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Rainwater control with ArcGIS simulations: Universitas Sebelas Maret campus area mapping

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ABSTRACT

The study aims to identify, map, and manage potential rainwater runoff across the Universitas Sebelas Maret (UNS) campus, Surakarta, using a spatial analysis approach based on the geographic information system (GIS). The research was motivated by the increasing volume of surface runoff caused by urban expansion within the campus area, particularly due to the rise of impervious surfaces, new building developments, and the reduction of infiltration zones. The methodology integrates empirical hydrological analysis using the Mononobe method to estimate design rainfall intensity, combined with spatial modeling in ArcGIS, including digital elevation model (DEM) data, land-cover maps, and existing drainage networks. Key surface parameters such as slope, elevation, and runoff coefficients were spatially analyzed to produce a surface runoff potential map. The GIS-based simulation allows for identifying high-risk flood-prone zones and estimating the volume of unabsorbed stormwater under different land-use conditions. The results indicate that approximately 19.7% of the UNS campus area is classified as a very high-runoff zone, primarily concentrated around parking areas, main access roads, and building clusters with impermeable surfaces. In contrast, green and vegetated areas effectively reduce runoff by up to 6.7%, demonstrating their role in maintaining local hydrological balance. The outcomes of this research provide a scientific foundation for implementing low impact development (LID) strategies, including rain gardens, infiltration wells, and permeable pavements. These measures are expected to support the UNS Green Campus Initiative, enhance drainage system efficiency, and serve as a replicable model for sustainable rainwater management in other university environments.

Keywords: rainwater management, ArcGIS, runoff simulation.

INTRODUCTION

Urban areas development leads to reduction of natural land ability to absorb rainwater. The replacement of land cover from porous soil surface to waterproof materials such as concrete and asphalt causes an increase in surface runoff and potential inundation (Marques, 2022). In this case, comprehensive area planning strategy, an effective drainage system, and the selection of suitable land cover materials play an important role in increasing infiltration capacity and recuing the drainage system burden (Ahmed et al., 2017).

The use of mapping and spatial analysis technologies such as ArcGIS has been proven to support inundation-prone areas (Amen, 2023). Based on the 2022 Surakarta City Disaster Risk Assessment Document (KRB), floods are classified as medium-risk disasters, with 129 incidents recorded and a vulnerability value of 0.8. Therefore, the Regional Spatial Plan (RTRW) of Surakarta City and the internal policies of educational areas such as Sebelas Maret University (UNS) are directed to increase infiltration capacity through the addition of green open spaces, the construction of new drainage, and the control of land use transfer (Ozturk et al., 2023).

This study uses the Mononobe method to calculate the maximum daily rainfall intensity, which is the basis for calculating the capacity of the drainage system as well as simulating surface runoff. The UNS campus, located in Jebres District, is an educational area with various functions ranging from academic facilities to sports facilities and green open spaces, such as stadiums and lakes that have important ecological roles.

However, the development of campus infrastructure-such as the construction of buildings and parking areas-has reduced the area of green open space, thereby reducing the permeability of the area and increasing the potential for inundation. Therefore, the concept of sustainable drainage is needed as a solution. This concept emphasizes the importance of seeping rainwater into the soil through strategies such as the construction of infiltration wells at strategic points and the use of permeable land cover materials (Belladona et al., 2024).

Land cover has a crucial role in regulating rainwater infiltration because each type of material has a different absorption rate (Vidaleti et.al, 2021). The increase in the watertight area increases the value of the curve number (CN), peak discharge, and water level elevation, which ultimately exacerbates the risk of flooding (Gautam et al., 2024). Uncontrolled runoff also leads to erosion and reduced environmental quality. Madhatillah and Rusli noted that land use changes are the main cause of the increase in runoff volume compared to other factors.

This study evaluates rainwater management in the UNS Campus area using spatial approaches and hydrological calculations to develop an area planning strategy that is more responsive to inundation risk. This strategy is also expected to be applied in other educational areas, especially in the tropics, while supporting the development of environmentally friendly areas.

Although previous studies have addressed flood mitigation in urban areas through risk mapping and hydrological analysis, most studies still focus on the macro scale (urban or watershed) and have not examined in detail the effect of microland cover changes in campus environments or educational areas on potential surface runoff and inundation points. In addition, previous studies have tended to assess flood vulnerability based only on topographic or precipitation parameters, without integrating ArcGIS-based spatial simulations with hydrological methods, such as Mononobe, to obtain quantitative estimates of actual runoff. This gap suggests that there is no comprehensive approach that combines spatial analysis, land characteristics, and rainfall intensity simultaneously on a tropical campus footprint scale.

This gap is important to fill because educational areas, such as the UNS Kentingan Campus, have vital ecological and social functions—namely as academic areas and green open spaces that also affect the balance of local water systems. Without a detailed understanding of runoff distribution patterns and inundation-prone points in the microscope, rainwater control efforts will be reactive and unsustainable. Thus, this research is important to develop a rainwater management model that is measurable and adaptive to the actual condition of campus land, as well as can be a reference for the application of the sustainable drainage system (SuDS) concept in other tropical educational areas.

The novelty of this research lies in the integrative use of GIS technology (ArcGIS Pro 3.1.5) with the Mononobe hydrological method to simulate the potential for rainwater runoff spatially on the micro scale of tropical education areas. This approach has not been widely applied in Indonesia, especially for campus environments that have complex land functions (academic buildings, roads, parking areas, green spaces, and water bodies). This study not only maps inundation-prone areas, but also examines the relationship between land cover, slope, and distance to water flow to determine the priority of intervention zones. Thus, the results obtained are not only descriptive, but analytical and applicable to sustainable drainage planning (SuDS).

This research contributes in two main aspects theoretical and practical contribution. This research provides a new conceptual model of rainwater runoff control based on microland characteristics, which combines tropical hydrological approaches with geographic information systems. This model can be a reference for similar studies in campus environments or tropical urban areas with high land cover dynamics. This research also provides spatial maps of actual flood and runoff vulnerability that can be used as a basis for decision-making in spatial planning, campus infrastructure development, and “green campus” policies. The results of this simulation also provide technical guidance for the determination of priority locations for the construction of infiltration wells, biopores or permeable surfaces to support sustainable drainage systems and local inundation risk reduction.

The direction of research on rainwater management and urban flood control shows an important shift towards a GIS and LID-based approach. Various international and national studies highlight the need for runoff control in increasingly dense urban areas, where changes in land cover accelerate runoff rates and increase the risk of inundation. Research by Aguiar et al. (2020) in Pato Branco, Brazil, shows that the GIS-based multicriteria approach is effective in determining priority areas for the implementation of sustainable urban drainage practices (SUDS), such as permeable pavement, green roof, and rain garden. This study confirms that the spatial maps from GIS analysis can be used as a basis for decision-making to reduce runoff and increase infiltration. A similar study by Fu, Hopton, and Wang (2021) assessed the performance of green infrastructure through the perspective of urban resilience, and found that the combination of green-blue infrastructure increases groundwater absorption and lowers the peak of flood discharge by up to 25%.

In Southeast Asia, research by Hasankhan et al. (2024) added that the application of hydromodification measures in the built environment has a significant effect on reducing drainage load. Their results show that LIDs not only control runoff, but also stabilize the hydrological regime in dense settlements. Meanwhile, Patel et al. (2024) used a SWMM model integrated with GIS to assess the efficiency of rainwater management in urban India. They prove that spatial modeling allows the design of drainage systems to be more efficient and adaptive to extreme rainfall variations.

Several studies in Indonesia have also shown similar directions. Priscannanda and Hindersah (2022) analyzed the effectiveness of three types of green infrastructure (vegetated filter strip, retention pond, and detention pond) in the Ciliwung Hilir watershed, DKI Jakarta. As a result, the combination of the three GIs was able to reduce runoff volume by more than 27 million m³. However, this study is macro and has not explained the spatial relationship between microland characteristics and actual runoff distribution. Wahyuni and Sachro (2024) examined the effect of land cover changes on flood hydrographic characteristics in the Jragung Dam, and found that an increase in the watertight area of as little as 2.5% can increase the peak discharge of floods by 6–7%. This study strengthens the evidence that land transformation is a major factor in the escalation of flood risk in catchment areas.

In terms of methods, recent research has largely used the Intensity–Duration–Frequency (IDF) curve to analyze the characteristics of extreme rainfall. The Mononobe method, which is widely used in tropical regions with limited pluviograph data, is still the main reference for calculating the intensity of the design rainfall. Carolina et al. (2022) and Yanti and Irawan (2021) show that the use of the Mononobe method can provide realistic estimates for drainage system design and retention pond capacity calculations, although the accuracy decreases at very short rainfall durations.

However, most of these studies have some important limitations. First, most studies were conducted at the macro scale (watershed or city) and have not touched on micro scales such as campus environments or residential blocks, where the interaction between land cover type, slope, and local drainage systems strongly determines runoff behavior. Second, the use of Mononobe and IDF methods is often not directly integrated with GIS-based spatial analysis, making it difficult to map the specific areas most at risk of inundation. Third, many studies focus only on the quantity of discharge or volume of runoff, without assessing other ecological and social effects such as increased infiltration, decreased surface temperature, or contribution to thermal comfort.

In addition, there are shortcomings in the validation aspect and uncertainty of the model. Many hydrological simulations are not tested against actual field data, making the results difficult to use as a basis for operational planning. In fact, in tropical contexts that have high rainfall and great spatial variability, empirical validation is key to producing reliable models. On the other hand, the implementation of green infrastructure in Indonesia still faces technical and policy obstacles, including limited land, lack of integration between spatial planning and drainage systems, and the absence of specific regulations that encourage the implementation of LID in educational areas or campuses.

Overall, the latest research direction shows significant advances in runoff modeling and sustainable drainage planning. However, there is still a knowledge gap in terms of the application of GIS-based hydrological models in micro scopes such as tropical campus areas, where land cover dynamics and complex drainage systems interact with each other. Therefore, research that integrates hydrological simulations (Mononobe method) with GIS spatial analysis at the site scale will be an important step to develop measurable, contextual, and sustainable rainwater control strategies, while strengthening the concept of green campus and local flood mitigation in Indonesia's educational areas.

METHOD

This study uses a mixed-method approach that combines quantitative and qualitative methods simultaneously. Quantitative methods were used in the spatial modeling process using ArcGIS Pro 3.1.5 software to analyze rainwater runoff based on land characteristics and rainfall. Qualitative methods were used to interpret the results of graphical visualizations and review patterns of spatial relationships in existing conditions and planning scenarios. This approach aims to gain a complete understanding of the dynamics of rainwater management in the study area.

The research is conducted at the Sebelas Maret University (UNS) Campus, located in Jebres District, Surakarta City, Central Java, Indonesia (Figure 1). The campus building has the characteristics of a green campus area with various supporting functions such as academic spaces, green open spaces, sports facilities, and parking areas. The study area was chosen because the area has been experiencing quite rapid physical development in recent years, with the construction of buildings and infrastructure having a direct impact on the area's catchment capacity.

In this study, five main parameters were analyzed, namely: Topographic elevation, Slope, Land cover, Rainfall, Distance to water flow. These five parameters were selected based on the results of literature reviews and expert opinions that stated that these factors have the most significant influence on flood event. Analytic hierarchy process (AHP) is used to determine the relative weight of each parameter that affect vulnerability to flood hazards. AHP is multicriteria decision-making technique that organizes a number of criteria into a hierarchy, evaluates the relative importance between criteria, and produces a final weight that represents the contribution of each factor to the decision.

Topographic elevation data is taken from the National Digital Elevation Model (DEMNAS) released by BIG in 2018. Slope data was obtained from DEMNAS data processing. Land cover data was obtained through a field survey conducted on April 1st-2nd, 2025 by the research team. Rainfall data was obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) for the period 2022 to 2024. The distance to the water flow is obtained from the processing of elevation and slope data in arcGIS. The data is then used as a calculation parameter in determining flood-prone points at the UNS Kentingan Campus.

The calculation of rainfall intensity with Mononobe Methode (formula 1) was carried out using maximum rainfall data per year in the period 2022–2024.

$$I = \left(\frac{CH_{maks}}{24}\right)\left(\frac{24}{t}\right)^{0.666} \quad (1)$$

where: I – rainfall intensity (mm/h), t – length of rainfall (hours), CH_{maks} – maximum rainfall in 24 hours (mm/day).

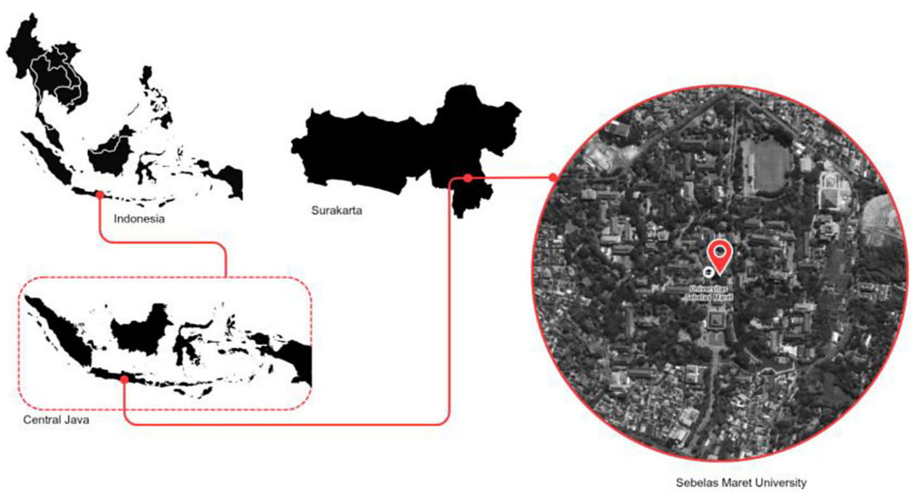

Figure 1. Location of Sebelas Maret University Campus in Surakarta City

All of the classified spatial data is then processed using ArcGIS software to compile layers of analysis, including elevation maps, land slopes, and land cover zoning. The mapping is carried out in a spatial grid based on the X and Y axes, which represent the size of the scaled map and allows the calculation of the area and runoff volume in each zone. The hydrological simulation was carried out by entering the parameters of the daily maximum rainfall calculated using the Mononobe method, a mathematical method commonly used in drainage planning in the tropics.

The Mononobe method is applied to obtain an estimate of rainwater load over a certain period of time, which is then used to calculate surface runoff discharge.

RESULTS AND DISCUSSION

Rainfall and rainfall intensity

Monthly rainfall data for the period 2022 to 2024 shows a significant upward trend, especially in 2023 and 2024. In 2022, the maximum monthly rainfall is relatively low, which is only about 15.00 mm. However, in 2023 there was a spike in rainfall with the highest peak reaching 493.10 mm in March, followed by February with 465.00 mm. This high trend continues in 2024 with the highest rainfall in January at 470.20 mm and February at 397.20 mm. The difference in rainfall between seasons is very clearly visible, with the lowest rainfall being just 2.00 mm in June 2023, indicating seasonal extreme conditions. The surge in rainfall from month to month indicates the potential risk of increased flooding if drainage and water infiltration systems are not properly managed (Table 1).

The final result is as showed in Table 2. Based on the calculations in Table 2, it was found that there has been an increase in the intensity of rain in the last 3 years with the results of the graph (Figure 2). This indicates a high potential for surface runoff that can occur in a short time if the rainwater management system is unable to accommodate the water discharge. This strengthens the urgency of implementing an adequate drainage system and optimizing green open space as a catchment area in areas with dense building activities such as the UNS Area.

Land use map

Mapping of land cover in the UNS Campus area shows an imbalance in distribution between natural catchment zones and watertight areas (Figure 3). Green open space (GOS) is concentrated on the east and south sides of campus, especially around lakes, stadiums, as well as zones adjacent to the city's GOS. This area has an important role in supporting rainwater infiltration and naturally retaining surface runoff. In contrast, the central and western parts of the campus are dominated by buildings and pavement, such as lecture halls and parking areas. The predominance of watertight materials in this region leads to a reduction in the

Table 1. Maximum rainfall

Month	Total rainfall by month (mm)		
	2022	2023	2024
January	15.00	279.20	470.20
February	15.00	465.00	397.20
March	14.00	493.10	259.30
April	15.00	166.20	397.20
May	13.00	150.00	86.70
June	14.00	2.00	36.00
July	5.00	-	8.00
August	8.00	-	-
September	8.00	-	130.00
October	9.00	42.00	24.00
November	5.00	66.00	293.00
December	9.00	79.90	355.00
Maximum rainfall flow per year (CHmax)	15	493.10	470.20

Note: BMKG Adi Soemarmo Air Force Base & Class I Central Java Climatology Station (2025).

Table 2. Final results of rain intensity calculation with the Mononobe method

Period		Rainfall intensity		
T (Menit)	T (jam)	Year 2022 (mm/h)	Year 2023 (mm/h)	Year 2024(mm/h)
5	0.08	27.16	892.88	851.42
10	0.16	17.11	562.52	536.39
20	0.33	10.79	354.60	338.13
40	0.66	6.80	223.46	213.08
60	1.00	5.19	170.59	162.66

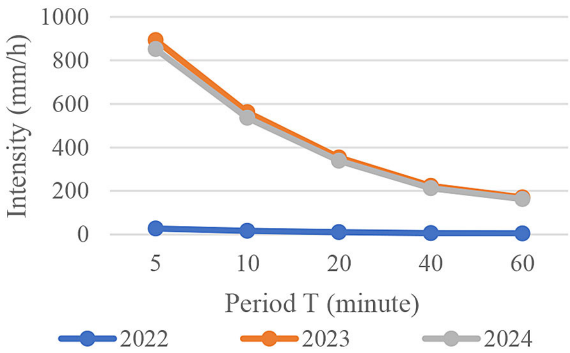

Figure 2. The relationship of intensity with rain duration

soil's capacity to absorb rainwater, thereby increasing the potential for runoff and inundation. This inequality has a direct impact on rainwater flow and vulnerability to local flooding in the campus area.

Flood vulnerability map

Based on the simulation, UNS Campus area is classified into five risk categories (Figure 4a) which classified into very low (6.7%), low (26.4%), moderate (19.0%), high (28.3%), and very high (19.7%) as seen in Figure 4b. The high-vulnerability zones (in red) are mainly located in the central and southern parts of the campus, which are also the areas with the highest building density based on the results of land cover maps. In contrast, area with larger green open spaces show low levels of vulnerability (green color).

These findings indicate a strong correlation between increased waterproofing land due to development and increased local inundation risk. Congested infrastructure, such as lecture buildings, main circulation routes, and parking areas, are the main factors that reduce infiltration capacity and increase the risk of flooding.

Runoff map

The surface runoff map shows the distribution of rainwater runoff in UNS campus area that occurs due to the inability of the soil to absorb water (Figure 5). Areas with high runoff (marked in red) are mostly found in areas dominated by buildings

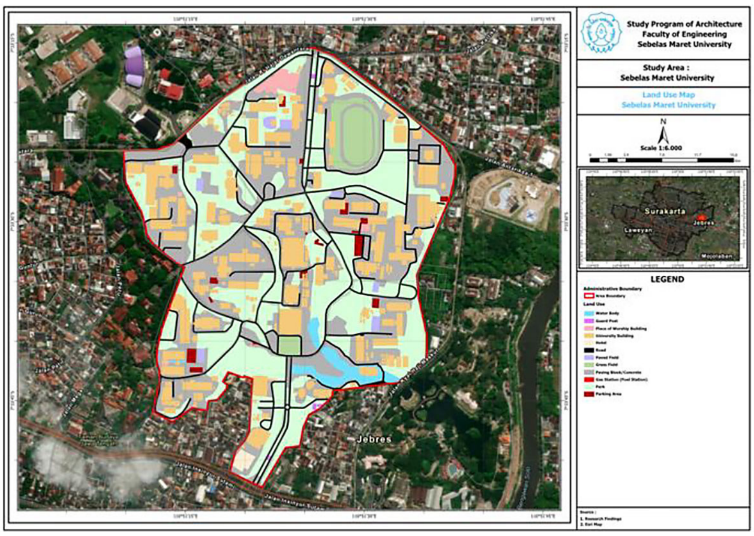

Figure 3. Land use map

a) b)

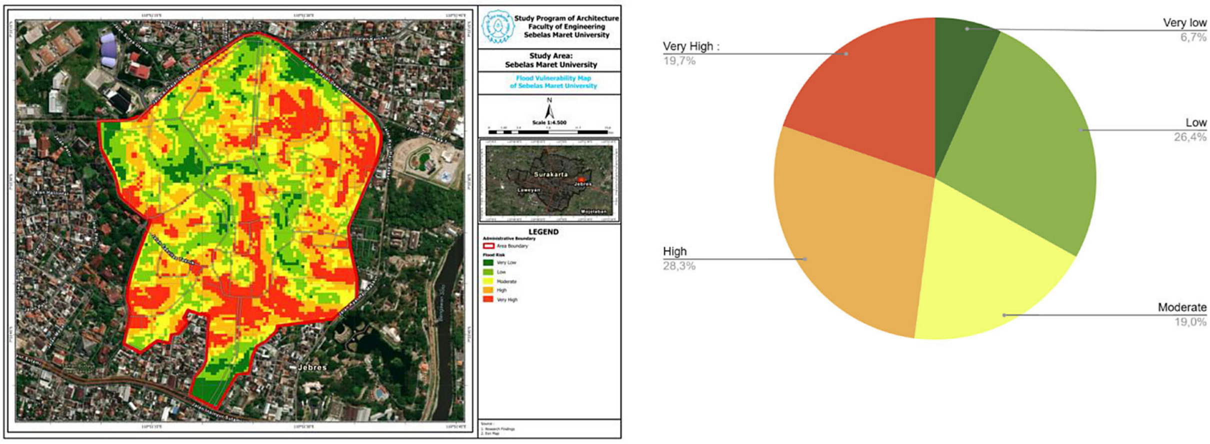

Figure 4. Flood vulnerability map

and pavement, such as faculty buildings, student activity centers, and areas around the rectorate.

These conditions suggest that areas with low permeability contribute significantly to increased surface runoff volumes, which ultimately increases the risk of inundation. The imbalance between the catchment zone and the watertight zone is the main cause of the formation of excess surface runoff.

Runoff flow map

The runoff flow map provides an overview of the direction and speed of rainwater flow on the campus ground surface. Zones with high flow velocities (red color) are found in areas with a considerable slope and impermeable surfaces, while slow-flow zones (green colors) are in flat or basin regions (Figure 6).

High flow speeds can accelerate water accumulation in downstream areas, potentially causing inundation if the drainage system is inadequate. On the other hand, zones with slow flows are at risk of becoming local inundation locations due to the slow movement of water out of the area.

Flood stream vulnerability map

The flood stream vulnerability map shows the level of inundation risk based on the accumulation of surface flows in the campus area. The high level of vulnerability zone marked in red is located in the central to southern part of the campus, which has a combination of runoff rates and high-water flow velocity (Figure 7). This high risk is closely related to the dominance of impermeable surfaces and fast water flow patterns that are

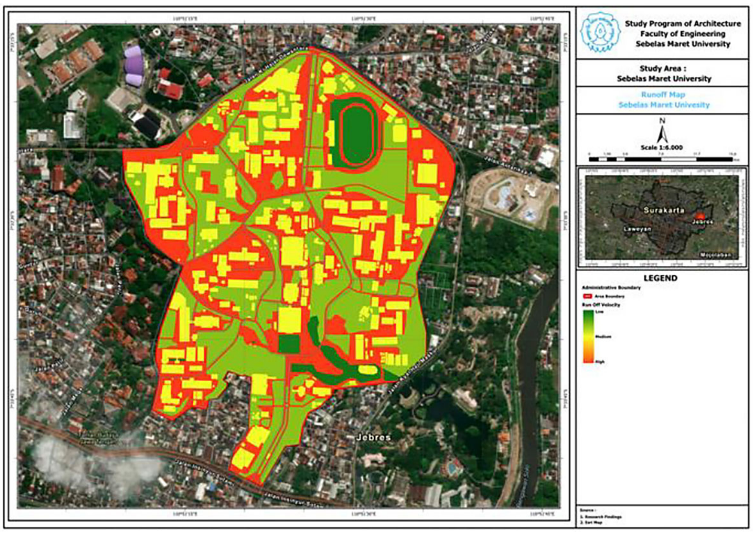

Figure 5. Runoff map

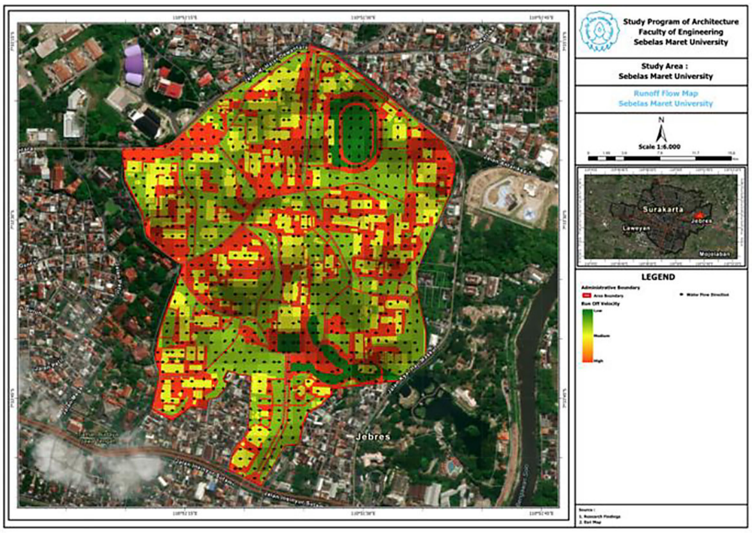

Figure 6. Runoff flow map

unable to accommodate the volume of rainwater quickly. This information is an important basis for planning technical interventions such as the construction of infiltration wells, biopore holes, and the rearrangement of micro-drainage systems that suit the contours of the land.

Previous flood flow vulnerability mapping showed that the central to southern areas of the UNS Campus had the highest level of inundation risk. This is due to a combination of the predominant watertight surface, the slope of the area that accelerates the surface flow, and the drainage system that is not optimal. To explore the existing conditions in more detail, a follow-up mapping of the seven main zones on campus, namely Zone A to Zone G (Figures 8–20) was carried out to understand the spatial distribution of runoff potential and water infiltration capacity in each area.

Based on hydrological analysis, Zone A has several high to very high inundation-prone points which include lakes, auditorium, library, and ICT buildings (Figure 8). The majority of these potential inundation points are caused by the type of land cover, such as paving blocks and asphalt, as well as the construction of campus facility buildings. The vulnerability of inundation in the lake area is in accordance with the function of the lake as a reservoir in the campus area (Figure 10a). Meanwhile, the potential for inundation that occurs in the ICT building (Figure 9b) and auditorium (Figure 9c) needs special

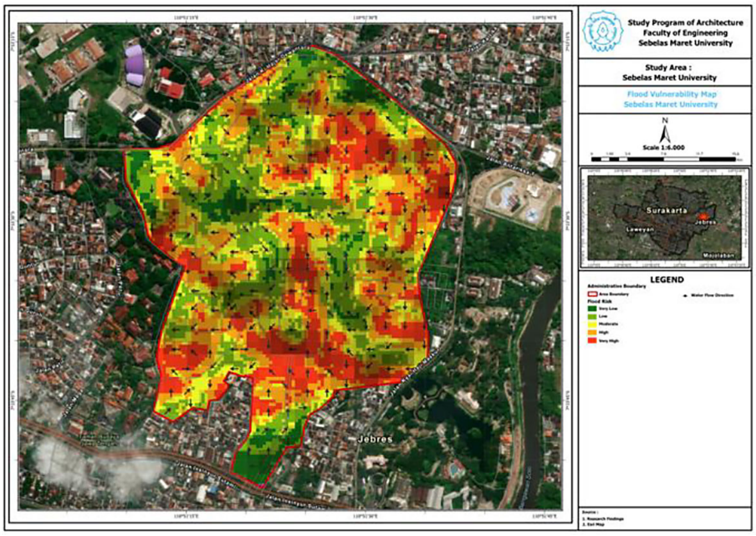

Figure 7. Flood stream vulnerability map

a) **b)**

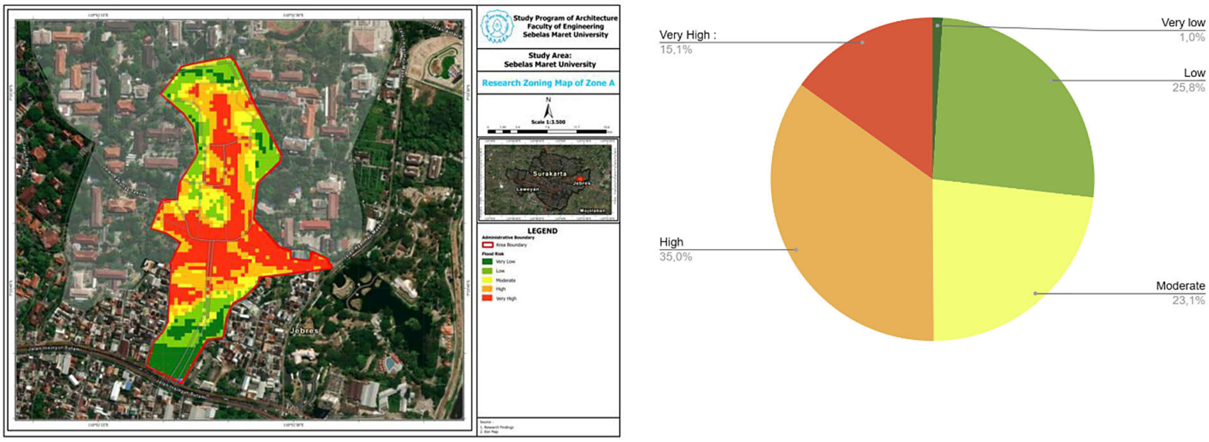

Figure 8. Map of zone A of UNS Kentingan Campus

a) **b)** **c)**

Figure 9. Some of the inundation-prone points in Zone A include: (a) UNS lake, (b) ICT building, (c) auditorium building

attention, especially because it functions as a campus facility.

Zone B has fewer high to very high inundation-prone points, which include the Faculty of Engineering field and river paths (Figure 10). The vulnerability of inundation in the field of the faculty of engineering (Figure 11a) is caused by the type of land cover in the form of concrete slabs. Meanwhile, the inundation on the river path is in accordance with its function (Figure 11b). In general, intervention in this zone is considered not too urgent to be carried out.

Zone C tends to be less prone to inundation when compared to other zones (Figure 12). The

a) **b)**

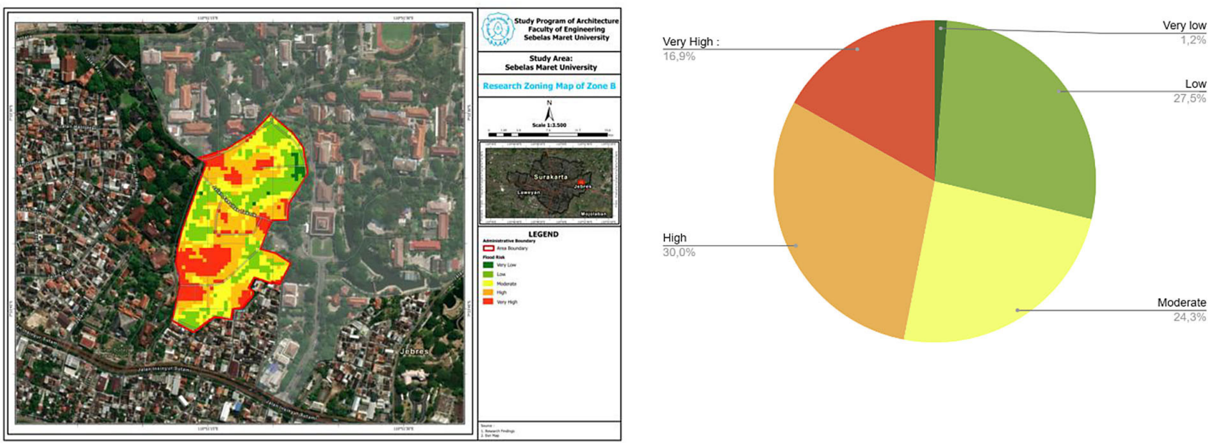

Figure 10. Map of zone B of UNS Kentingan Campus

small inundation point is in the area of the Faculty of Social and Political Sciences (FISIP) building, the gate of the Faculty of Economics and Business (FEB), and the campus gate from the Faculty of Law (FH) which leads to Ki Hajar Dewantara street. The potential point of inundation in the FEB building area occurs due to the use of paving blocks as land cover, building construction, and lower elevation than the surrounding area (Figure 13a). The inundation-prone point at the FEB gate occurs due to the use of asphalt and paving blocks as land covers, as well as the elevation of the area lower than the surrounding area (Figure 13b). Meanwhile, access to the exit gate on campus is included in the

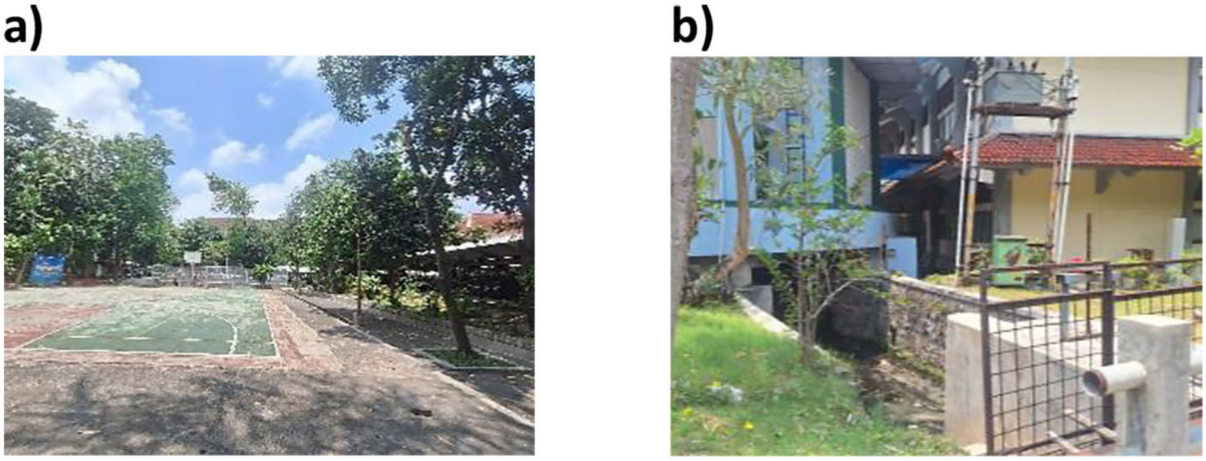

Figure 11. Some of the inundation-prone points in zone B include: (a) engineering field, (b) Sungai water

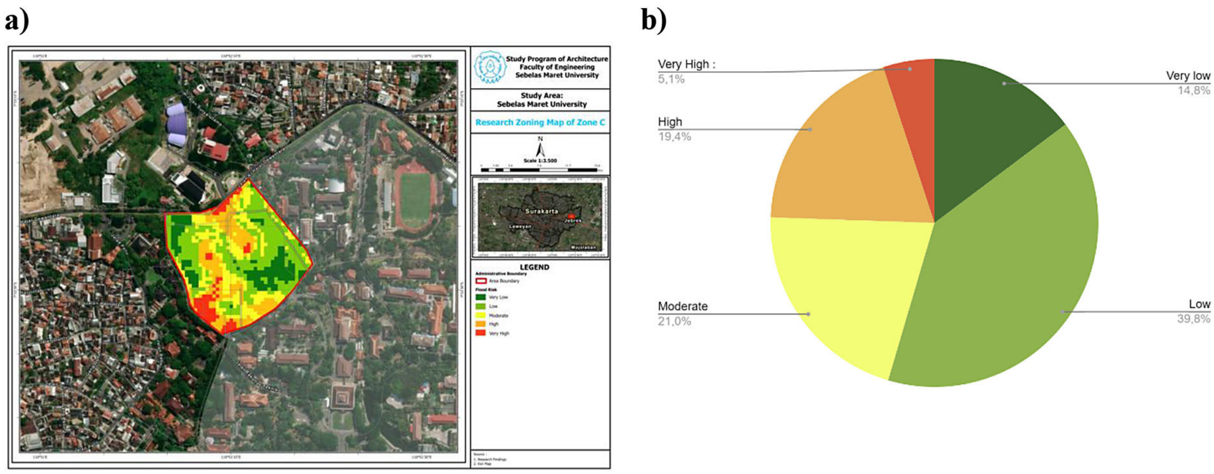

Figure 12. Map of zone C of UNS Kentingan Campus

Figure 13. Some of the inundation-prone points in Zone C include: (a) FISIP building, (b) FEB gate, (c) access to the campus exit gate

inundation-prone point because it uses asphalt as a land cover (Figure 13c). Interventions can be prioritized in the FISIP Building area because it is a supporting facility for lecture activities. Zone D of the UNS campus tends to be safe from potential inundation (Figure 14). Minor inundation spots occur in some areas, but they can be ignored because they are relatively small and located in less vital locations. The potential point of inundation in Zone E is concentrated in the campus stadium area which is an open green area (Figure 15). This point tends to have a lower elevation than the surrounding area. Although it is a point prone to inundation, the land cover material in this area is grass so as long as there is good enough drainage, water can be absorbed well (Figure 16).

Zone F contains numerous very high inundation-prone area situated between the south side of the Javanology building and the north side of the Faculty of Medicine (Figure 17). The inundation area is caused by the type of land cover in the form of paving, as well as the significant slope of the ground surface in the area (Figure 18).

Zone G has several high to very high distributions of flood-prone points located on the road access of the Faculty of Agriculture (Figure 19).

Figure 16. Inundation-prone points at UNS stadium

a) b)

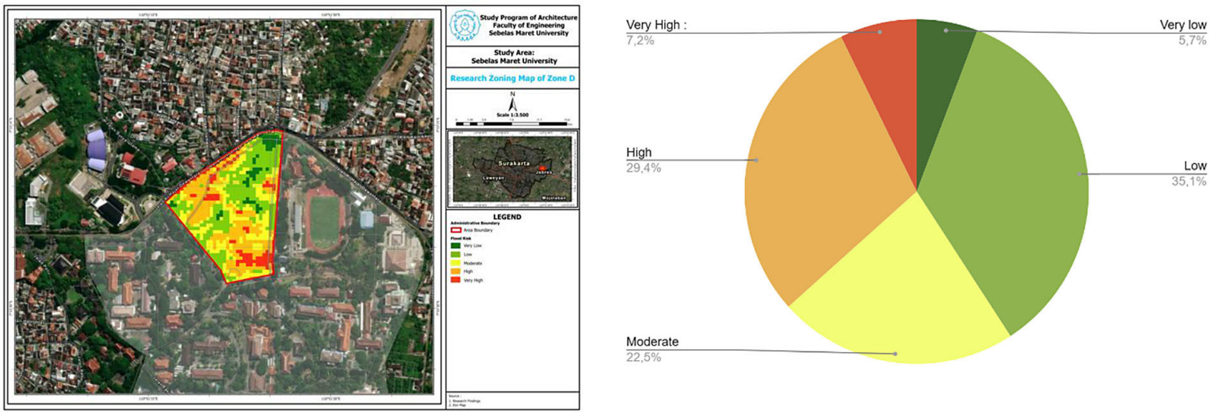

Figure 14. Map of zone D of UNS Kentingan Campus

a) b)

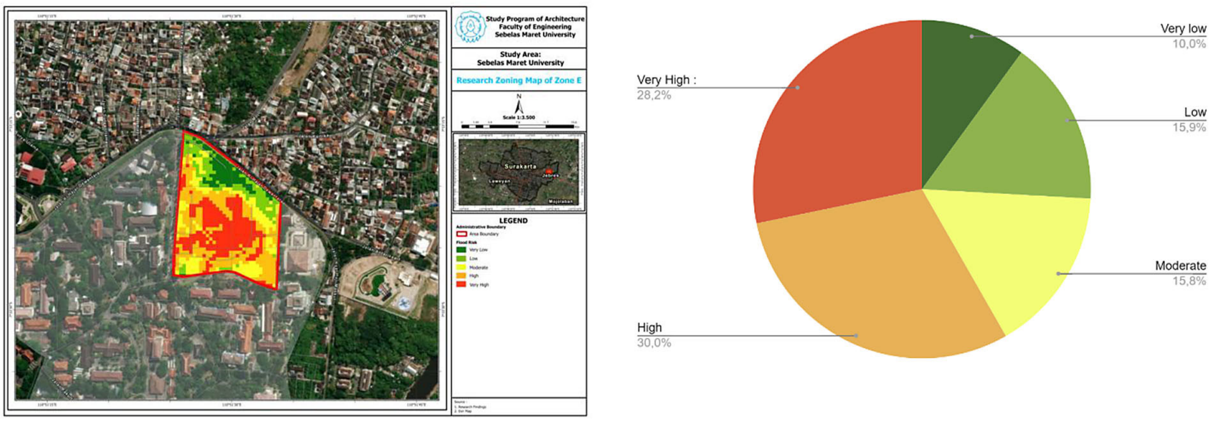

Figure 15. Map of zone E of UNS Kentingan Campus

a) b)

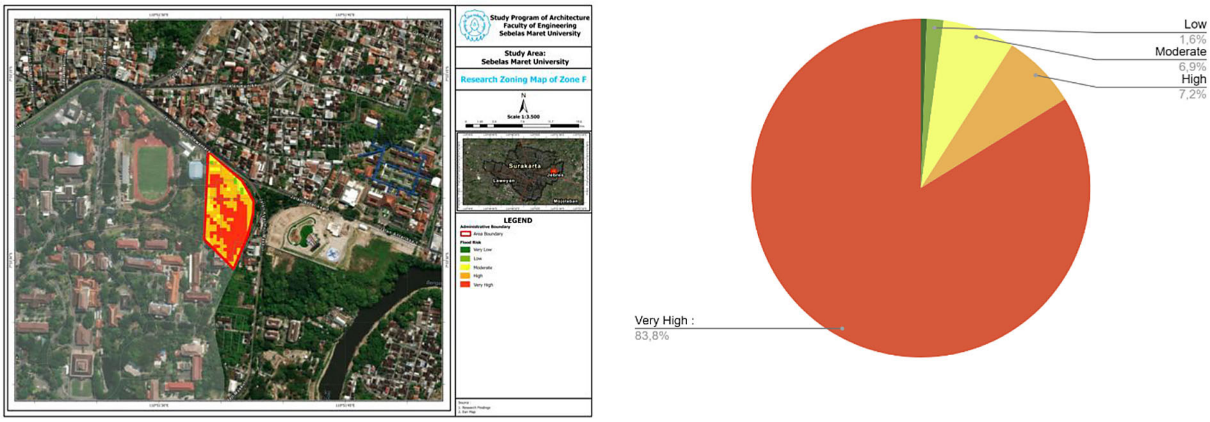

Figure 17. Map of zone F of UNS Kentingan Campus

Figure 18. Inundation-prone points in the southern area of Javanologi

a) b)

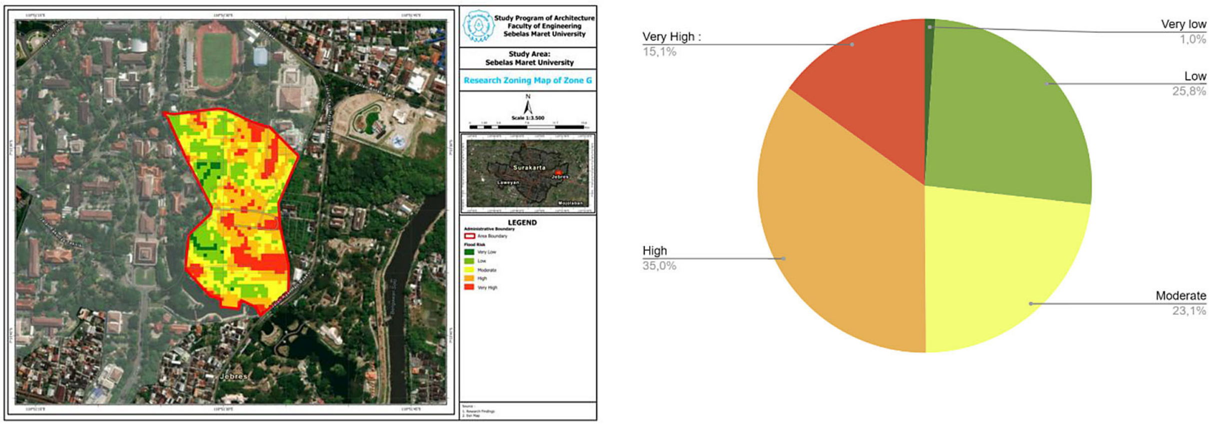

Figure 19. Map of zone G of UNS Kentingan Campus

Figure 20. The point prone to inundation in Zone G, namely the road access of the Faculty of Agriculture

The cause is the difference in soil elevation so that water flows into the lower area (Figure 20).

CONCLUSIONS

The UNS Kentingan Campus area has several points prone to inundation and potential flooding, especially in zones with low soil slopes and land covers such as asphalt, concrete slabs, and paving blocks. Some inundation-prone points are reservoir areas/water bodies so they are assessed according to their function. However, most inundation occurs not at the point of the water body. Among the seven zones, Zones A, E and F have a larger total area prone to inundation than other zones. Zone A is the area with the most urgent intervention priority because there are various campus facilities, such as auditoriums, libraries, and ICT buildings used by the academic community. Interventions, among others, can be carried out by 1) the use of porous land covers, such as permeable paving, 2) improvement of drainage systems, 3) the addition of open water channels or water collection canals in natural basin areas.

Zone F (the Javanology building and the north side of the Faculty of Medicine) areas that must receive attention: 83.8% of the flooded risk area, then zone E (the campus stadium area) 28.2%, then zone B (Faculty of Engineering field and river paths) 16.9%, then zone A (lakes, some auditoriums, libraries and ICT buildings) 15.1%, then zone G (Faculty of Agriculture) 15.1%, then zone C (the Faculty of Social and Political Sciences (FISIP) building, the gate of the Faculty of Economics and Business (FEB), and the campus gate from the Faculty of Law (FH)) is the smallest; 5.1%. Of the area of the entire UNS area that is included in the maximum vulnerability, the area is 110,376 m^2, and the minimum vulnerability is 37,465 m^2.

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