doi: 10.37905/jgeosrev.v8i1.35670 ejurnal.ung.ac.id/index.php/jgeosrev

Vol. 8, No. 1, January 2026: 94-107

Jambura Geoscience Review

p-ISSN 2623-0682 | e-ISSN 2656-0380

Department of Earth Science and Technology, Universitas Negeri Gorontalo

Spatiotemporal Analysis Of Flood Inundation Using MNDWI At Rawa Pening 2019-2025

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ARTICLE INFO

Article history:
Received: 28 November 2025
Accepted: 23 December 2025
Published: 15 January 2026

Keywords:
Flood inundation; MNDWI; Rawa Pening Lake; Sentinel-2; Spatiotemporal Analysis

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ABSTRACT

Flood inundation around Rawa Pening Lake has intensified in recent years, yet long-term patterns of inundation extent and persistence remain poorly quantified. This study aims to analyse the interannual and spatial dynamics of flood inundation in the Rawa Pening lake-basin system during 2019–2025 and to identify riparian zones that experience recurrent flooding. Sentinel-2 Level-2A imagery was processed within a 3 km riparian buffer to compute the Modified Normalized Difference Water Index (MNDWI), apply a histogram- and visually based threshold for water extraction, and generate annual maximum inundation and seasonal wet-season inundation-frequency metrics. The classification achieved high overall accuracy (93.1%), supporting the reliability of the derived inundation products. The multiyear results reveal strong year-to-year variability in maximum inundation and show that floodwater consistently concentrates in low-lying southern and southeastern riparian sectors, particularly within Banyubiru and Tuntang subdistricts, while western and northern sectors experience smaller and less persistent flooding. The combination of maximum inundation extent and inundation-frequency maps provides complementary insight into extreme events and recurrent flood exposure, enabling a clearer distinction between episodic and chronic flood impacts on riparian agriculture and settlements. These findings demonstrate the value of multitemporal MNDWI analysis and an ecologically defined buffer zone for monitoring lake-basin flooding and offer a spatial basis for prioritizing riparian conservation, land-use regulation, and flood-risk reduction around Rawa Pening.

How to cite: Amalia, S. (2026). Spatiotemporal Analysis of Flood Inundation Using MNDWI at Rawa Pening 2019-2025. *Jambura Geoscience Review, 8*(1), 94-107. https://doi.org/10.37905/jgeosrev.v8i1.35670

1. INTRODUCTION

Indonesia, as an archipelagic country with a tropical climate and high rainfall, is highly vulnerable to flooding (Kemenko PMK, 2023). In 2024, floods occurred 1,109 times nationally, making them the most frequent disaster that year (Alfathi, 2025). Semarang Regency is particularly prone to inundation because it lies in a basin surrounding Lake Rawa Pening, where excess rainwater is easily retained when environmental capacity is exceeded (Giyanto et al., 2022). In 2024, the lakeside villages of Rowosari (Tuntang) and Rowoboni (Banyubiru) were inundated to depths of up to 50 cm after one night of heavy rain, affecting dozens of households (BPBD, 2024; Persada, 2024). Climatological records for Banyubiru indicate annual rainfall of about 2,167 mm with 126 rainy days in 2024, substantially higher than around 1,600 mm in 2019 (Pemerintah Kabupaten Semarang, 2025). The data indicate that climate variability (high rainfall and heavy rainfall intensity) and land-cover changes that alter surface runoff patterns likely play an important role in flood dynamics (Aji et al., 2021; Cahyati et al., 2025).

Flood inundation patterns in the Rawa Pening basin are influenced not only by climatic factors but also by basin morphology, lake water-level fluctuations, and land-cover changes over time (Zhang et al., 2021). Therefore, spatiotemporal analysis is required to identify annual variations in flood extent and location so that areas experiencing recurrent flood inundation can be accurately delineated (Kontar et al., 2021). Remote sensing technology, particularly Sentinel-2 imagery, provides adequate spatial and temporal resolution for long-term monitoring of inundation (Yang at al., 2020). Water-index-based studies have demonstrated the effectiveness of spectral analysis for rapid flood-inundation detection.

Among spectral indices, the Modified Normalized Difference Water Index (MNDWI) enhances water–nonwater contrast using the Green and SWIR bands and is widely applied for flood inundation detection (Laonamsai et al., 2023). In this study, the MNDWI threshold was set using histogram separation and visual checks on Sentinel-2 true color composites, while noting possible misclassification over dense aquatic vegetation, moist surfaces, and shadowed pixels (Deng et al., 2024; Kareem et al., 2023). Most previous studies in the Rawa Pening and surrounding regions focused on single-year or short-term observations, leaving long-term inundation dynamics insufficiently explored (Pranadiarso et al., 2022). For instance, a single-period spectral index has been applied for flood mapping in urban areas, and static flood-vulnerability maps based on physical-parameter overlays have also been produced. In contrast, this study analyzes seven years (2019–2025) of multitemporal Sentinel-2 data to derive actual inundation dynamics and inundation-frequency patterns in the Rawa Pening lake-basin system.

The gap in understanding long-term flood behavior in the Rawa Pening basin highlights the need for interannual and multitemporal analysis. Unlike previous studies that mainly produced short-term flood maps for 2021–2023 (Muhammad et al., 2023) or examined spatiotemporal variations using NDVI (Sari et al., 2024), this research applies a seven-year (2019–2025) spatiotemporal analysis of Sentinel-2 imagery processed with the Modified Normalized Difference Water Index (MNDWI), which is more effective for delineating floodwater and detecting inundation than vegetation-based indices (Sulandari et al., 2024). The extended time coverage also goes beyond flood-vulnerability mapping in Latambaga by Benardi et al., which focused on validating vulnerability zoning from regional physical parameters. By combining multitemporal MNDWI with inundation-frequency analysis within a 3 km riparian buffer, this study introduces a methodological approach that has not previously been applied to flood studies in Rawa Pening and provides a more comprehensive view of actual inundation dynamics (Purwanto et al., 2025). The urgency of this research is reinforced by the increasing intensity of flood inundation around Lake Rawa Pening, changes in land cover, and their impact on the agricultural sector. Repeated flood inundation has been shown to reduce productivity and increase the risk of crop failure, making accurate mapping of affected areas an important requirement for disaster mitigation and spatial planning (Fauzan et al., 2025). The spatiotemporal MNDWI analysis is expected to provide relevant scientific information for local governments in sustainable regional management and hydrological risk reduction (Al-Ali et al., 2024; Cheng et al., 2024).

This study therefore aims to analyse spatiotemporal changes in flood inundation in the Rawa Pening Lake area during 2019–2025 and to identify locations that experience repeated flooding based on MNDWI processing and GIS-based spatial analysis (Sur et al., 2021). The novelty of this work lies in integrating annual maximum inundation mapping with wet-season inundation-frequency analysis within an ecologically defined 3 km riparian buffer to distinguish episodic flood extent from recurrent flood exposure in a shallow tropical lake-basin system. The results of this study are expected to provide a scientific basis for flood mitigation, spatial planning, and hydrological risk monitoring in areas directly affected by the Rawa Pening Lake hydrological system.

2. METHOD

2.1. Research Location

The research area is located in the Rawa Pening Lake basin, Semarang Regency, which functions as a hydrological depression with seasonal flood inundation driven by rainfall variability and surface runoff (Triana & Wahyudi, 2020). The analysis focuses on four surrounding subdistricts—Ambarawa, Banyubiru, Bawen, and Tuntang that exhibit marked interannual changes in water coverage and flood exposure. The study area was limited to a 3 km buffer from the lakeshore to represent the riparian landscape most responsive to lake-catchment hydrological interactions, including recurrent overbank inundation and land-water material exchange (Graziano et al, 2022; Hilary et al., 2021). Recent work on buffer zone management at Rawa Pening also emphasizes the need to delineate a broad lake-fringing zone to safeguard water quality and ecosystem services, supporting the use of an extended buffer for integrated hydrological assessment (Kalmah et al., 2022). In this context, the 3 km distance was selected as an ecological–hydrological envelope that includes the main floodprone riparian areas and tributary confluences, whereas narrower buffers commonly used in waterquality studies would not capture the full spatial extent of seasonal inundation in this shallow lakebasin system (Hilary et al., 2021; Nada et al., 2023).

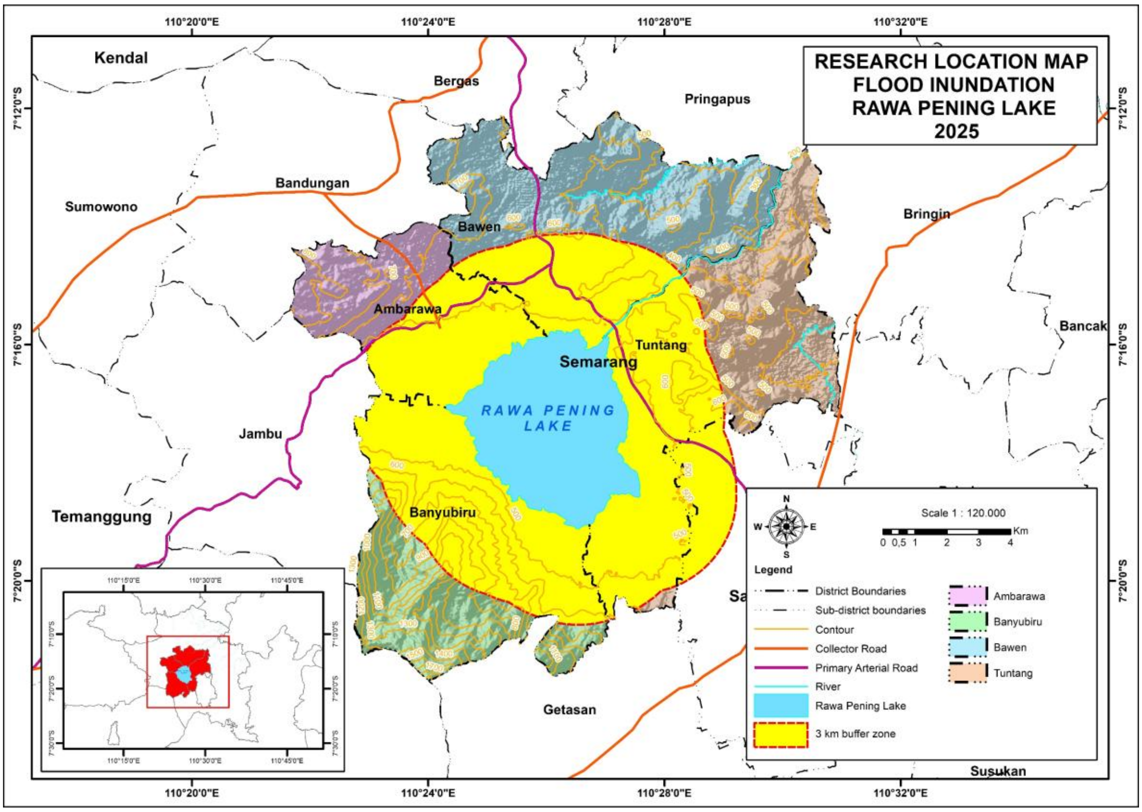


Figure 1. Map of the research location

2.2. Data and Data Sources

The main research data comprises Sentinel-2 Level-2A imagery from 2019–2025, using Green (B3) and SWIR (B11) bands for MNDWI computation with atmospheric correction for floodinundation analysis (Guo et al., 2021). Wetseason (October–March) images within the 3 km buffer with cloud cover below 20% were selected, cleaned using Scene Classification Layer, and combined into wetseason composites to derive maximum inundation extent and frequency (Hasan et al., 2023; Li et al., 2023; Samela et al., 2022). Supporting datasets include administrative and lake boundaries and the 3 km buffer representing riparian zones, standardized before integration in GEE and ArcGIS (Güvel et al., 2022; Kenranto et al., 2024).

Table 1. . Data and data sources

Data	Data Source	Resolution	Description
Sentinel-2 L2A (2019-2025)	ESA	10 - 20m	B3 & B11 for MNDWI
Administrative Boundaries	BIG	-	Area restrictions
Lake Boundaries	BIG	-	Reference water areas
3 km buffer	Analysis results	-	Modification of study boundaries

2.3. Preprocessing (Cloud masking and clipping)

Data collection was carried out using Sentinel-2 Level-2A imagery from 2019 to 2025, where the Green (B3) and SWIR (B11) channels were used as the basis for calculating MNDWI. The SCL (Scene Classification Layer) band was used to identify and exclude poor atmospheric pixels such as cloud shadows, medium clouds, high clouds, thin cirrus, and snow/ice, so that only valid pixels were retained in the masking process (Li et al., 2023). Supporting data such as administrative boundaries, lake boundaries, and 3 km buffers were prepared in shapefile format and combined at the area cropping stage to ensure consistent spatial analysis boundaries (Güvel et al., 2022).

The initial processing was conducted in Google Earth Engine (GEE), where clouds and cloud shadows were removed by masking Sentinel-2 Scene Classification Layer classes corresponding to cloud shadow, medium and high cloud, thin cirrus, and by applying an additional scene-level cloud filter to exclude images with residual contamination in the wet-season set (Thapa et al., 2025). All remaining images were clipped to the 3 km buffer and converted to MNDWI-based binary water/nonwater masks using an empirically adjusted threshold, after which seasonal (October–March) composites were generated and visually inspected on selected dates to confirm that the extracted inundation patterns and cloud removal were consistent with flood extents visible in the original imagery (Odiji et al., 2024).

2.4. MNDWI Calculation

The initial stages of processing in GEE included SCLbased masking of poor atmospheric pixels, image cropping to the 3 km buffer as the study boundary, calculation of the MNDWI index from the Green-SWIR bands, creation of October–March seasonal composites to reduce temporal noise, and transformation of the MNDWI index into a binary water/nonwater raster using a fixed threshold greater than 0 (Laonamsai et al., 2023).
Equation (1) was applied for MNDWI calculation:

$$\text{MNDWI} = \frac{(Green - SWIR)}{(Green + SWIR)} \quad (1)$$

The MNDWI formula enhances the spectral difference between water and non-water surfaces by utilizing the reflectance contrast between the Green and SWIR bands. Water bodies typically exhibit high reflectance in the Green band and strong absorption in the SWIR band, resulting in positive MNDWI values, whereas built-up areas, vegetation, and soil tend to produce negative values (Laonamsai et al., 2023).

2.5. Flood Classification (Threshold > 0)

The choice of this fixed threshold was justified by referring to previous MNDWI-based waterextraction studies, inspecting histograms of MNDWI values for representative water and nonwater samples, and visually comparing the resulting water masks with reference water patterns on multiple dates, which together indicated that the threshold provides a reliable separation of inundated and noninundated surfaces for subsequent spatial analysis.

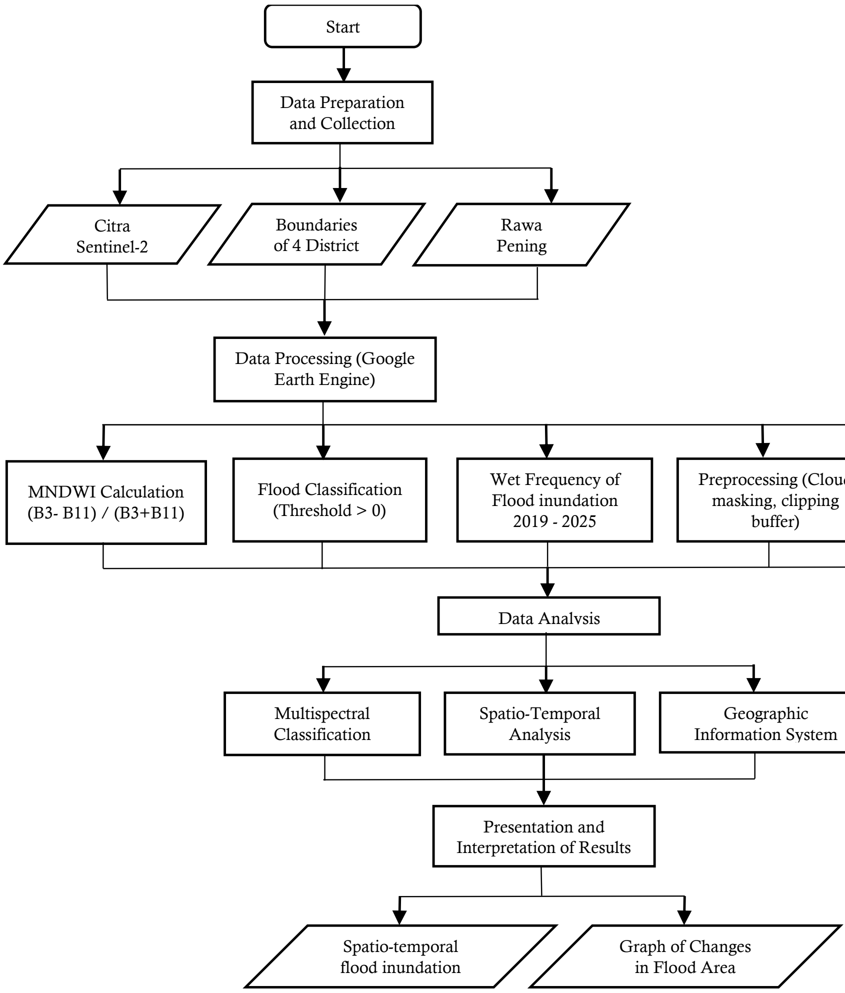


Figure 2. Research method flowchart

2.6. Parameters and Data Analysis

Table 2. Analysis Parameters

Parameter	Function
MNDWI value	Water pixel identification
Annual inundation threshold	Water/non-water separation
Annual inundation area	Spatial dynamics analysis
Inundation frequency	Detection of recurrent inundation areas
3 km zonal	Local hydrological sensitivity analysis

Analysis parameters are used to describe the characteristics of flooding quantitatively, ranging from the identification of water pixels based on MNDWI index values to the separation of flooding classes using predetermined thresholds. The analysis was performed using a raster calculator, spatial-temporal overlay, and zonal statistics in ArcGIS to generate spatial parameters that describe the dynamics of flooding during seven years of observation (Samela et al., 2022).

2.7. Accuracy Assessment of Water/NonWater Classification

Table 3. Confusion matrix for water/non-water classification

Classified	Water	Non-water	Row total	User Accuracy
Water	13	2	15	86,6%
Non-water	0	14	14	100%
Total (Producer)	13	16	29	
Producer Accuracy	100%	87,5%		

An accuracy assessment was conducted using 29 visually interpreted validation samples within the 3 km buffer (15 water and 14 nonwater), which were compared with the MNDWI-based binary classification and summarized in a 2 × 2 confusion matrix; 13 of 15 water samples were correctly classified and two were mapped as nonwater, while all 14 nonwater samples were correctly classified, yielding producer's accuracies of 100% (water) and 87.5% (nonwater), user's accuracies of 86.6% (water) and 100% (nonwater), and an overall accuracy of 93.1%, indicating that the chosen MNDWI threshold reliably separates inundated and noninundated areas.

2.8. Spatial and Zonal Analysis (GIS)

The resulting inundation products were subsequently exported to ArcGIS for threshold refinement, multitemporal overlay, and zonal flood statistics for administrative and landuse units (Güvel et al., 2022). The next step was carried out in ArcGIS, including histogram-based threshold refinement to ensure more accurate separation of water/non-water pixels (Scarpetta et al., 2025). The annual inundation maps were then overlaid to extract spatial and temporal patterns of inundation change for the period 2019–2025 (Ding et al., 2025). The next step was to perform zonal statistics on a 3 km buffer area using pixel area rasters to quantitatively calculate the inundation area in each analysis zone (Kalmah et al., 2022). All results were visualized through thematic maps and inundation trend graphs.

3. RESULTS AND DISCUSSION

The results of this study characterize flood dynamics in the Rawa Pening Lake area using MNDWI derived from Sentinel-2 imagery for 2019–2025. Maps, graphs, and tables are used to interpret temporal changes in inundation and to relate them to previous work on shallow-water flood mapping (Bati et al., 2023). The analysis focuses on annual inundation extent, spatial distribution of flooded areas, and seasonal inundation frequency as indicators of riparian hydrological response, which is strongly influenced by climate variability, topography, and land-use change (Pena-Regueiro et al., 2020).

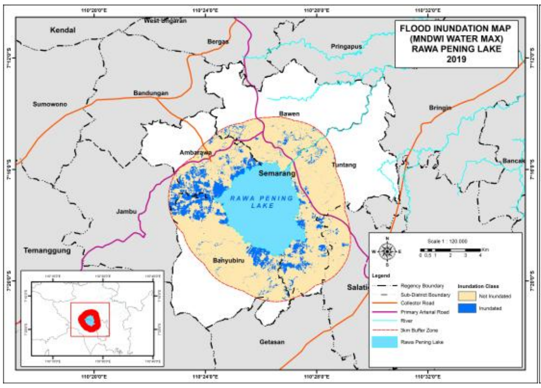
To reduce redundancy, the Results are presented following the order of the figures and tables, beginning with annual maximum inundation, followed by interannual change, wet-season flooding frequency, subdistrict zonal statistics, and finally the temporal trend. The Discussion then interprets each output in relation to landscape controls and climatic variability (Verdyansyah et al., 2025).

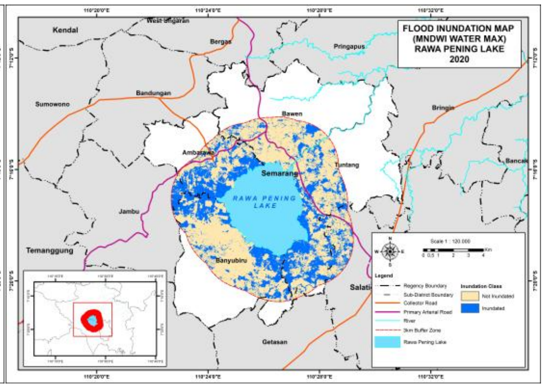
3.1. Results

Flood analysis in Rawa Pening Lake area used the MNDWI index from Sentinel-2 imagery for 2019–2025. This study covers annual maximum flood inundation, spatial changes between years, seasonal flooding frequency (Wet Frequency), and zonal flood statistics by subdistrict to interpret local hydrological dynamics. The combined use of "water maximum" (extreme extent) and "wet frequency" (recurrence) provides information for distinguishing episodic versus recurrent inundation in the riparian buffer.

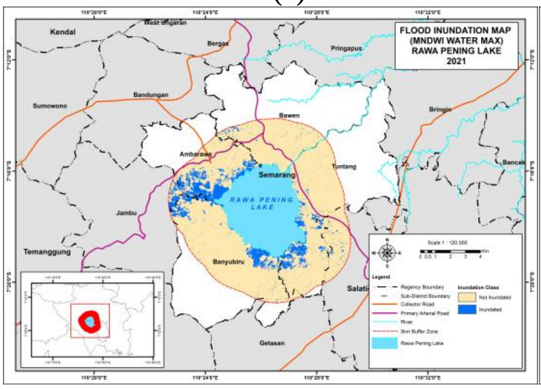
Maximum inundation mapping shows significant fluctuations between years. In 2019, the inundation area was 2,721.15 ha, increasing to 5,045.07 ha in 2020; from 2021 to 2024, inundation showed moderate variations before reaching its lowest of 2,385.48 ha in 2025. These changes reflect regional hydrometeorological variability influenced by ENSO–MJO dynamics, including La Niña that enhanced rainfall over Indonesia from late 2020 to 2022, consistent with reported increases of 54–90% in rainfall and 11–70% in rainy days during La Niña relative to normal conditions (Gangwisch et al., 2021; Harahap et al, 2023a).

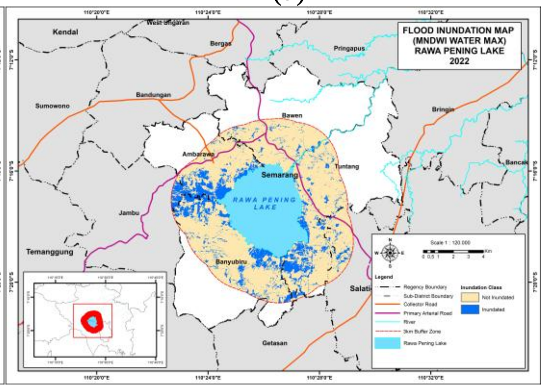
The MNDWI-based water/non-water classification achieved 93.1% overall accuracy, with producer's and user's accuracies above 85% for both classes, providing a reliable basis for analyzing inundation patterns. Flooding expands mainly in southern and southeastern sectors of the 3 km buffer, where maximum inundation increased by 85% from 2019 to 2020 and declined to 53% below the 2020 peak by 2025. This concentration in the south-southeast reflects low-lying riparian plains and inflow channels promoting water convergence and sediment deposition, whereas steeper terrain in the west and north enhances drainage and limits floodwater persistence (Lahay, 2022; Lo et al., 2022).



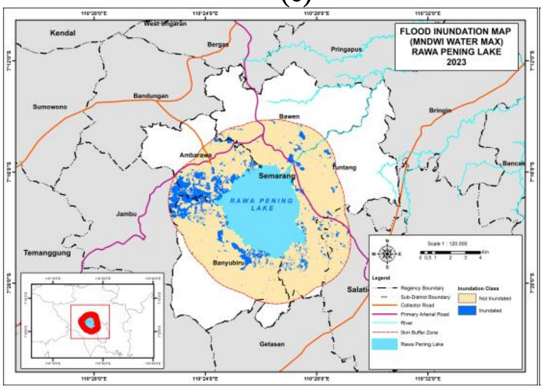


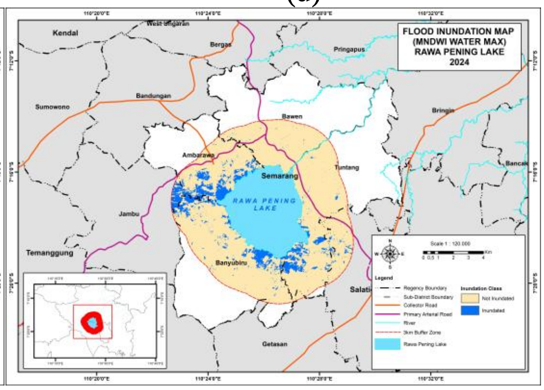
(a) (b)



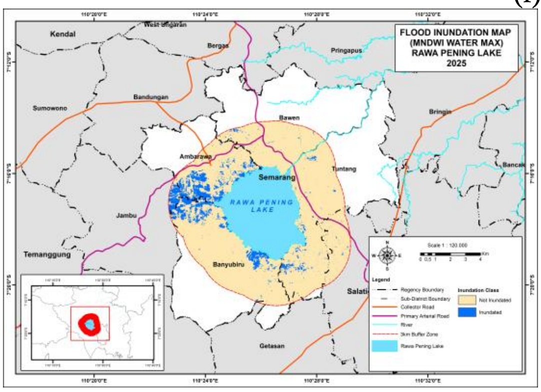


(c) (d)





(e) (f)



(g)

Figure 3. a) 2019, b) 2020, c) 2021, d) 2022, e) 2023, f) 2024, g) 2025 Flood Inundation Map (MNDWI Water Max 2019-2025).

The MNDWI-based water/non-water classification achieved an overall accuracy of 93.1%, with producer's and user's accuracies above 85% for both classes, providing a reliable basis for analysing inundation extent and spatial patterns. Spatially, flooding expands mainly in the southern and southeastern sectors of the 3 km buffer, where maximum inundation increased by about 85% from 2019 to 2020 and then declined to a level in 2025 that is roughly 53% lower than the 2020 peak. This concentration of flooding in the south–southeast reflects low-lying riparian plains and main inflow channels that promote water convergence and sediment deposition, whereas the relatively higher and steeper terrain in the west and north enhances drainage and limits floodwater persistence (Lahay, 2022; Lo et al., 2022).

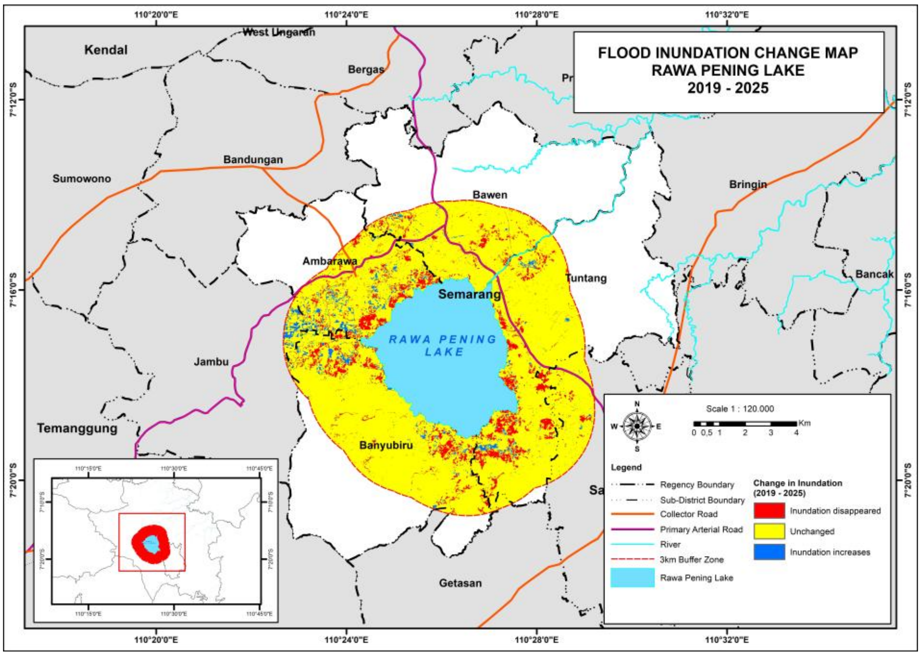


Figure 4. Flood Inundation Change Map 2019-2025

Frequency analysis of seasonal flooding shows that the areas with the highest rate of repeated flooding are located on the edges of the lake, particularly in the subdistricts of Banyubiru and Tuntang. These areas are flooded almost every rainy season due to soil saturation and relatively low water levels. In contrast, rice fields and settlements on the outer edge of the 3 km buffer zone show low to moderate flooding frequency. These findings are consistent with the characteristics of wetlands that are prone to repeated flooding during wet periods (Hasan et al., 2023).

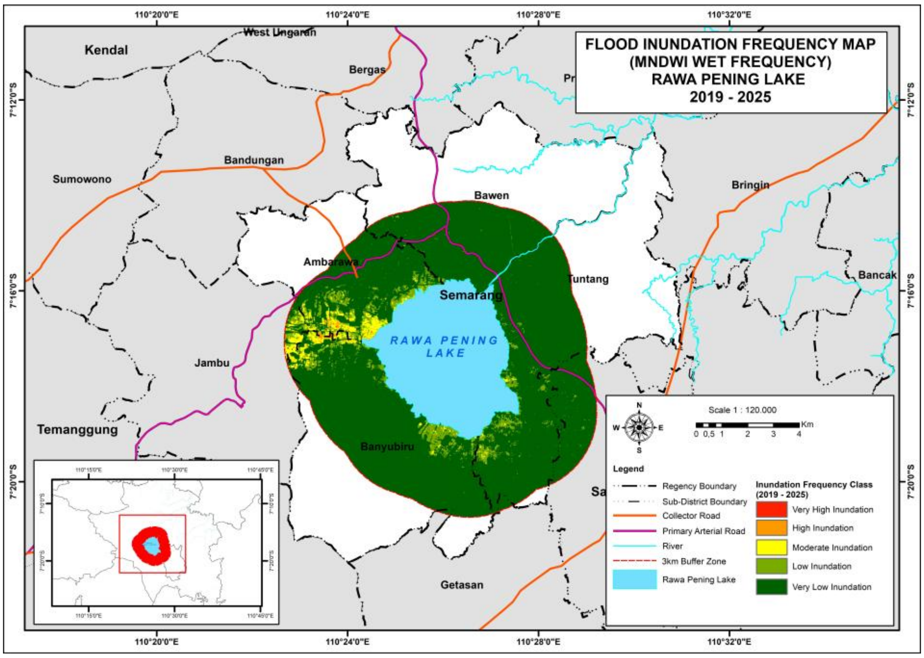


Figure 5. Flood Inundation Frequency Map 2019-2025

Table 4. Inundation Area by Subdistrict (ha) 2019-2025

Sub-District	2019	2020	2021	2022	2023	2024	2025	Mean
Tuntang	714,10	1640,86	899,74	1148,37	654,69	664,25	484,21	886,60
Banyubiru	856,15	1517,04	962,80	1281,99	1000,45	987,58	952,13	1079,73
Ambarawa	818,65	1123,25	800,79	795,30	802,02	735,50	673,65	821,31
Bawen	250,04	427,48	239,21	278,56	252,41	178,29	178,26	257,75

The statistical zones by sub-district show that Banyubiru and Tuntang consistently have the largest inundation areas, while Ambarawa has moderate inundation intensity and Bawen has the lowest inundation. This distribution indicates the influence of elevation and the proximity of the area's hydrology to the lake, as explained in the topography-based inundation vulnerability study (Criss & Nelson, 2022). Bar charts and line graphs show that 2020 and 2022 were the years with the highest inundation for all subdistricts, in line with records of high rainfall anomalies in those years (Haraha et al., 2023).

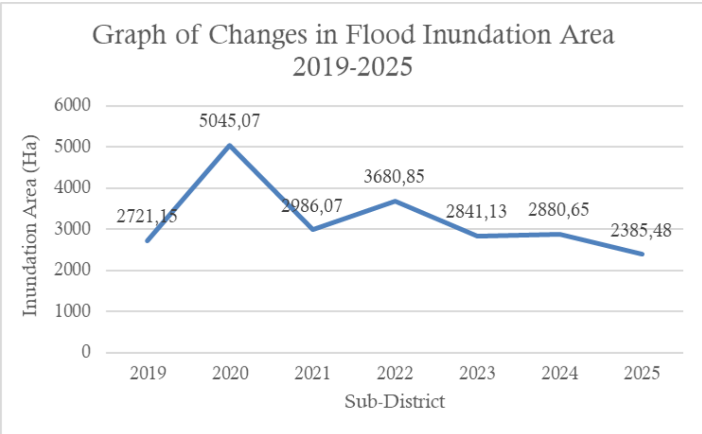


Figure 6. Graph of Changes in Flood Inundation Area 2019-2025

Based on the trends in Figure 6, it can be seen that 2020 and 2022 are the periods with the highest inundation area, while 2025 shows the most significant decline. This pattern is consistent with records of high rainfall anomalies in peak years and drier hydrological conditions in years with low inundation (Yamamoto et al., 2021). The decline in inundation towards 2025 indicates a possible shift in regional climate conditions or local hydrological changes that affect the lake's storage capacity. Taken together, Figure 6 and Table 4 confirm that the interannual signal is coherent across both total-area and zonal statistics outputs.

3.2. Discussion

The spatial and temporal patterns revealed in this study indicate that flood inundation in the Rawa Pening Lake basin is strongly modulated by interannual hydrometeorological variability, with maximum flooded area increasing by about 85% from 2019 to 2020 and then decreasing by roughly 53% between the 2020 peak and the 2025 minimum. These pronounced annual fluctuations coincide with years affected by ENSO–MJO activity and La Niña episodes, during which independent studies have documented substantial positive wet-season rainfall anomalies and increases in the number of rainy days in Central Java and other parts of Indonesia compared with neutral years (Gangwisch et al., 2021b). This correspondence supports (but does not by itself prove) a climate-driven component in the observed inundation peaks, consistent with the sensitivity of shallow lake floodplains to seasonal climatic oscillations.

Spatially, the dominance of inundation expansion in the southern and southeastern sectors reflects the geomorphological setting of the Rawa Pening wetland–lake system, where low-lying relief, sediment-laden inflow channels, and shallow lacustrine margins favour water convergence and long hydroperiods (Lo et al., 2022). These conditions lead to greater flood persistence than in the western and northern sectors, where relatively higher, more dissected terrain and ongoing sediment accretion and land-use modification are likely to enhance drainage efficiency and deflect flood pathways (Wang et al., 2024).

Seasonal flooding frequency and zonal statistics by subdistrict show that lake-fringing zones in Banyubiru and Tuntang consistently experience the highest recurrence of inundation, indicating a combination of low elevation, high soil saturation, and strong hydraulic connectivity to lake water levels (Riley & Stillwell, 2023). This concentration of recurrent flooding in low-relief sectors with dense inflow networks matches topography-based flood-vulnerability patterns reported elsewhere in Central Java (Fitriansyah et al., 2025) and provides a process-based explanation for the observed decline in inundation toward 2025, when reduced rainfall and possible changes in catchment hydrological properties appear to limit the spatial extent of seasonally flooded areas in a manner similar to other tropical lake basins in Southeast Asia (Boyaj & Vijayaraghavan, 2025).

The strengths of this study lie in the use of seven years of multitemporal Sentinel-2 imagery, which enables the characterization of interannual flooding variability, the integration of water maximum and wet frequency metrics that provide complementary spatial–temporal information, and the application of a 3 km ecological buffer that more closely represents the hydrological influence zone of the lake compared with administrative units. Zonal statistics by subdistrict further translate these inundation patterns into directly usable indicators for spatial planning and local flood-mitigation strategies.

Despite these strengths, several limitations should be acknowledged. The MNDWI index is sensitive to aquatic vegetation, water turbidity, and residual cloud shadows, which may lead to under- or overestimation of inundated area in densely vegetated or optically complex waters (Tesfaye & Breuer, 2023). The number and timing of cloud-free Sentinel-2 images vary between years, so wet-season composites may represent different sampling densities, introducing uncertainty into interannual comparisons. Validation relies on visual interpretation rather than extensive in situ water-level or flood-extent measurements, and quantitative rainfall or lake-level time series were not explicitly integrated into the analysis, limiting the ability to attribute inundation changes unambiguously to specific hydrometeorological drivers. These constraints should be considered when interpreting the results and point to the need for future work that couples multisensor remote sensing with ground observations and hydrometeorological datasets (Rahmadi et al., 2021; Ahmad et al., 2025).

4. CONCLUSIONS

This study shows that multitemporal Sentinel-2 imagery combined with MNDWI-based classification and zonal statistics is effective for characterizing interannual and spatial patterns of flood inundation in the Rawa Pening lake-basin system, thereby meeting the objective of mapping spatiotemporal inundation dynamics (2019–2025) and delineating recurrently flooded riparian zones using annual maximum inundation and wet-season inundation-frequency metrics within a 3 km buffer. Inundation within the 3 km riparian buffer responds sensitively to year-to-year hydrometeorological variability and consistently concentrates in low-lying southern and southeastern riparian zones, identifying Banyubiru and Tuntang as priority areas for flood-risk reduction and riparian management. These outputs provide a spatial basis for prioritizing riparian conservation, land-use zoning, and flood-mitigation planning around Rawa Pening.

The joint use of maximum inundation extent and inundation-frequency metrics provides complementary insight into extreme and recurrent flooding and offers a transferable framework for lake-basin flood monitoring and spatial planning. However, reliance on optical indices, variable cloud-free image availability, and the limited integration of hydrometeorological and in situ data introduce uncertainty and constrain causal attribution. Future work should integrate multiyear optical–SAR observations, rainfall and water-level time series, and field-based validation to refine inundation estimates and strengthen their use for riparian land-use zoning and adaptation strategies around Rawa Pening.

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