International Journal of GEOMATE, Aug., 2024 Vol.27, Issue 120, pp.49-59
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2024.120.4450
Geotechnique, Construction Materials and Environment

HYDRAULIC MODELING FOR FLOOD CONTROL SCENARIOS IN AKELAKA WATERSHED, NORTH MALUKU, INDONESIA

*Idhar Sahdar[1], Dede Rohmat[2], Wati Asriningsih Pranoto[1] and Solehudin[3]

[1]Civil Engineering, Tarumanagara University, Indonesia; [2]Gheography Education, Indonesia University of Education; [3]Graduated of Water Resources Management, Bandung Institute of Technology, Indonesia

*Corresponding Author, Received: 20 Feb. 2024, Revised: 04 June 2024, Accepted: 11 June 2024

ABSTRACT: The Akelaka River experiences annual flooding, which inundates agricultural lands and settlements. The riverbanks of the Akelaka are relatively natural, covered with bushes and marsh grass. Given the site conditions, there are opportunities to combine ecohydraulics and structural flood control measures. Ecohydraulics flood control methods include reforestation upstream and planting vegetation along the riverbanks. Structural flood control methods encompass dredging, widening, diking, and creating retention ponds. The effectiveness of these treatments was evaluated using hydraulic modeling in HEC-RAS. The required data for this research included rainfall, terrain, land cover, site conditions, and technical plans for the proposed flood control measures. Results show that ecohydraulics flood control can reduce inundation by up to 32% for a 5-year return period and 39% for a 25-year return period. Retention ponds can reduce inundation by 47% and 50% for the 5-year and 25-year return periods, respectively. Dredging, widening, and diking nearly eliminate flood inundation for both the 5-year and 25-year return periods. While the structural approach (dredging, widening, diking) significantly reduces flood inundation, it may cause sedimentation and a decrease in the function of these structures over time. Therefore, combining ecohydraulics and structural flood control is the optimal strategy. Structural measures provide immediate relief from flooding, while ecohydraulics offer long-term sustainability. This recommended strategy has proven effective in reducing flood inundation, offering a reliable solution to the recurring flooding problem on the Akelaka River.

Keywords: Flood Control, Ecohydraulics, Structural, HEC-RAS

1. INTRODUCTION

Floods are a frequent phenomenon in various parts of the world. Between 2000 and 2018, global flood inundation reached approximately 2.23 million km², affecting around 290 million people [1]. As a tropical country, Indonesia experiences significantly higher rainfall than high-latitude regions, leading to a high potential for flooding. According to the Meteorological, Climatological, and Geophysical Agency (BMKG) in Indonesia Statistics 2023, the average annual rainfall in Indonesia is about 2,898 mm/year [2]. In the Maluku region, rainfall ranges between 3,000 and 3,700 mm/year.

Java Island has the highest flood vulnerability in Indonesia , with notable flood-prone areas including the Jakarta Region [3,4], Lower Citarum , and Upper Citarum in the Bandung Basin region, such as Majalaya, Dayeuhkolot, and surrounding areas . Additionally, Semarang City, the capital of Central Java, experiences numerous flood spots due to high inflow discharge from upstream and tidal activity[5-8]. The high flood risk in several rivers on Java Island has prompted the development of flood monitoring systems to mitigate losses [9,10].

One such system has been implemented on the Ciliwung River, one of the 13 rivers flowing through the Jakarta Region. At the Katulampa Weir in Ciliwung Upstream, an ultrasonic sensor detects the water level. When the water level reaches a certain height, the sensor sends a warning message to relevant parties, helping the government and other stakeholders mitigate flood disasters downstream of the Ciliwung River [11].

Furthermore, on the Citarum River in West Java Province, the Ministry of Public Works and Housing of the Republic of Indonesia, in collaboration with the Korea International Cooperation Agency (KOICA), is developing a flood monitoring system. This system, known as the Flood Forecasting Warning System (FFWS), utilizes rainfall forecasting processed by FFWS software to predict water levels and river discharge at various warning posts along the Citarum River [12].

The frequent floods on Java Island, spanning from west to east, have led to numerous flood studies due to the island's dense population. However, remote regions outside Java, such as North Maluku, also face significant flooding hazards. Watersheds in North Maluku are characterized by small areas with steep river slopes, such as the Akelaka River on Halmahera Island . Figure 1 illustrates the flood-prone locations on Java Island and their relative position to the research location in North Maluku.

.

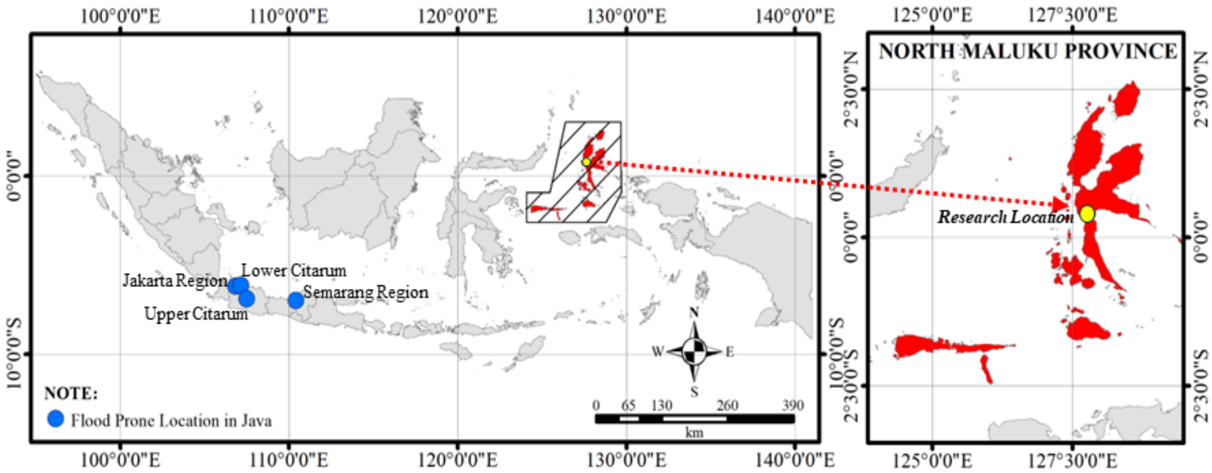

Fig.1 Flood Prone Location in Java Island and Their Relative Position to The Research Location in North Maluku

The Akelaka Watershed, the focus of this research, is located in North Maluku, approximately 2,434 km from Jakarta. The watershed area is relatively small, covering less than 100 km². However, sediment accumulation in the river reduces its capacity, leading to flooding during heavy rains. Annually, floods on the Akelaka River affect agricultural land, settlements, and roads, resulting in harvest failures for farmers, damaged buildings, and disrupted transportation, ultimately causing economic losses. The riverbanks are predominantly natural, covered with bushes and swamp grass, with some areas cultivated for agriculture. Thus, finding effective flood control methods that reduce inundation while preserving the ecosystem is challenging.

Flood control in Indonesia primarily focuses on structural approaches, such as dredging, widening, diking, and retention ponds. Structural measures, like barriers, are effective in controlling floods. However, embankments can sometimes cause problems, especially if they are unable to handle larger flood discharges [13]. Additionally, embankments can disrupt the natural ecosystem and reduce the river's aesthetic appeal. Moreover, river dredging, widening, and retention ponds have short-term effectiveness due to sedimentation.

The most ideal and long-term flood control method is to restore the natural ecosystem of a river or watershed, known as ecohydraulics. Ecohydraulics combines ecological and hydraulic concepts, focusing on water management from an environmental perspective. Reforestation in the upper catchment areas increases infiltration and reduces runoff, while planting vegetation along riverbanks decreases water velocity and erosion, thereby reducing sedimentation in river channels [14].

Ecohydraulics can be implemented through reforestation in upstream watersheds and planting vegetation along riverbanks [15]. Besides reducing flood peaks, reforestation in upstream areas is highly effective in maintaining water sources during dry seasons [14,16]. However, implementing reforestation in upper catchments can be challenging and often fails without proper community involvement and respect for local wisdom [17]. Each region in Indonesia has unique local wisdom, which should be incorporated into planning and implementation. For example, in Selat Village, Buleleng District, Bali Province, local wisdom includes awig-awig, the existence of Pecalang, and artifacts with shrines in the forest. Research into local knowledge about reforestation could be valuable [18,19].

The impact of ecohydraulics flood control takes time as the planted vegetation needs to grow and develop to increase soil infiltration rates. Since flood control often requires immediate effects, combining ecohydraulics with structural flood control methods like dredging, widening, diking, and retention ponds is the best solution. Structural measures provide short-term relief, while ecohydraulics offers long-term solutions. This approach means that when existing structures are damaged, new flood control structures may not be necessary as ecohydraulics measures, like upstream reforestation and riverbank vegetation, function optimally.

However, most previous research has focused on either ecohydraulics or structural approaches. For example, research on Morra Creek in Italy applied only ecohydraulics and achieved effectiveness below 50% [20]. Other studies involving ecohydraulics used complex numerical modeling requiring high computer specifications, while simpler studies showed better results with numerical modeling [21,22]. Numerical modeling is often used to assess the effectiveness of structural flood control measures like dams, retention ponds, and barriers [23,24]. Research combining ecohydraulics and structural flood control approaches is rare, and this study aims to fill that gap by integrating both methods.

2. RESEARCH SIGNIFICANCE

This study emphasizes flood control in the Akelaka River, which combines ecohydraulics and structural in hydraulic modeling. Some software is available to open channel modelings, like Mike Flood, Tuflow, and HEC-RAS. Results are relatively similar, but HEC-RAS is the only open-source software. HEC-RAS was developed in 1995 in the US and is now widely used worldwide for 1D, 2D, and combined 1D-2D models. Therefore, this research uses HEC-RAS for hydraulic modeling.

3. STUDY SITE

In Indonesia's water resources management, the Akelaka watershed is located in the South Halmahera River Region. Administratively, this location is in Oba District in Tidore Islands City, North Maluku Province. Akelaka River is a tributary of the Akebale River, which goes through Payahe Bay, Tidore Islands City. Morphometric, this watershed has an area of around 45.72 km^2, the length of the main river is 19.95 km, and the river branching index is around 4.26. The watershed's slope is dominated by hilly land 55%, flat 26%, step 11%, and heavy 8%. Areas with wavy-steep slopes are found in the middle and upstream of the watershed, while plain land is found downstream, which is a location that is highly prone to flooding. Regarding elevation, Akelaka Watershed has a height of 5-750 msl. The land cover of this watershed is dominated by secondary dry forest (82%), mixed dry land of agriculture (14%), bushes (2%), and rice fields and transmigration settlement of 1% each. In the middle and upstream areas of the watershed, the dominant land cover is bushes and forests, while there is much agricultural land in the downstream areas.

The Akelaka Watershed area is less than 100 km^2 and includes a small watershed. From the field survey results, some segments of the Akelaka riverbank are still quite natural, with good vegetation conditions. However, several segments have been developed for agricultural activities. Floods are not a serious threat when they inundate unproductive land, such as bushes or forests. However, floods will become a problem when they impact productive agricultural or residential areas and transportation. Therefore, floods can cause losses, including material, economic, and lives, especially in flood-prone locations. A map of the Akelaka Watershed and flood-prone locations can be seen in Fig.2.

Floods in the Akelaka River are a routine phenomenon that occurs almost yearly. Floods have inundated agricultural lands, roads, and residential areas, the largest of which occurred in 2017. At that time, the daily rainfall recorded at the Tayawi Rain Station was 149 mm/day, and after further analysis, this rainfall was equivalent to a 39-year return period. This flooding inundated around 1243 houses in Koli Village, Kosa Village, and Transmigration Areas. In addition, this flooding inundated the Kahoho Irrigation Area and submerged the access road. The height of the inundation varied between 0.4-0.7 m.

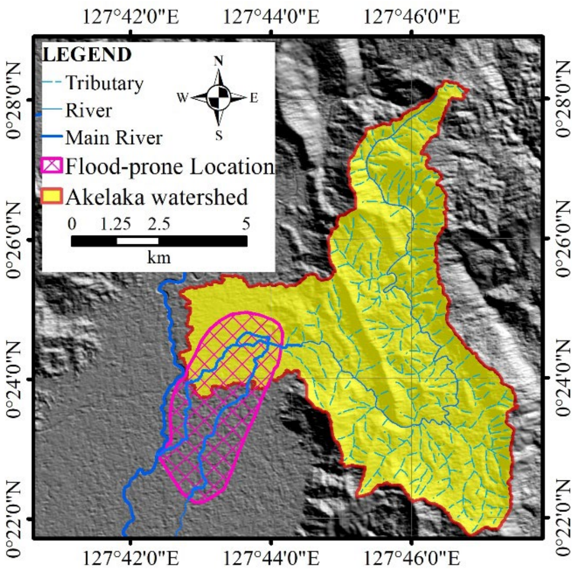

Fig.2 Akelaka Watershed Boundary and Flood-Prone Locations

4. MATERIALS AND METHOD

Fig.3 shows the research process, starting with data collection, field orientation, watershed geometry analysis, rain and flood analysis, and numerical flood modeling using the HEC-RAS 2D model. Hence, it can ultimately produce recommendations for flood control that must be carried out, both ecohydraulics and structurally.

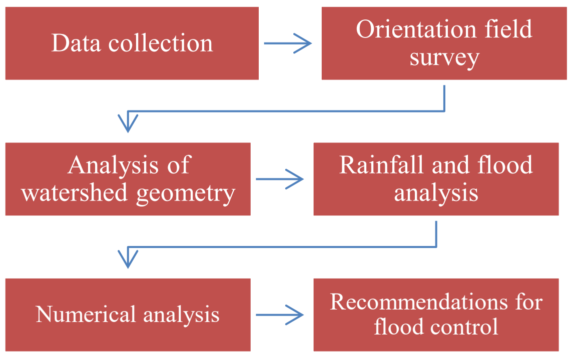

Fig.3 General Research Flowchart

Data collection included secondary maps, a Digital Elevation Model (DEM), rain data, and a terrain raster. Secondary maps, including the Digital Elevation Model (DEM), were taken from the Geospatial Information Agency (BIG). In contrast, rainfall and terrain raster data were taken from the

River Basin Development Agency of North Maluku (BWS Maluku Utara). The terrain raster was data from previous topographic measurements at this location, where the contour lines had been converted to raster using the ArcGIS software. The next stage was field orientation, namely identifying river conditions by tracing along the river channel and identifying historical flood sites, especially the flood events 2017. Identifying this flood site as a basis for calibrating flood inundation modeling was essential.

After the required data was available and the orientation had been completed, the next step was to carry out a watershed morphometric analysis to obtain the area of the watershed, length of the main river, the average slope of the watershed, and drainage coefficient which would be used for flood analysis. The drawing of watershed boundaries used the "hydrology" tool in the spatial analysis tool in ArcGIS. The DEM as the basis for drawing watershed boundaries was the Republic of Indonesia National DEM (DEMNAS) published by BIG with a resolution of 8x8 m. Watershed boundary analysis began using the fill–flow Direction – Flow Accumulation – Watershed tool [25]. All of these stages are available directly in ArcGIS software.

Then, planned rainfall analysis was carried out for the next stage, where the rain data was taken from Ake Tayawi station over 13 years (2009-2021). The length of this data was considered sufficient for planned flood analysis in Indonesia, as referenced in the National Standard of Flood Analysis Number 2415:2016 [26]. The planned rainfall was analyzed using four methods, Normal, Gumbel, Log Normal, and Log Pearson III, to determine which method to choose; this study used the chi-square and Smirnov-Kolmogorv tests. Since the data was only from one rain station, the data was multiplied by the area reduction factor (ARF) before being used [26]. The next step was to change daily rain into hourly rain intensity by using the Mononobe equation with the assumption that the duration of the rain was three hours. Hourly rain intensity and watershed geometric characteristics were input in the Nakayasu method flood calculation to obtain the planned flood hydrograph for several return periods.

Numerical analysis was calculated using HEC-RAS 6.3.1 software with 2D models to assess the effectiveness of the hydraulics flood management concept. The disadvantage of the HEC-RAS model is that it is more challenging to stabilize than Mike Flood, but HEC-RAS is free. As explained at the beginning, the terrain was taken from the results of field measurements carried out by BWS Maluku Utara, where the contour lines have been converted into .tif data with a pixel size of 1.5x1.5 m. The mesh size in the 2D flow area was 20x20 m and was detailed to 5x5 m on the riverbank using the curve linear break lines function. There are three boundary condition inputs: one upstream in the form of a stage hydrograph and two downstream due to a two-branched river channel, both of which use normal depth. The running model was carried out using unsteady flow analysis with a computation interval of 10 minutes, mapping output interval, hydrograph output interval, and detailed output interval of 20 minutes each. Differences in input and output modeling time will affect the model's accuracy. The flow chart of hydraulic modeling in HEC-RAS can be seen in Fig.4.

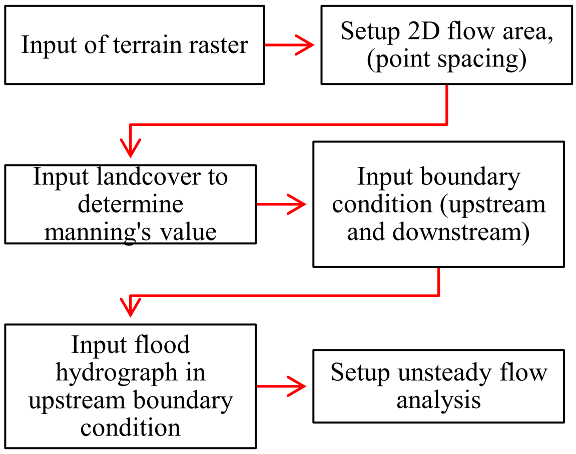

Fig.4 Flow Chart of Hydraulic Modeling in HEC-RAS

Before modeling for various scenarios, the inundation model is verified by the 2017 flood inundation. Multiple scenarios can be modeled if the model verification is similar to the 2017 flood inundation. There are two main handling concepts whose effects on flood control are studied: ecohydraulics and structural flood control (dredging, widening, diking, and retention pond). Modeling scenario is divided into one existing scenario and six flood control scenarios, such as 1) ecohydraulics, 2) retention pond, 3) ecohydraulics+retention pond, 4) dredging, widening, diking, 5) dredging, widening, diking, and retention pond, 6) dredging, widening, diking, and ecohydraulics. Six flood control scenarios are carried out to evaluate the treatment's effect on flood inundation reduction.

Ecohydraulics flood control is modifying land cover in the upstream watershed to reduce the flow coefficient value. Besides that, the concept of ecohydraulics is to carry out greening along riverbanks. In the HEC-RAS model, this concept is expressed in changes to manning parameters, wherein the existing conditions of the actual land cover currently exist. Meanwhile, with the ecohydraulics concept, it is assumed that the riverbank will be planted with grass so that the manning value will change by the land cover. Besides hydraulics, structural flood control was conducted by dredging, widening, diking, and retention pond. The method to input structural modeling in HEC-RAS 2D is terrain editing. In the case of dredging and widening, the analyst selects and adds modifications to the terrain – lines – channel and determines the width and river bed elevation. Meanwhile, choose terrain modification - lines - high ground, and determine the embankment elevation to make a barrier. Then, to create a retention pond structure, select the polygon in terrain modification. Determine the bottom elevation of the pond. The shape of the polygon represents an area of the retention pond.

The solution of the model uses the SWE-ELM equation (Shallow Water Equations, Eulerian-Lagrangian Method), and running uses eight cores CPU. The equation of SWE-ELM is:

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

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

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

In the equation, ρ is the fluid density, g is gravity acceleration, "η" Is the fluid depth, the function of x, y, and t, and (u, v) It is the 2D vector of the fluid's horizontal flow velocity. The paper explains this in more detail [27].

5. RESULT AND DISSCUSION

5.1. Rainfall and Flood Analysis

As previously explained, this study used only rainfall data from one station (Ake Tayawi Station) from 2009 to 2021 (13 years). Based on the data, the maximum annual rainfall is between 43 and 140 mm/day. Fig.5 provides more details on the maximum rain yearly.

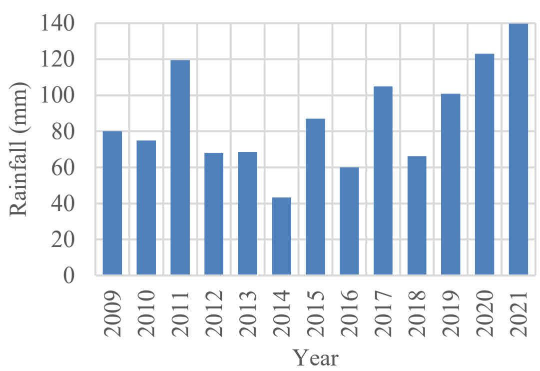

Fig.5 Annually Maximum Rainfall in Ake Tayawi

The annual maximum rainfall data was then analyzed for planned rainfall, where of the four methods used (Normal, Log Normal, Gumbel, and Log Pearson III), the Log Pearson III method was the most appropriate based on the chi-square and Smirnov-Kolmogorov tests. A parameter value of Log Pearson III based on the chi-square test is $x^2_b < x^2_{cr}$, and the Smirnov-Kolmogorov test is $D_{max} < D_{critical.}$ However, before being used for flood calculations, the planned rainfall was multiplied by the area reduction factor (ARF). The area of the Akelaka watershed is 45.72 km^2, so the ARF value is 0.95. The analysis of ARF value refers to the Indonesia National Standard (SNI) 2415:2016 about Calculation Procedures for Planned Flood Discharge [26]. Based on SNI 2415:2016, the watershed with an area between 1 – 30 km^2 has an ARF value of 0.99, 10 – 30 km^2 has an ARF value of 0.97, and if the watershed area 30 – 3000 km^2, the ARF value uses equation 1.152 – 0.1233 Log A, where "A" ia watershed area in "km^2". Specifically, the ARF calculation for Akelaka Watershed is:

$$1.152 - 0.1233 \text{ Log } (45.72) = 0.95 \quad (4)$$

The ARF value will differ for each watershed; it depends on the area of the watershed being studied, and the smaller the area, the smaller the ARF value will be. Table 1 shows the planned rainfall values before and after being multiplied by the ARF value. The rainfall value was then analyzed for intensity and inputted into the Nakayasu flood calculation, as seen in Fig.6.

Table 1 Planned Rainfall Without and With ARF

Return period	Planned rainfall (mm/day)	
	Without ARF	With ARF
2-year	81	77
5-year	110	104
10-year	126	120
25-year	145	138

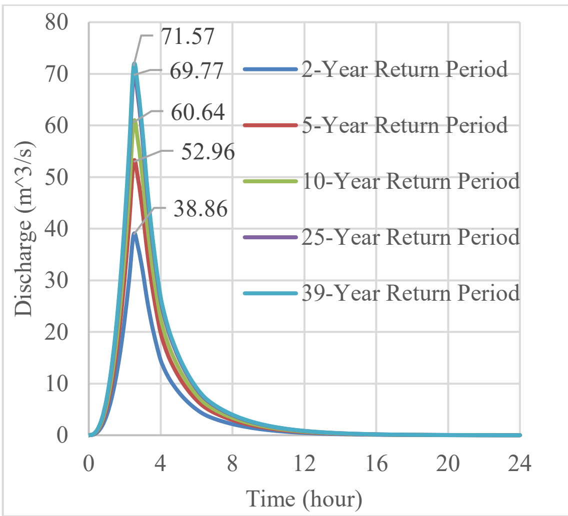

Fig.6 Nakayasu Flood Hydrograph

Fig.6 shows that the 2017 flood had a peak hydrograph of 71.57 m3/s, equivalent to a 39-year return period flood. Next, the 2017 flood discharge will be calibrated and verified using the hydraulic model.

5.2. Model Verification and Existing Modeling

This modeling is a continuation of the analysis that has been carried out. [12]. However, it was carried out in a 1D model and needed to provide satisfactory results. Its results must describe flood inundation better and combine ecohydraulics and structural flood control. For this modeling, hydraulic analysis uses the HEC-RAS 2D model.

The initial stage in this analysis was the inundation model verification based on the floods that occurred in 2017, at which time rainfall was recorded at 149 mm/day or the equivalent of a 39-year return period. Therefore, the verification used a flood return period of 39 years. The verification compares the inundation pattern and depth between the 2017 flood event and the modeling result. Based on the study results, there were similarities in the pattern and depth of flood distribution between the model results and conditions at the site. It is indicated that the model was acceptable because when compared with events on the site, it showed identical results (although not the same).

The analysis showed that the estimated inundation height for submerging agricultural land and some residential areas varied between 0.3 and 1.5 m. Fig.7 shows the results of the verification of the flood inundation study.

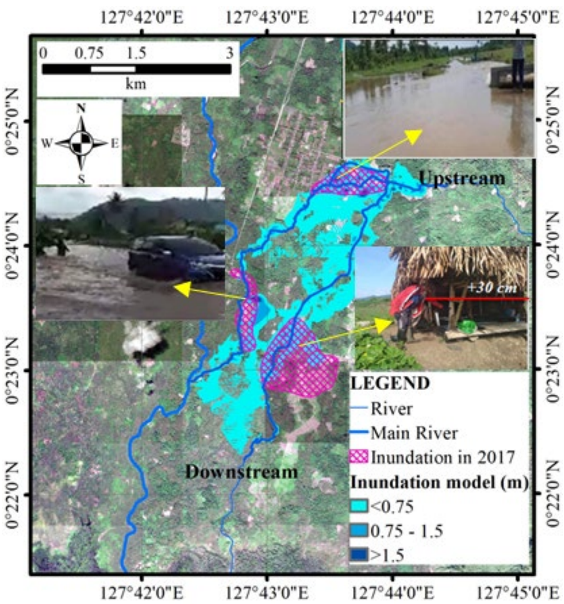

Fig.7 Model Verification by Flood Inundation in 2017

Since there were similar patterns between the model and the 2017 flood inundation, the modeling continued analyzing existing floods. The assessment of existing flood inundation in this modeling was only carried out in two return periods, namely the five and 25-year return periods. A hydrograph input was used with a peak discharge of 52.96 m^3/s in 5 year return period and 69.77 m^3/s in 25 year return period. The analysis result can be seen in Fig.8 and Fig.9.

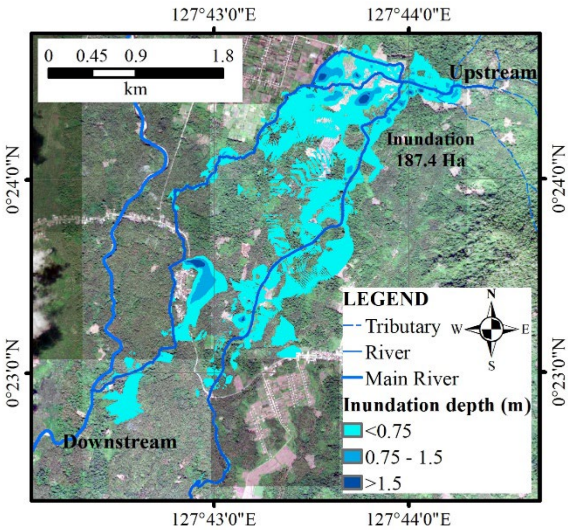

Fig.8 Existing Flood Modeling in a 5-Year Return Period

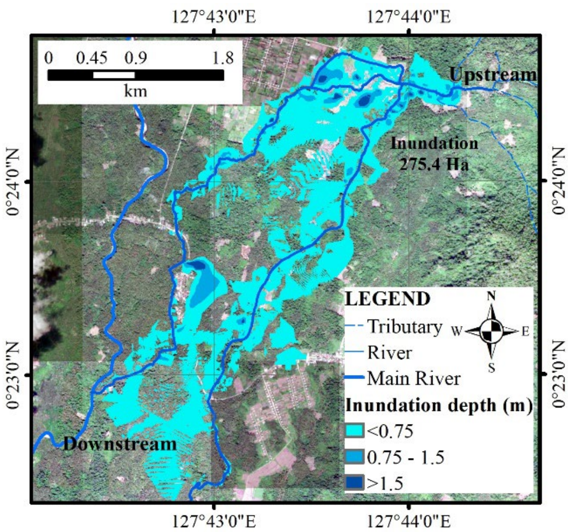

Fig.9 Existing Flood Modeling in 25-Year Return Period

5.3. Flood Control Modeling

Flood management was conducted using two approaches, namely ecohydraulics and structural flood control. The former of the ecohydraulics concept was planting vegetation along riverbanks and Reforestation in the upstream watershed to increase infiltration and reduce runoff, ultimately reducing flood discharge. However, this is a long-term solution that needs time and seriousness in its implementation. The existence of the reforestation scenario upstream was able to reduce the runoff coefficient, which ultimately reduced the flood peak from 52.96 m^3/s to 42.95 m^3/s for 5-year return period and 69.77 m^3/s to 56.59 m^3/s for 25 year return period. About 6.2 km^2 of land has to be converted into forest or rehabilitated degraded forests.

Based on the modeling results, using ecohydraulics to plant vegetation along riverbanks did not significantly decrease the inundation area, but the water speed slowed, reducing the riverbank erosion. The aspect that had the most influence on reducing inundation area was the result of Reforestation upstream as follows:

- The existing 5-year return period is 187.38 ha → Reforestation to 127.77 ha, reduced by 32%
- The existing 25-year return period is 275.37 ha → Reforestation to 168.13 ha, reduced by 39%

The next model was constructing retention ponds at the junction between the right and left in an upstream branch of the Akelaka River. The area of these retention ponds is 10.44 ha, with a storage capacity of 417,600 m^3. Along the planned retention ponds, building a perimeter barrier with a height of 1-2 m and a total length of 1.5 km is recommended. Three outlets were scheduled to be built for the existing river in the retention ponds. The outlet was in the form of a threshold, which was recommended for use rather than a sluice gate for ease of operation. Sluice gate operations are more complex than threshold, whereas threshold does not require special operations. Flood water will automatically flow over the threshold if the water level is above the threshold. The threshold elevation of the three outlet points must be adjusted so that more flood water flows towards the river channel, which has a greater capacity. Even though flood control was carried out without doors, water gates were still needed for flushing activities.

The analysis results showed that the retention ponds positively reduced the width and height of flood inundation downstream in the following details.

- The existing 5-year return period is 187.38 ha, and → retention pond is 98.40 ha, reduced by 47%
- The existing 25-year return period is 275.37 ha, and → retention pond is 137.80 ha, reduced by 50%

The third flood control is dredging, widening, and diking. Fig.10 shows the river segments that need dredging, widening, and diking. However, only some segments must be dredged, widened, and diked simultaneously.

A more detailed explanation of the six segments needed for it can be seen in Table 2.

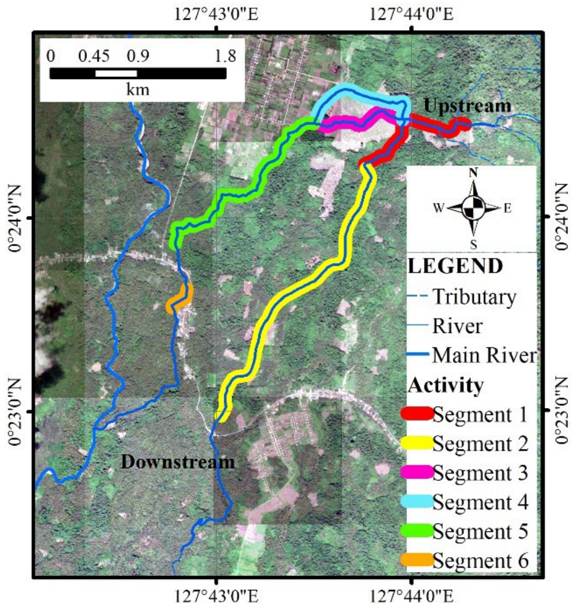

Fig.10 Scheme of Dredging, Widening, and Diking

Table 2 Detail of River Dredging, Widening, and Diking

Segment	Long of Segment (km)	Activity
Segment 1	1.29	Dredging, widening, and diking
Segment 2	2.90	Dredging and widening
Segment 3	0.95	Dredging and widening
Segment 4	1.20	Dredging and widening
Segment 5	2.07	Dredging and widening
Segment 6	0.25	Dredging, widening, and diking

Based on the modeling results, dredging, widening, and diking are very effective for flood inundation reduction, namely as follows:

- The existing 5-year return period is 187.38 ha → 0 ha, reduced by 100%
- The existing 25-year return period is 5.35 ha → 168.13 ha, reduced by 98%

Compared with ecohydraulics and retention ponds, dredging, widening, and diking of flood control is the most effective way. The remaining inundation in the 25-year return period mainly occurred in bushland, which is manageable. Meanwhile, ecohydraulics and retention pond flood control can only reduce 32% and 47% in the 5-year return period flood. In a 25-year return period, ecohydraulics and retention ponds can reduce inundation by 39% and 50%, respectively. A comparison of inundation areas with several flood control scenarios can be seen in Fig.11 for a 5-year return period and Fig.12 for a 25-year return period.

Even though dredging, widening, and diking were seen as the most effective ways to reduce flood inundation, there are other solutions than this due to sedimentation factors and changes in river morphology.

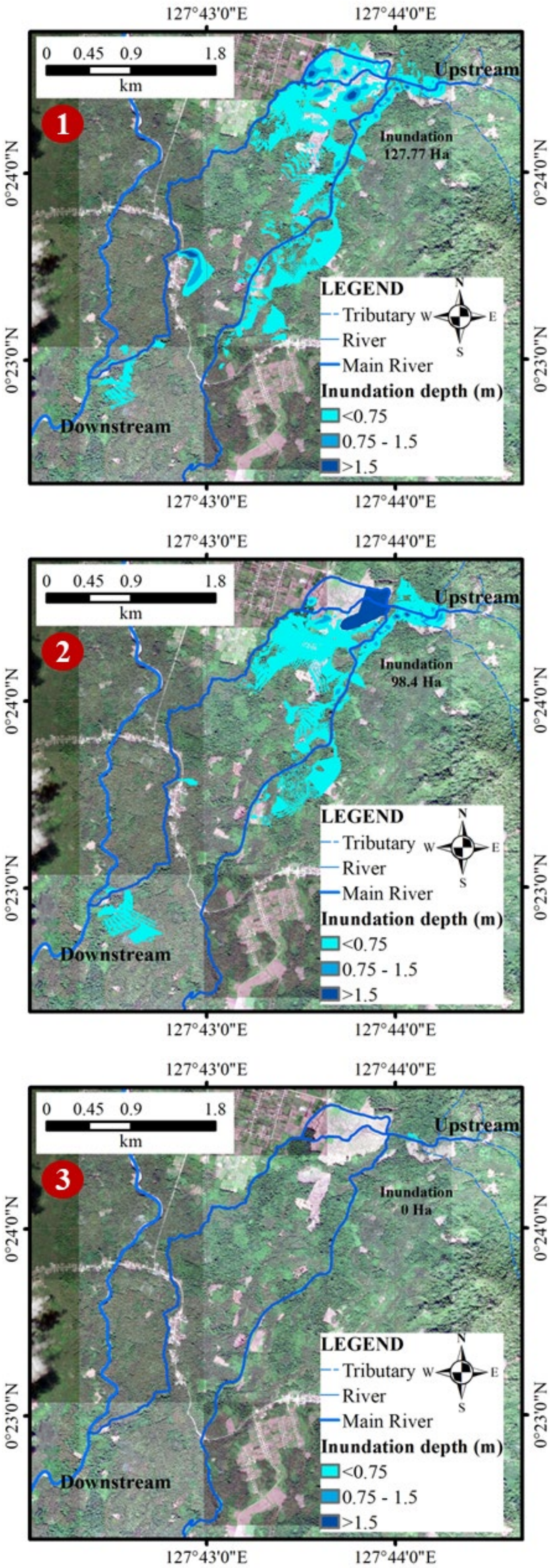

Fig.11 Flood Control Scenarios with 5-Year Return Period for (1) Ecohydraulics, (2) Retention Pond, (3) Dredging, Widening, and Diking

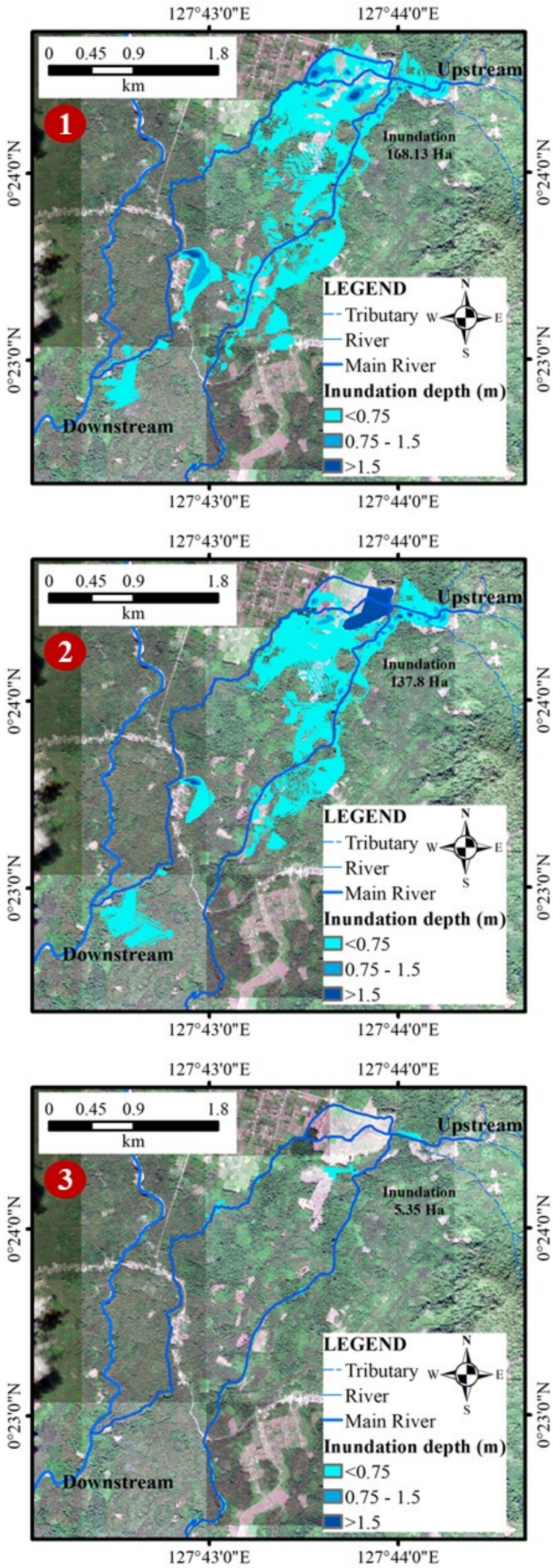

Fig.12 Flood Control Scenarios with 25-year Return Period for (1) Ecohydraulics, (2) Retention Pond, (3) Dredging, Widening, and Diking

Ecohydraulics are predicted to provide a longer dredging, widening, diking, and reduction function life by controlling river discharge. Combining two flood control (ecohydraulics and structural) will be more complex than structural flood control. However, a combination of ecohydraulics and structural applications could be the best choice for flood control. Structural methods effectively reduce flooding in the short term, while ecohydraulics can increase the service life of structural controls. In the long term, ecohydraulics control can reduce runoff rates and increase infiltration rates so that flooding in the rainy season will decrease and water availability in the dry season will increase. Furthermore, Reforestation in the upper catchment will reduce erosion and sedimentation.

Since the combination of eco-hydraulics and structural approaches is essential for flood control, a combination of modeling was carried out with several scenarios, namely (0) Existing, (1) Ecohydraulics, (2) Retention Pond, (3) Ecohydraulics+Retention Pond, (4) Dredging, Widening and Diking, (5) Dredging, Widening and Diking+Retention Pond, (6) Dredging, Widening and Diking+Ecohydraulics. A recapitulation of the results of flood inundation modeling with several scenarios can be seen in Fig.13.

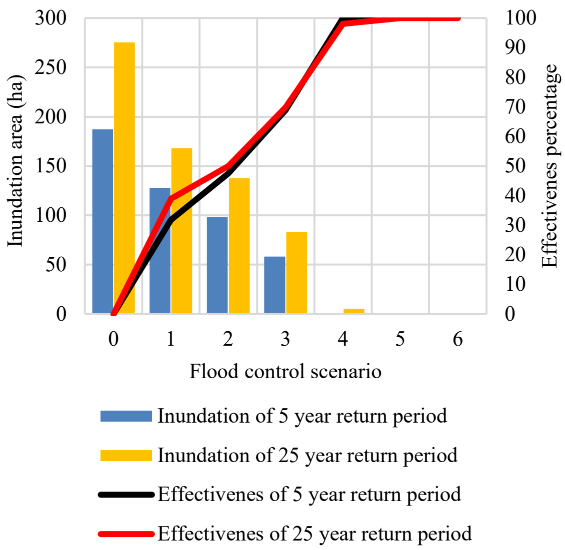

Fig.13 Summary of Flood Control Scenario Modeling

6. CONCLUSIONS

Based on three flood control scenarios, dredging, widening, and diking are the most effective methods, reducing the inundation area by 100% for a 5-year return period and 98% for a 25-year return period. In contrast, ecohydraulics and retention pond flood control methods each reduce the inundation area by ≤50%. While dredging, widening, and diking are highly effective in the short term, they do not offer a long-term solution due to sedimentation and increased discharge from land cover changes.

Combining ecohydraulics with dredging, widening, and diking presents an ideal approach. The structural methods provide immediate flood reduction, while ecohydraulics offers long-term benefits. Reforestation upstream increases infiltration and reduces runoff, ultimately decreasing flood peaks and sediment deposition in rivers. Planting vegetation along riverbanks helps reduce flow velocity, minimizing the potential for riverbank erosion and subsequent sedimentation.

To achieve sustainable flood control, the government needs to implement an integrated strategy that incorporates both structural measures and ecohydraulics, including reforestation activities upstream and vegetation planting along riverbanks. Ecohydraulics flood control can provide long-term benefits, but its implementation faces challenges such as the need for extensive land acquisition along riverbanks, which is difficult in densely populated urban areas. Additionally, successful reforestation in upstream areas requires involving local wisdom.

Future research could explore the role of local wisdom in reforestation and flood control. Another promising research topic is the multifunctional use of retention ponds. Using retention ponds solely for flood control offers limited benefits; however, these ponds could also serve as sources of raw water and irrigation, enhancing their value.

7. REFERENCES

[1] Tellman B., Sullivan J.A., Kuhn C., Kettner A.J., Doyle C.S., Brakenridge G.R., and Erickson T., Slayback D.A., Satellite observations indicate the increasing proportion of the population exposed to floods. Nature, vol. 596, no. 7870, 2021, pp. 80–86.

[2] BPS, Catalog : 1101001, Stat. Indonesia. Jakarta. vol. 1101001, p. 1-790, 2020.

[3] Yana M. S., Setiawan L., Ulfa E. M., and A. Rusyana, Penerapan Metode K-Means dalam Pengelompokan Wilayah Menurut Intensitas Kejadian Bencana Alam di Indonesia Tahun 2013-2018, J. Data Anal., vol. 1, no. 2, pp. 93–102, 2018, doi: 10.24815/jda.v1i2.12584.

[4] Budiyono Y., Aerts J. C. J. H., Tollenaar D., and Ward P. J., River flood risk in Jakarta under scenarios of future change, Nat. Hazards Earth Syst. Sci., vol. 16, no. 3, pp. 757–774, 2016, doi: 10.5194/nhess-16-757-2016.

[5] Prawirakusuma A., Darsono S. L. W., Kuntoro A. A., and Hatmoko W., Flood Characteristics in the Lower Citarum River, Indonesia and Their Possible Management Practices, Int. J. GEOMATE, vol. 25, no. 111, 2023, pp. 202–211, doi: 10.21660/2023.111.3993.

[6] Rohmat F. I. W., Sa'adi Z., Stamataki I., Kuntoro A. A., Farid M., and Suwarman R.,

Flood modeling and baseline study in urban and high population environment: A case study of Majalaya, Indonesia, Urban Clim., vol. 46, no. 10, 2022, p. 1-14, doi: 10.1016/j.uclim.2022.101332.
[7] Burnama N. S., Rohmat F. I. W., Farid M., and Wijayasari W., Utilization of quantile mapping method using cumulative distribution function (CDF) to calibrated satellite rainfall GSMaP in Majalaya watershed, IOP Conf. Ser. Earth Environ. Sci., vol. 1165, no. 1, 2023, pp. 0–8, doi: 10.1088/1755-1315/1165/1/012006.
[8] Fauzi M., Sudono I., Subrata O., Galihsukma L., and Nugraha T., Effect of the Nanjung tunnel construction against flood inundation in Dayeuhkolot, IOP Conf. Ser. Earth Environ. Sci., vol. 437, no. 1, 2020, pp.1-8, doi: 10.1088/1755-1315/437/1/012048.
[9] Setyani R. E., and Saputra R., Flood-prone Areas Mapping at Semarang City by Using Simple Additive Weighting Method, Procedia - Soc. Behav. Sci., vol. 227, 2016, pp. 378–386, doi: 10.1016/j.sbspro.2016.06.089.
[10] Setiyono H., Bambang A. N. B., Helmi M., and Yusuf M., Effect rainfall season on coastal flood in Semarang City, Central Java, Indonesia, Int. J. Health Sci. (Qassim)., vol. 6, 2022, pp. 7584–7595, doi: 10.53730/ijhs.v6ns1.6618.
[11] Indrasari W., Iswanto B. H., and Andayani M., Early Warning System of Flood Disaster Based on Ultrasonic Sensors and Wireless Technology, IOP Conf. Ser. Mater. Sci. Eng., vol. 335, no. 1, 2018, pp. 1-7, doi: 10.1088/1757-899X/335/1/012005.
[12] Sahdar I., Rohmat D., Pranoto W. A., and Suyono T., Structural Flood Control Model Based on Eco-Hydraulic in Small Watersheds (Case Study of the Akelakahalmahera River), ARPN J. Eng. Appl. Sci., vol. 18, no. 6, 2023, pp. 599–608, doi: 10.59018/032384.
[13] Auerswald K., Moyle P., Paul Seibert S., and Geist J., HESS Opinions: Socio-economic and ecological trade-offs of flood management-benefits of a transdisciplinary approach, Hydrol. Earth Syst. Sci., vol. 23, no. 2, 2019, pp. 1035–1044, doi: 10.5194/hess-23-1035-2019.
[14] Ziana Z., Azmeri A., Yulianur A., and Meilianda E., The eco-hydraulics base as flood mitigation to overcome erosion and sedimentation problems: A case study in the Lae Kombih River, Indonesia, J. Water L. Dev., no. 55, 2022, pp. 229–239, doi: 10.24425/jwld.2022.142326.
[15] Ziana Z., Azmeri A., Yulianur A., Meilianda E., and Mubarak M., Mapping of Flood Inundation and Eco-hydraulic Analyses to Minimize Flood Discharge in Tributaries, Aceh Int. J. Sci. Technol., vol. 12, no. 1, 2023, pp. 126–138, doi: 10.13170/aijst.12.1.31120.
[16] Susilawati C. L. and Hartono, Mbay city's eco-hydraulic concept leads to sustainable water supply and management, IOP Conf. Ser. Earth Environ. Sci., vol. 794, no. 1, 2021, pp. 1-7, doi: 10.1088/1755-1315/794/1/012019.
[17] Tañagras J., Macuha R., and Herrera E., Impact Evaluation of Land Use–Land Cover Change on the Hydrology of Salipit River Basin Cavite, Philippines, Int. J. GEOMATE, vol. 25, no. 110, 2023, pp. 140–147, doi: 10.21660/2023.110.3852.
[18] Ginting S. and Bengkel B., the Role of Local Wisdom in Supporting Policies Deforestation Supervision in Langkat Regency, North Sumatra, Dia, vol. 20, no. 02, 2022, pp. 243–262, doi: 10.30996/dia.v20i02.6422.
[19] Christian P. I., The role of local wisdom in controlling deforestation, Int. J. Dev. Sustain., vol. 6, no. 8, 2017, pp. 876–888.
[20] Lama G. F. C., Giovannini M. R. M., Errico A., Mirzaei S., Padulano R., Chirico G. B., and Preti F., Hydraulic efficiency of green-blue flood control scenarios for vegetated rivers: 1D and 2D unsteady simulations, Water (Switzerland), vol. 13, no. 19, 2021, pp. 1-19, doi: 10.3390/w13192620.
[21] Sanz-Ramos M., López-Gómez D., Bladé E., and Dehghan-Souraki D., A CUDA Fortran GPU-parallelised hydrodynamic tool for high-resolution and long-term eco-hydraulic modeling, Environ. Model. Softw., vol. 161, 2023, pp. 1-12, doi: 10.1016/j.envsoft.2023.105628.
[22] Pertiwi N., Combination of Ecological and Hydraulical in River Management (Case Study at Lawo River South Sulawesi), Proceedings of the 2nd Makassar International Conference on Civil Engineering (MICCE), 2015.
[23] Wu S. J., Yang J. C., and Tung Y. K., Risk analysis for the flood-control structure under consideration of uncertainties in design flood, Nat. Hazards, vol. 58, no. 1, 2011, pp. 117–140, doi: 10.1007/s11069-010-9653-z.
[24] Moon H., Kim J., Chen J., and Yoon S., Mitigating Urban Flood Hazard: Hybrid Strategy of Structural Measures, Int. J. Disaster Risk Reduct., vol. 108, 2023, pp. 1-23, 104542, 2024, doi: 10.1016/j.ijdrr.2024.104542.
[25] Sobatnu F., Irawan F. A., and Salim A., Identifikasi dan Pemetaan Morfometri Daerah Aliran Sungai Martapura Menggunakan Teknologi GIS, J. Gradasi Tek. Sipil, vol. 1, no. 2, 2017, p. 45-52, doi: 10.31961/gradasi.v1i2.432.
[26] Badan Standardisasi Nasional, SNI 2415:2016 - Tata cara perhitungan debit banjir rencana, 2016.
[27] Acheampong J. N., Gyamfi C., and Arthur E., Impacts of retention basins on downstream

flood peak attenuation in the Odaw river basin, Ghana, J. Hydrol. Reg. Stud., vol. 47, 2023, p. 1-20, doi: 10.1016/j.ejrh.2023.101364.