JOURNAL OF EARTH SCIENCE AND GEOMATICS INDONESIA
Volume 1 (2026), Page 20-25

Integrated SAR and Optical Approach for Multi-Temporal Flood Mapping in Bandar Lampung

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Received: February 12, 2026
Revised: May 17, 2026
Accepted: May 28, 2026
Published: June 10, 2026

Citation: Darmawansyah, R.. (2026). Integrated SAR and Optical Approach for Multi-Temporal Flood Mapping in Bandar Lampung. Journal of Earth Science and Geomatics Indonesia, 1, 20-25.

Abstract

Flooding is one of the most frequent hydrometeorological disasters in urban coastal regions, including Bandar Lampung, Indonesia. This study aims to analyze the spatial and temporal distribution of flood inundation in 2017, 2019, and 2022 using Sentinel-1 Synthetic Aperture Radar (SAR) and Sentinel-2 optical imagery. Flood detection was performed using the Normalized Difference Water Index (NDWI) derived from Sentinel-2 data and backscatter coefficient thresholding from Sentinel-1 imagery. The results show that Rajabasa, Panjang, and Kedamaian sub-districts experienced recurrent flood events, with Rajabasa exhibiting the largest increase in inundation area, reaching approximately 2.2 km^2 in 2022. The integration of SAR and optical data enhances the reliability of flood detection under varying weather conditions, particularly in cloud-covered areas. These findings provide valuable geospatial information to support flood mitigation strategies and sustainable urban planning in Bandar Lampung.

Keywords: flood mapping; multi-temporal analysis; sentinel-1; sentinel-2; ndwi; bandar lampung

1. Introduction

Flooding is one of the most significant hydrometeorological hazards affecting rapidly urbanizing regions worldwide. Coastal and low-lying cities are particularly vulnerable due to increasing impervious surfaces, land-use change, and climate variability (IPCC, 2021). In Indonesia, flood disasters occur frequently and are strongly associated with extreme rainfall intensity, watershed degradation, and uncontrolled urban expansion (BNPB, 2022). In addition, urban flooding has been widely linked to rapid land-use changes and reduced infiltration capacity, which significantly increase surface runoff (Mason et al., 2010; Rahman et al., 2019).

Remote sensing has become an essential tool for flood monitoring due to its ability to provide spatially continuous and multi-temporal observations. Optical satellite imagery, such as Sentinel-2, enables water body detection using spectral indices including the Normalized Difference Water Index (NDWI) (McFeeters, 1996). Furthermore, modifications of NDWI have been developed to enhance water feature extraction in complex environments (Xu, 2006). However, optical sensors are often limited by cloud cover during heavy rainfall events. In contrast, Synthetic Aperture Radar (SAR), such as Sentinel-1, overcomes this limitation by penetrating cloud cover and providing backscatter information sensitive to surface water (Schumann & Moller, 2015).

Recent studies have demonstrated the effectiveness of integrating SAR and optical data to improve flood detection accuracy (Clement et al., 2018; Li et al., 2019; Martinis et al., 2015). Additionally, global-scale surface water mapping studies highlight the importance of multi-source data integration for improving water detection reliability (Pekel et al., 2016). Nevertheless, in Indonesia, flood mapping studies have predominantly focused on major metropolitan areas such as Jakarta and Semarang, while multi-temporal analyses in secondary cities such as Bandar Lampung remain limited. Furthermore, most existing studies rely on single-event flood mapping, which restricts a comprehensive understanding of temporal flood dynamics and spatial variability.

Therefore, this study aims to analyze the spatial and temporal distribution of flood inundation in Bandar Lampung for the years 2017, 2019, and 2022 using Sentinel-1 and Sentinel-2 imagery. Specifically, this study seeks to quantify flood extent changes at the sub-district level and evaluate the effectiveness of integrating SAR and optical data. The findings are expected to provide valuable insights for improving flood mitigation strategies and supporting sustainable urban development.

2. Materials and Methods

2.1 Study Area

The study area covers Bandar Lampung City, Indonesia (5°20'–5°35' S; 105°15'–105°37' E). The city is characterized by coastal plains in the eastern and southern regions and hilly terrain in the western part. Rapid urban expansion over the past decade has significantly increased built-up areas, contributing to higher flood vulnerability.

2.2 Data

This study utilized multi-source geospatial datasets, including Sentinel-1 Ground Range Detected (GRD) imagery with VV polarization and 10 m spatial resolution, Sentinel-2 Level-2A imagery with 10 m resolution, administrative boundary shapefiles, and a Digital Elevation Model (DEM). Sentinel-1 data were acquired in ascending orbit, while Sentinel-2 images were selected with cloud cover less than 10%. The acquisition dates were chosen to represent peak rainfall periods in 2017, 2019, and 2022.

2.3 Sentinel-2 Processing

Flood detection using optical imagery was performed by applying the Normalized Difference Water Index (NDWI), expressed as:

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

where Green and NIR represent the reflectance values of the green and near-infrared bands, respectively. Water bodies were extracted using a threshold value of NDWI > 0, following McFeeters (1996). In addition, improved formulations of NDWI have been shown to enhance water detection accuracy in urban and mixed land-cover environments (Xu, 2006). The threshold was further refined through visual interpretation and histogram analysis to ensure optimal separation between water and non-water classes.

2.4 Sentinel-2 Processing

SAR data processing included radiometric calibration, speckle filtering using the Lee filter, terrain correction, and conversion to backscatter coefficient (dB). Flooded areas were identified using a threshold of approximately −17 dB. This threshold was determined based on histogram analysis and supported by previous studies (Twele et al., 2016; Li et al., 2019; Martinis et al., 2015), and adjusted to maximize the contrast between water surfaces and surrounding land features. SAR-based flood mapping has been widely recognized for its capability to detect inundation under cloud-covered conditions and during extreme weather events (Schumann & Moller, 2015).

2.5 Multi-Temporal Analysis

Flood extent was calculated for each sub-district for the years 2017, 2019, and 2022. Spatial overlay analysis was performed to identify recurrent and persistent flood-prone areas, enabling the assessment of temporal flood dynamics. Multi-temporal approaches have been shown to provide a more comprehensive understanding of flood patterns compared to single-event analyses (Clement et al., 2018; Pekel et al., 2016).

2.6 Multi-Temporal Analysis

Validation was conducted through visual interpretation of high-resolution imagery from Google Earth. The detected flood areas were compared with reference imagery to ensure consistency and minimize classification errors. Due to the limited availability of ground truth data during flood events, quantitative accuracy assessment could not be performed. However, visual validation provides a reasonable level of confidence in the flood delineation results.

3. Results

The results of multi-temporal flood mapping in Bandar Lampung for 2017, 2019, and 2022 are presented in Figure 1, Table 1, and Figure 2, illustrating the spatial distribution, quantitative extent, and temporal trends of flood inundation.

Figure 1 shows the spatial distribution of flood inundation derived from the integration of Sentinel-1 and Sentinel-2 data. Flood-prone areas are predominantly concentrated in low-lying and highly urbanized regions. Rajabasa, Panjang, and Kedamaian sub-districts consistently experienced flooding across all observation years. In 2017, flood inundation was relatively limited and spatially scattered. By 2019, the flooded area expanded, particularly in Rajabasa and Panjang. In 2022, flood extent increased significantly, becoming more extensive and spatially continuous, especially in Rajabasa. The quantitative results are summarized in Table 1.

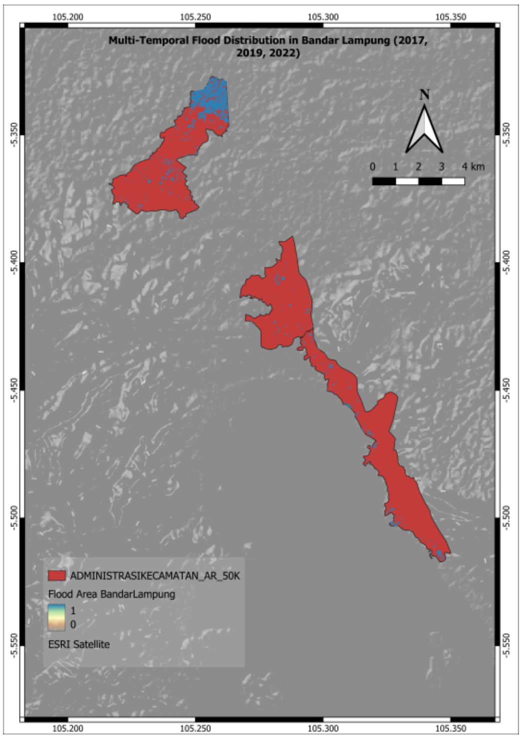

Figure 1. Multi-temporal flood distribution in Bandar Lampung (2017, 2019, 2022).Annual NDVI trend (2015–2024) for Pelalawan Regency, derived from MODIS MOD13Q1 composites.

Table 1. Annual NDVI, rainfall, and burned area in Pelalawan Regency (2015 to 2022) based on MODIS and CHIRPS datasets.

Sub-district	2017	2019	2022
Kedamaian	0.25	0.20	0.18
Panjang	0.60	0.20	0.38
Rajabasa	0.87	1.99	2.20

Table 1 confirms that Rajabasa experienced the most substantial increase in flood extent, rising from 0.87 km² in 2017 to 2.20 km² in 2022 (approximately 153%). Panjang shows fluctuating values, while Kedamaian remains relatively stable with minor variations.

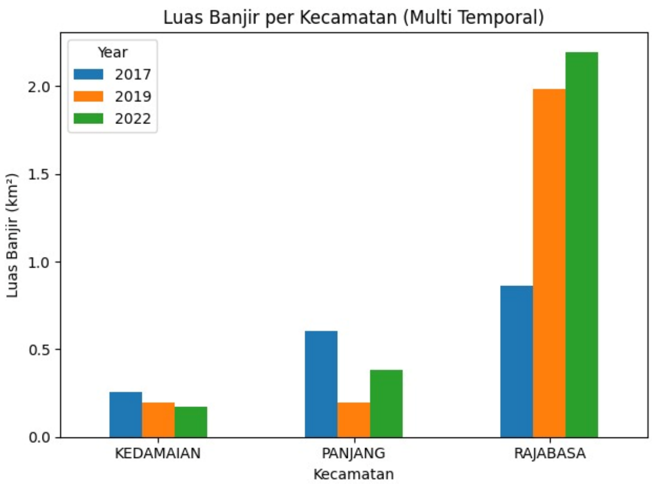

Figure 2. Flood extent comparison per sub-district in 2017, 2019, and 2022.

The temporal trend shown in Figure 2 highlights a consistent increase in flood extent in Rajabasa, indicating growing flood vulnerability. In contrast, Panjang exhibits variability, which may be influenced by interannual rainfall variation or drainage conditions, while Kedamaian shows relatively stable conditions.

The observed increase in flood extent, particularly in Rajabasa, is likely associated with rapid urban expansion, which increases impervious surfaces and reduces infiltration capacity, leading to higher surface runoff during rainfall events. The integration of Sentinel-1 SAR and Sentinel-2 optical imagery significantly improves flood detection reliability, as SAR data enable observation under cloud-covered conditions while optical data provide more accurate surface water delineation under clear conditions.

These findings are consistent with previous studies in urban coastal environments, where flood expansion is strongly linked to land-use change and increased surface runoff. However, this study does not explicitly incorporate rainfall data or land-use change analysis, which may also influence flood patterns. Therefore, future research is recommended to integrate these factors to achieve a more comprehensive understanding of flood dynamics.

4. Conclusions

This study demonstrates that the integration of Sentinel-1 SAR and Sentinel-2 optical imagery provides a reliable and effective approach for multi-temporal flood mapping in urban environments. The results reveal significant spatial and temporal variations in flood extent across Bandar Lampung, with Rajabasa exhibiting the most substantial increase in inundation area, indicating growing flood vulnerability.

The findings highlight the influence of urban development, particularly the expansion of impervious surfaces, which reduces infiltration capacity and increases surface runoff. Variations observed in Panjang and Kedamaian further suggest that local environmental and infrastructural conditions play an important role in shaping flood dynamics.

This study contributes to geospatial flood monitoring by providing a multi-temporal analysis at the sub-district scale in a secondary Indonesian city, demonstrating the advantage of integrating SAR and optical data for improving flood detection under varying weather conditions.

However, this study is limited by the absence of quantitative validation and supporting environmental variables such as rainfall, land-use change, and detailed topographic analysis. Future research should incorporate these factors to enhance the accuracy and understanding of flood dynamics.

Overall, the results provide valuable insights to support flood mitigation strategies, urban planning, and disaster risk management in Bandar Lampung and other similar urban areas.

5. Declaration of Interest

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6. Acknowledgement

The author would like to thank the European Space Agency (ESA) for providing Sentinel data and Institut Teknologi Sumatera (ITERA) for academic support.

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