Journal of Infrastructure Planning and Engineering

Journal homepage: ejournal.warmadewa.ac.id

e-ISSN: 2829-5153

Impact of watershed degradation in the Mati River watershed, a typical urban river, on integrated and sustainable flood management

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Received 15 July 2026; revised 6 October 2026; accepted 12 October 2026; published 20 October 2026

ABSTRACT

The Mati River is an urban river used for irrigation but is highly susceptible to flooding and waterlogging during the rainy season. This is driven by dense residential settlements, solid waste, obstructing transverse river structures, altered surface runoff from land use changes, a gentle bed slope, tidal estuary influences, and inadequate river cross-sections with capacity-reducing bottlenecks. The watershed spans heavily populated areas across West Denpasar and Kuta Districts. This study investigates the factors contributing to watershed degradation and identifies the most dominant factor for sustainable flood management across technological, economic, environmental, socio-cultural, and institutional dimensions. The research utilized a mixed-methods approach. Quantitative analysis calculated design flood discharge using the Nakayasu Synthetic Unit Hydrograph and channel capacity via Manning's equation. Qualitative analysis relied on expert interviews to evaluate the five multidimensional factors. The findings identified ten factors influencing flood management, with technological factors being the most significant. Six factors heavily influence watershed degradation and flood conveyance: technology (five elements), environmental (two elements), economic (one element), socio-cultural (one element), and institutional (one element). Ultimately, the technological aspect exerts the most dominant influence, specifically the variability and inadequacy of the river's cross-sectional geometry, which restricts its capacity to convey flood flows.

Keywords: flood; mati river; watershed management

1 Introduction

Urban river watersheds in the world and Indonesia face numerous challenges, including rapid land use conversion, solid waste accumulation, water pollution, inadequate river cross-sections, in-stream infrastructure that may obstruct water flow, low river gradients, and tidal influences in downstream areas [1], [2], [3]. Under these conditions, flooding and waterlogging have become the most common problems, occurring almost every rainy season within many urban watersheds. As an urban river, Mati River has the potential to serve as a model for river development through an integrated approach that harmonizes various factors, including technical, economic, environmental, socio-cultural, and institutional considerations. The integration of these factors is expected to provide a sustainable model for urban river development [4],[5],[6],[7]. Mati River originates in the Sempidi area, where its primary water source is residual irrigation return flow from the Kapal Irrigation scheme in Badung Regency. The river then flows through densely populated areas in West Denpasar District and Kuta District, Badung Regency, before discharging into the sea. The river is approximately 19 km long and drains a watershed covering about 52 km^2 [8]. In terms of water utilization, the river is equipped with three diversion weirs—Lange Weir, Dadas Weir, and Umadwi weir which are operated primarily for irrigation purposes. From a hydrological perspective, these weirs represent potential overflow points during high-flow events. In addition to these structures, several hydraulic infrastructures have been constructed along the river, including bridges, trash racks, flood control pumping stations, and an automatic pneumatic crest gate located near the river mouth.

Despite these flood mitigation facilities, flooding and waterlogging continue to occur at several

https://doi.org/10.22225/jipe.5.2.2026.105-112

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How to Cite: I. G. L. M. Parwita, M. Mudhina, and I. P. D. H. Ardana, "Impact of watershed degradation in the Mati River watershed, a typical urban river, on integrated and sustainable flood management," *Journal of Infrastructure Planning and Engineering*, vol. 5, no. 2, pp. 105 - 112, October, 2026.

locations during the rainy season, with incidents recurring almost every year. Areas that are particularly vulnerable to flooding include Padangsambian, Padangsumbu, Munang-Maning, Dewi Sri Street, Legian, Seminyak, Kuta, and the surrounding areas. The primary factors contributing to flooding include the accumulation of solid waste, channel constriction, the river's relatively mild gradient, increasing rainfall intensity, and extensive land use conversion throughout the watershed.

Several studies on the sustainability of water resources management have been conducted, including those by Arne Finger [4], Rubin [9], Dewan Sumber Daya Air Nasional [10], Soleh [11], and Batica [12]. These studies have examined various factors associated with watershed degradation that may potentially lead to challenges in water resources management. Most of the existing studies have focused primarily on technological aspects, such as river cross-sectional capacity and flood control structures; economic aspects, particularly high land prices in urban areas; and environmental aspects, including environmental pollution. In addition to examining these three aspects, the present study incorporates socio-cultural and institutional dimensions, with particular emphasis on the role of traditional customary villages within the study area in supporting sustainable flood management. This integrated perspective is intended to provide a more comprehensive understanding of the factors influencing watershed degradation and flood management, particularly in an urban river system. The research employed both quantitative and qualitative approaches. The quantitative approach involved an analysis of the river's flow capacity to evaluate its ability to convey design flood discharges. The qualitative approach consisted of in-depth interviews with experts and key stakeholders to obtain comprehensive perspectives on the technological, economic, environmental, socio cultural, and institutional factors influencing watershed degradation and flood management [13],[14], [15].

2 Data and Methods

2.1 Data

This study utilized several types of data relevant to the research objectives. Hydrological data consisted of annual maximum daily rainfall records obtained from the Regional Office III of the Indonesian Agency for Meteorology, Climatology, and Geophysics in Denpasar. Rainfall data were collected from three rainfall stations: Ngurah Rai, Sanglah, and Kapal, covering a 20-year observation period from 2005 to 2024.

Data required for the design flood analysis, including watershed area and river length, were obtained from the Bali–Penida river basin organization. Additional data describing the current condition of the watershed were collected through field surveys and direct observations. These data included the river flow system, land use, the condition of hydraulic structures crossing the river, flood-prone and inundated areas, as well as the socio-economic and cultural characteristics of the local communities. In this study, the technological factors considered include variations in river cross-sectional geometry, limited riverbank areas, extensive land-use conversion, infrastructure that may obstruct or impede flood flow, and tidal influences. The economic factor is represented by high land prices, which create challenges for implementing river normalization and widening measures. Environmental factors include water pollution and sedimentation. From the socio-cultural perspective, the study considers the limited development of a widespread river-cleaning culture among local communities. Meanwhile, from the customary institutional perspective, the absence of strict customary regulations prohibiting waste disposal into river areas is also considered a contributing factor to watershed degradation and flood management challenges. The effects of watershed degradation were evaluated across six dimensions: technological, social, economic, environmental, socio-cultural, and institutional. Data were collected through interviews with experts and stakeholders involved in flood management and watershed management systems.

2.2 Methods

This study employed both quantitative and qualitative research approaches . The qualitative component involved expert judgment from specialists in water resources management, including academics, practitioners, and government officials from relevant institutions such as the Bali–Penida River basin organization, the Public Works and Spatial Planning Agency of Badung Regency, and the Public Works and Spatial Planning Agency of Denpasar City.

Hydrological data quality was evaluated using the Rescaled Adjusted Partial Sums (RAPS) test and an outlier test. The most appropriate probability distribution for rainfall frequency analysis was selected based on the statistical characteristics of the data, namely the coefficients of skewness (Cs), variation (Cv), and kurtosis (Ck). The selected design rainfall was subsequently estimated using the Log Pearson Type III distribution [16], [17].

The design flood discharge was calculated using the Nakayasu Synthetic Unit Hydrograph method, while river channel capacity was evaluated using the Manning equation [18], [19]. Watershed degradation was assessed through a structured questionnaire administered to a panel of experts. The questionnaire evaluated watershed conditions from five perspectives: engineering and technological aspects,

economic aspects, environmental conditions, socio-cultural aspects, and institutional capacity.

3 Results and Discussion

3.1 Design Rainfall Analysis

The design rainfall analysis was carried out using annual maximum daily rainfall data collected from three rainfall stations: Ngurah Rai, Sanglah, and Kapal. The rainfall records covered a 20-year observation period from 2005 to 2024. The design rainfall was estimated using the Log Pearson Type III distribution, which was selected based on the statistical characteristics of the rainfall data. The analysis results are presented in **Table 1** as follows.

Table 1. Design rainfall of the Mati river watershed

No.	Time Period (T) (year)	G	Designed rain (mm)
1	2	0,025	125,36
2	5	0,851	143,46
3	10	1,274	153,73
4	20	1,566	161,25
5	25	1,712	165,15
6	50	1,981	172,58
7	100	2,226	179,62
8	200	2,445	186,17
9	1000	2,902	200,59

3.2 Flood Design

The design flood analysis was performed using the Nakayasu Synthetic Unit Hydrograph method based on the estimated design rainfall and the existing watershed morphometric characteristics. The resulting design flood hydrographs were then calculated for the selected return periods. The results of the design flood analysis are presented in **Figure 1**.

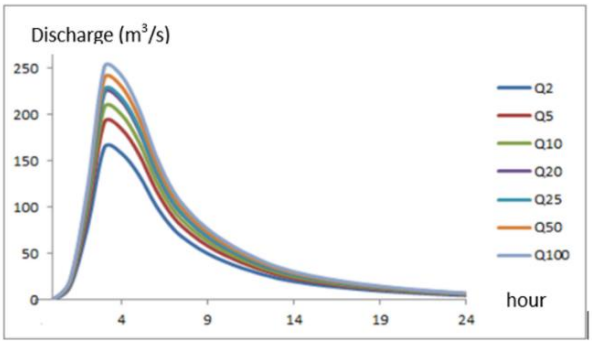


Figure 1. Design flood hydrograph of the Mati river
Source: Analysis, 2026

3.3 Capacity Analysis of the Tukad Mati Watershed

The channel capacity analysis indicates that, under the 25-year return period flood (Q25), several reaches of the Tukad Mati River are unable to convey the design flood discharge, resulting in flooding and overbank inundation. This condition is primarily attributed to the limited channel cross-sectional capacity and the relatively mild channel slope, both of which reduce the river's flow conveyance. In addition, several diversion weirs, namely Lange Weir, Dadas Weir, and Umadwi Weir, contribute to flooding and waterlogging because they extend across the river channel and provide limited flow capacity during high-flow events. At several bridge crossings, hydraulic bottlenecks occur due to reduced channel width and insufficient bridge clearance, thereby restricting floodwater conveyance and causing upstream backwater effects. The channel capacity of the Tukad Mati River for each river reach is summarized in **Table 2.**

Table 2. Mati river capacity

No	Segment	Length (m)	Width (m)	Depth (m)	Capacity (m^3/sec)	Q_{25} (m^3/sec)	Information
1	River upstream - Gatot Subroto bridge	10,69	25	10	637,36	77,65	
2	Gatot Subroto – Gunung Agung bridge	2,180	24	10	604,39	96,86	
3	Gunung Agung bridge- Resimuka bridge	1,250	12	5	94,97	118,86	Overflow
4	Resimuka bridge-Lange weir	556	10	5	74,66	145,03	Overflow
5	Lange weir- Mahendradata bridge	789	13	7	165,98	146,44	
6	Mahendratdata bridge - Buana Raya bridge	139	20	5	181,05	150,79	
7	Buana Raya bridge-Teuku Umar bridge	431	14	5	115,89	153,82	Overflow
8	Teuku Umar bridge- Mahendradata bridge	300	24	5	225,75	159,37	
9	Mehendaradata bridge -Dadas weir	1,200	14	3	104,6	165,93	Overflow
10	Dadas Weir- Gunung Soputan bridge	250	12	5	115,89	168,46	Overflow
11	Gunung Soputan bridge - Umadwi bridge	75	25	5	94,97	169,21	Overflow
12	Umadwi bridge- sunset road bridge	2,400	22	6	309,64	168,46	
13	Sunset road bridge-Nakukla bridge	1,200	14	8	397,22	169,21	
14	Nakula bridge-Yudistira bridge	65	24	7	183,33	193,44	Overflow

15	Yudistira bridge-Patih Jelantik bridge	425	24	6	294,59	205,55	
16	Patih Jelantik bridge-Raya Kuta bridge	425	14	7	367,53	206,2	
17	Raya Kuta bridge -Blambangan bridge	450	24	5	115,89	210,49	Overflow
18	Blambangan bridge- Surfer Girl bridge	700	16	6	294,59	214,78	
19	Surfer Girl bridge-Ngurah Rai bridge	100	30	7	218,78	219,32	Overflow
20	Ngurah Rai bridge - estuary	800	30	7	483,58	226,39	

Source: analysis, 2026

3.4 Mati Watershed Degradation

Based on the analysis of available flood discharge data and current watershed conditions, this study evaluates watershed degradation contributing to river overflow across several regions. The researchers conducted in-depth interviews with seven experts and practitioners to explore the factors contributing to flood problems in the study area. To date, flood management in river systems has often been implemented in a fragmented and sectoral manner, with solutions primarily focused on civil engineering interventions. However, from the perspective of integrated and sustainable watershed management, addressing watershed degradation requires the involvement of multiple sectors and stakeholders. Furthermore, management strategies should be tailored to the specific characteristics of each watershed, as the physical, environmental, socio-economic, and institutional conditions vary considerably from one river system to another [9], [10], [11]. Urban rivers are traditionally subjected to considerable pressure due to the high density of residential development along their banks and the exceptionally high land values in surrounding areas. As a result, conventional river normalization measures, such as channel widening and realignment, are often difficult to implement because of land acquisition constraints and the significant economic costs involved [12], [13], [14],[15]. The analysis of the impacts of watershed degradation was conducted through interviews with experts, including academics, practitioners (consultants and contractors), government officials from agencies responsible for water resources and river management (the Public Works Agency). Based on the analysis, five perspectives on watershed degradation factors were identified, namely technological, economic, environmental, socio-cultural, and institutional. The overall analysis identified five major dimensions of watershed degradation in the Mati River watershed, represented by ten associated parameters. These comprise five technological parameters, one economic parameter, two environmental parameters, one socio-cultural parameter, and one institutional parameter. Among these dimensions, technological factors were identified as the most dominant contributors to watershed degradation affecting flood management. The most critical technological issue is the inadequate river cross-sectional capacity, characterized by highly variable and, in many reaches, insufficient channel dimensions to accommodate design flood discharges. This condition significantly reduces the river's conveyance capacity and increases the likelihood of flooding. These findings indicate that effective flood management in the Mati River watershed requires priority attention to improving the river's hydraulic capacity, while simultaneously integrating economic, environmental, socio-cultural, and institutional measures within a comprehensive and sustainable watershed management framework.

a. Technological Factors

Five technological factors were identified as having a significant influence on watershed degradation and flood management in the Mati River watershed.

1) River cross-section

The Mati River exhibits highly variable cross-sectional dimensions along its course, ranging from approximately 10 m at the Resi Muka Bridge to about 45 m at the pneumatic crest gate movable weir near the river mouth. Between these locations, the river width varies considerably. In addition, the river has a relatively mild average bed slope, which reduces the efficiency of downstream flow conveyance. As an urban river, both sides of the Mati River watershed are densely occupied by residential and commercial buildings, making river widening or channel normalization practically impossible. Consequently, the river cross-section has become a critical factor influencing watershed degradation and flood management.

The expert survey indicated that 85.71% of respondents considered the river cross-section to be significant influential, while the remaining 14.29% considered it to have a very significant influence on watershed degradation and flood management. Hydraulic analysis further showed that, under the 25-year return period flood discharge, 9 out of the 20 river segments experience overtopping and flooding. In other words, the existing river channel capacity is insufficient to convey the design flood discharge, highlighting the need for integrated structural and non-structural flood management measures.

2) Limited river riparian zone

In relation to Indonesian regulations governing river riparian areas, including Law No. 17 of 2019 on

Water Resources, which emphasizes river protection, water-related disaster mitigation, and the sustainable utilization of river corridors, Government Regulation No. 38 of 2011 on Rivers, and Minister of Public Works and Housing Regulation No. 28/PRT/M/2015 on the Delineation of River and Lake Riparian Boundaries, the Mati river Watershed generally lacks adequate riparian zones that could function as temporary flood buffer areas.

The absence of sufficient river setbacks is primarily due to intensive urban development along both riverbanks, which has significantly reduced the natural floodplain available for flood storage and flow conveyance. Consequently, the river's capacity to accommodate floodwaters has been substantially diminished, increasing the likelihood of flood events. Based on the expert assessment, 28.57% of respondents considered the limited riparian zone to be very influential, while 71.43% considered it to have a significant influence on flood occurrence within the Mati River watershed.

3) Extensive land use conversion

Land use conversion in the Mati River watershed, which is classified as an urban watershed, has occurred at a very high rate. Much of the watershed is now characterized by high-density residential development, making it one of the most densely populated areas in Bali Province. As of 2024, only approximately 137 ha of productive paddy fields remained in West Denpasar District, making it the district with the smallest area of rice fields in Denpasar City.

This extensive conversion of agricultural land to urban uses has significantly increased the watershed runoff coefficient and surface runoff, thereby reducing infiltration capacity and exacerbating flood risk. According to the expert assessment, 57.16% of respondents considered land use conversion to be significant influential, while the remaining 42.84% regarded it as having a very significant influence on flood occurrence in the Mati River watershed. These findings indicate a strong consensus that rapid urbanization and the expansion of impervious surfaces have substantially contributed to increased flood hazards within the watershed. Moreover, 57.14% of respondents stated that urban infrastructure associated with land use conversion has a very significant contribution to flooding, while 42.86% considered its contribution to be significant.

4) Infrastructure that reduces river conveyance capacity

Several hydraulic and transportation infrastructures have contributed to the reduced conveyance capacity of the Mati River because their dimensions are smaller than the hydraulic requirements. For example, the Teuku Umar Barat Bridge has a vertical clearance of only 1.2 m, which significantly restricts the passage of flood flows during high-discharge events. As floodwaters rise, the limited clearance creates a bottleneck effect, reducing the bridge's ability to safely convey floodwaters and increasing the risk of upstream inundation.

Similarly, several bridge structures have insufficient channel widths. For instance, the Resi Muka Bridge has a span of only 10 m, whereas hydraulic analysis indicates that a width of approximately 18 m is required to adequately accommodate the design flood discharge. These undersized bridge openings constrict the river channel, reduce its hydraulic capacity, and contribute to higher upstream water levels during flood events. Overall, inadequately designed or undersized infrastructure represents a significant factor that limits the flood-carrying capacity of the Mati river and increases flood vulnerability within the watershed. The results of the analysis indicate that 42.86% of respondents stated that in-stream structures have a significant influence, while 57.14% considered them to have a very significant influence on flood occurrence

5) Influence of tidal fluctuations

The results of this study indicate that the construction of the pneumatic crest gate movable weir at the mouth of the Mati River has significantly reduced the influence of tidal backwater effects from the sea. By preventing seawater intrusion during high tides, the structure improves downstream flow conditions and enables floodwaters to be discharged more rapidly to the sea, thereby enhancing the river's flood conveyance capacity.

These findings are consistent with the opinions of the experts interviewed. 42.86% of respondents stated that tidal fluctuations have no significant influence on flooding in the Mati River watershed, while 57.14% considered their influence to small influence. This suggests that, following the operation of the pneumatic crest gate, tidal effects are no longer regarded as a major contributing factor to flood occurrence in the watershed.

b. Economic factors

Analysis and expert interviews revealed that one of the most significant economic factors associated with watershed degradation and flood management in the Mati River watershed is the exceptionally high land value within the watershed. The high cost of land acquisition presents a major constraint to river normalization and channel improvement programs. Consequently, when flooding occurs, widening the river channel or restoring its floodplain is often not feasible because the cost of land acquisition is prohibitively expensive.

The expert assessment indicated that 42.86% of respondents considered high land prices to be significant influential in limiting the implementation of flood control programs, while the remaining 57.14% regarded them as having a very significant

influence on flood management in the Mati river watershed. These findings highlight that economic constraints, particularly the high value of urban land, constitute a major barrier to implementing structural flood mitigation measures, emphasizing the need for integrated flood management strategies that combine engineering solutions with land-use planning and non-structural approaches.

c. Environmental factors

1) Solid waste reducing river conveyance capacity

The accumulation of solid waste within the river channel has the potential to reduce the river's conveyance capacity and increase the risk of flooding during the rainy season. Although a debris-screening facility has been installed along the Sunset Road section of the Mati River to intercept floating waste, debris that bypasses the screening system can still obstruct flow and contribute to localized flooding.

The expert assessment indicated that 28.57% of respondents considered the small influence of solid waste on reducing river capacity to be minor, 42.86% regarded it as significant influence, and 28.57% considered it very significant influence in contributing to flood occurrence. However, field observations conducted along the Mati River watershed showed that, in general, the river channel contains relatively little accumulated solid waste. This suggests that although waste can locally obstruct flow and reduce hydraulic capacity, it is not currently the primary factor responsible for flooding within the watershed.

2) Sedimentation reducing river conveyance capacity

Field observations indicate that the Mati River has a relatively gentle longitudinal slope, as reflected by its meandering channel from the middle reach (approximately the Monang-Maning area) to the river mouth. The presence of several movable weirs further decreases the effective hydraulic gradient, thereby reducing flow velocity and promoting sediment deposition within the river channel.

The river reach extending from Sunset Road to the Kuta area exhibits considerable sediment accumulation, indicating that sedimentation is a significant issue affecting the hydraulic performance of the Mati River. The accumulated sediment reduces the effective cross-sectional area of the channel, thereby decreasing its flood conveyance capacity and increasing the likelihood of flooding during high-flow events. According to the expert assessment, 28.57% of respondents considered sedimentation to have a small influence, 42.86% regarded it as having a significant influence, and 28.57% considered it to have a very significant influence on reducing river capacity and contributing to flood occurrence in the Mati River watershed.

d. Socio-cultural factors

Socio-cultural factors are closely related to the community's social values, cultural practices, and level of public awareness regarding the protection and preservation of river functions. Field observations and expert assessments identified one key socio-cultural factor contributing to watershed degradation in the Mati River watershed, namely the lack of widespread public awareness of the importance of maintaining river cleanliness and protecting the river environment.

The analysis indicates that community awareness plays an important role in preserving river functions and reducing flood risk. According to the expert assessment, 14.29% of respondents considered public awareness to have no influence, 28.57% regarded it as having a small influence, 28.57% considered it to have a significant influence, and the remaining 28.57% assessed it as having a very significant influence on watershed degradation and flood occurrence. These findings suggest that strengthening community participation, environmental education, and public awareness programs should form an integral part of sustainable watershed and flood management in the Mati River watershed, complementing structural and engineering-based flood mitigation measures.

e. Institutional Factors

Formal institutions, including the Bali–Penida River Basin Agency, the Badung Regency Public Works and Spatial Planning Agency (PUPR), and the Badung Regency Environmental and Sanitation Agency, have played important roles in the management of the Mati River watershed. However, the role of customary village institutions, which maintain close relationships with local communities, needs to be further strengthened.

Customary institutions have considerable potential to support sustainable river management through community-based initiatives, such as preventing the disposal of solid waste into the river, promoting environmental stewardship, and encouraging compliance with local customary regulations aimed at preserving river functions. Strengthening the involvement of these institutions can enhance community participation and complement the efforts of government agencies in reducing watershed degradation. According to the expert assessment, 28.57% of respondents considered the role of customary institutions to have a small influence, 42.86% regarded it as having a significant influence, and 28.57% considered it to have a very significant influence in reducing watershed degradation in the Mati River watershed.

The contribution of each factor from the technological, economic, environmental, socio-cultural, and institutional dimensions is illustrated in **Figure 2**.

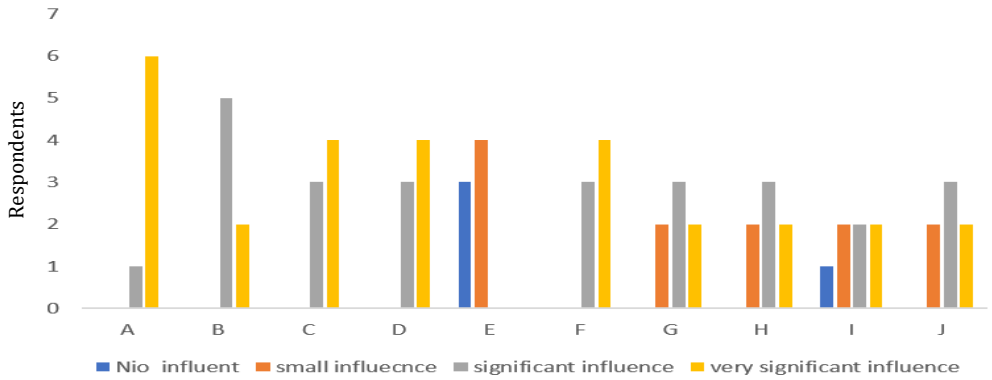


Figure 2. Contribution of each factor to watershed degradation

Note:
A: variations in river cross-sections; B: limited riverbank; C: high rates of land-use; D: infrastructure that reduces the river's flood; E: tidal effects; F: high land prices; G: river pollution; H: sedimentation; I: the absence of a widespread culture of river cleanliness; J: the lack of customary institutions for river management and cleanliness

4 Conclusion

The results of this study indicate that ten factors, categorized into five dimensions, influence flood management in the Mati River watershed. These consist of five technological factors, one economic factor, two environmental factors, one socio-cultural factor, and one institutional factor. Among these, the technological dimension, particularly the river cross-sectional capacity, was identified as the most influential factor.

The cross-sections of the Mati River vary considerably along its course, with several reaches experiencing significant channel constrictions. Considering that the watershed is located within a major tourism area where land values are exceptionally high, widening the river channel is economically and socially difficult to implement. Hydraulic analysis further indicates that nine of the twelve river reaches are unable to convey the 25-year return period design flood, resulting in overtopping and flooding during extreme rainfall events.

Based on these findings, it is recommended that integrated and sustainable flood management should prioritize improving flood control infrastructure capable of rapidly evacuating excess floodwater from the Mati River. One practical measure is the installation of pumping systems to enhance drainage capacity during peak flood events, thereby reducing flood inundation in urban areas. The role of indigenous communities within customary villages in the study area can make a positive contribution by strengthening customary institutions in waste management through regulations that impact overall flood control.

5 Acknowledgement

The authors would like to take this opportunity to thank their colleagues in the Civil Engineering Department of the Bali State Polytechnic for their assistance and support. We also extend our thanks to the Bali Penida River Basin Center and related agencies for their assistance with the data.

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