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Assessing Coastal Soil Capacity and Flood Risk in Kulon Progo Coastal Area, Indonesia

Ikrom Mustofa[a]*, Niesa Hanum Mistoro[a], M. Said Ramdlan[b], Dewi Wulandari[a]

[a]Department of Environmental Engineering, Faculty of Civil Engineering and Planning, Universitas Islam Indonesia, Sleman, 55584, Indonesia

[b]Department of Environmental Engineering, Faculty of Engineering, Universitas Nahdlatul Ulama NTB, Mataram, 83125, Indonesia

*Corresponding author: ikrommustofa@uii.ac.id

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Abstract

The coastal areas of Kulon Progo, including the salt marshes, play a vital role in mitigating hydrometeorological disasters by regulating water flow. However, rapid land-use changes driven by the construction of Yogyakarta International Airport (YIA) have altered the region's environmental balance. This study investigates the water retention capacity of coastal soils in Kulon Progo and examines how differences across land-use types may influence flood risks. Rather than tracking changes over time, the study uses cross-sectional comparisons and historical land-use and flood data to infer potential impacts of land transformation on hydrological hazards. Field investigations using standard soil physical property analysis were conducted at nine sites across three villages (Jangkaran, Palihan, and Glagah) in Kulon Progo to capture variations in soil characteristics related to land use changes from the airport development and its buffer zones. Bulk density ranges from 1.16 g/cm³ to 2.18 g/cm³, particle density between 2.46 g/cm³ and 5.15 g/cm³, and porosity levels from 48.16% to 66.67%. Areas near converted lands show higher density and lower porosity, reducing infiltration and increasing surface runoff. Historical flood data from the Regional Disaster Management Agency (BPBD) indicates rising flood frequency over the past decade, especially after major land conversions. This trend aligns with the study's findings, as areas with lower porosity experience recurrent flooding. The reduced absorption capacity due to increased soil compaction is a key factor driving flood risks. This research supports Indonesia's Nationally Determined Contributions (NDC) roadmap for climate adaptation by providing empirical evidence for disaster risk reduction. The findings highlight the need to preserve salt marshes and integrate soil management into land-use planning to enhance climate resilience and mitigate future flood risks in the Kulon Progo coastal region.

Keywords: Climate adaptation, Coastal soil, Flood risk, Kulon Progo, Land-use change.

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1. Introduction

The coastal area of Kulon Progo in the Special Region of Yogyakarta, Indonesia is increasingly vulnerable to hydrometeorological disasters, especially flooding (Mustofa *et al.,* 2025). The increasing of flood events, especially coastal floods and river floods over the past decade have become evidence of this vulnerability. Although there have been vital salt marshes that play critical role play a critical role in managing water flows and mitigating the impacts of extreme weather, flood events are inevitable (Nurhidayah *et al.,* 2022). Salt marshes, which act as natural barriers, are being disrupted by urban expansion, leading to increased flood risk and weakening the region's long-term resilience to climate change (Gedan *et al.,* 2009). Additionally, the construction of Yogyakarta International Airport (YIA) and the supporting facilities around these coastal areas in 2018 resulted in significant land use changes (Ramadhani *et al.,* 2022).

Conversion of agricultural land to impermeable surfaces significantly impacts the hydrological cycle and increases flooding risks (Prasena & Shrestha, 2013). The study by Sugianto *et al.* (2022) also proves the relationship between flood events and land use change, such as deforestation and urbanization can affect hydrological characteristics and increase flood risks. In alignment with the Nationally Determined Contributions (NDC) roadmap on adaptation, Indonesia aims to strengthen its capacity to reduce the risks of climate change, including the management of critical ecosystems, such as coastal zones as well as the communities' ability to to withstand hydrometeorological disasters (MoEF, 2020).

Furthermore, land use change into impervious areas will affect the reduction in infiltration capacity and leading to increasing surface runoff and causing flooding during heavy rains. Understanding variations in soil infiltration rate across different land-use categories is also important to monitor and mitigate the existing ecosystem vulnerabilities (Saco *et al.,* 2021). However, research regarding the impact of soil physical properties on this function remains limited and the existing research focuses primarily on the visible impacts of flood events (Ningsih & Mutaqin, 2024). Furthermore, this lack of empirical data limits and comprehensive studies especially in Kulon Progo's coastal areas,limits the ability of policymakers and planners to develop effective strategies for flood prevention and climate adaptation.

This study aims to assess differences in soil water capacity, especially the infiltration rate in the coastal areas of Kulon Progo, in relationship with land use changes and the increasing flood events. By comparing soil conditions across different land-use zones and aligning them with historical land-use and flood data, this study offers empirical insights into how current soil characteristics, shaped by land-use categories, may influence hydrometeorological hazards and provides valuable insights for flood mitigation and land use planning that aligns with disaster risk reduction and climate adaptation goals strategies, including conserving salt marshes.

2. Methods

2.1 Study Area

The research was conducted in the coastal region of Kulon Progo, located in the Yogyakarta Special Region, Indonesia, as shown in Figure 1.

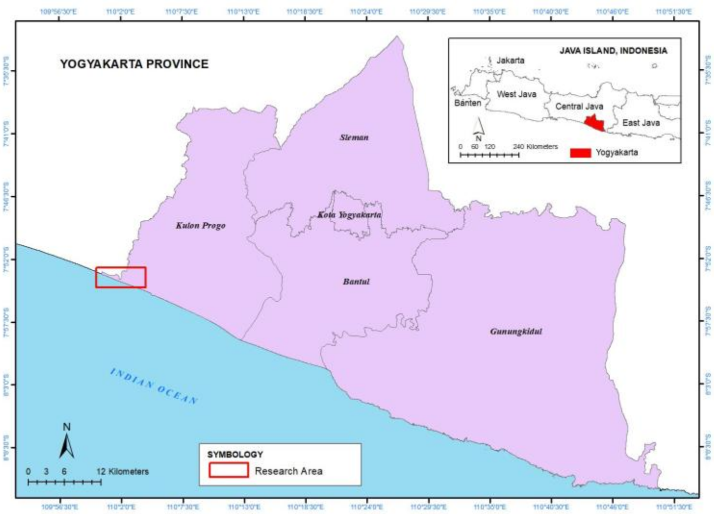

Figure 1. Study site located in Kulon Progo District

This area forms part of the southern coastal plain of Java Island and is characterized by sandy soil deposits, salt marshes, and coastal vegetation (Wulandani *et al.,* 2024). In addition to a tropical monsoon climate where heavy rainfall often exacerbates the risk of flooding, this coastal region lies adjacent to the Indian Ocean, which makes it highly susceptible to hydrometeorological hazards, especially coastal flooding, and sea-level rise.

The study conducted at nine sites across three villages (Jangkaran, Palihan, and Glagah) in Kulon Progo focusing on three distinct zones (natural zone, agricultural zone, and urban-converted zone) to capture different stages of land-use categories (Figure 2). The natural zone consists of salt marshes and coastal dunes have function as buffer areas by absorbing and retaining stormwater. The agricultural zone, located near the YIA buffer area, is primarily used for seasonal crops and has recently been pressured by the expanding urban infrastructure as a consequence of YIA construction. The urban-converted zone comprises areas directly affected by airport development and urban expansion, leading to increased impervious surfaces that reduce the soil water capacity. This area is also a priority focus for climate change adaptation and disaster risk resilience in vulnerable coastal regions under Indonesia's Nationally Determined Contributions (NDC) roadmap.

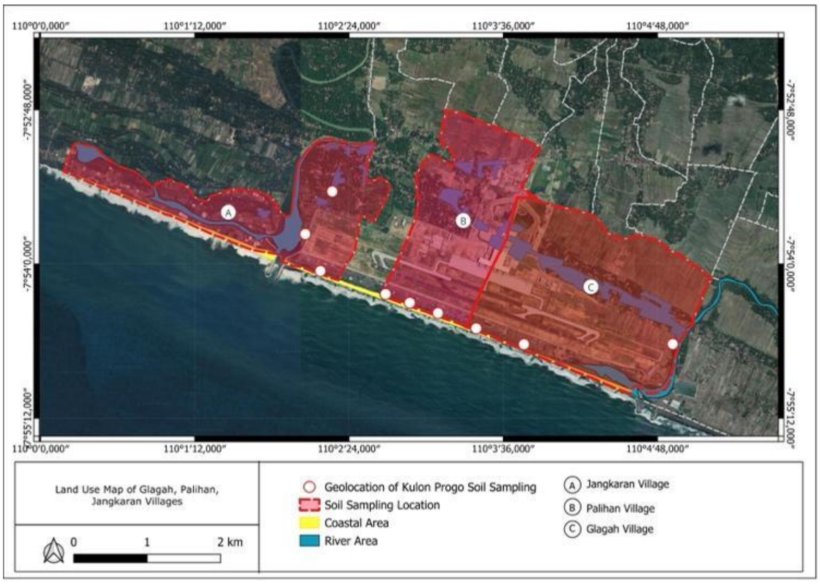

Figure 2. Specific study location

2.2 Soil Sampling and Analysis

The analysis of soil physical properties was conducted across three distinct zones in the Kulon Progo coastal region to evaluate the land use changes that influence soil water capacity and lead to increasing flood risks in these coastal areas. In each zone, soil samples were collected at a depth of 0–30 cm with core boring soil technique, as this surface layer is the most critical for accurate measurement of physical properties and the upper soil layers are most affected by surface runoff, infiltration capacity, and land-use changes. After the collection of samples, laboratory analyses were conducted using standard soil analysis procedures commonly applied in Indonesia. Bulk density was measured using the core method following the USDA Soil Survey Manual (2017), which involves collecting undisturbed soil samples with known volume. Particle density was determined using the pycnometer method based on ASTM D854, widely adopted in Indonesian soil laboratories. Soil porosity was calculated indirectly using the relationship between bulk density and particle density, following the formula:

$$\text{Porosity (\%)} = \left(1 - \frac{Bulk\ Density}{Particle\ Density}\right) x\ 100$$

These methods ensure consistent and reliable evaluation of soil's water retention characteristics and are in line with standard practices used for environmental and land-use impact assessments in Indonesia. The natural zone, including salt marshes, was expected to show higher porosity by its looser soil structure promoting higher soil infiltration rate and soil water capacity. In contrast, the agricultural and urban-converted zones, which have experienced soil disturbance and compaction by land use changes, were anticipated to show lower porosity, leading to reduced water retention and higher runoff potential. The results of the soil analysis were later integrated with flood event data and land-use change assessments to establish a comprehensive understanding of the flood dynamics in the Kulon Progo coastal area.

2.3 Land-use Change Analysis

The land-use change analysis focused on assessing land-use differences and spatial patterns in the three distinct zones over the past decade, particularly after the construction of Yogyakarta International Airport (YIA). Data from satellite imagery, official land-use maps, and reports from local authorities were compared to identify major transitions in these zones, including the conversion of natural salt marshes and agricultural fields into urban infrastructure.

This study also highlights the changing of the local hydrology cycle and integrates with soil properties data to understand the relationship between land-use categories of the results in increasing flood events. To assess changes in the local hydrological cycle, this study employed an integrative, indicator-based approach. Instead of direct hydrological modeling, we inferred alterations based on three key components: (1) spatial analysis of land-use change using satellite imagery and official maps; (2) measured variations in soil physical properties (bulk density, porosity, and particle density); and (3) historical flood event data obtained from BPBD Kulon Progo. These parameters jointly represent essential aspects of the hydrological cycle, such as infiltration capacity, surface runoff potential, and water retention. This approach aligns with methods used in similar hydrological impact assessments under land-use change scenarios (see Prasena & Shrestha, 2013; Sugianto *et al.,* 2022; Smith *et al.,* 2016).

2.4 Flood Event Data Collection

Flood event data was collected from official records by the Regional Disaster Management Agency (BPBD) Kulon Progo which included annual flood frequency, affected areas, flood severity, and temporal patterns over the past decade. The data also provides the number of flood events per year, the geographical distribution of flooded areas, and the duration of each event. This quantitative approach ensured consistency and accuracy in tracking the development of flood risks across the coastal region. The changing amount of flood events after the construction of Yogyakarta International Airport (YIA) is important to analyse as the major infrastructure project has significantly altered the landscape and hydrological patterns. These findings were integrated with the soil property analysis and land-use change assessment to explore the relationship between altered land surfaces and the increased flood risk in the Kulon Progo coastal region.

2.5 Data Analysis

The data analysis in this study involved a combination of descriptive and comparative analysis to understand the relationship between soil properties, land-use changes, and flood frequency in the Kulon Progo coastal area. Descriptive analysis was used to interpret the soil data focusing on the differences in soil characteristics across the three zones, which are Jangkaran, Palihan, and Glagah which enabled a qualitative understanding of soil water capacity in relation to land-use variations may affect the excessive surface runoff that can lead to flood events. To further explore the relationship between soil properties and flood frequency, the study analysed flood event data from BPBD Kulon Progo. This analysis focused on identifying temporal patterns of flood occurrence and how these align with soil conditions and land-use changes. By correlating flood frequency with the soil characteristics in each zone, the study sought to determine whether areas with reduced soil retention capacity are more prone to flooding.

The analytical framework supports a deeper understanding of how land-use changes and soil degradation contribute to hydrological risks. The findings align with Indonesia's Nationally Determined Contributions (NDC) roadmap, emphasizing the importance of building climate resilience through sustainable land management and disaster risk reduction. While the primary focus of quantitative analysis was on flood frequency due to the availability and reliability of consistent data across locations, other flood-related information such as severity, affected areas, and temporal distribution patterns were used qualitatively to support and contextualize the findings. These data were particularly useful in identifying high-risk zones, verifying soil condition impacts on flood vulnerability, and interpreting spatial trends in flood occurrence. This integrated approach ensured a more comprehensive understanding of flood dynamics in relation to soil and land-use variations.

3. Results and Discussion

3.1 Coastal Soil Characteristics in Kulon Progo

3.1.1 Overview of Soil Sampling and Study Area

This study was conducted in three villages in the Kulon Progo Coast, namely Jangkaran, Palihan, and Glagah, to represent different regional conditions, especially to see the various variations in soil characteristics in land use changes due to the construction of the airport and its buffer areas. In Jangkaran, the sample points include sandy soil located around the airport and river, agricultural areas, and areas with quite diverse vegetation. Meanwhile, in Palihan, the sample points are dominated by uniform vegetation, especially at points near the coastline and airport. Sampling locations were also carried out in Glagah with most of them being peat and sandy soil areas close to the river.

Table 1. Overview of soil sampling areas

Loc.	Village	Types of Land Use	Distance from Shoreline (m)	Loc.
1.1	Jangkaran	Natural zone	467	**1.1**
1.2	Jangkaran	Natural zone	46	**1.2**
1.3	Jangkaran	Agricultural area	1172	**1.3**
2.1	Palihan	Urban-converted zone	37	**2.1**
2.2	Palihan	Urban-converted zone	44	**2.2**
2.3	Palihan	Natural zone	35	**2.3**
3.1	Glagah	Agricultural area	921	**3.1**
3.2	Glagah	Agricultural area	63	**3.2**
3.3	Glagah	Urban-converted zone	31	**3.3**

3.1.2 Bulk Density

Bulk density in various soil samples of Kulon Progo shows quite comprehensive variations, ranging from 1.16 g/cm³ to 2.18 g/cm³ (Figure 3). The differences that occur in various soil samples are due to the variety of different soil compositions, varying soil densities, and organic matter content in them. The results of the study showed that lower bulk density indicates a looser soil structure, resulting in higher pore space to allow for much better infiltration and water storage capacity (Khaerudin *et al.,* 2017). Conversely, higher bulk density at some points indicates a denser soil composition, so that its water infiltration capacity is much lower.

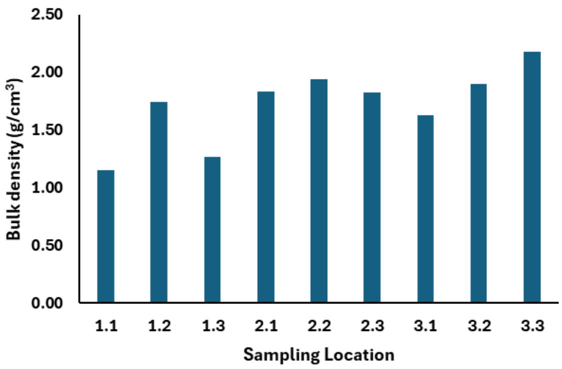

Figure 3. Soil bulk density

The lowest bulk density is 1.16 g/cm³ which is located in sample 1.1, located in Jangkaran, right in the area near the river downstream. This location has a combination of peat and sand soil types, with a fairly high water storage capacity. This area is also a salt marsh area that has not been widely used for domestic activities by the community. In addition, sample point 1.3, which is also located in Jangkaran Village has a fairly low bulk density, which is 1.27 g/cm³ with sandy soil characteristics and has diverse vegetation. This vegetation cover also functions as a water reservoir and reduces soil compaction, thus allowing for an increase in the soil's capacity to store water (Hoorman *et al.,* 2011).

The highest bulk density value is in sample 3.3 located on the downstream riverbank in Glagah, at 2.18 g/cm³. This fairly high bulk density indicates the presence of denser soil with fairly limited pore space, which can inhibit water infiltration. Sample points located in Palihan Village (samples 2.1, 2.2, and 2.3) also have fairly high bulk density values, ranging from 1.82 g/cm³ to 1.94 g/cm³. All points in Palihan are close to Yogyakarta International Airport (YIA) which is related to massive changes in soil structure.

Land use changes are indicated to affect the distribution of bulk density (Spurgeon *et al.,* 2013). In general, areas located near the airport area show high bulk density figures, due to increased human activities and environmental pressures, which contribute to soil compaction (Smith *et al.,* 2016). In contrast, areas located farther from the airport, particularly those with natural vegetation cover, exhibited lower bulk density, suggesting a higher potential for water infiltration compared to more developed zones.

3.1.3 Particle Density

The particle density of the soil samples varied between 2.46 g/cm³ and 5.15 g/cm³, indicating the diversity of material composition in the various land uses (Figure 4), containing clay and heavy materials (Ruhlmann *et al.,* 2006). The lowest particle density (2.46 g/cm³) was found in sample 1.3, namely the Jangkaran area, indicating soil content with high organic matter, including low mineral content. This organic-rich soil better retains water. This characteristic occurs in areas with natural vegetation and organic matter that accumulates over time. In contrast, sample 1.2 from Jangkaran Village had the highest particle density of 5.15 g/cm³, indicating a high mineral content. This composition can reduce the soil's ability to absorb water, so when it rains, runoff will increase in the area.

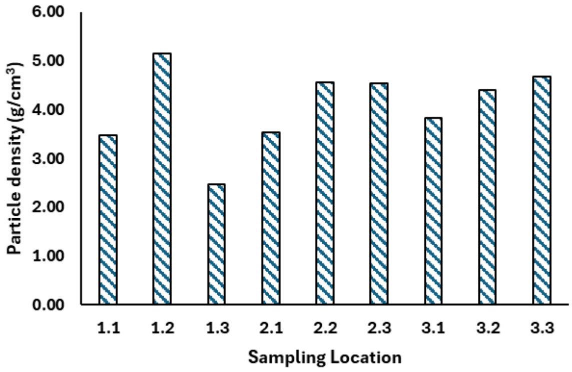

Figure 4. Particle density from soil sampling areas

The differences in particle density of each sample point indicate the presence of various soil formation processes including human activities (Huang *et al.,* 2020). The results show that soil samples collected around YIA airport have much higher particle density values, such as in samples 2.1, 2.2, and 2.3 from Palihan, which are located near airport. This indicates that land use, including the construction of various infrastructures with massive soil compaction, can change the physical structure of the soil. This condition also has the potential to reduce the formation of macropores as a medium for water infiltration.

Peat or sandy soil conditions have different contributions to flood vulnerability due to differences in particle density. For example, point 3.3 in Glagah Village, located on the riverbank near the airport, shows a fairly high density with a mixed peat and clay soil structure. This condition worsens during the rainy season, which can increase flood intensity. In contrast, point 1.1 from Jangkaran has a lower particle density with a sandy soil form that has a loose structure to facilitate more significant water infiltration. These findings are in line with the direction of Indonesia's Nationally Determined Contribution (NDC) roadmap, which emphasizes the need for sustainable land management in efforts to reduce climate-related disaster risks, especially in coastal areas with high vulnerability.

The particle density values observed in this study, ranging from 2.46 to 5.15 g/cm³, exceed the typical range for natural mineral soils, typically 2.60 to 2.75 g/cm³ (Amoozegar *et al*., 2023). This anomaly may be attributed to several factors. First, the presence of heavy minerals such as iron oxides or titanium-bearing compounds, which are common in coastal and volcanic-influenced regions like Kulon Progo, can elevate particle density values. Second, anthropogenic influences, particularly from the recent construction of Yogyakarta International Airport and its supporting infrastructure, may have introduced construction debris, compacted materials, or industrial residues into the soil matrix. These materials, often denser than natural soil particles, could significantly affect particle density measurements. Further geochemical analysis would be necessary to quantify the contribution of these materials, but their potential presence helps explain the observed deviations.

3.1.4 Soil Porosity

Soil porosity obtained from a combination of bulk density and particle density values has quite diverse results at various sample points, ranging from 48.16% to 66.67%, which indicates the diversity of soil's ability to store water (Figure 5). This difference occurs due to the specific characteristics of bulk density and particle density in each region, especially in relation to changes in land use and human activities in it. For example, sample point 1.1 has the highest porosity (66.67%), which is a downstream and sandy area with a looser and less dense soil structure, including rich in organic matter. High porosity allows good water infiltration and reduces excessive runoff during rain or high tides from the sea. In contrast, point 2.1, which comes from an area near the airport has the lowest porosity (48.16%), which indicates a denser soil structure, so that water absorption is more limited.

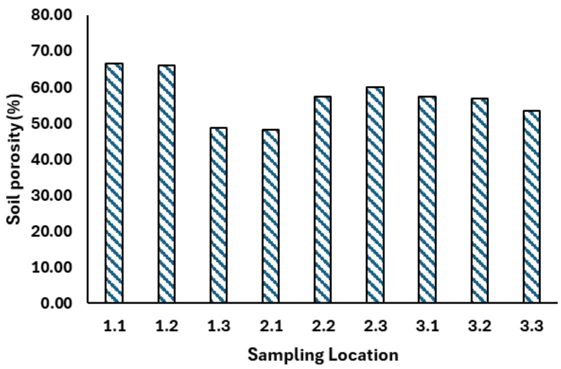

Figure 5. Soil porosity from soil sampling areas

Land-use changes driven by infrastructure development impact the spatial distribution of soil porosity. Almost all sampling points located near infrastructural activities, particularly in areas of YIA, present lower porosity values. For example, samples 2.1 and 2.2 from Palihan, which are located close to the airport buffer zone, consistently show lower porosity. This condition occurred as mechanical disturbances and soil compaction in the results of construction activities and land-use conversion. Compacted soils have fewer macropores, which are essential for water infiltration, causing rainwater to accumulate on the surface and increasing the risk of flooding. In contrast, natural and agricultural zones such as sample 1.3 in Jangkaran, which shows a relatively higher porosity, retain more natural soil structure with less disturbance, allowing for better water absorption and reduced surface runoff.

The variation in soil porosity across the study area also reflects different soil-forming processes and environmental conditions. Areas with higher porosity, such as sample 3.1 from Glagah, which is located near an agricultural area, generally have more organic content and less compaction, allowing for better water storage. This characteristic plays a crucial role in regulating surface water flow, as it reduces the immediate impact of heavy rainfall by absorbing and holding water within the soil matrix. Conversely, areas with lower porosity, such as sample 3.3 from a riverbank downstream, exhibit more compacted and dense soil conditions that are less capable of infiltrating water, making these areas more vulnerable to hydrometeorological hazards.

The implications of these porosity differences are significant for coastal flood management. Soils with higher porosity act as natural buffers against flooding by enhancing infiltration rates and retaining excess rainfall, thereby reducing surface water flow. This capacity is particularly important in low-lying coastal regions, where poor drainage can exacerbate flooding risks. However, in areas where land-use change has led to increased soil compaction and lower porosity, the ability of the soil to absorb and retain water is compromised. This condition accelerates surface runoff, increases flood frequency, and heightens the vulnerability of human settlements and infrastructure to flood-related disasters.

3.2 The Impact of Land-use Change on Soil Capacity

The land use cover map of Kulon Progo District before the development of Yogyakarta International Airport (YIA) which is situated in Temon Sub-district, indicates that the coastal area was predominantly covered by mixed dryland agriculture and open spaces such as grassland, with few built-up areas (Figure 6). The settlements were spreaded, and dominantly surrounded by water bodies and vegetation. This coastal zone exhibited a largely permeable surface condition that supported natural drainage, infiltration, and water retention. The absence of large-scale infrastructure or impervious surfaces suggests that, prior to YIA development, the coastal area maintained a relatively undisturbed hydrological balance and ecological function.

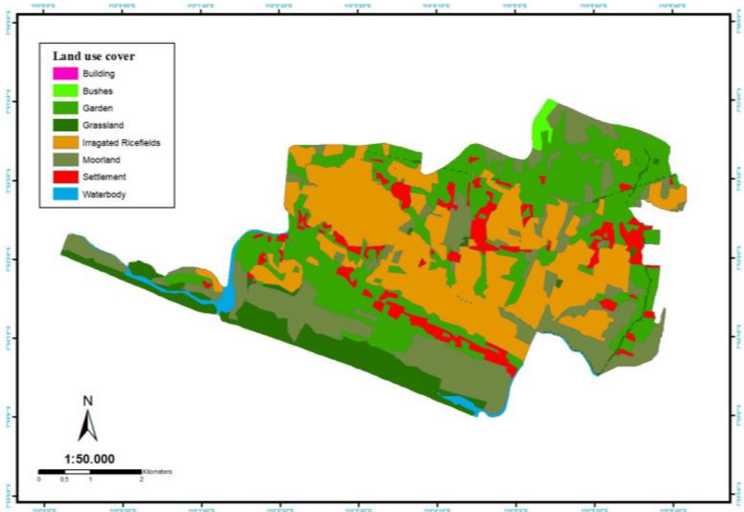

Figure 6. Land use cover in Temon before YIA construction, Kulon Progo

The constructions of YIA which are associated with land conversion, have significantly altered soil properties (Ning, 2024). Between 2017 and 2023, 19.73 Ha of vegetation and 282.59 Ha of grassland to airport infrastructures which reduce organic matter inputs for soil fertility (Ning, 2024). The loss of the vegetation covers disturbed natural processes such as photosynthesis and carbon sequestration which lower the production of oxygen and increase the carbon dioxide level (Utami, *et al.,* 2024). These changes pose long-term risks for soil degradation, particularly in surface layers, as land conversion for infrastructure development, including airport, can significantly reduce soil organic carbon due to increased impervious surfaces (Ding *et al.,* 2022).

These land cover changes are also supported by recent findings from Utami *et al.* (2024), who reported that the significant expansion of built-up areas in Kulon Progo due to YIA development led to increased surface temperatures and reduced water infiltration capacity. The conversion of vegetated and permeable land into airport infrastructure has resulted in higher soil bulk density and lower porosity, particularly in areas surrounding the development zone. These changes indicate more compacted soils with reduced aeration and water-holding capacity (Khaerudin *et al.,* 2017), contributing to long-term degradation of soil quality and reduced resilience of the local environment to climate variability. These transformations demonstrate how large-scale infrastructure projects can result in differences in both chemical and physical soil systems.

3.3 Trends in Flood Occurrence in Kulon Progo

Flood events, like river flooding and coastal floods, often occur in Kulon Progo areas (Mustofa *et al.,* 2024) that are significantly influenced by hydrometeorological factors including the frequency, intensity, and amount of heavy precipitation, river morphology conditions, and changes in land use in urban and coastal areas (Mustofa *et al.,* 2025). The Yogyakarta International Airport (YIA) has impacted the local hydrological dynamics, primarily soil infiltration and surface runoff, due to large-scale infrastructure development that altered land cover and drainage patterns (Utami *et al.,* 2024). In this study, hydrological impacts were inferred from indirect indicators such as changes in soil bulk density and porosity, as well as documented increases in flood frequency in the surrounding areas. Changes in soil properties also have a significant impact on the water retention capacity in these areas (Lal, 2020). The decreasing soil porosity and the increasing bulk density have reduced the soil's permeability led to excessive surface runoff and increased the potential flooding events in the areas with low infiltration rates.

3.3.1 Analysis of Historical Flood Trends

Data from the Kulon Progo Regional Disaster Management Agency (BPBD) in Figure 7 over the past decade shows that before 2017 the frequency of flood events rarely occurred, while after 2018 the year of starting the construction of YIA, it increased particularly in areas around the airport and the southern coast of Kulon Progo. The construction of runways, roads, and commercial areas leads to the increasing of impervious surface and reducing the infiltration rates that cause higher surface runoff (Ndaru, 2025). The finding from soil sampling reveals that areas with bulk density exceeding 1.8 g/cm^3 show significantly higher surface runoff rates than areas where soil porosity remains intact. These findings align with the increasing flood events recorded by BPBD after 2018 that highlight the impact of changes in soil characteristics and hydrological systems.

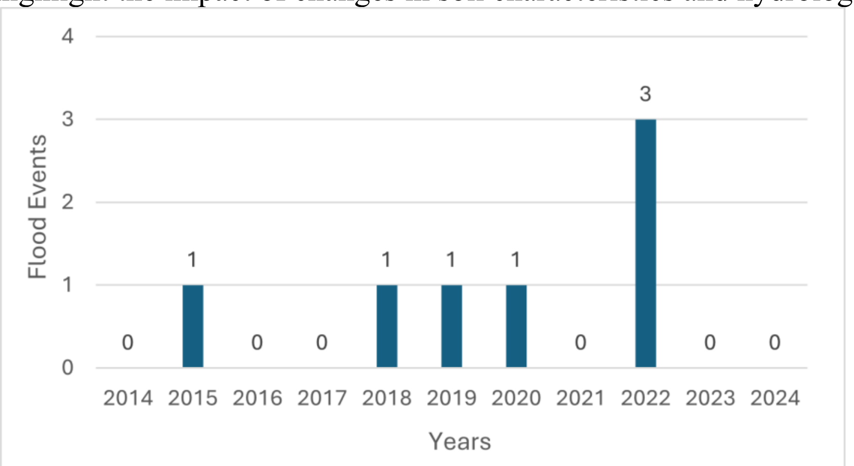

Figure 7. Annual flood frequent trend (BPBD, 2023)

3.3.2 Relationship between Rainfall, Drainage, and Flood Occurrence

High-intensity rainfall due to climate change also has an impact on increasing the risk of flooding in Kulon Progo. High-intensity rainfall events especially over short periods of time, can cause higher surface runoff particularly in areas that lack of drainage systems (BMKG, 2023). Research conducted by Fadilah *et al.,* (2023) observed that sedimentation in drainage systems around YIA causes narrowing of channels and increasing flood inundation. Furthermore, research conducted by Puspa *et al.* (2020) observed that during the dry season, the Serang River's estuary located at Glagah Beach in Kulon Progo often experiences sedimentation due to the overflow of sand sediment deposits accumulated by wind and coastal waves. This phenomenon inhibits the flow of water to the sea, so that the high river discharge cannot be drained efficiently, leading to water overflow and contributes to river flooding in the upstream areas of the Serang River. Figure 8 presents the condition of the Serang River's estuary, which experiences blockage due to sedimentation, thus becoming a factor causing river flooding. The study also mentions the impact on the physical and morphological conditions of the coast around the construction of YIA including the Serang River's estuary potentially increasing the risk of coastal and river flooding which primarily because the sand sediment is trapped at the estuary and the high rate of longshore sediment transport along the coast.

Figure 8. Condition of the Serang River Estuary blocked by sediment (Puspa *et al.,* 2020)

3.3.2 Most Flood-Prone Zones

Figure 9 presents a flood risk map of Kulon Progo Regency, which has been adapted to include English labels and key locations relevant to this study, such as Glagah, Palihan, and Yogyakarta International Airport (YIA), to better illustrate their exposure to flood risks. Based on this map from BPBD Kulon Progo, several areas are very prone to flooding, especially the southern coastal areas around Glagah and Palihan. On this map, the red area indicates areas with a high flood risk, the yellow area indicates areas with a moderate flood risk, and the green area indicates areas with a low flood risk. Flood-prone areas are mostly located along river basins and lowland areas near coastal areas which experience an increased risk of flooding due to the loss of natural water catchment areas and high sedimentation in the river estuary. Meanwhile, the buffer zone around YIA also experiences increased flooding due to high surface runoff that cannot be fully accommodated by the airport drainage system (BNPB, 2022). The flood risk map presented in Figure 8 also shows that areas with low infiltration capacity due to changes in soil structure correspond to flood-prone zones. The red area on the flood risk map is the area with the highest flood vulnerability, especially in zones with soil porosity below 30% and bulk density exceeding 1.9 g/cm³. In addition to flood frequency, qualitative data on flood severity and affected areas provided by BPBD were utilized to validate spatial vulnerability patterns shown in the flood risk map. For example, coastal areas in Glagah and Palihan, consistently marked as high-risk zones, also correspond with records of frequent and severe flooding events affecting residential and agricultural zones. These patterns support the interpretation that soil compaction and reduced infiltration capacity in built-up areas significantly contribute to flood intensity and spatial extent.

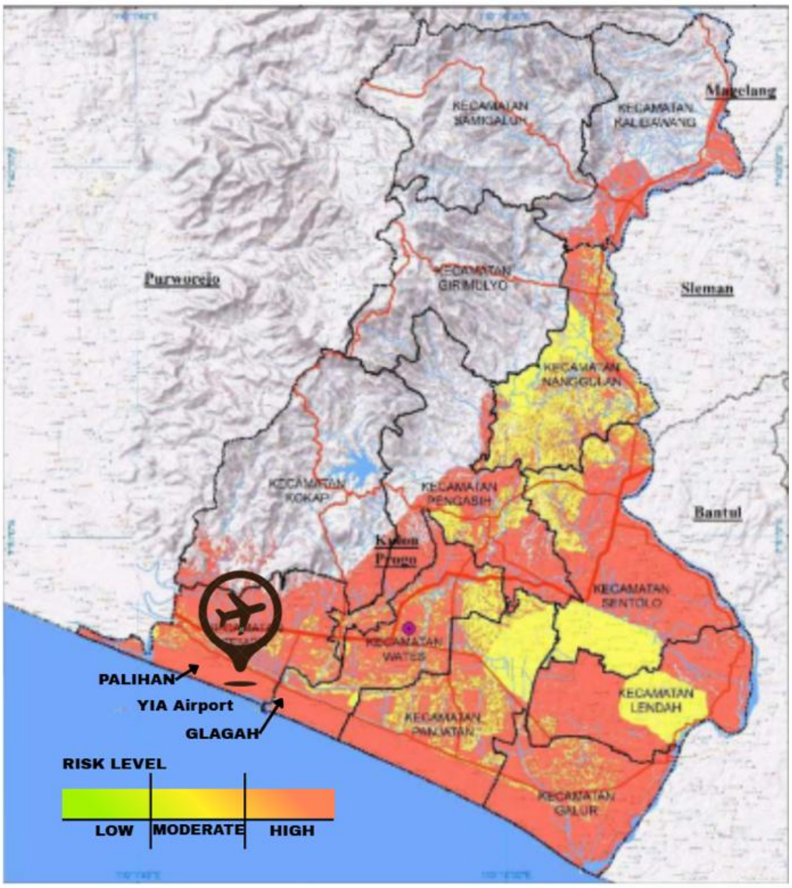

Figure 9. Flood risk map of Kulon Progo (BPBD, 2023)

Figure 9 presents The Flood Capacity Map of Kulon Progo Regency shows that the capacity and resiliency of regions to deal with disasters varies and shows the readiness of infrastructure and flood control systems throughout the region. In this map, green areas indicate areas with high flood mitigation capacity, which is usually located in urban areas that have better drainage systems, yellow indicates medium capacity, and red indicates low-capacity zones where stormwater management infrastructure is inadequate which is usually located in rural and coastal areas. Historical data on flood severity and duration were also used qualitatively to contextualize the classification of low-capacity zones in Figure 10. Many of these areas have experienced prolonged and intense flooding events over the past decade, supporting the interpretation that poor soil infiltration and inadequate infrastructure directly correlate with reduced flood mitigation capacity. This qualitative insight strengthens the link between land-use change, soil degradation, and hydrological vulnerability. Areas with lower infiltration rates tend to have weaker flood mitigation capabilities that suggests the increase in flood events is not only a result of extreme rainfall events but rather a combination of changes in soil properties, expansion of impermeable surfaces, and limitations in drainage systems.

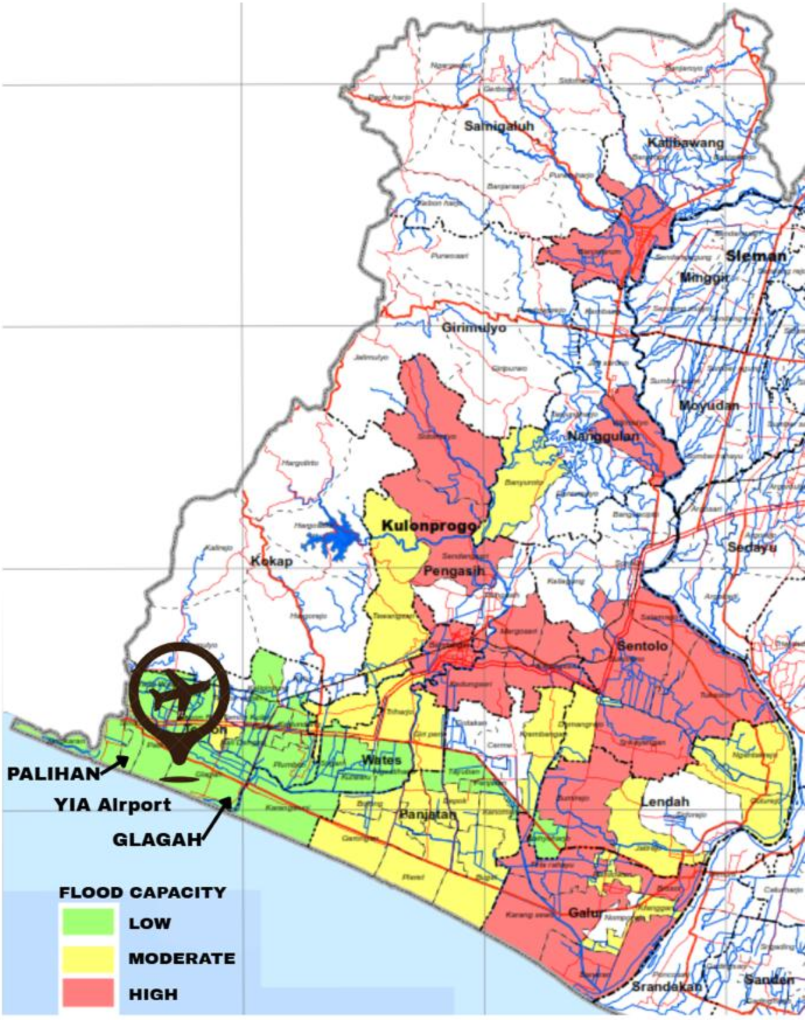

Figure 10. Flood capacity map of Kulon Progo Regency (BPBD, 2023)

3.4 Implications for Flood Mitigation and Climate Adaptation Policies

This study finds the increase in flood events in Kulon Progo is closely related to land use changes, high-intensity rainfall, and reduced soil infiltration capacity, that impact higher surface runoff. A comprehensive flood mitigation strategy is needed by integrating the stormwater management infrastructure, restoration of natural infiltration zones, and improved land-use policies to ensure long-term flood resilience. The primary step in mitigating flood risk involves increasing drainage capacity in the areas surrounding YIA. However, these efforts must be complemented by regular maintenance to prevent sediment buildup, which can clog drainage channels and exacerbate flooding. In addition, wetland restoration and the development of buffer zones in riparian and coastal areas can play an important role in increasing natural infiltration rates, thereby reducing direct surface runoff into the drainage system. By integrating land-based flood mitigation strategies, the areas with high bulk density (>1.8 g/cm³) which lower infiltration rates can implement bioretention systems that can increase the absorption of rainwater and reduce the surface runoff. The stricter spatial planning policies should be implemented to prevent uncontrolled urban expansion in high-risk flood zones coupled with stricter regulations on watershed management and coastal land use will be essential to ensure that land modification does not further compromise flood resilience. Finally, the integration of advanced flood early warning systems is important especially in areas with limited flood mitigation capacity, as illustrated in Figure 9. One of the keys to minimizing the impacts of future flood events can be done by strengthening community preparedness through real-time flood forecasting, adaptive response mitigations, and local emergency planning.

The findings of this study highlight the crucial role of soil capacity in mitigating flood risks and supporting climate resilience, aligning with Indonesia's Nationally Determined Contributions

(NDC) roadmap. The observed variations in soil porosity, bulk density, and particle density across different land-use types indicate that land conversion, particularly near Yogyakarta International Airport (YIA), has led to soil compaction and reduced infiltration capacity, increasing flood vulnerability. These changes contradict the NDC's goals of disaster risk reduction and sustainable land management, emphasizing the urgent need for policies that balance development with environmental resilience. By preserving critical soil functions, Indonesia can strengthen coastal adaptation strategies and mitigate the increasing risks posed by climate change-induced hydrometeorological hazards.

To address these challenges, sustainable land management strategies should focus on preserving and restoring natural buffers such as salt marshes, wetlands, and mangrove forests, which enhance water retention and infiltration. Additionally, implementing green infrastructure solutions like permeable pavements and vegetated swales can help mitigate the negative impacts of urban development on soil permeability by reducing surface runoffand enhancing natural drainage. These approaches not only strengthen hydrological resilience but also align with nature-based adaptation strategies to improve long-term flood mitigation efforts in coastal regions.

Furthermore, continuous monitoring of soil properties and flood patterns is essential to ensure that land management policies remain adaptive to changing environmental conditions. Regular assessments of soil bulk density, porosity, and infiltration rates can provide valuable insights into how land conversion affects hydrological responses, allowing for more evidence-based policy adjustments. Integrating flood event data with soil capacity analysis will enable better prediction of high-risk areas, supporting proactive disaster risk reduction strategies. By prioritizing sustainable land-use planning, Indonesia can enhance its climate resilience, reduce coastal flood risks, and effectively align with its NDC commitments for disaster mitigation and adaptive capacity-building.

4. Conclusion

The findings of this study highlight the crucial role of soil capacity in mitigating flood risks and supporting climate resilience, aligning with Indonesia's Nationally Determined Contributions (NDC) roadmap. The observed variations in soil porosity, bulk density, and particle density across different land-use types indicate that land conversion, particularly near Yogyakarta International Airport (YIA), has led to soil compaction and reduced infiltration capacity, increasing flood vulnerability. These changes contradict the NDC's goals of disaster risk reduction and sustainable land management, emphasizing the urgent need for policies that balance development with environmental resilience. By preserving critical soil functions, Indonesia can strengthen coastal adaptation strategies and mitigate the increasing risks posed by climate change-induced hydrometeorological hazards.

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