on the local watershed area were used. This study only observed the hydrological system from Jatiluhur to the downstream and treated the upstream regions as the input boundary condition. The analysis used the GIS approach with ArcGIS 10.8 software. The input data needed for this analysis were Merit-Hydro DEM [33], local flow records, and river cross-section from Citarum Water Authority (Balai Besar Wilayah Sungai Citarum, henceforth BBWSC), and the land cover data from the Indonesian

Geospatial Agency (Badan Informasi Geospasial, henceforth BIG).

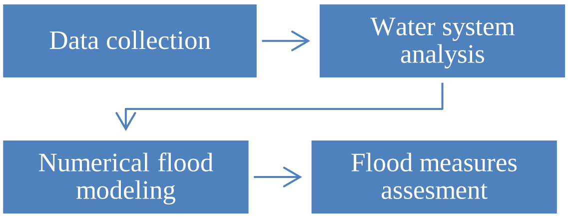

Fig.3 General methodology

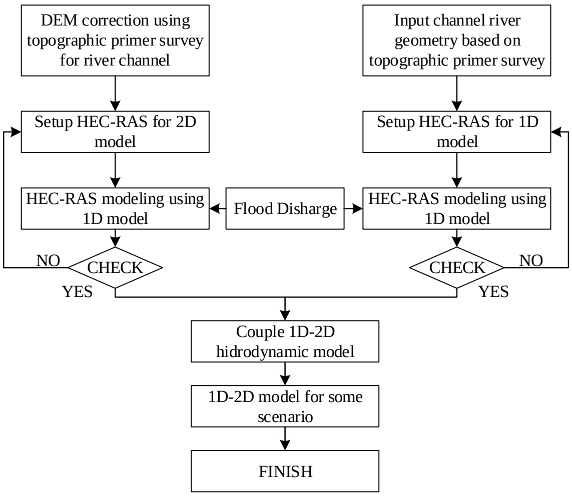

Fig.4 Flowchart of numerical flood modeling

The water system analysis is based on river and canal schemes around the study location. Water discharge records in rivers or irrigation canals are used to calculate flood discharges from the other channels that don’t have stream gauges, e.g., from weir local discharge. From the water system analysis, the process continued with the numerical flood modeling. Flood inundation can be modeled using one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D) hydrodynamic models. In this study, the simulation was carried out using the coupled 1D-2D hydrodynamic model to determine the flood water level elevation with the aid of HEC-RAS (Hydrological Engineering Center River Analysis System) software of the US Army Corps of Engineers (USACE) [34]. The data included in the numerical model were DEM, cross-sections, land cover, and hydrological data. The Merit-Hydro DEM [33] has been updated with the primarily surveyed river cross-section from BBWSC to calculate spatial data input for flood modeling. The HEC-RAS lateral structure combines 1D and 2D hydrodynamic models when water spills from the river to the bank and flows into a 2D flow region using this lateral structure system. For 2D area, each cell has a grid size of 200 m × 200 m. The modeled river cross sections were 100 meters spaced for the 1D river flow part. The flow chart of numerical flood modeling analysis is shown in Fig.4.

The 1D-2D model was chosen to get more accurate flood simulation results [35]. The watershed boundary for this modeling was upstream at the confluence of the Cibeet River with the Citarum River and downstream at its estuary. The upstream boundary used a flow hydrograph/reservoir release from BBWSC, while the downstream boundary used mean sea level. The flood event modeled was the flood in February 2021, including data extending to February 15–28, 2022. The flood was chosen as the largest well-recorded flood in the area, therefore being the representative event to characterize flood in the LCR. Note that 2010 was reported to be larger (1,600 m^3/s in 2010 versus 1,141 m^3/s in 2021); however, the data was not well-collected, and the flood was mainly caused by reservoir mismanagement. The historical inundation of the flood that occurred in 2021 is used as a calibration for HEC-RAS modeling results.

After the modeling, the process was followed by assessing flood management measures. The flood measures being considered are floodways with two different proposed sizes, flood estates, and their combinations. This process assessed different measures' changes in flood inundation areas and calculated the economic benefit and construction cost. The step concluded with assessing the benefit-cost ratio to select which measure is the best without discussing flood reservoir operation for flood retention, despite being important to study. However, there is a strong recommendation for future study direction, especially since the cascade reservoirs present a complicated challenge of being operated by three parties with different operational objectives.

5. RESULT AND DISCUSSION

5.1 LCR River System

The river system of LCR is shown in Fig.1. It is essential to note that Citarum is a large river, with the study area only downstream of Jatiluhur Dam. The analysis did not include flows from the UCR, nor the changes affected by the cascade dams (Saguling, Cirata, and Jatiluhur) [36]. The LCR starts at the tailrace of Jatiluhur Dam, where the streamflow meets Curug Weir. The weir divides the flow into East Tarum and West Tarum irrigation canals, each designed to convey 50 m^3/s water. The West Tarum Canal was used to carry water to the West Tarum irrigation area and the Jakarta Metropolitan Area (JMA). However, due to ongoing land cover conversion, the conveyed water is almost exclusively used for the growing JMA needs. The East Tarum canal conveys water to the East Tarum irrigation area.

In contrast to the West Tarum Canal, the East Tarum Canal water is almost exclusively used for irrigation.

After the Curug Weir, the Citarum River continues to Walahar Weir. The weir divides the flow into the North Tarum canal for irrigation water. Downstream from there, the Citarum River then meets the Cibeet River. At around 500 meters after the confluence point, there is a Tanjungpura stream gauge, whose data was used for this study's modeling purpose. Fig.5 shows the daily average flow of the second half of February 2021, consisting of the peak daily average flow at 1,141 m³/s on February 20, 2021, which roughly continues the day after at 1,126 m³/s. The flow gradually increases from February 18 at 319 m³/s and decreases to 450 m³/s on February 24. Its flow increased to 681 m³/s in the following days and decreased to 310 m³/s.

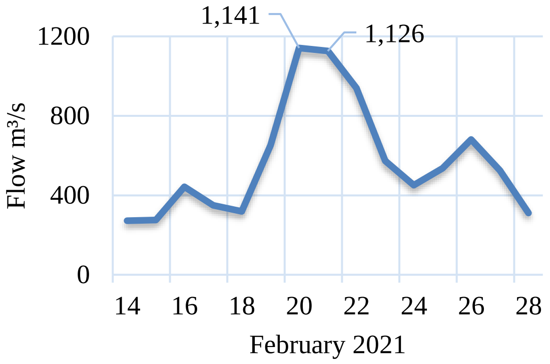

Fig.5 Daily average hydrograph at the snapshot event (second half of February 2021)

5.2 Options for Flood Control Measures

To control and reduce the impact of flooding on the LCR, the BBWSC considers several flood control scenarios. LCR floodway is considered to reduce flooding. The floodway is a combination of artificial and enhanced natural channels. Floodways are an effective solution to reduce flooding. Several existing floodways are currently operating and can control flooding effectively, such as the west canal flood and east canal flood in Jakarta, West Java's Cisangkuy Floodway [37,38], and the Chao Phraya Watershed, Thailand [39]. Determining the position of the floodway that must be considered is the outlet location. Although the floodway effectively reduces flooding in certain river segments, the flood discharge will increase again at the outlet point if the floodway outlet meets again with the original river downstream. The floodway outlet planned for the LCR is in the sea, so the output discharge from the floodway will no longer affect the Citarum River downstream.

The floodway intake is located 6.8 km downstream of the Citarum-Cibeet confluence at the Tunggakjati area (Fig.2). The floodway intercepts high flow, then flows the water eastward through an artificial channel for 8.5 km before flowing into a 17.5 km natural channel down to the sea (Fig.2). Considering that its artificial channel meets with the natural channel, one of the things that must be considered is the capacity of these natural channels. The natural channel capacity must sufficiently drain Citarum and its natural flow. The dimension of the floodway is a 6-meter-deep trapezoidal channel with either 30 or 60 m top width. The other measurement was the flood estate, where a certain plot of land is purchased as a designated flooded area. There is already a plan whose rightful owners indicate the willingness for such a plan, as presented in Fig.2. The total area of the flood estate is three km², located at Telukbuyung, 48 km downstream from the Citarum-Cibeet confluence. The combined measures are also considered with the following six scenarios:

1. existing condition,
2. floodway 30 m,
3. floodway 60 m,
4. flood estate,
5. floodway 30 m + flood estate, and
6. floodway 60 m + flood estate.

5.3 Numerical Modeling

The model solved using HEC-RAS 2D model that allows the users using SWE-ELM (Shallow Water Equations, Eulerian-Lagrangian Method) approach to running the scenarios [40] and run on six CPU cores. The shallow water equations are:

$$\frac{\partial(\rho\eta)}{\partial t}+\frac{\partial(\rho\eta u)}{\partial x}+\frac{\partial(\rho\eta v)}{\partial y}=0 \quad (1)$$

$$\frac{\partial(\rho\eta u)}{\partial t}+\frac{\partial}{\partial x}\left(\rho\eta^2+\frac{1}{2}\rho g\eta^2\right)+\frac{\partial(\rho\eta uv)}{\partial y}=0 \quad (2)$$

$$\frac{\partial(\rho\eta v)}{\partial t}+\frac{\partial(\rho\eta uv)}{\partial x}+\frac{\partial}{\partial y}\left(\rho\eta v^2+\frac{1}{2}\rho g\eta^2\right)=0 \quad (3)$$

where, "η" is the fluid depth as a function of $x, y,$ and t, and (u, v) is the 2D vector of the fluid's horizontal flow velocity, g is acceleration due to gravity. More details are described in [40].

The LCR's main area is from the Citarum-Cibeet meeting to Muara Gembong. The total river section length is 82 km. First, input the geometric data, such as the cross sections of the river. The available surveyed cross-section was every 100 meters, for this model input one cross-section every 500 meters. The 2D area used 200m×200m rectangular grids. For the areas around the river meanders, irregular grids were used and formed using HEC-RAS built-in breakline-based irregular mesh generator [41–43]. The same irregular break-line generated mesh approach was used on the floodway and flood estate cells. The results of SWE simulation are water depths, velocities, and flow patterns. In total more than 11,000 cells were generated for the study area. The 2D terrain built using the Lagrangian approach combined with MERIT-DEM elevation except for the floodway and flood estate areas, where the elevation was adjusted based on the measure designs. BIG's land cover map was used to determine Manning's roughness of the 2D area. Between the 1D channel and 2D overland area, HEC-RAS built-in lateral structures were used. The elevations of the lateral structures were adjusted to the adjacent terrain. For the timestep, the model used Courant number-based adaptive time steps. The model was initially set with a 1-minute time step with a maximum timestep of 16 minutes (4 times doubling) and a minimum timestep of 0.23 seconds (8 times halving). Based on the simulation results, modification of the floodway design can be made.

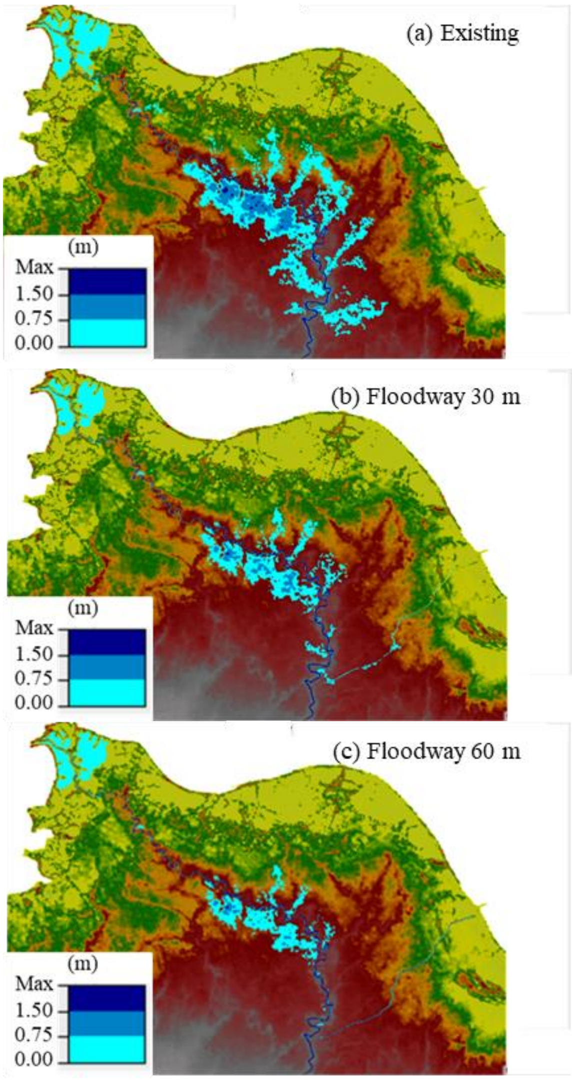

Fig.6 HEC-RAS model results for scenario (a) Existing, (b) Floodway 30, and (c) Floodway 60

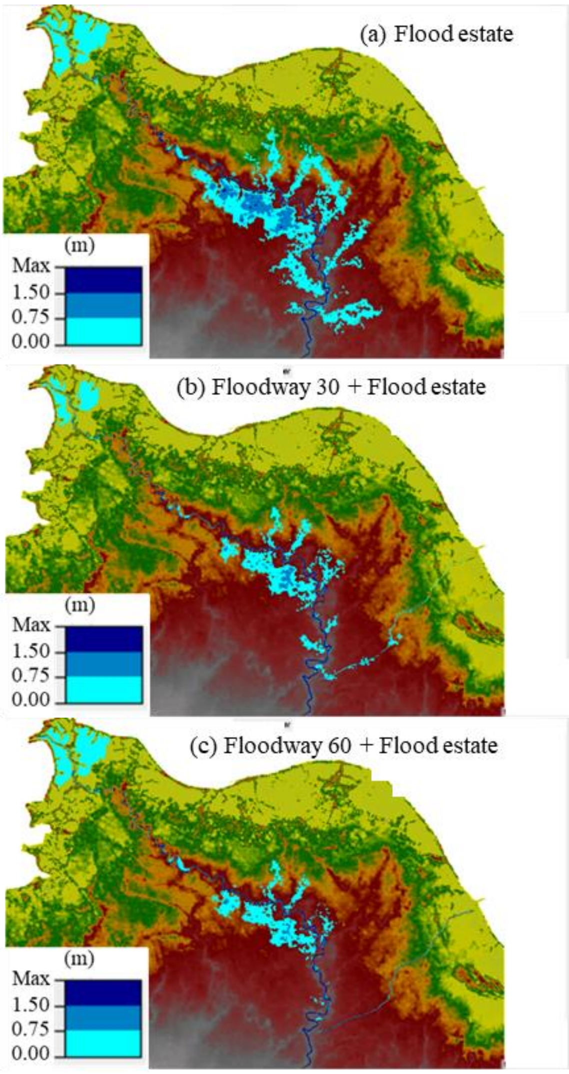

Fig.7 HEC-RAS model results for scenario (a) Flood estate, (b) Floodway 30 + flood estate, and (c) Floodway 60 + flood estate

The numerical model results for the six scenarios are presented in Fig.6 and Fig.7. Distinct blue color gradation indicates different inundation depths. The modeling results show that for the existing condition, the flow would result in 13,602 ha of flood (Fig.6a), with inundation overflow mainly towards the left-hand side of the river and some overflow points to the right-hand side. By applying a 30-m wide floodway, the inundation visibly decreased to 6,527 ha with GIS calculation (Fig.6b). Further increasing the floodway width to 60 m decreased the flood to 4,905 ha (Fig.6c). Considering the application of flood estate, the modeling results show that the flood reduced to 11,234 ha (Fig.7a). A combination of flood estate measurement and the floodway options yielded 4,983 and 4580 ha of flood inundation for the 30- and 60-m floodway options, respectively (Fig.7b, c). Fig.6 and 7 show the inundation map for six scenarios, while the inundation area calculation is shown in Fig.8.

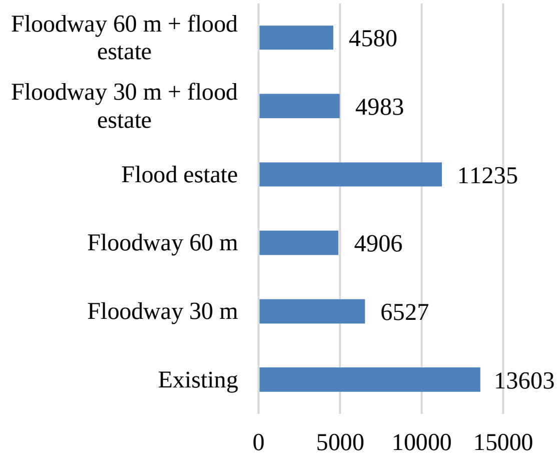

Fig.8 Inundation area comparison for the six scenarios (ha)

Table 1 Resulting of economic loss for each scenario

Scenario	Inundation area (ha)	Economic loss (million USD)	Benefit (million USD)	Construction cost (million USD)	Benefit-cost ratio
Existing	13,602	16.8	-	-	-
Floodway 30 m	6,527	5.9	10.9	12.5	0.87
Floodway 60 m	4,905	3.9	12.9	30.5	0.42
Flood estate	11,234	12.7	4.2	17.9	0.23
Floodway 30 m + flood estate	4,982	4.4	12.4	24.1	0.52
Floodway 60 m + flood estate	4,579	3.2	13.6	42.1	0.32

5.4 Benefit Cost Calculation

The analysis continued with the calculation of benefits and costs. The calculation methodology followed presented for the loss due to flood [44]. The flood map for each scenario was intersected with the land cover shapefile with the result in the total flood inundation area for each land cover class, with an economic loss or exposure cost associated [44] where the values are specific to the Indonesian case.

The resulting economic loss for each scenario is presented in Table 1, with the economic loss ranging from 16.8 million USD (existing condition) to 3.2 million USD (floodway 60 + flood estate). Its benefit was reduced economic loss when moving from the existing condition to the selected measure. For the construction cost, a bill of quantity was estimated for each scenario, which then became the basis for calculating construction cost. The calculated benefit and cost for each scenario are presented in Table 1, whose ratio appears in the last column. The ratio indicates the scenario performance relative to the construction cost. As is shown, the floodway 30 m scenario performed the best with a 0.87 benefit-cost ratio. However, other more expensive scenarios yielded more reduced economic loss (thus higher benefit) with a lower benefit-to-cost proportion. The ratio values were all under 1.0, which might look bad initially, but the ratio compared the economic loss of a single flood event to a capital cost. Therefore, the benefit of the measure increased by the number of flood events. The detailed calculation of compounded benefit, possibly with a more sophisticated statistical approach, is left for future studies.

6. CONCLUSIONS

Citarum River is the third longest river in Java, and although it flows entirely through West Java, it is essential for national security regarding water, food, and energy. Annual flooding occurs upstream and downstream of the river. BBWS Citarum conducted a thorough field assessment in LCR to evaluate the location of the levee breach. In existing conditions, the potential of overflow occurs downstream, which is relatively flat. The overflow occurs in the left and right bank stations of the LCR. Types of land cover that are inundated include rice fields, gardens, plantations, settlements, and other economic activities, such as industrial and commercial areas. It impacts social community activities, agriculture, and economic losses. The downstream Citarum river water system was analyzed using the HEC-RAS 1D–2D model with SWE-ELM approach analysis and calibrated using the flood inundation that occurred in 2021. The study conducted six floodway scenarios as flood control plan in LCR: (1) existing condition, (2) floodway 30 m, (3) floodway 60 m, (4) flood estate, (5) floodway 30 m + flood estate, and (6) floodway 60 m + flood estate. The overflow points in the HEC-RAS model were shown according to the observations.

The results show that the floodway 30 m scenario is the best scenario with a benefit-cost ratio of 0.87. Sharing the excess water load using the downstream Citarum floodway system is proposed as an innovative solution. This system is divided into two segments: the 8.5 km long floodway segment, starting from Tunggakjati Village, West Karawang District, and ending in Sindangkarya Village, Kutawaluya District. From this position, the floodway continues using natural rivers to the sea for 17.8 km. In addition, it is planned to build a flood estate downstream of the floodway outlet. In addition, it is planned to build a flood estate downstream of the floodway outlet. Based on the analysis, the availability of infrastructures eliminates some inundation. The combination of treatment floodway width of 60 m and flood estate only reduced 66% of inundation from 13.602 ha to 4.579 ha. However, flood treatment with a floodway of 30 m is the most effective from an economic perspective. Treatment with a floodway of 30 m can reduce 52% of flood inundation to 6.527 ha with a benefit-cost ratio of 0.87. Therefore, this study recommends treatment with a floodway of 30 m.

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