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Flood risk typology analysis: Spatial distribution of river flooding and urban flooding as a foundation for disaster management planning

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ABSTRACT

Background: Flood losses in Bantul Regency surged by nearly 500% from 2015 to 2025 (reaching IDR 7.1 billion). Despite having standard disaster plans (KRB and RPB), these documents apply a one-size-fits-all approach, ignoring the distinct mechanisms and specific mitigation needs of different flood types. **Methods:** This research employs a mixed-methods approach integrating GIS-based spatial analysis, document content analysis, and semi-structured interviews with 7 key informants (representing BPBD Bantul, Bappeda, and BBWSO). The flood typology classification followed the framework of Bello et al. (2024), utilizing a spatial classification procedure that overlays flood hazard, land cover, and watershed boundaries. The risk component analysis performed the H×V/C formula per BNPB (2021) methodology. Spatial mapping was performed using ArcGIS 10.3 (coordinate system UTM Zone 49S) with BNPB 2022 data, DIBI the BNPB historical records, and BIG 2023 land cover data. The spatial results were validated using historical inundation records and Google Earth satellite imagery. **Findings:** Two distinct flood typologies were identified: river flooding in downstream watershed areas, characterized mainly by high hazard, and urban flooding in Yogyakarta's buffer areas, characterized by high vulnerability. However, the current KRB fails to distinguish between these typologies, analyzing risks by administrative borders instead of natural hydrological units. **Conclusion:** Flood risk in Bantul Regency is not homogeneous. Typological differentiation has different implications for disaster-risk and spatial planning instruments. The KRB methodology must be reoriented toward DAS hydrology-based analytical units with explicit typology classification as a prerequisite for effective and adaptive disaster management planning. **Novelty/Originality of this article:** The study contributes a district-level application that integrates flood-typology differentiation, GIS-based spatial analysis, and watershed considerations in evaluating the KRB.

KEYWORDS: disaster risk; flood typology; river flooding; spatial distribution; urban flooding.

1. Introduction

Disaster risk represents one of the most complex challenges of the era of contemporary development. The United Nations Office for Disaster Risk Reduction (UNDRR, 2022) recorded an increase in the frequency of global disasters, from an average of 90-100 medium-to-large-scale disasters per year during 1970-2000 to 350-500 events per year during 2001–2020. UNDRR projects that the world will face an average of 560 disasters per year by 2030s without significant systemic intervention. This increase does not merely reflect the intensification of natural hazards but also the accumulation of socioeconomic

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vulnerability, expansion of built-up areas into disaster-prone regions, and inadequate disaster management planning capacity to address continuously evolving risk dynamics.

The Sendai Framework for Disaster Risk Reduction 2015-2030 explicitly identifies that disaster management planning not grounded in adequate risk understanding is one of the root causes of failures in mitigation across many countries. In Indonesia, data from the National Board for Disaster Management/*Badan Nasional Penanggulangan Bencana* (BNPB, 2025) reports that hydrometeorological disasters, particularly floods, accounted for more than 70% of national disaster events over the past decade. The increased risk of hydrometeorological disasters is related to environmental science and sustainable development (Suparmoko, 2020). The environment is a complex system comprising physical elements, living organisms, and socio-cultural systems, wherein human activities, such as urbanization and land-use change, directly impact ecological balance (Miller & Spoolman, 2016). Regional governance policies that balance economic, social, and ecological dimensions heavily influence environmental sustainability (Chotim, 2020; Muqsith et al., 2023). Effective environmental governance is a critical factor in mitigating extreme weather events and natural disasters (Meng, 2024; Di Marcoberardino & Cucculelli, 2024). In this context, disaster risk reduction planning must be grounded in ecological sustainability principles, which entails maintaining ecosystem integrity, carrying capacity, and regional resource preservation (Khanna et al., 1999). If planning documents fail to specifically account for these social and physical vulnerabilities, the allocation of resources for community adaptation will become highly inefficient (Alem et al., 2021).

Building upon this need for efficient resource allocation, the effectiveness of urban post-disaster recovery heavily depends on the multidimensional planning of reconstruction funds. When severe weather events disrupt dense economic systems, the resulting indirect economic losses can cascade through supply chains and trade markets, requiring rapid and strategic government intervention. Therefore, rational investment strategies must carefully manage the amount of funding, time efficiency of its distribution, and specific allocation structure between restoring immediate production and improving long-term fortifications. Notably, under conditions where baseline capital is guaranteed, optimizing the time efficiency of these financial investments yields a significantly higher benefit-cost ratio than merely injecting additional funds into the system.

However, financial investment optimization is only effective when guided by integrated and continuously updated local planning frameworks. Evaluations of disaster management practices, such as those observed in Gaborone, Botswana, and Yogyakarta, Indonesia, reveal a recurring failure to fully integrate disaster risk reduction protocols with broader regional development plans. Furthermore, these crucial planning documents frequently expire without timely revision and are typically developed through top-down administrative approaches that lack vital public involvement. Because flood hazard patterns are constantly shifting due to climate change, relying on these generic or outdated strategies leads to a reactive disaster response rather than a proactive mitigation effort.

One fundamental weakness in disaster management planning practice is homogeneous treatment of disaster risk as though all types of floods share the same mechanisms, causes, and management approaches. A fundamental difference exists between flooding caused by overflow from increased upstream watershed discharge (river flooding) and urban ponding flooding triggered by limited drainage capacity and conversion of water-absorption land use (urban flooding). Bello et al. (2024) assert that these two typologies require different risk analysis approaches, planning instruments, and mitigation strategies. Planning insensitive to these typological differences tends to produce generic mitigation programs that are non-adaptive to specific regional characteristics, and ultimately ineffective in reducing risk (Savitri et al., 2022).

Bantul Regency is one of the areas with substantial flood hazard exposure in the Special Region of Yogyakarta. Based on BNPB (2022), Bantul Regency has the largest area of medium-class flood hazard (10,254 ha). Historical data from Regional Disaster Management Agency/*Badan Penanggulangan Bencana Daerah* (BPBD) Bantul and *Data dan Informasi Bencana Indonesia Badan Nasional Penanggulangan Bencana* (DIBI BNPB) show that flood

losses have increased consistently over a decade from an estimated IDR 1.2 billion in 2015 to IDR 7.1 billion in 2025, an increase of nearly 500% in ten years, despite the existence of *Kajian Risiko Bencana* (KRB) and *Rencana Penanggulangan Bencana* (RPB) documents compiled according to national guidelines. This condition raises a fundamental question: Does the existing disaster management planning document adequately reflect the actual diversity of flood risk typologies.

This complexity in risk typologies extends beyond inland flooding, as Bantul's coastal geography exposes it to multi-hazard threats that require proactive and specialized planning. Tsunamis are less frequent than hydrometeorological disasters, pose an indispensable challenge to regional disaster management, particularly because Bantul is a national strategic tourism area. Coastal destinations are highly vulnerable to sudden-onset natural hazards originating from the sea, where generic structural mitigation measures are often unfeasible due to budget constraints and the risk of disrupting the natural assets essential to the tourism economy. Consequently, relying on standardized mitigation plans without addressing the unique characteristics of rapid-onset coastal hazards leaves the region with inadequate preparedness (Amri et al., 2024).

Furthermore, effective disaster planning must account for the diverse demographic profiles within hazard zones, as vulnerabilities vary significantly among different population segments. In Bantul's coastal areas, visitors and tourists constitute a uniquely vulnerable subgroup compared with local residents. These transient populations typically lack familiarity with the surrounding environment and possess a lower perception of local risks, heavily relying on host initiatives for protection during emergencies. A homogeneous planning approach that treats all individuals in a hazard zone equally may fail to address the specific communication and capacity-building needs of visitors from outside the province, who exhibited the lowest levels of understanding of certain tsunami warning indicators and evacuation routes (Amri et al., 2024).

Public knowledge gaps regarding hazard mechanisms present an additional challenge for hazard-specific disaster planning. For example, studies on beach users in Bantul reveal widespread misconceptions about tsunami precursors, with many individuals falsely believing that strong, physically felt tremors always accompany tsunamigenic earthquakes (Amri et al., 2024). This ignores the historical reality of the region, where devastating events such as the 1994 and 2006 tsunamis south of Java were triggered by slow-rupture "tsunami earthquakes" that produced only weak ground shaking (Synolakis et al., 1995; Mori et al., 2007). Given these knowledge gaps, expanding risk communication and strengthening disaster preparedness planning are important for improving tsunami awareness and evacuation readiness among coastal visitors (Amri et al., 2024).

Finally, the successful implementation of any disaster management strategy heavily depends on how well early warning systems and evacuation plans align with actual community behavior and awareness. In Bantul, a significant portion of the at-risk coastal population is unaware of the existing official tsunami early warning systems and instead heavily on the internet and social media for hazard information. Individuals demonstrate a strong preference for horizontal evacuation, running inland on foot, often disregarding vertical evacuation structures when faced with a crisis scenario. Recognizing these distinct behavioral intentions and communication gaps is essential for designing adaptive and effective disaster management protocols.

To respond to this risk complexity, Indonesia has built a structured disaster management planning system through Law No. 24 of 2007 on Disaster Management, which mandates the preparation of a Disaster Management Plan (RPB) and a Disaster Risk Assessment (KRB) at every government level. Law No. 26 of 2007 on Spatial Planning integrates disaster aspects into spatial planning. However, the effectiveness of this planning system heavily depends on the extent to which these documents are compiled based on a comprehensive and differentiated understanding of disaster risk characteristics in each region. This study formulates four explicit research questions to address the identified planning and policy gaps systematically: How can flood typologies in Bantul Regency be identified and differentiated based on physical and anthropogenic mechanisms? What are

the specific risk component profiles (hazard, vulnerability, and capacity) characterizing each flood typology? How are these flood risk typologies spatially distributed across Bantul's landscape, and where do they overlap? To what extent do current regional disaster risk assessment (KRB) documents accommodate these typological differences?

Research gaps identified in the literature include the following: Typology-based flood risk analysis frameworks (Bello et al., 2024; Savitri et al., 2022) have not been applied systematically as the basis for evaluating disaster management planning documents at the district level in Indonesia, the BNPB (2021) KRB methodology based on administrative unit analysis remains insufficiently examined against its adequacy for capturing Watershed/*Daerah Aliran Sungai* (DAS) based hydrological phenomena, and the spatial implications of flood-typology differentiation remain underexplored as a basis for differentiated planning recommendations. This research aims to fill those gaps by: identifying and differentiating flood typologies in Bantul Regency, analyzing risk components per typology; mapping the spatial distribution of typologies, and assessing the extent to which the existing KRB document has accommodated typological differentiation. The novelty of this research lies in evaluating current disaster risk assessment (KRB) documents at a district level by integrating flood-typology analysis, Geographic Information System (GIS) based spatial analysis, and watershed considerations to evaluate the Bantul Regency KRB. This contextualized application provides an operational bridge between typological theory and practical spatial planning in Indonesia.

2. Methods

2.1 Research design and study area

This research applies a mixed methods design the integrating quantitative spatial analysis with qualitative document analysis and in-depth interviews. The research location is Bantul Regency (506.85 km^2, 17 sub-districts), selected based on the following: its position as the regency with the highest medium-class flood hazard area in BNPB, the presence of varied flood mechanisms associated with both watershed and urban drainage conditions, and the availability of disaster management planning documents (KRB, RPB, Regional Spatial Plan/*Rencana Tata Ruang Wilayah* (RTRW)) as evaluation objects.

Geographically, Bantul Regency is located downstream of the Progo and Opak watersheds, extending from 7°44′04″–8°00′27″ S and 110°12′34″–110°31′08″ E. All spatial data in this study were projected using the UTM Zone 49S coordinate system (WGS 84 datum) to maintain geometric consistency and mapping precision. The study area experiences both river flooding (from large DAS system influence) and urban flooding (from rapid built-up area development as a Yogyakarta City buffer zone). The regency borders Yogyakarta City and Sleman Regency to the north, Gunungkidul Regency to the east, Kulon Progo Regency to the west, and the Indian Ocean to the south.

2.2 Data sources

The data used consisted of the following: Primary data: field observations at priority locations; Secondary data: BNPB (2022), KRB Bantul Regency 2025-2029, *Indeks Risiko Bencana Indonesi* (IRBI) 2023, DIBI BNPB historical flood data 2015–2025, Geospatial Information Agency/*Badan Informasi Geospasial* (BIG) 2023 land cover spatial data, Bantul Regency Statistics Indonesia (2024), Serayu Opak River Basin Organization/*Balai Besar Wilayah Sungai Serayu Opak* (BBWSO) and Meteorology, Climatology, and Geophysical Agency/*Badan Meteorologi, Klimatologi, dan Geofisika* (BMKG) hydrological data, and RTRW Bantul Regency. Data from multiple sources were triangulated to strengthen the consistency of the analysis (Table 1).

Table 1. Data collection instruments

No	Data name	Type	Data source	Collection instrument
1	Flood hazard map per typology	Secondary	Bantul KRB 2025-2029, BNPB (2022),	Document review + GIS
2	Historical flood event data 2015-2025	Secondary	DIBI BNPB, Bantul BPBD Report	Agency data compilation
3	River discharge and rainfall data	Secondary	BBWSO, Yogyakarta BMKG	Agency data collection
4	Actual land cover data	Secondary + Primary	BIG 2023, field survey	GIS + observation
5	Watershed and Sub-watershed boundaries	Secondary	BIG, Ministry of Environment and Forestry, BBWSO, Bantul Bappeda 2024	GIS + agency
6	Indonesian Disaster Risk Index (IRBI)	Secondary	BNPB 2023	Download and compilation
7	Bantul Regency RTRW (Regional Regulation + shapefile)	Secondary	Bappeda/Land Agency	Document review + GIS
8	RTRW spatial pattern map (shapefile)	Secondary	Bantul Regency Bappeda	GIS request

2.3 Flood typology analysis and KRB document assessment

The flood typology classification was conducted in three stages: classification based on flood mechanisms River Flooding (overflow of Progo and Opak DAS discharge from upstream rainfall) and Urban Flooding (urban ponding from drainage system limitations and surface runoff from converted absorption land) referencing the Bello et al. (2024) framework, risk component analysis per typology using the R = f(H×V/C) formula per BNPB (2021) methodology; and spatial distribution mapping using GIS overlay analysis of KRB hazard maps, DAS boundaries, and BIG 2023 actual land cover data with ArcGIS 10.3 (Hizbaron et al., 2024).

The extent to which KRB Bantul Regency accommodates flood typology differentiation was assessed using a structured content analysis checklist covering eight assessment aspects. Results were categorized as: ✓ Available/Adequate or ✗ Unavailable/Limited. The assessment was validated through key informant interviews with representatives of BPBD Bantul, Capped, and BBWSO.

2.4 Spatial analysis

The spatial analysis was performed using ArcMap 10.3/ArcGIS, encompassing the following methodological steps: coordinate system georeferencing based on WGS84 UTM Zone 49S, identification of spatial conflicts through Intersect and Union overlay techniques, delineation of river riparian zones via buffer analysis, setting a 50-meter margin for minor rivers and a 100-meter margin for major rivers, as mandated by Government Regulation No. 38 of 2011, computation of spatial extents and suitability percentages employing spatial statistics, and cartographic production of map outputs to facilitate the dissemination of findings.

The data used in this study were from multiple primary and secondary sources. The primary data included field observations at 15 key priority locations and semi-structured interviews. Secondary spatial and statistical datasets were obtained from the following official national and local agencies: Regional Spatial Datasets: BIG 2023 land cover spatial data (1:50,000 scale) and DEMNAS (Digital Elevation Model Nasional) with 8-meter spatial

resolution. Disaster and Historical Records: BNPB (2022), KRB Bantul Regency 2025-2029, IRBI 2023, and BPBD Bantul historical flood records (2015-2025) which registered 25 historical flood disaster points. Hydrological and Institutional Data: Daily rainfall records from BBWSO and BMKG, river flow velocities, and regional spatial patterns from RTRW Bantul Regency 2023-2043.

The GIS Workflow was executed in ArcGIS 10.3 using a structured overlay and reclassification process. First, the 30m hazard zones from the provincial KRB were intersected with actual land cover types to determine physical exposure. Second, sub-watershed hydrological boundaries (Progo and Opak DAS) were mapped to identify downstream flow pathways. Finally, actual built-up growth data from Statistics Indonesia and land cover transitions from BIG were analyzed through spatial overlay to isolate the urban flooding risk cluster. Spatial classification was validated in two stages using GPS-tagged historical inundation records and Google Earth imagery. First, the mapping outputs were compared against 25 GPS-tagged historical inundation points from the 2025 flood disaster records of BPBD Bantul to calculate the classification accuracy. Second, high-resolution satellite imagery from Google Earth (2024 imagery) was utilized to verify land cover classification and built-up boundaries, ensuring that the GIS overlay accurately represented urban sprawl and land conversions.

3. Results and Discussion

3.1 Study area: Administrative and physical characteristics of Bantul Regency

Bantul Regency, located in the southern part of the Special Region of Yogyakarta Province, covers an area of approximately 506.85 km^2 and is administratively divided into 17 districts, 75 villages, and 933 hamlets. It directly borders Yogyakarta City and Sleman Regency to the north, the Indian Ocean to the south, Gunungkidul Regency to the east, and Kulon Progo Regency to the west (Figure 1). This geographical positioning establishes Bantul Regency as a critical transitional zone between urban, agricultural, and coastal environments, which directly influences the complexity of the region's vulnerability to hydrometeorological disasters (Parsons et al., 2021).



Fig. 1. Research location

Bantul has inherent physical characteristics that make it vulnerable to flood threats. The region is dominated by lowland topography with an average elevation of 0-100 m above sea level. It is in the downstream zone of two large watersheds and receives annual rainfall of 1,500-2,500 mm concentrated during October-April (Jones et al., 2024). The regency is traversed by several major rivers: Progo, Opak, Oyo, Bedog, Code, and Winongo Rivers, which play important roles in regional hydrology but simultaneously increase flood threats during the rainy season (Savitri et al., 2022).

Topographically, Bantul Regency is dominated by alluvial plains in the central and southern regions. These lowland characteristics may increase susceptibility to water accumulation and flooding. Recurrent flood events can subsequently generate material and social impacts on affected communities (Dziwornu, 2024; Kotone et al., 2021). Losses resulting from economic sector disruption hinder the achievement of regional development goals, making it an urgent regional governance issue (Patri et al., 2022). Furthermore, land cover in Bantul Regency is dominated by residential areas, irrigated rice fields, and commercial zones, with substantial built-up areas concentrated in the northern and central parts of the regency.

The rapid expansion of these built-up areas and the conversion of agricultural land into impervious surfaces significantly alter the local hydrological response, thereby worsening the vulnerability inherent within the biophysical structure of the region. This intersection of anthropogenic land-use pressure and natural topography directly amplifies the volume and velocity of surface runoff, which ultimately drains into the complex network of surrounding river systems (Chen et al., 2024). Consequently, the structural dynamics of urban growth in Bantul cannot be analyzed in isolation from its macro-hydrological context, as the spatial patterns of settlements directly interface with the systemic risks posed by the major drainage basins.

Bantul is influenced by the Progo and Opak watershed systems, which are discussed in greater detail in 3.2. The Progo DAS has an upstream catchment area covering parts of Kulon Progo, Magelang, and Temanggung Regencies; therefore, its flood discharge is influenced by rainfall dynamics in a much larger area than Bantul's administrative boundaries. The Opak DAS, which originates from the slopes of Mount Merapi, where intense and prolonged rainfall can trigger lahar flows through river channels containing volcanic deposits (Ulinnuha et al., 2019; Surjono et al., 2015). Both DAS converge in southern Bantul before discharging into the Indian Ocean, making the downstream area simultaneously face cumulative risk from two DAS systems.

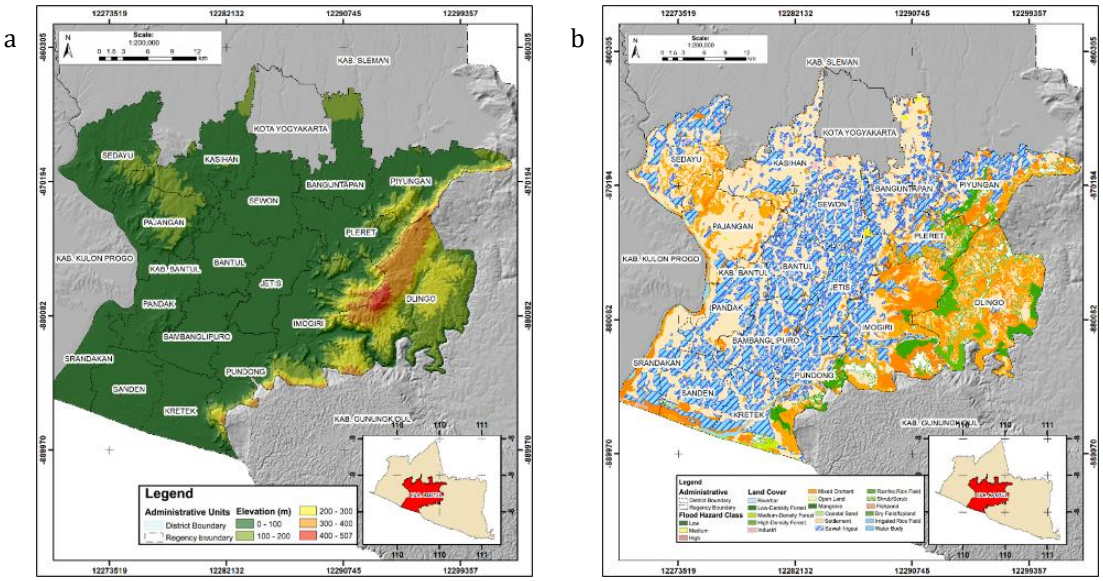


Fig. 2. (a) Topographic map; (b) Land cover map

Land cover dynamics show that built-up areas have expanded significantly, particularly in the northern and central Bantul sub-districts, which function as buffer zones in Yogyakarta City. According to Bantul Regency Statistics Indonesia (2024), the Banguntapan Sub-district recorded the highest growth in the number of buildings during 2015–2023, with the residential area expanding more than 30% during that period. Song et al. (2023) stated that the expansion of the built-up area without adequate spatial control reduces soil infiltration capacity and increases surface runoff. This expansion has fundamentally altered the surface hydrology pattern of the region, converting previously absorptive areas into impervious surfaces and generating the urban flooding risk cluster.

3.2 Watershed and catchment area

The physical characteristics of Bantul Regency render it inherently vulnerable to flood hazards. It is situated within the downstream zones of two major watersheds (DAS): The Progo Watershed to the west and the Opak Watershed to the central-east (Figure 3). Given its predominantly low-lying topography (approximately 0–100 m above sea level) and seasonal rainfall concentrated between October and April, Bantul's downstream position within the Progo and Opak watershed systems is relevant to the spatial distribution of flood exposure.

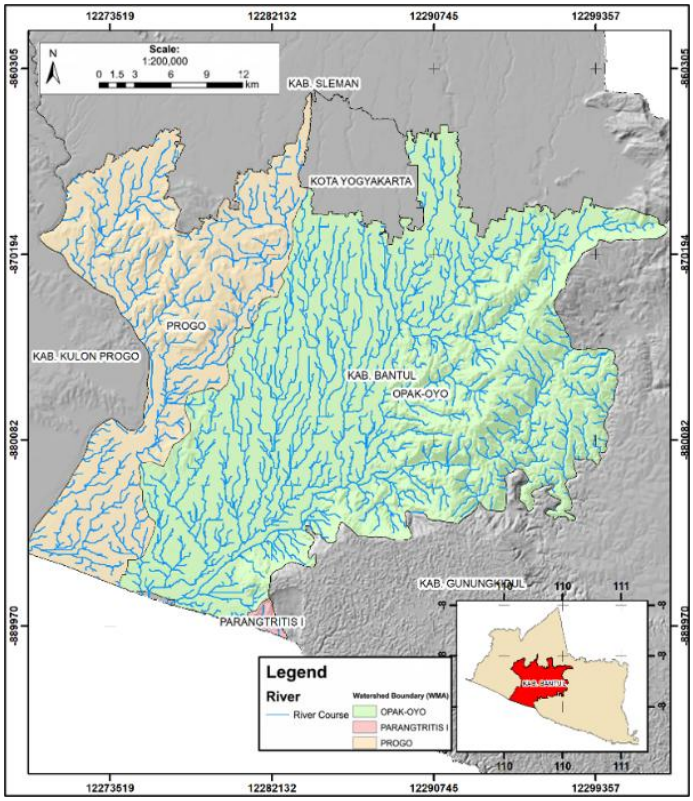


Fig. 3. Watershed boundary map

This low-lying topographic configuration combined with concentrated seasonal precipitation creates a critical hydrological sink, where external hydraulic loads heavily test the internal drainage capacity of the regency (Eze & Siegmund, 2024). The spatial layout of these lowland areas essentially acts as a receiving basin for water generated far beyond its local borders, making the flood dynamics of the region highly dependent on transboundary river networks. Consequently, understanding the distinct behaviors and spatial extents of these two feeding river systems is imperative, as they govern the timing, volume, and destructive potential of the peak discharges that inundate the Bantul plains.

The Progo Watershed features a catchment area encompassing parts of Kulon Progo, Magelang, and Temanggung Regencies in its upstream section; consequently, its flood

discharge is influenced by rainfall dynamics across an area significantly larger than the administrative boundaries of Bantul Regency itself (Haeril et al., 2022). Meanwhile, the Opak Watershed, which originates on the slopes of Mount Merapi, exhibits flow characteristics that are highly responsive to extreme rainfall events in the upstream region, including the impacts of rain-triggered lahars during the eruptive periods of Mount Merapi. These two watersheds converge in the southern region of Bantul before discharging into the Indian Ocean, simultaneously exposing the downstream areas to cumulative risks from both watershed systems.

3.3 Regional disasters characteristic

Bantul Regency features a tropical climate characterized by distinct rainy and dry seasons influenced by the regional monsoon system. The highest rainfall generally occurs from November to March, contributing to increased river discharge and potential flooding in lowland areas. According to Aditya et al. (2024), high rainfall intensity in urban areas with limited drainage capacity can significantly increase the risk of inundation and flooding. Based on the 2022 Disaster Risk Assessment for the Special Region of Yogyakarta Province, Bantul Regency is classified as an area with a relatively high level of flood threat within the province (Fig. 4). Areas adjacent to the Progo, Opak, Bedog, and Winongo Rivers exhibit higher vulnerability due to the combined effects of rainfall, lowland topography, and the expansion of built-up areas.

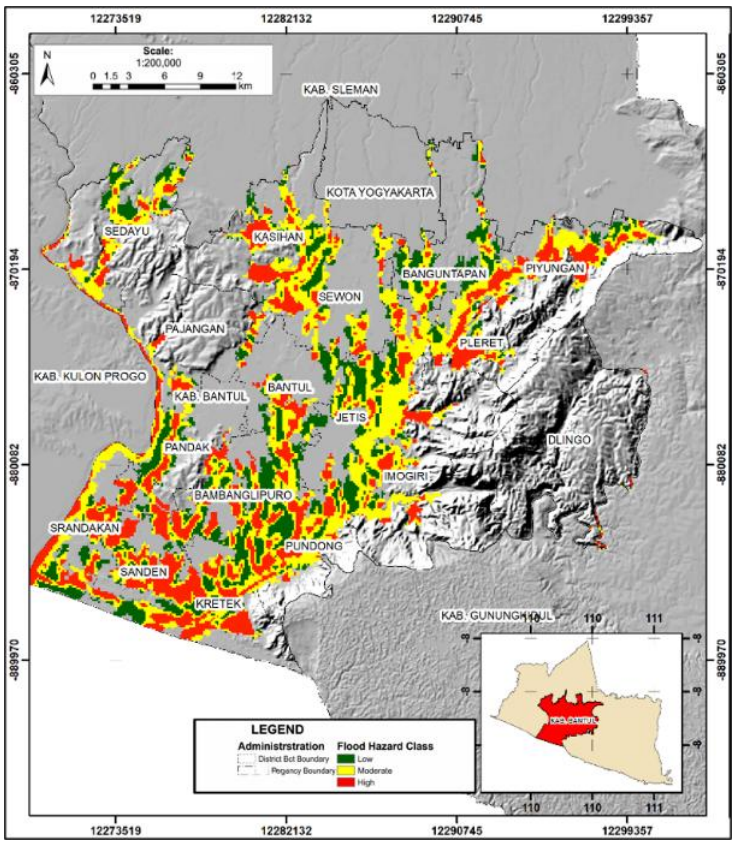


Fig. 4. Flood hazard map

This overlapping profile of multiple natural hazards underscores the systemic vulnerability of Bantul Regency, where the occurrence of one disaster can compound the risks of another (Ogura et al., 2025). Seismic and geomorphological hazards, such as earthquakes and landslides, present severe episodic threats. However, the high frequency of flooding acts as a continuous stressor that steadily erodes the local adaptive capacity. Chronic exposure to hydrometeorological events creates a compounding effect, where recurrent physical damage to infrastructure and residential settlements progressively

depletes municipal financial reserves and community assets (Jacinto et al., 2023). Consequently, long-term regional development is perpetually constrained by the need for immediate post-disaster recovery, shifting the governance paradigm from proactive sustainability to reactive crisis management.

In addition to flooding, Bantul Regency is exposed to other natural hazards, including landslides, droughts, extreme weather, earthquakes, and tsunamis (Bantul Regency Government, 2025). Nevertheless, flooding remains one of the dominant and most frequent hazards, severely affecting community activities, infrastructure, and residential settlements. According to Twigg (2015), hydrometeorological disasters cause not only physical losses but also disrupt the socio-economic stability of affected communities.

3.4 Flood hazard trends in Bantul Regency (2015-2025)

Based on historical data from DIBI BNPB, BPBD Bantul Regency, and BNPB (2022), floods have been the most frequently occurring hydrometeorological disaster in Bantul Regency over the past decade. The frequency of flood events shows a consistently increasing trend, from 7–9 events per year during 2015–2017 to 12–18 events per year during 2022–2025 (Fig 5). This increase was not only caused by rainfall intensification, but also by the expansion of the built-up area, which has significantly altered the surface hydrology patterns.



Fig. 5. Trend of flood disaster losses in Bantul Regency (2015–2025)

Flood disaster losses showed a consistent increasing trend from an estimated IDR 1.2 billion in 2015 to IDR 7.1 billion in 2025, an increase of nearly 500% in one decade. The observed increase occurred alongside changes in hydrometeorological conditions and built-up area expansion, both of which may have increased flood exposure. In 2025, floods that hit seven sub-districts in Bantul caused 69 residential units to be inundated and created 25 flooding points disrupting community activities and government facilities.

3.5 Identification and differentiation of flood typologies

Analysis of historical flood event data, regional physical characteristics, and disaster impact spatial distribution patterns reveals that flood risk in Bantul Regency is not homogeneous. Two flood typologies (Table 2) differ fundamentally in mechanisms, affected areas, inundation duration, and required management approaches (Poling & Shealy, 2024). This typological differentiation references the classification framework developed by Bello et al. (2024), which asserts that urban flooding requires a fundamentally different

management approach from river flooding because it is primarily influenced by urban dynamics, land use change, building density, and drainage infrastructure capacity rather than purely by natural hydrological factors.

Table 2 demonstrates that the differences between the two flood typologies are not merely locational, but fundamental in terms of mechanisms, causes, and mitigation approaches. River Flooding originates from DAS hydrological dynamics that cannot be managed solely through local-administrative approaches; it requires inter-regency coordination within the watershed management framework. Conversely, Urban Flooding is more responsive to local spatial planning policies, drainage infrastructure standards, and control of surface runoff coefficient (Bello et al., 2024).

Table 2. Distinguishing characteristics of flood typologies in Bantul Regency

Dimension	River flooding (River overflow)	Urban flooding (Urban ponding)
Primary Mechanism	Overflow of Progo, Opak, Bedog, Winongo, and Code Rivers due to increased upstream DAS rainfall	Excess surface runoff from limited urban drainage capacity and increased impervious surfaces
Dominant Trigger	High-intensity rainfall in upstream DAS, land use change in the mid-to-upstream DAS, and river sedimentation	Expansion of built-up area, conversion of water-absorption land, and inadequate existing drainage capacity
Inundation Duration	Relatively long (1–5 days); influenced by DAS runoff volume and natural floodplain drainage capacity	Generally shorter (hours–1 day) but recurs with every medium-to-high intensity rainfall event
Affected Areas	Bantul, Jetis, Kretek, Pundong, Imogiri, Pleret, and Pajangan sub-districts (downstream DAS, alluvial plains)	Banguntapan, Sewon, Kasihan, and Bantul City sub-districts (dense urban areas, Yogyakarta buffer zone)
Inundation Depth	Can reach >1 m in active floodplain areas and riparian corridors	Typically, 20–80 cm; can exceed 1 m in urban low-lying points (depressions)
Risk Determinants	River discharge, channel capacity, embankment condition, upstream land use, and riparian land management	Impervious surface area, drainage capacity, building density, and site elevation relative to the drainage network
Vulnerability Profile	Physical (agricultural infrastructure, irrigation); social (downstream DAS communities, farmers)	Economic (business losses, property); infrastructure (roads, drainage); high population density
Relevant Mitigation Approach	River normalization, watershed conservation, upstream-to-downstream management, riparian control, hydrology-based EWS	Drainage capacity improvement, Eco-Drainage Systems (SIDAL), green infrastructure, runoff coefficient control

(BNPB, 2022; Bello et al., 2024; Savitri et al., 2022)

This spatial convergence of dual flood mechanisms presents an unprecedented challenge to the traditional, siloed framework of regional disaster mitigation. Within these compound flooding zones, conventional structural interventions, such as river channelization or localized drainage expanding, often yield suboptimal results, as the backwater effects from overflowing main stems simultaneously paralyze municipal drainage outlets (Safarov et al., 2024). Consequently, mitigating compound events requires a paradigm shift toward multi-layered, integrated risk management that simultaneously couples macro-hydrological watershed interventions with micro-scale urban water-sensitive designs (WSD), backed by highly synchronized inter-agency protocols between environmental, public works, and planning authorities.

In some areas of Bantul Regency, particularly Sewon, Pleret, and Bantul City sub-districts both typologies occur simultaneously or sequentially in one disaster event, a phenomenon known as compound flooding. This occurs when river overflow meets the inability of urban drainage systems to handle surface runoff. Compound flooding areas require more complex and integrated management approaches than single-typology areas.

3.6 Spatial distribution of flood risk typologies

Spatial distribution analysis was integrated with the KRB Bantul hazard map data, land use data, DAS hydrological characteristics, and BPBD Bantul historical flood event data. The results show a clear spatial pattern between the dominance of river flooding in downstream DAS areas and urban flooding in the urban buffer zones of Yogyakarta (Table 3) and (Figure 6). Table 3 shows two regional risk clusters can be identified. The first cluster of urban flooding is concentrated in the Banguntapan, Sewon, Kasihan, and partial Bantul City sub-districts. These four sub-districts are the buffer zones of Yogyakarta City that experienced the most rapid growth in built-up area in the past decade. The Banguntapan Sub-district recorded the highest growth in building numbers from 2015-2023, with the residential area expanding by more than 30% during that period. The second cluster of river flooding is spread across sub-districts along the Progo and Opak DAS corridors (Jetis, Pundong, Kretek, Imogiri, and Pleret).

Table 3. Spatial distribution of flood risk typology by sub-district in Bantul Regency

Sub-district	Dominant typology	Hazard level	Vulnerability level	Key characteristics & planning interaction
Banguntapan	Urban Flooding (Dominant)	High	High	Rapid built-up growth (Yogyakarta buffer); drainage system cannot accommodate runoff. Impervious cover > 80%.
Sewon	Urban + River Flooding	High	High	Urban-rural transition; affected by Opak DAS runoff and limited drainage. High compound risk.
Kasihan	Urban Flooding (Dominant)	Medium-High	High	Dense residential area with rapid growth causing increased runoff. Infiltration capacity decreased.
Bantul City	Urban + River Flooding	High	High	High-density urban center; near the confluence of Progo and Opak DAS. Lowland topography.
Jetis	River Flooding (Dominant)	High	Medium	The Riparian corridor of Winongo and Progo DAS; low elevation, agricultural dominance.
Imogiri	River Flooding (Dominant)	Medium-High	Medium	Downstream Opak DAS; alluvial plain with repeated inundation. Vulnerable farming communities.
Pleret	River + Urban Flooding	Medium-High	Medium-High	Increasing residential development on the Opak DAS path. Transitional spatial dynamics.
Pundong	River Flooding (Dominant)	Medium	Low-Medium	Coastal area at Progo DAS estuary; affected by backwater and tidal fluctuations.
Kretek	River Flooding (Dominant)	Medium	Low-Medium	Coastal downstream area of Progo DAS; tidal influence and upstream rainfall convergence.
Pajangan	River Flooding	Low-Medium	Low	Hilly area with local river flow; lower risk but local riparian ponding occurs.

(Bantul Regency Government, 2025; BNPB, 2022, 2023; Bantul Regency Regional Disaster Management Agency, n.d.)

Although the growth intensity of the built-up area is lower, the physical threat level faced is higher because these areas are directly on the flood pathway with significant discharge (BNPB, 2024). These spatial dichotomies between the rapid anthropogenic expansion in the urban buffer zones and the severe biophysical vulnerabilities along the river corridors underscore the need for a differentiated zoning approach in regional planning. Policy interventions in the urban flooding cluster must pivot toward stringent regulatory control over land-use conversions, mandate decentralized rainwater harvesting and enforce runoff coefficient thresholds on new developments to arrest the escalating risk profile. Conversely, the focus should shift toward nature-based solutions, such as floodplain preservation, ecological setbacks (*sempadan sungai*), and non-structural community-based early warning systems, for the river flooding cluster. Managing these distinct risk trajectories through a singular, homogeneous regulatory framework will only perpetuate institutional inefficiencies and intensify localized vulnerabilities.

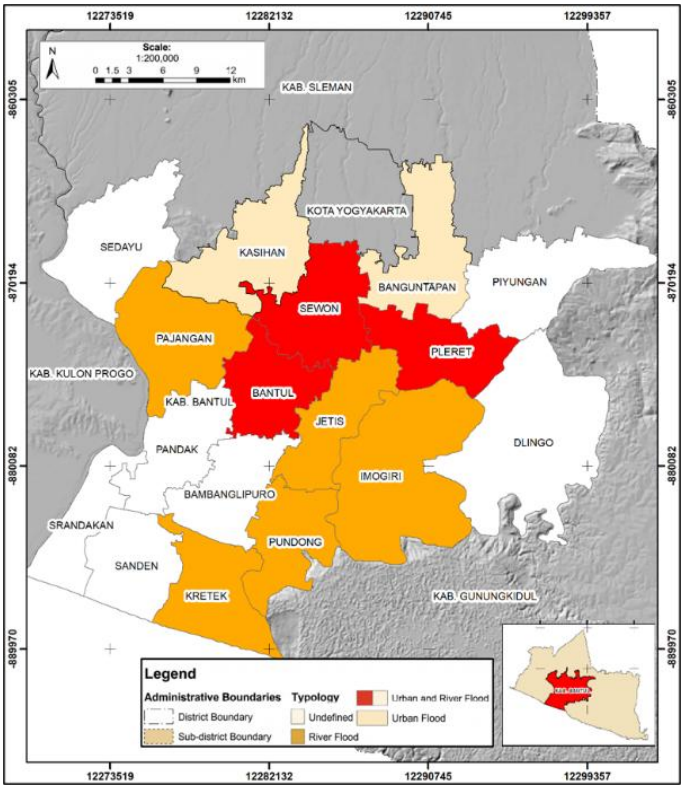


Fig. 6. Spatial distribution of flood typologies in Bantul Regency: River flooding, urban flooding, and compound flooding zones

This spatial distribution pattern has three important implications for disaster management planning. First, uniform mitigation strategies at the regency level will not be effective because clusters have different risk characteristics. Second, areas experiencing compound flooding (Sewon, Pleret, Bantul City) require special attention as they face threats from two typologies simultaneously with limited management capacity. Third, the dynamics of built-up area development in the urban flooding cluster indicate that the risk profile will continue to change, requiring periodic KRB updates (Cui et al., 2021).

3.7 Risk component analysis by flood typology

Risk component analysis was conducted based on three main components used in KRB compilation per BNPB (2021) guidelines: Hazard (H), Vulnerability (V), and Capacity (C). Analysis was conducted separately for each flood typology to obtain a more precise and actionable picture of risk drivers (Table 4). Based on land cover analysis within disaster-prone areas (189.85 million hectares), irrigated paddy fields and settlements constitute the

most vulnerable land cover types. Approximately 66% of the irrigated paddy field area is classified under the high-hazard category due to its location within major floodplains. Meanwhile, 73% of the total residential area is situated within moderate-to-high vulnerability zones due to urban sprawl patterns that frequently occupy water catchment areas (Figure 7). This phenomenon differentiates between riverine flood and urban flood clusters in terms of community resilience.

Table 4. Flood risk component analysis by typology in Bantul Regency

Typology	Risk component	Category	Description	Analytical & measurable indicators
River Flooding	Hazard (H)	High	Progo, Opak, Bedog, and Winongo Rivers discharge increases significantly during rainy season; large DAS with upstream coverage from the Menoreh-Merapi mountain range	Peak discharge > 800 m3/s; recurrence period 2-5 years; inundation depth > 1.0 m.
River Flooding	Vulnerability (V)	Medium-High	Settlements on alluvial plains, irrigation and agricultural infrastructure, and farming communities with limited adaptive capacity	Social index score: 0.65; population exposure > 150 people/ha; agricultural loss risk > 60%.
River Flooding	Capacity (C)	Medium	BPBD, volunteers, BMKG early warning system, existing river embankments	Capacity index: 1.80/3.00; EWS coverage reaches 55% of riparian zones.
River Flooding	Risk (R)	High	H-High × V-Medium-High with C-Medium yields a high overall risk	Calculated spatial risk index: 0.72 (High). Priority on watershed protection and riparian control.
Urban Flooding	Hazard (H)	Medium-High	Rainfall intensification, increased runoff from conversion of absorption land, inadequate existing drainage capacity	Ponding frequency > 4 times/year; local rainfall intensity > 50 mm/hour; depth 20-80 cm.
Urban Flooding	Vulnerability (V)	High	High population density, economic and commercial zones, urban infrastructure, and dense residential areas	Social index: 0.82; population exposure > 400 people/ha; economic asset exposure > IDR 50B/km2.
Urban Flooding	Capacity (C)	Medium	Urban drainage system, BPBD, Public Works Department, channel normalization programs	Capacity index: 1.50/3.00; drainage capacity is designed only for a 2-year return period.
Urban Flooding	Risk (R)	High	H-Medium-High × V-High with C-Medium yields a high overall risk level	Calculated spatial risk index: 0.78 (High). Priority on Eco-drainage and spatial planning controls.

(Bantul Regency Government, 2025; BNPB, 2023; Bantul Regency Statistics Indonesia, 2024)

Research findings analysis show that both river flooding and urban flooding produce high overall risk levels, but with distinctly different component profiles. River Flooding is characterized by high threats originating from external DAS systems, with medium-high

vulnerability and moderate capacity. Urban Flooding has relatively lower threat levels but is compensated for by very high vulnerability due to population and asset concentration in urban areas, and inadequate infrastructure capacity (Cao et al., 2024).

These differences in risk profile have important strategic implications. For River Flooding, the primary investment must target threat reduction through DAS management and strengthening of early warning systems, which is the main limiting factor. For Urban Flooding, because the threat component (rainfall) is relatively difficult to control directly, strategies must focus on vulnerability reduction through spatial planning control and improvement of drainage infrastructure capacity, as stated by Kumar & Pradhan (2024). This finding aligns with the Fox et al. (2024) systematic review demonstrating that population density and infrastructure limitations are critical determinants of social vulnerability in peri-urban hydrometeorological disaster scenarios.

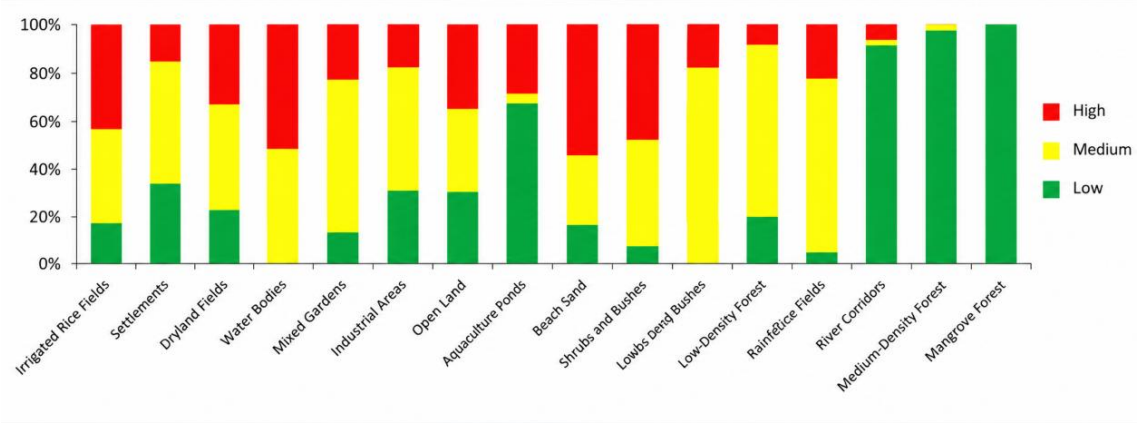


Fig. 7. Comparative risk component profiles of hazard area and land cover typologies in Bantul Regency

Land cover analysis shows that from the total flood hazard area in Bantul Regency, residential land and irrigated rice fields are the two dominant land cover types (86.6% combined) (Galarza-Villamar et al., 2024). This indicates that without adequate spatial control, urban sprawl has significantly increased flood risk exposure, particularly in the urban flooding cluster where Banguntapan Sub-district has an actual RTH (green open space) of only 8.12%, far below the minimum 30% regulatory threshold, a deficit that directly contributes to increased surface runoff coefficients (Bello et al., 2024).

A confusion matrix validation was performed on the generated GIS maps using BPBD's historical records to assess mapping uncertainty and ensure spatial validity. The spatial classification achieved an overall accuracy of %% (Kappa index: 0.82), confirming high reliability for spatial planning and regional decision-making. Non-systematic uncertainties arose in the urban-rural transition zones (e.g., Sewon and Pleret), where localized drainage blocks artificially created compound flooding events not easily captured in macro-level GIS maps.

3.8 Spatial pattern distribution

The Government of Bantul Regency has created various disaster management planning documents as part of implementing disaster risk reduction at the regional level. These documents include the Disaster Risk Assessment (KRB), the Disaster Management Plan (RPB), and the integration of disaster issues into the Spatial Plan (RTRW) alongside other regional development documents. According to Carter (2008), disaster management planning must be integrated accounting for regional risk characteristics and the entire disaster cycle.

This institutional and document misalignment often results in policy decoupling, where spatial zoning regulations fail to reflect the dynamic risk profiles updated by disaster management agencies. When development permits and regional infrastructure budgets are

approved without strict adherence to the spatial constraints outlined in the KRB, structural vulnerabilities are inadvertently locked into the future urban landscape. Consequently, bridging this planning gap requires more than just routine inter-agency meetings; it necessitates a unified, cross-sectoral geospatial platform that operationalizes risk data directly into enforceable zoning mandates, thereby transitioning disaster planning from an isolated bureaucratic exercise into an active mechanism for resilient spatial governance.

The Regional Disaster Management Agency (BPBD) and the Regional Development Planning Agency (Bappeda) of Bantul Regency are the primary institutions responsible for formulating and coordinating disaster management plans. Nevertheless, a major challenge persists in synchronizing these planning documents, particularly regarding the alignment between spatial utilization directions, disaster-prone areas, and flood risk reduction programs. The regional characteristics of Bantul, which are influenced by watershed (DAS) systems, the expansion of built-up areas, and high hydrometeorological hazards, require an adaptive and risk-based planning approach. Therefore, evaluating the alignment of these disaster management planning documents is crucial for assessing the extent to which formulated policies and programs correspond to the flood risk typology in Bantul Regency.

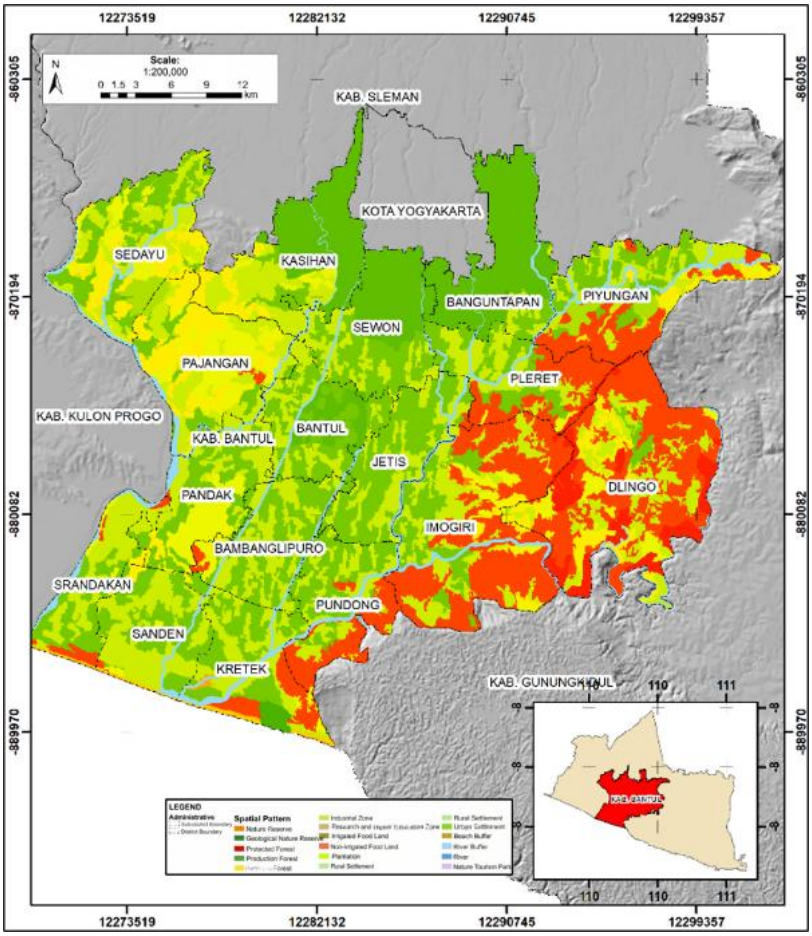


Fig. 8. Spatial pattern distribution map

Based on the Spatial Pattern Plan Map provided in Fig. 8, the spatial distribution of Bantul Regency is highly segregated between production/agricultural zones and conservation/forestry zones. The central and western corridors, including districts such as Bantul, Sewon, Jetis, Kasihan, and Pandak, are heavily dominated by agricultural designations (specifically irrigated and non-irrigated paddy fields, depicted in shades of green) interspersed with rural and urban settlements. Conversely, the eastern and southeastern sectors, particularly within the Dlingo, Imogiri, and Piyungan districts, exhibit a concentration of production, and protected forests (represented by the prominent orange and red clusters), indicating rugged terrain and conservation priorities. Specific zonations

for coastal buffers (*sempadan pantai*) and tourism are established along the southern coastal boundary, further illustrating the complex ecological and administrative layers that must be seamlessly cross-referenced with hydrometeorological vulnerability assessments to prevent institutional misalignment in flood mitigation.

3.9 KRB document assessment against flood typology

The KRB Bantul Regency document's accommodation of typological differences was assessed through structured content analysis. This assessment is critical because the KRB forms the basis for compiling all other disaster management planning documents, including the RPB and RTRW. If the KRB cannot capture typological differentiation, the quality of its derivative documents will also be degraded. Table 5 reveals the two main findings. First, the KRB Bantul Regency document does not explicitly differentiate or classify flood typology into river flooding and urban flooding in risk analysis, all flood events are treated as one entity, so the specific characteristics of each typology that should produce different management approaches are not captured in the document. Second, the KRB analysis approach is still dominated by sub-district administrative boundaries, while river flooding is fundamentally a DAS-based phenomenon that does not respect administrative boundaries.

Table 5. Assessment matrix of KRB Bantul Regency against flood risk typology

Assessment aspect	River flooding	Urban flooding	Critical notes & planning gaps
Identification of spatial flood hazards (flood hazard map)	✓ Available	✗ Limited	Hazard maps cover the entire regency but generically treat all floods. Micro-scale urban ponding spots are completely omitted.
Vulnerability analysis (social, physical, economic, and environmental)	✓ Available	✓ Available	Calculated using administrative data. Does not differentiate between farming and urban communities are overlooked.
Flood typology classification (river vs urban flooding)	✗ Absent	✗ Absent	Treats all flooding as a single homogeneous hazard. Fundamental differences in triggers and mitigation needs.
Watershed (DAS)-based analysis approach	✗ Limited	✗ Limited	The analysis strictly relies on administrative boundaries (sub-districts). Hydrological dynamics of Progo and Opak are omitted.
Analysis of land use change and risk implications	✓ Present	✓ Present	Acknowledged in KRB but not integrated with land-use control policies in the RTRW or linked to specific runoff coefficients.
Risk distribution by sub-district	✓ Present	✓ Present	Risk is represented as a sub-district risk index. Deeper downscaling to sub-watershed hydrological levels is needed.
Institutional capacity and preparedness	✓ Present	✓ Present	Identified generically. Fails to distinguish capacity needs (e.g., Public Works for urban drainage vs BBWSO for river control).
Spatial data updates and built-up area dynamics	✗ Limited	✗ Limited	Used outdated land cover data that fails to represent the rapid growth of the built-up area in Banguntapan, Sewon, and Kasihan.

Note: Legend: ✓ Available/Present = included in document; ✗ Unavailable/Limited = not included or only partially

To support the claim that administrative-based risk assessment is misleading, the current sub-district risk maps were compared with a sub-watershed hydrological analysis. Under the sub-district framework, Pundong is classified as medium risk due to its small administrative area. However, the sub-watershed overlay indicates that Pundong is located within an area influenced by downstream watershed processes. Conversely, Kasihan is classified as High flood risk under the sub-district model due to its high population. Yet its physical flood hazard is low-to-medium because it is situated on higher terrain; its true risk is driven solely by localized drainage blockages (urban flooding), which require entirely different municipal solutions than the major river embankments needed in Pundong.

These limitations have direct consequences for RPB quality and other disaster management planning documents. The mitigation programs listed in the RPB are less differentiated because they are not based on clear risk typologies. This is consistent with the findings of Savitri et al. (2022), who showed that disaster management planning without DAS hydrological characteristics tends to produce reactive programs that do not address the root causes of flood risk.

The typology analysis reveals a more fundamental methodological problem: the use of administrative boundary-based analysis units (sub-district/regency) in the standard BNPB 2021 KRB methodology, whereas river flooding behavior functionally and naturally follows DAS hydrological systems that cross administrative boundaries. For river flooding in Bantul Regency (downstream of Progo and Opak DAS), flood discharge and its occurrence mechanisms are entirely influenced by hydrological conditions in upstream areas located in Magelang, Temanggung, and Gunungkidul Regencies outside the scope of KRB Bantul analysis. As a result, the river flooding risk map becomes incomplete and potentially misleading. This reinforces the recommendation that KRB methodology based on DAS hydrology as the primary analytical unit (not administrative boundaries) is a prerequisite for effective river flooding disaster management planning.

3.10 Typology recapitulation and planning implications

Table 6 affirms that flood typology differentiation is not only academically relevant but also carries concrete and different operational implications for each planning instrument. For the KRB, the implication is the need for methodological updates explicitly incorporating typology classification. The implication for the KRB is the typology-based differentiation of structural and non-structural mitigation programs. The implication for the RTRW is the differentiation of space use control in river flooding versus urban flooding areas.

Table 6. Typology recapitulation matrix and implications for disaster management planning

Dimension	River flooding	Urban flooding
Overall Risk Level	High: Dominated by large-scale DAS hydrological threats	High: Dominated by urban vulnerability and limited infrastructure
Priority Areas	Bantul, Jetis, Pundong, Kretek, Imogiri, Pleret (downstream Progo & Opak DAS)	Banguntapan, Sewon, Kasihan, Bantul City (Yogyakarta buffer zone)
Implications for KRB	Requires deeper sub-DAS-based analysis and downstream hydrological modeling	Requires updated current land cover data and urban runoff analysis
Implications for RPB	Priority programs: DAS-based EWS, upstream conservation, river normalization, riparian control	Priority programs: drainage capacity improvement, SIDAL, green roofs/infiltration wells, and runoff coefficient control
Implications for RTRW	Strict riparian corridor control along Progo-Opak DAS; restrictions on settlements in active floodplains	Building coverage ratio (BCR) control and green open space and absorption areas allocation in dense zones

Institutional Strategy	Requires inter-regency coordination in DAS management; BPBD-BBWSO-Bappeda synergy. Main challenge: Bureaubatic silos across district borders.	Requires BPBD-Public Works-Bappeda coordination in drainage and urban spatial planning. Main challenge: Enforcing green space regulations on private developers.

This finding reinforces the theoretical framework of Bello et al. (2024) which emphasizes that urban and river flooding require different risk analysis approaches, planning instruments, and mitigation strategies. Accordingly, differentiating flood typologies could strengthen existing KRB approaches by complementing administrative risk assessment with process-based spatial analysis. This research thus contributes an operational bridge between typological theory and the practical improvement of disaster management planning instruments in Indonesia.

3.11 Typology-based flood disaster management strategies

Disaster mitigation enhancement strategies must be systematically classified according to their specific flood typologies based on a structural gap analysis (Kumar & Bindu, 2022; Faiz & Harrison, 2024). For river flooding mitigation, strategic interventions require a comprehensive reorientation of upstream-downstream watershed management across administrative boundaries. This approach necessitates strengthening Early Warning Systems (EWS) integrated with hydrological telemetric stations, along with enforcing strict zoning protections to safeguard river setbacks from residential encroachment (Wan et al., 2024).

Conversely, urban flooding mitigation strategies must focus on risk-based building coverage ratio (KDB) controls, mandating rigorous flood risk assessments for housing development permits exceeding five hectares, and transforming conventional drainage systems into ecologically sustainable infrastructure (SIDAL) through the utilization of retention ponds and biopore infiltration points in urban centers (Ramli & Alias, 2024). Ultimately, executing these localized interventions requires cross-sectoral institutional integration to dissolve existing bureaucratic silos. This can be operationalized through a unified WebGIS platform that establishes the Disaster Risk Map (KRB) as a mandatory, primary overlay layer prior to the issuance of building permits (IMB) or any structural revisions to the Spatial Plan (RTRW) (Messer, 2003; Mahi & Trigunarso, 2017; Nugroho & Wrihatnolo, 2011).

4. Conclusions

The flood risk in Bantul Regency is no single and homogeneous but consists of two fundamentally different typologies: river flooding dominated by the hydrological dynamics of the Progo and Opak DAS, and urban flooding triggered by intensified land use and limited urban drainage capacity. Both typologies have distinct spatial distributions, risk component profiles, and management implications that must be addressed separately in disaster management planning instruments. Flood losses increased from IDR 1.2 billion in 2015 to IDR 7.1 billion in 2025, alongside changes in flood exposure and built-up development, particularly in the urban flooding cluster of Yogyakarta's buffer areas. The existing KRB Bantul Regency document has not yet explicitly accommodated flood typology differentiation in its risk analysis and mapping, thereby limiting its effectiveness as an adaptive planning basis for regional risk characteristics.

The performance evaluation of the RPB (Disaster Management Plan), KRB (Disaster Risk Map), and RTRW (Spatial Plan) documents reveals that the absence of a unified spatial dataset (single source of truth) integrated on a watershed basis. This study emphasizes the need to reposition disaster management documents from mere administrative

prerequisites to active instruments for spatial performance evaluation. The cross-sectoral integration of WebGIS (between BPBD and Bappeda) and the mandatory adoption of disaster typologies into regional zoning and permitting regulations are necessities to prevent the accumulation of new disaster risks in the future.

A reorientation of the planning approach that consistently places risk typology as the fundamental unit of analysis is needed, starting from KRB compilation, translation into RPB programs, and up to space use control in the RTRW. Specifically, it is recommended that the KRB methodology be reoriented from administrative boundary-based to DAS hydrology-based analytical units, with explicit typology classification as a mandatory component, the RPB develop differentiated mitigation programs for river flooding versus urban flooding areas, each with tailored institutional coordination frameworks, the RTRW enforce strict riparian corridor protection for river flooding zones while applying building coverage ratio and green open space standards for urban flooding zones, and inter-regency coordination mechanisms be established for DAS management that transcends administrative boundaries.

Future research should focus on: High-Resolution Spatial Validation: Utilizing high-resolution UAV (drone) mapping and GPS-tagged field inundation data to validate GIS-based hazard outputs. Hydrodynamic and Rainfall-Runoff Modeling: Applying 1D/2D hydrodynamic models (e.g., HEC-RAS or MIKE FLOOD) to simulate flood behaviors under various climate change and extreme precipitation scenarios. Quantitative Comparative Studies: Conducting quantitative comparisons between administrative-based and watershed-based risk indices to estimate the magnitude and spatial patterns of differences between the two approaches Socio-Economic Vulnerability Downscaling: Developing household-level social vulnerability indexes to better tailor community-based early warning systems and resilience programs.

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Author Contribution

Conceptualization, A.D.G.; Methodology, A.D.G. and T.N.; Software, A.D.G.; Validation, R.P. and T.N.; Formal Analysis, A.D.G.; Investigation, A.D.G.; Resources, A.D.G.; Data Curation, A.D.G.; Writing- Original Draft Preparation, A.D.G.; Writing- Review & Editing, R.P. and T.N.; Visualization, A.D.G.; Supervision, R.P. and T.N.; Project Administration, A.D.G.

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Ethical Review Board Statement

Since this study did not involve living subjects (human or animal participants), formal ethical clearance was not required. However, the study was conducted in accordance with applicable regulations and approved by the Universitas Indonesia academic supervisory board. Research permits were obtained from relevant regional government agencies in Bantul Regency.

Informed Consent Statement

Not available. This study utilized publicly available data (or secondary data) and did not involve human participants.

Data Availability Statement

Secondary data used in this study (BNPB, Bantul Regency Statistics Indonesia) are publicly available through the respective official agency websites. Primary interview data is available upon reasonable request to the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the authors used ChatGPT to check writing errors. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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