Investigating the Effectiveness of the Present & Future Flood Management Approaches in an Interbasin River Network: The Case of Seluna River System, Indonesia

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ABSTRACT

Flood disasters in Indonesia are frequent and devastating because of heavy monsoon rains, rapid urbanization, and environmental degradation. The SELUNA river system is a complex interbasin river network in the Central Java Province that consists of four main rivers. Despite existing flood control measures, SELUNA river system continues to suffer significant flood damage every year because of rapid urbanization and the disturbance of a national road in the downstream area. Therefore, this study examines the effectiveness of existing flood management approaches and presents an end-to-end approach (i.e., climate model outputs, hydrological simulations, damage assessments of crops and buildings, and policy proposals based on evidence-based information) for efficient flood disaster management under climate change. The multi-model GCM results revealed that future annual rainfall will increase by ~4–34% (11.6% on average) under the representative concentration pathway (RCP)8.5 scenario, and extreme rainfall intensity will increase by ~1.3–1.61 (1.46 on average) times. This significant increase in extreme rainfall intensity highlights the heightened risk of flooding in the region under future climatic conditions. Flood simulation and damage assessment showed that the inundation area, housing, and crop land damage will be twofold in the future climate compared to the past climate with existing river diversion facilities from the Serang River to the Juana River. Four scenarios were developed to determine the most effective approach to reduce flood damage. Scenario 3 (i.e., diversion rate of 0.3 with widening channel geometry in the Juana River) shows that high inundation areas (>2.0 m) are reduced by 60%. Scenario 4 (i.e., diversion rate of 0.3 with widening channel geometry in the Juana River and retention pond in the upstream Serang River) shows an 86% reduction in high inundation areas, with affected housing areas decreasing by 89% and cropland by 92%. Based on the evidence-based results obtained in this study, several policies are proposed for mitigating flood damage and supporting sustainable development under climate change conditions in this complex river network.

Keywords: Interbasin, SELUNA River System, Climate change, Rainfall-runoff inundation model, Damage Assessment

INTRODUCTION

Indonesia is an archipelagic country in Southeast Asia, situated along the equator, and experiences a tropical climate with two distinct seasons: rainy and dry. This climatic pattern, combined with its geographical features, makes Indonesia particularly vulnerable to hydrometeorological disasters. Floods are the most frequent and devastating natural hazards and pose significant challenges to the infrastructure, economy, and population of the country. Data on disaster events from 2016 to 2021 in Indonesia show that 74.10% of the disasters were hydrometeorological (BNPB, 2022). Floods account for 43.5% of these events, making them the most prevalent type of disaster.

Java Island, the most populous and economically significant island of Indonesia, is particularly prone to flooding. Its dense population and extensive infrastructure make flood events particularly disruptive. Floods occur frequently every year in many areas of the island, with Central Java Province being a priority area. This is because of its strategic importance as it connects multiple provinces on Java. Floods in the region have caused significant economic and transportation disruptions.

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The SELUNA river system is located in Central Java Province. SELUNA river system consists of four main rivers: the Serang, Lusi, Wulan, and Juana. The catchment area is 6,772 km², and this basin forms a complex system in which the Serang River diverts water to the Juana River via the Wilalung floodgates. The flood control system in the SELUNA river system began in 1918 with the construction of the Wilalung system by building the Wilalung flood gates and continued in 1987 with the implementation of the CIWA system. The core concept of the CIWA scheme was to deactivate the Wilalung floodgate by closing those that lead to the Juana River. The Wulan River, located downstream of the Wilalung floodgates, cannot handle the 100-year flood discharge of 840 m³/second (PUPR, 2016). Consequently, the flood discharge was still directed at a maximum of 300 m³/second. As a result, flooding occurs annually. In February 2024, heavy rainfall in the basin caused the levees along the Wulan River to breach at several locations. In addition, a national road passes through the downstream area of the basin. This road connects multiple provinces on Java. Therefore, when floods hit this basin, they cause significant economic and social disruption.

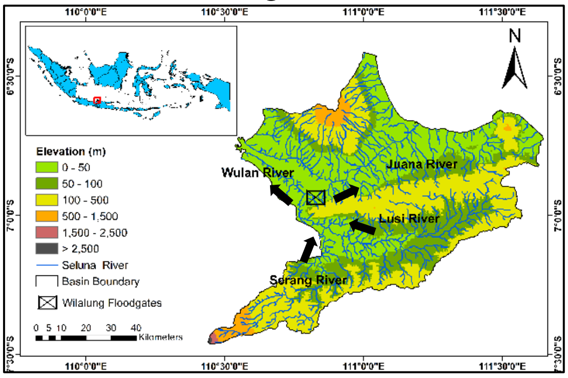

Figure 1 Location of Seluna River System

This study investigated the effectiveness of current flood management in the SELUNA river system, considering climate change, and propose possible developments to mitigate flood risk within the interbasin.

THEORY AND METHODOLOGY

This study assessed the impact of climate change, analyzed the hydrological conditions of the interbasin to understand flood behavior, assessed current operation of river facilities, and proposed possible developments for mitigating flood risk in the future.

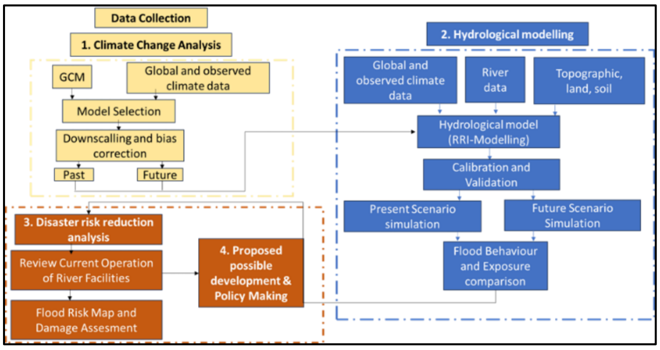

Figure 2 Research Framework

Climate Change Analysis

Climate change analysis was performed using the Coupled Model Intercomparison Project Phase 5 (CMIP5). Future climate projections were generated using general circulation models (GCMs) under the representative concentration pathway (RCP)8.5 scenario. The GCMs were selected based on their ability to represent regional-scale climates using seven key meteorological elements. Ground-observed rainfall data from 1991 to 2018 were obtained from nine rain gauges and underwent downscaling and bias correction using the Data Integration and Analysis System (DIAS). The DIAS CMIP5 tool greatly simplifies the selection and processing of GCM outputs for hydrological and water resource applications at the basin scale (Kawasaki et al., 2017). Historical climate data cover the period 1980–2005, whereas projections for the near future span 2048–2073. Future climate projections were used as inputs for hydrological modelling.

Hydrological Modelling

The rainfall-runoff-inundation (RRI) model, a two-dimensional model capable of simultaneously simulating rainfall -runoff and flood inundation (Sayama et al., 2012), was employed for hydrological modeling. A basin-scale RRI model was developed to simulate both past and future climate conditions to understand flood behavior and exposure comparisons. The model was calibrated using the flood event of February 2024 and validated using a flood event in November 2022. The model performance was evaluated using the Nash-Sutcliffe efficiency (NSE) for hydrograph comparisons between the simulated and observed discharge data. Additionally, the flood extent results from the model were compared with flood extent data obtained from Sentinel-1 imagery. Hydrological modeling was conducted for return periods of 25, 50, and 100 years for both past and future conditions to assess changes in flood risk and behavior.

Disaster Risk Reduction Analysis

Flood risk maps were created using outputs from hydrological modeling and assessed using geographic information system (GIS) to delineate flood inundation areas. Damage assessments for housing and cropland within the basin were conducted using GIS by overlaying land-cover data on flood inundation maps. Additionally, current operation of river facilities was reviewed for future scenarios to identify potential improvements that could enhance efficiency and reduce flood damage.

Proposed Possible Development

Scenarios were used as alternatives to reduce flood damage within the interbasin. The RRI model was used to simulate all scenarios and evaluate the damage for both housing and cropland areas.

DATA COLLECTION

Rainfall data within the SELUNA river basin from 1991 to 2024, obtained from seven rain gauges, were collected from Dinas Pusdataru. For calibration and validation, the observed discharge data from the Tawangharjo station were, sourced from the BBWS Pemali Juana. The topography dataset of the digital elevation model (DEM) with a spatial resolution of 15 arcsec, flow direction, and flow accumulation were obtained from HydroSHEDS. Land-cover data from WorldCover 2021 v200 were obtained from the ESA.

RESULTS AND DISCUSSION

1) Rainfall Pattern during 1991 - 2018

The spatial distribution of rainfall during 1991 – 2018 was divided into two periods, as shown in Figure 3. The first period was from 1991 to 2004, and the second period was from 2005 to 2018 to understand the rainfall patterns within the interbasin. During the first period (1991–2004), high rainfall only occurred in the northwestern part of the basin. However, in the second period (2005–2018), high rainfall extended to the southwestern part of the basin, indicating an increasing rainfall pattern over 13 years.

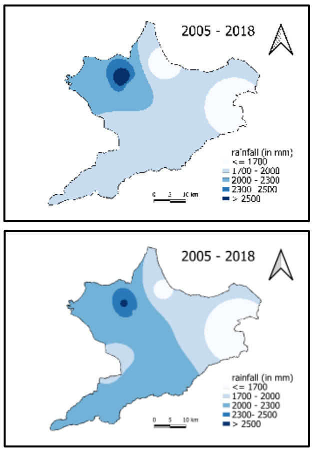

Figure 3 Spatial Distribution of Rainfall

2) Climate Change Analysis

Future climate projections were generated using observed rainfall data from 1991 to 2018. These datasets were collected and provided by DIAS. GCMs were assessed for their ability to simulate regional climate patterns across seven key meteorological elements: precipitation, air temperature, outgoing longwave radiation, sea-level pressure, zonal wind, meridional wind, and sea surface temperature. GCM models MRI-CGCM3, MPI-ESM-LR, GFDL-ESM2M, CMCC-CMS, and CNRM-CM5 were selected. All five selected GCMs indicated an increasing trend under future climatic conditions (Figure 4). Additionally, all selected GCMs showed an increasing trend in the frequency of extreme rainfall events exceeding 50 mm/day, except for GFDL-ESM2M, which showed a similar occurrence in the past (Figure 5).

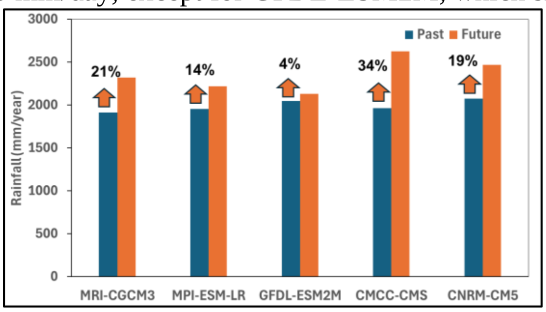

Figure 4 Effect of Climate Change on Annual Rainfall

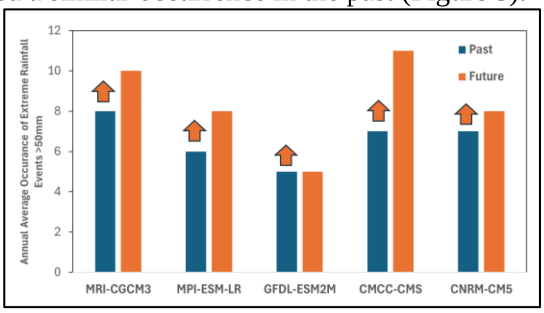

Figure 5 Effect of Climate Change on Extreme Rainfall

A frequency analysis conducted on five GCMs for future conditions revealed a notable increase in rainfall intensity over various return periods. Specifically, the analysis shows average factor increases of 1.33 for the 10-year return period, 1.42 for the 25-year return period, 1.51 for the 50-year return period, and 1.61 for the 100-year return period. These findings highlight the anticipated rise in rainfall due to climate change, indicating a trend toward more frequent and severe flooding events in the future. This underscores the need for adaptive flood management strategies to mitigate the anticipated increases in flood risk.

3) Hydrological Modelling

The RRI calibration was conducted using flood events in February 2024 and obtained an NSE of 0.718 (Figure 6), whereas the model was validated using flood events in November 2022 and obtained an NSE of 0.646 (Figure 7). The hydrograph indicates that the calibrated model is capable of simulating the peak discharge, timing of discharge, and base flow. In this study, the flood extent from February 2024 was compared with flood extent data from Sentinel-1 imagery (Figure 8). Flood patterns based on the simulated and Sentinel-1 data were well matched, particularly at the confluence point between the Juana and Serang rivers.

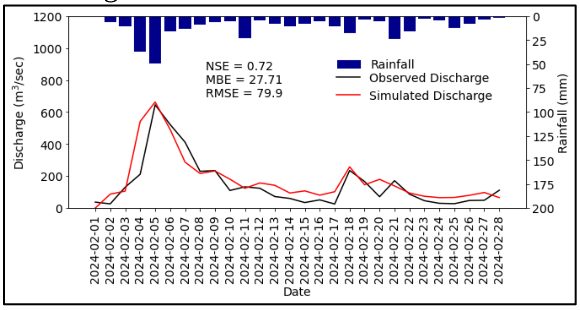

Figure 6 Hydrograph -Calibration

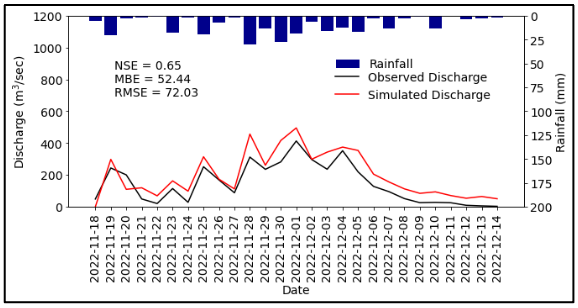

Figure 7 Hydrograph -Validation

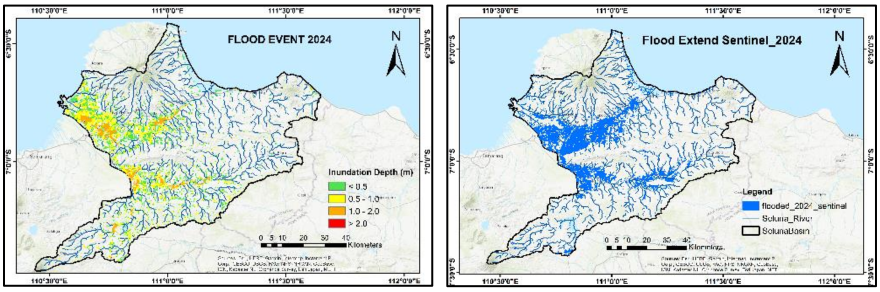

Figure 8 Simulated (Left) and Sentinel-1 (Right) flood patterns

Figure 9 shows a comparison between the past and future inundation for different return period flood events. In the future, the extent of flooding will widen, and inundation will increase. Current flood control focuses on reducing damage from the confluence area of the Serang and Juana rivers to the downstream area. However, in the future 25-year return period, we must consider the high inundation before the confluence point of the Serang and Juana rivers. The results indicate that the current flood control infrastructure, including the Wilalung flood gate, is increasingly inadequate for handling anticipated future flood volumes. This inadequacy is particularly evident in downstream areas of the Wulan River, where the convergence of floodwaters from multiple tributaries poses a significant flood risk.

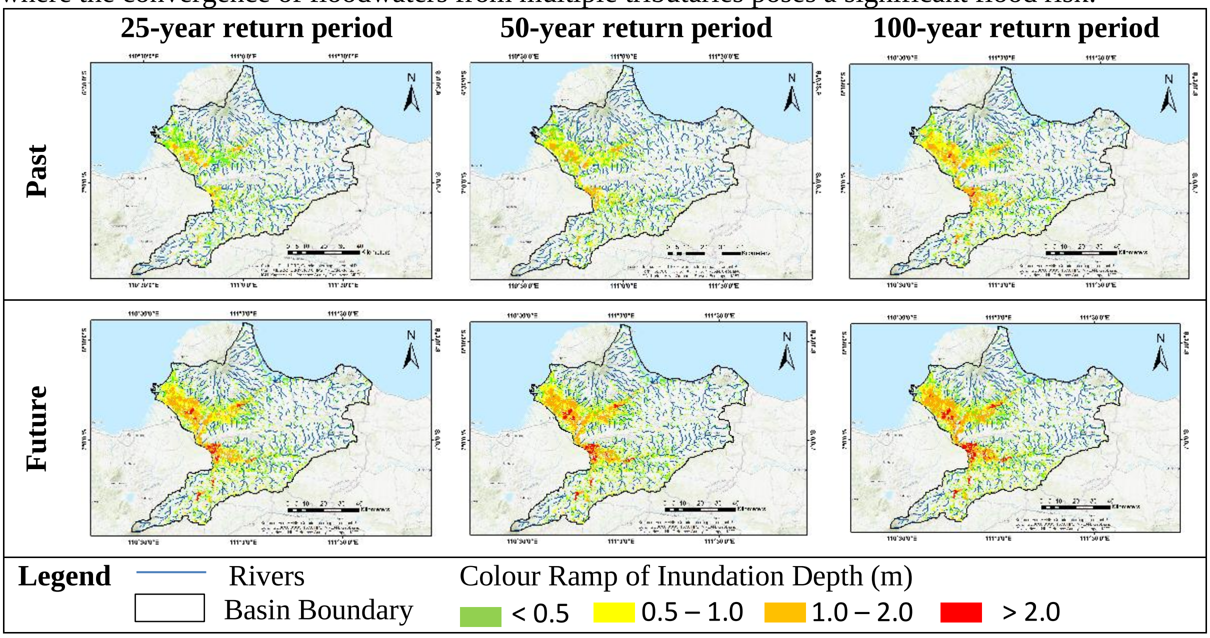

Figure 9 Inundation Depth for Various Return Periods

4) Disaster Risk Reduction Assessment

4.1. Damage Assessment

The flood damage assessment compared current and future scenarios, revealing a marked increase in potential flood damage under future climate conditions. The damage caused by the flood inundation of housing and croplands was calculated for each return period. The increased frequency and severity of flood events are expected to result in extensive damage to housing and croplands. Comparing the total area inundated in the 25-year return period between the past and future conditions, the total inundation area in the future is expected to be almost twice that of the past. Additionally, the area of affected houses will more than double (Table 1). These findings suggest that without significant upgrades to the flood control infrastructure, the region will face increasing damage from future flood events.

Table 1 Inundation Area Comparison of Past Climate and Future Climate Projections

Return Period	Inundation depth (m)	Area per depth inundation (km^2)					
		Past	Future	Housing (Past)	Cropland (Past)	Housing (Future)	Cropland (Future)
25 years	< 0.5	426.8	476.0	19.3	281.4	36.2	251.1
	0.5–1.0	298.8	545.3	13.0	202.4	27.9	344.9
	1.0–2.0	64.1	299.6	2.6	50.0	11.9	238.3
	> 2.0	0.2	65.8	0.0	0.2	2.3	46.5
Total		**789.9**	**1,386.7**	**34.9**	**534.0**	**78.2**	**880.9**

4.2 Current Operation of River Facilities

The Wilalung flood gate, which is critical for diverting water from the Serang River to the Juana and Wulan rivers, is currently operating at capacity. The Wilalung floodgates originally comprised 11 gates. Of these, two gates directed water to the Wulan River and functioned well, whereas nine gates directed water to the Juana River, with only three of these operations and six broken owing to sedimentation. The original operation of the Wilalung floodgates was designed to divert 1,350 m^3/s of water from the Serang River, with 1,000 m^3/s diverted to the Juana River and 350 m^3/s released to the Wulan River. However, under current conditions, only three gates are operational, each capable of opening to a maximum of 1.5 m and passing 70.5 m^3/s. Thus, when fully open, the three operational gates can release a total of 211.5 m^3/s of water. Current operation of the Wilalung flood gates with the assumption that three gates are fully open was simulated on the RRI model. As a result, by diverting water, the damage in the downstream Wulan River area is reduced, and national roads remain safe from high inundation. However, high inundation occurred in the middle part of the Juana River in the area before the floodgates.

4.3 Proposed possible development

To effectively mitigate flood risks in the SELUNA river system, four scenarios were developed and analyzed.

1) Scenario 1: Existing Condition with Diversion Rate of 0.3 and Existing Channel Geometry.
   Maintaining a diversion rate of 0.3 with existing channel geometry reduces downstream inundation but widens the overall flood-affected area, causing high inundation in the Juana River.
2) Scenario 2: Reduced Diversion Rate to 0.2 with Existing Channel Geometry.
   Reducing the diversion rate to 0.2 while maintaining the existing channel geometry leads to several improvements. The high-inundation areas (>2.0 m) were reduced by 29%. The inundation of housing areas was reduced by 17%. Cropland areas that experienced high inundation were reduced by 34%.
3) Scenario 3: Diversion Rate of 0.3 with Proposed New Channel Geometry in Juana River.
   This scenario assumes a diversion rate of 0.3 while implementing a new channel geometry in the Juana River. Widening the channel is not feasible because of the numerous houses built near the river, particularly in the downstream areas. Therefore, the channel geometry can be modified by changing the river width from the upstream to the middle stream of the Juana River and the depth channel geometry along the Juana River. The results indicate that medium inundation depths (1.0–2.0 m) are reduced by 19% and high inundation areas (>2.0 m) are reduced by 60%, with affected housing areas decreasing by 62% and cropland by 62%.
4) Scenario 4: Diversion Rate of 0.3 with New Channel Geometry and Retention Pond.
   In this scenario, a diversion rate of 0.3 is assumed, with the proposed new channel geometry and the addition of a retention pond. Owing to the extensive cropland within the basin, the utilization

of these areas as temporary retention ponds has been proposed. The results show that high-inundation areas (>2.0 m) are projected to be reduced by 86%, with affected housing areas decreasing by 89% and cropland by 92%.

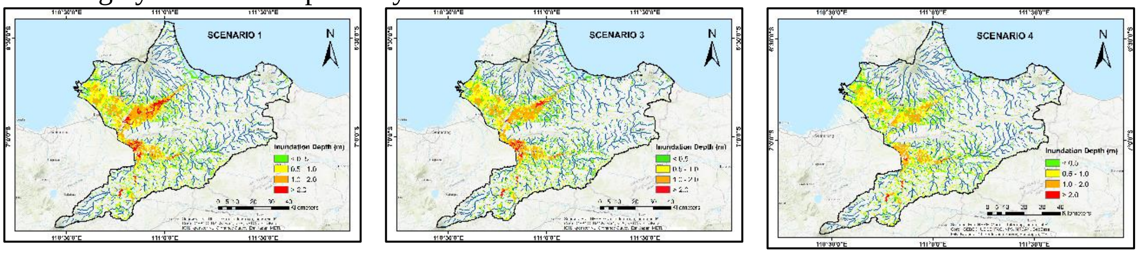

Figure 10 Inundation area for Scenarios 1, 3, and 4

CONCLUSION AND RECOMMENDATIONS

This study aimed to investigate the effectiveness of the current flood control management system in an interbasin SELUNA river system considering the impacts of future climate change. Climatological analysis revealed that the selected GCMs indicate an increasing trend of high rainfall events under future climate conditions. Specifically, the analysis for a 25-year return period projects a 1.42 increase in rainfall. Hydrological simulations using the RRI model demonstrated that the existing flood control infrastructure, including the Wilalung floodgates, is increasingly inadequate for managing anticipated future flood volumes. The total inundation area is expected to be almost two times greater in the future compared to that in the past. These findings suggest that without significant upgrades to the flood control infrastructure, the region will face increasing damage from future flood events. To address this challenge, four scenarios were developed to explore alternative strategies to reduce flood damage. Among these scenarios, Scenario 3, which involved modifying the channel geometry in the Juana River, was projected to reduce high-inundation areas (>2.0 m) by 60%. Scenario 4, which combined the new channel geometry with retention ponds, showed an even greater reduction of 86% in high-inundation areas. Given the extensive cropland within the interbasin, Scenario 4 proposes the utilization of these areas as temporary retention ponds. The successful implementation of Scenario 4 necessitates close collaboration and coordination between river management authorities and the agricultural sector to effectively manage the timing of cropland use and to select appropriate crop types. Additionally, it is essential to establish a compensation scheme for farmers whose lands are used as temporary retention ponds, ensuring they are adequately compensated for any potential loss of income. This approach aims to temporarily store water without damaging croplands, thus preserving agricultural productivity and mitigating flood risks. These findings suggest that significant infrastructure upgrades and policies for cropland management should be proposed to mitigate flood damage and support sustainable development under climate change in this complex river system.

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