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Integrated Flood Risk and Embankment Stability Modeling in the Comoro River, Timor-Leste using HEC-RAS and GIS

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Abstract

Dili, the capital city of Timor-Leste, is increasingly vulnerable to flooding due to its geomorphological characteristics and rapid urban expansion. The Comoro River, the largest of several rivers traversing the city, has experienced multiple significant flood events in recent years most notably in March 2020, April 2021, and February 2022 resulting in severe damage to infrastructure and disruption to local communities. Urban development has led to watershed degradation, sediment accumulation, reduced channel capacity, and embankment overtopping, exacerbating flood risks in densely populated areas. This study aims to assess flood risk and evaluate embankment resilience using an integrated modeling approach. Design flood discharge was estimated using the Log Pearson Type III distribution and the Nakayasu synthetic unit hydrograph, with validation through Chi-Square and Kolmogorov-Smirnov goodness-of-fit tests. Hydraulic simulations were conducted using HEC-RAS 6.1.0 programme, while flood inundation mapping was performed with ArcGIS 10.3 to identify critical flood-prone zones and guide mitigation strategies. Results indicate a peak discharge of 192.141 m^3/s for a 25-year return period flood. Mitigation measures proposed include embankment construction and river normalization at vulnerable cross-sections. HEC-RAS simulations demonstrate that these interventions significantly reduce flood inundation. The embankment slope stability factor was calculated at 7.55, indicating a high level of structural safety. The estimated cost for implementing these flood control measures is USD 571,366.87. This study provides a replicable framework for flood hazard modeling and infrastructure planning in urban river systems, contributing to climate-resilient development and evidence-based decision-making in Southeast Asian contexts.

Keywords: flood risk assessment; hydraulic modeling; hec-ras; gis integration; urban watershed; river embankment

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INTRODUCTION

Dili, the capital city of Timor-Leste, is geographically situated between Lat 8°31'5.19"S, Long 125°43'4.14"E and Lat 8°33'19.97"S, Long 125°28'54.46"E. It is traversed by several rivers, including

Becora, Becussi, Maloa, Manleu, and most notably, the Comoro River. Due to its coastal location and surrounding topography, Dili is highly vulnerable to flooding, particularly during periods of intense rainfall (Watlet et al., 2020). Over the past few years, the city has experienced multiple severe flood events most notably on March 13, 2020; April 4, 2021; and February 21, 2022 which have caused extensive damage to roads, embankments, and public infrastructure. These recurring disasters underscore the urgent need for a comprehensive flood risk assessment and mitigation strategy (Ashok & Umamahesh, 2019; Estelaji et al., 2024; Khatooni et al., 2025; Peker et al., 2024; Tabasi et al., 2025; Watlet et al., 2020; Ziwei et al., 2023).

Moreover, rapid urban expansion driven by population growth has significantly altered the natural landscape and degraded the quality of the watershed. The construction of residential areas, commercial zones, and transportation networks has often proceeded without adequate hydrological planning (Tabasi et al., 2025). As a result, sedimentation has increased, channel capacity has diminished, and riverbanks have become more prone to erosion and overtopping (Stone et al., 2022). These conditions exacerbate flood risks and reduce the resilience of urban infrastructure, especially in densely populated areas adjacent to the Comoro River.

Despite the severity of the problem, conventional flood mitigation efforts in Dili have largely been reactive and fragmented. Emergency embankments and ad hoc dredging operations are frequently implemented without a thorough understanding of the hydrodynamic behavior of the river system (Ziwei et al., 2023). Such interventions may offer temporary relief but fail to address the underlying causes of flooding. In the absence of data-driven planning and predictive modeling, these measures risk being ineffective or even counterproductive in the long term (Ashok & Umamahesh, 2019; Peker et al., 2024; Weihua et al., 2012).

To overcome these limitations, this study adopts an integrated approach that combines hydraulic modeling using HEC-RAS with spatial analysis through GIS (Purwanto et al., 2024). HEC-RAS enables simulation of river flow and flood scenarios based on design discharge values, while GIS facilitates the visualization of flood-prone areas and supports spatial decision-making (Sabara et al., 2022). Together, these tools provide a robust framework for identifying critical zones, evaluating mitigation options, and optimizing infrastructure placement (Peker et al., 2024).

In order to ensure the reliability of the hydraulic inputs, statistical methods such as Log Pearson Type III and Nakayasu Synthetic Unit Hydrograph are employed to estimate design flood discharges (Sujitapan et al., 2024). Goodness-of-fit tests, including Chi-Square and Kolmogorov-Smirnov, are used to validate the distribution models (Daffaedra et al., 2023). This probabilistic approach enhances the accuracy of flood predictions and supports the development of resilient engineering solutions tailored to local conditions (Diani et al., 2019).

Beyond flood modeling, the study also evaluates the structural integrity and slope stability of proposed embankments . A safety factor of 7.55 indicates that the embankment design is structurally sound and capable of withstanding hydraulic pressures during peak flood events (Estelaji et al., 2024). However, this raises a critical question: can physical infrastructure alone adequately address the multifaceted nature of urban flooding, or is a broader, systems-based strategy required?

Accordingly, the primary objective of this research is to assess flood risk in the Comoro River basin and propose targeted mitigation strategies that enhance infrastructure resilience. By integrating hydraulic and spatial modeling, the study aims to support evidence-based planning and sustainable flood management in Dili. Ultimately, this approach offers a replicable framework for other flood-prone urban areas and contributes to adaptive policy development for climate-resilient infrastructure.

METHOD

Study Area and Geological Context

The study area is located in Dili, the capital city of Timor-Leste, situated along the northern coastline of the island. Geographically, Dili spans from latitude 8°31'5.19"S, longitude 125°43'4.14"E to latitude 8°33'19.97"S, longitude 125°28'54.46"E see in **Figure 1**, encompassing a rapidly urbanizing landscape intersected by several river systems. Among these, the Comoro River is the most prominent, serving as the primary drainage channel for the region. Other tributaries include the Becora, Becussi, Maloa, and Manleu rivers, which collectively contribute to the hydrological complexity of the basin.

The Comoro River basin is characterized by a mixed topography of coastal plains and surrounding hills, with elevations ranging from sea level to approximately 200 meters. The upstream catchment area consists of steep slopes and weathered lithologies, which accelerate surface runoff during intense rainfall events (Al-Ghozali et al., 2021; Ziwei et al., 2023). Downstream, the river traverses densely populated urban zones, where land use changes and infrastructure development have significantly altered the natural flow regime. The study area used in this research is the Comoro River watershed. The Comoro River Basin, with its outlet at Loja Agricultura, covers an area of 195.61 km^2 with a total river length of 8.43 km. In accordance with the scope of this study, flood control measures were implemented at Posto Dom Aileixo, Dili District. The Comoro River itself flows from Railaco - Ermera to its confluence with the Aileu River.

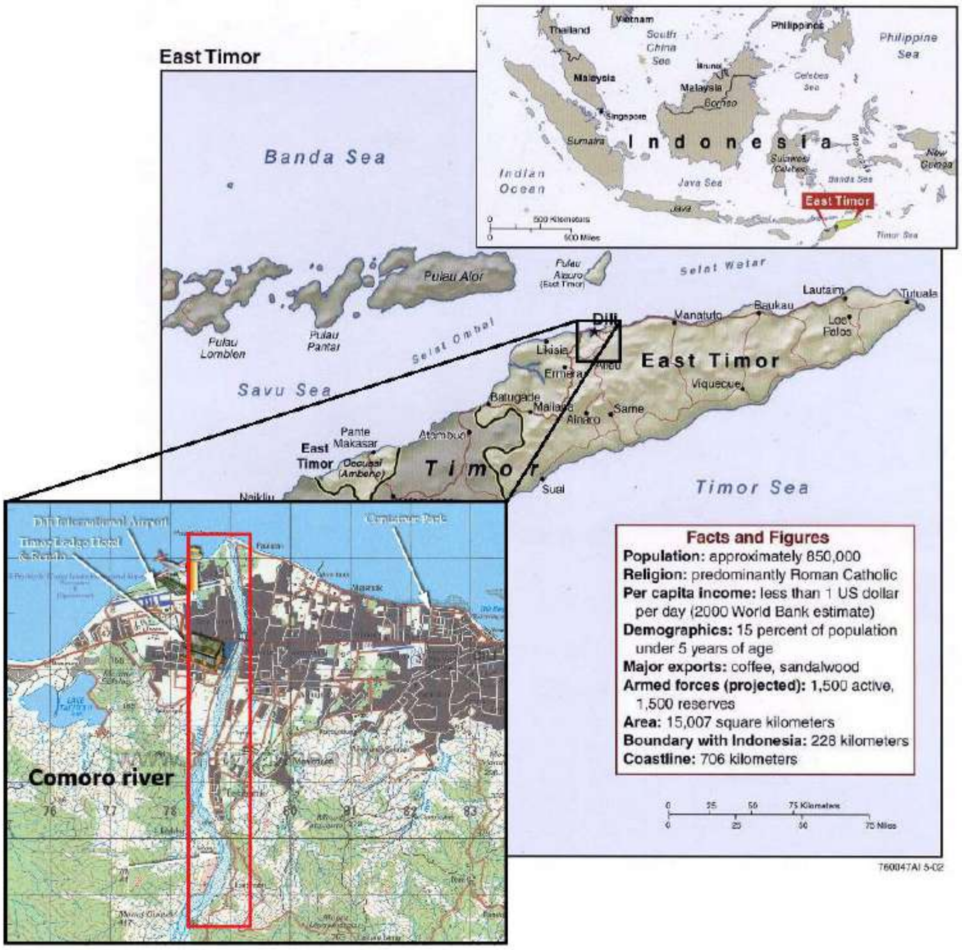

Figure 1. Geographic location of East Timor and detailed map of Dili city showing the Comoro river area

Research Instruments and Data Collection Procedures

In conducting this study, various instruments and supporting devices were used to support the process of data collection, analysis, and visualisation. The main instruments used included a Total Station, which was used for topographic measurements and precise spatial data acquisition in the field. In addition, computers or laptops were used as media for data processing and operating analysis software. For documentation and tabular data processing, Microsoft Office software, specifically Word and Excel, was used. Spatial analysis and mapping were carried out with the help of ArcGIS 10.3, as well as other supporting tools such as ArcSWAT and HecGeoRAS for the integration of hydrological and river geometry data. Meanwhile, hydraulic simulations and flood profile analyses were carried out using HEC-RAS 6.1.0 programme, which was the main software used in this study.

The data used in this study consists of primary data and secondary data collected through various methods and sources. Primary data in the form of water level (TMA) was obtained directly from interviews and observations of communities living around the Comoro River. This information was used to determine the maximum flood level that had ever occurred and became an important reference in validating the flood model (Baba et al., 2020; Peker et al., 2024).

Meanwhile, the secondary data includes several important components. First, topographic data in the form of a Digital Elevation Model (DEM) was obtained from Global Mapper software, which was used to construct a land surface model and river geometry. Second, annual discharge data for the Comoro River was collected from relevant agencies, namely ANAS IP and DNMG, although this data did not undergo a calibration process due to limited historical information. Third, daily rainfall data from three stations Railaco (Ermera), Manleuana (Dili), and Remexio (Aileu)—also sourced from ANAS IP and DNMG, was used in the design flood discharge calculations. Fourth, administrative and land use maps for Dili District were obtained from the Timor-Leste Ministry of Agriculture and were used for spatial analysis and identification of affected areas (Khatooni et al., 2025). Finally, Comoro River measurement data in the form of longitudinal and cross-sectional river sections were also obtained from Global Mapper and were used as geometric inputs in HEC-RAS modelling.

Research Design

The research design **(Figure 2)** was designed to organise the most feasible research steps to determine the influential variables or to determine the order of research. The research design refers to the hypothesis being tested.

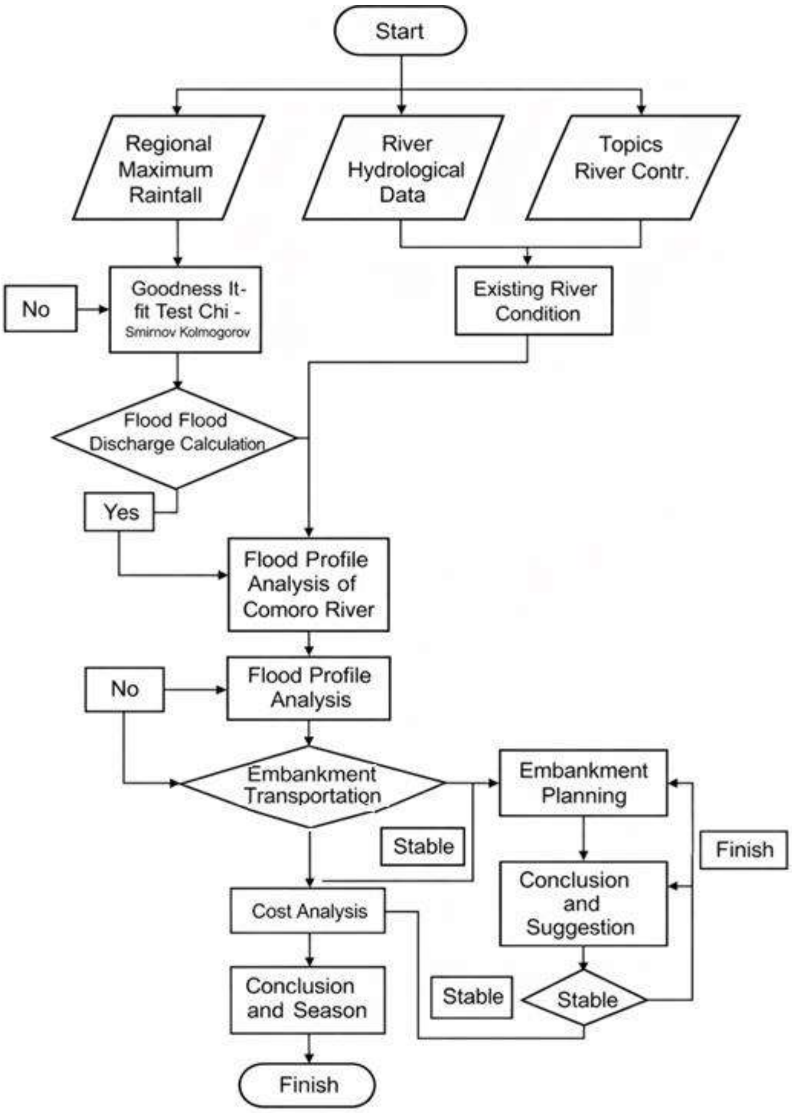

Figure 2. Research flow chart

Data Analysis Techniques

This study focuses on existing flood management or control alternatives in the Comoro River, examining several control methods and their effectiveness in reducing flooding downstream of the Comoro River **(Table 1)**.

Table 1. Methods used for calculation analysis

No	Parameters	Analysis	Methods	Supporting Data
1.	DAS Delineation	- Creation of watershed boundaries - Thiessen polygons	ArcGIS 10.3 and ArcSWAT	- Global Mapper - Rain Station Coordinates
2.	Rainfall and design discharge of the Comoro River	- Rainfall and design discharge - Frequency distribution suitability test	- Log Pearson Type III - HSS Nakayasu - HSS Snyder - HSS Limantara - Chi Square - Smirnov Kolmogorov	Daily rainfall data from 2012 to 2021
3.	Hydraulics Flow	- Flow profile - Flood distribution	HEC-RAS 6.1.0 programme	- Flood Discharge - Global Mapper - Measurement Data
4.	Flood distribution in relation to land use and administration	- Flood distribution map	ArcGIS 10.3	- Flood Depth Distribution based on HEC-RAS Analysis - Administrative and Land Use Map

Sources : The results of this research

RESULTS AND DISCUSSION

The design flood discharge used in this study is a 25-year return period flood discharge using Nakayasu's synthetic unit hydrograph (HSS) method. The 25-year return period peak discharge is 192,141 m^3/s. The peak discharge occurs during the fifth hour of rainfall, which is shown in the unit hydrograph computation summary graph can be seen in **Figure 3**.

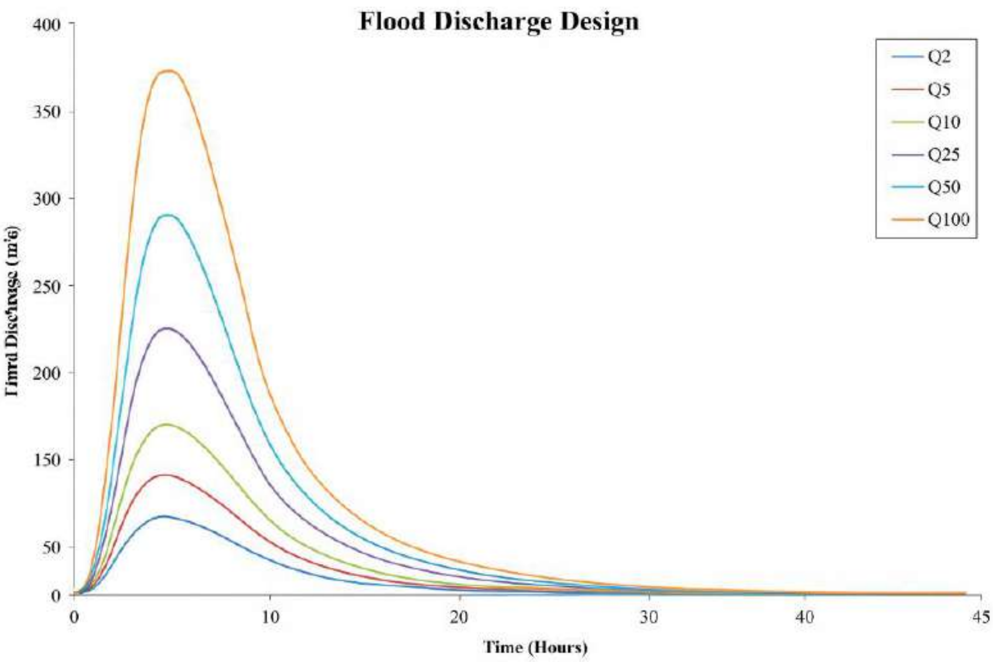

Figure 3. Design flood hydrograph in the Comoro watershed

The designed flood discharge data was then used for hydraulic analysis using the HEC-RAS 6.0.1 programme. When running HEC-RAS using 2D on the terrain map, water runoff was observed at several markers, as shown in the **Figure 4**.

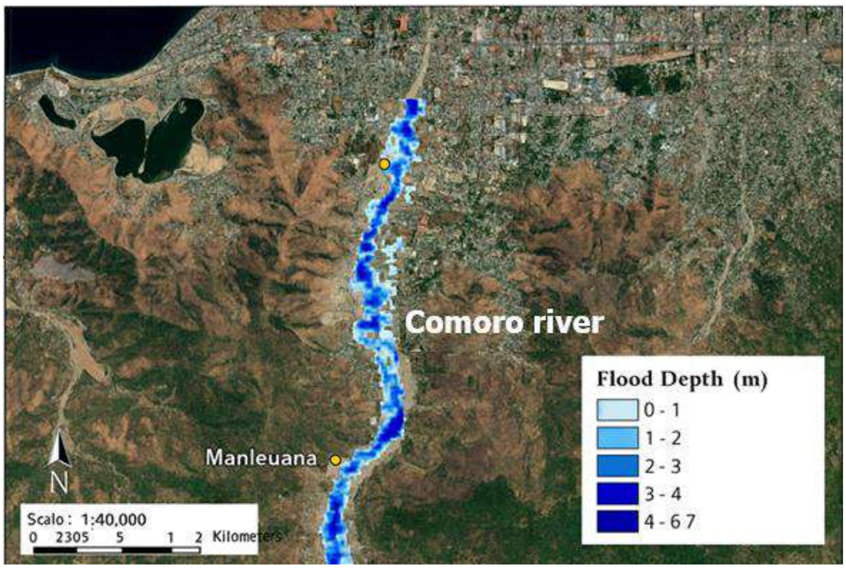

Figure 4. Map of flooding on the Comoro river

The **Figure 4** shows that there are several river markers that overflow, requiring mitigation measures to prevent flooding. The mitigation measures proposed in this study are the construction of earth embankments on the right and left sides of the river (Kapugu et al., 2022; Listyani et al., 2023). These embankments will be able to withstand the river's flood discharge rate. The width of the embankment is based on the planned flood discharge. The height of the embankment is also based on the planned flood discharge (Prastowo et al., 2019; Triani et al., 2021; Umam et al., 2024, 2025). In this study, the planned flood discharge Q25th is 192,141 $m^3/s25$, so according to Suyono Sosrodarsono, the planned height is 0.6 m with an embankment width of 3 m.

Figure 5. Location of embankment construction and normalisation

The locations of the embankments planned in this study are at marker 20619 with a length of 180.9 m, marker 19375 with a length of 204.4 m, marker 18019 with a length of 224.9 m, marker 16592 with a length of 228.2 m, marker 14440 with a length of 225.9 m, marker 9279 with a length of 219.5 m, marker 8559 with a length of 262.7 m, marker 7697 with a length of 297.6 m, marker 2515 with a length of 322.3 m, and marker 1458 with a length of 205.5 m. Thus, the total length of the embankment on the Comoro River is approximately 2,371.9 metres or 2.371 kilometres, stretching from upstream to downstream (Ashok & Umamahesh, 2019; Estelaji et al., 2024; Khatooni et al., 2025; Peker et al., 2024; Tabasi et al., 2025; Weihua et al., 2012; Ziwei et al., 2023).

Table 2. Recapitulation of flood debits after embankment construction and river normalization

Name of River	Stake	El. Boundary River		El. MAB	Overflow height		Information	
		Left	Right	Q25th	Left	Right	Left	Right
		(m)	(m)	(m)	(m)	(m)		
Comoro River	20619	103.2	103.2	102.9	0.00	0.00	Not overflowing	Not overflowing
Comoro River	20026	99.8	99.88	99.44	0.00	0.00	Not overflowing	Not overflowing
Comoro River	19375	94.7	94.7	94.08	0.00	0.00	Not overflowing	Not overflowing
Comoro River	18705	92.3	92.25	92.25	0.00	0.00	Not overflowing	Not overflowing
Comoro River	18019	88.6	88.6	88.12	0.00	0.00	Not overflowing	Not overflowing
Comoro River	17281	84.15	84.32	83.54	0.00	0.00	Not overflowing	Not overflowing
Comoro River	16592	82.2	82.2	81.9	0.00	0.00	Not overflowing	Not overflowing
Comoro River	15843	82	82	81.29	0.00	0.00	Not overflowing	Not overflowing
Comoro River	15125	77.36	77.31	76.88	0.00	0.00	Not overflowing	Not overflowing
Comoro River	14440	75	75	74.35	0.00	0.00	Not overflowing	Not overflowing
Comoro River	13699	74.44	74.43	73.01	0.00	0.00	Not overflowing	Not overflowing
Comoro River	13081	67.75	67.73	67.38	0.00	0.00	Not overflowing	Not overflowing
Comoro River	12403	66.48	66.91	66.21	0.00	0.00	Not overflowing	Not overflowing
Comoro River	11727	65.14	65.14	64.52	0.00	0.00	Not overflowing	Not overflowing
Comoro River	11006	62.45	62.27	61.66	0.00	0.00	Not overflowing	Not overflowing
Comoro River	10268	60	60.18	58.58	0.00	0.00	Not overflowing	Not overflowing
Comoro River	9279	57	57	55.86	0.00	0.00	Not overflowing	Not overflowing
Comoro River	8559	55.1	55.1	54.21	0.00	0.00	Not overflowing	Not overflowing
Comoro River	7697	50.6	50.6	50.29	0.00	0.00	Not overflowing	Not overflowing
Comoro River	6721	44.25	44.61	42.47	0.00	0.00	Not overflowing	Not overflowing
Comoro River	5760	43.85	43.76	41.62	0.00	0.00	Not overflowing	Not overflowing
Comoro River	4668	37.89	37.92	37.25	0.00	0.00	Not overflowing	Not overflowing
Comoro River	2515	29.7	29.7	29.35	0.00	0.00	Not overflowing	Not overflowing
Comoro River	1458	23.2	23.2	22.64	0.00	0.00	Not overflowing	Not overflowing
Comoro River	784	21.15	21.15	20.75	0.00	0.00	Not overflowing	Not overflowing

Sources : The results of this research

Table 3. Factor of safety (FS) calculation results

Left of FS	Slice no	C	ϕ	Wn (kN/m)	αn(°)	Sin αn	Cos αn	bn	tan ϕ	Wn. Sin αn	Wn. tan ϕ	c. bn	Fs right side	mαn	(cn. bn+ Wn. tan ϕ*1/ mαn
7.55	1	10	10	6.82	42	0.67	0.74	2.1	0.18	4.56	1.20	21	7.55	0.76	29.26
	2	10	10	11.28	34	0.56	0.83	2.0	0.18	6.31	1.99	20	7.55	0.84	26.11
	3	10	10	11.80	23	0.39	0.92	2.1	0.18	4.61	2.08	21	7.55	0.93	24.83
	4	10	10	9.79	14	0.24	0.97	2.0	0.18	2.37	1.73	20	7.55	0.98	22.26
	5	10	10	6.24	6.0	0.10	0.99	1.9	0.18	0.65	1.10	19	7.55	1.00	20.26
	6	10	10	1.95	1.0	0.02	1.01	1.7	0.18	0.03	0.34	17	7.55	1.00	17.34
				Total						**18.53**		**Total**			**139.96**

Sources : The results of this research

After planning the construction of embankments and river normalisation, the next step will be to run the HEC-RAS 6.0.1 programme. This is to review the impact of the embankment construction and river normalization (Ziwei et al., 2023). The river will continue to be run using a 25-year return period discharge (Adji & Bahtiar, 2016; Chatterjee et al., 2023; Mutri et al., 2024; Sujitapan et al., 2024). Through the analysis conducted, it was found that the construction of the embankment and river normalisation is sufficient to mitigate flooding with a 25-year return period that may occur on the Comoro River **(Figure 5)**. Therefore, the planning of the embankment dimensions and normalisation can be considered safe against future flooding. It is hoped that the communities around the Comoro River **(Table 2**) affected by flooding can maintain the buildings so that they will last longer and flooding can be comprehensively mitigated. Next, the stability of the embankments at several cross sections of the Comoro River will be calculated in the **Table 3**.

Based on the calculations in the table above, it can be seen that the FS of the Comoro River embankment is 7.55, which is considered safe as it exceeds the FS limit of 1.5. Therefore, the embankment is considered safe. Based on the cost analysis that has been carried out, it can be seen that the total cost required for the construction of the embankment and normalisation of the Comoro River is 571,366.87 USD. These findings confirm that the proposed embankment and river normalization measures are technically sound and economically feasible, providing a resilient solution for flood mitigation in the Comoro River basin.

CONCLUSION

Based on hydraulic modeling conducted using HEC-RAS 6.1.0, this study confirms that the Comoro River is subject to a design flood discharge corresponding to a 25-year return period, with a peak flow rate of 192.141 m^3/s. To mitigate this risk, embankment construction and river normalization were proposed at critical flood-prone cross-sections. Simulation results demonstrate that these interventions effectively reduce flood inundation, with a calculated slope stability factor (FS) of 7.55 well above the safety threshold of 1.5 indicating robust structural integrity. The total estimated cost for implementing these flood control measures is USD 571,366.87. While the proposed engineering solutions are technically sound, future research should incorporate environmental impact assessments (EIA) to evaluate long-term ecological consequences. Additional considerations include sediment transport dynamics, urban waste accumulation, and ongoing land-use changes, all of which influence hydraulic behavior and model reliability. Moreover, integrating tidal data is recommended to account for downstream flood interactions in coastal segments of the river. Overall, this study provides a replicable framework for flood risk mitigation in urban river systems, supporting evidence-based infrastructure planning and climate-resilient development in Timor-Leste and similar contexts.

AUTHOR CONTRIBUTIONS

Conceptualization, KM and HTT; methodology, EW; software, RJ; validation, AA, SO, and KM; formal analysis, HTT; investigation, EW; resources, RJ; data curation, AA; writing—original draft preparation, SO; writing—review and editing, KM; visualization, HTT; supervision, EW; project administration, RJ; funding acquisition KM.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

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