Spatiotemporal Flood Characterization and Early Warning Development in the Rokan Watershed Using Sentinel-1 SAR and Water Level Data

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Abstract : *The Rokan Watershed in Sumatra frequently experiences severe flooding, with the most prolonged inundation recorded between late 2023 and early 2024, lasting more than three months. However, the long-term spatiotemporal characteristics of floods in this region remain poorly understood, and an effective early warning developmnet has yet to be developed. This study aims to characterize flood dynamics over a 10-year period (2014-2024) and establish a foundation for a flood early warning development in the Rokan Watershed. Flood extent was derived from Sentinel-1 Synthetic Aperture Radar (SAR) imagery using a threshold-based classification applied to VH polarization. The use of SAR data enables consistent flood mapping under cloudy and low-light conditions. All processing was conducted on Google Earth Engine via Google Colab to ensure efficient and reproducible analysis. Validation using 439 ground reference points yielded an overall accuracy of 83.8%. The results indicate significant inundation events in 2014, 2018, 2019, and particularly during 2023-2024, reflecting an increasing trend in both flood frequency and spatial extent. Comparison with water level observations from BWSS III stations revealed a time lag between upstream water level rise and flood occurrence. For instance, when the Lubuk Bendahara Station records water levels above 220 cm during the late-year rainy season, downstream flooding in Bonai Village typically occurs within 4-9 days. These findings enhance understanding of flood behavior in the Rokan Watershed and contribute to the development of data-driven flood early warning systems in tropical river basins.*

Keywords: flood dynamics, Sentinel-1 SAR, early warning systems, Google Earth Engine

Introduction

Flooding is among the most frequent natural hazards in Indonesia, with severe implications for human safety, infrastructure, and economic activities. In the Rokan watershed, flood events have become a recurrent issue during the wet season. in addition to rainfall events, is also influenced by other factors such as land cover change, inadequate drainage capacity, and sedimentation. Historical records and field observations highlight that large-scale inundation frequently disrupts communities, damages transportation networks, and interrupts agricultural production (Novita et al,.2014).

Efforts to mitigate floods in the Rokan watershed encompass a range of structural and non-structural measures, including land-use management, drainage improvement, and the development of early warning systems. Structural mitigation, while effective, often require substantial time and huge cost for their implementation. At the same time, the effectiveness of mitigation analysis is often constrained by the availability of hydrological data (Chan N.W et al., 2020). The hydrological data of Rokan Watershed is frequently incomplete and limited in duration, thereby restricting the depth of analysis that can be performed. Contributing factors include the limited number of discharge measurement instruments and irregular practices in data storage and management. These limitations not only hinder the development of robust hydrological analyses, but also complicate the planning of effective and efficient water infrastructure.

Given these constraints, there is a growing need for practical and cost-effective solutions that can be implemented more rapidly to enhance community preparedness. Therefore, the development of early warning system represents one of the most straightforward and practical approaches to be applied. For flooding in river basin, water level data can be used as the reference to develop the early warning system by providing timely information on river conditions. However, the existing monitoring network is unevenly distributed. Most water level observation stations of Rokan River are located in upstream area, while the main river downstream remains largely unmonitored until it reaches the lower floodplain.

Given these challenges, this study aims to develop a flood early warning approach for the Rokan Watershed by linking satellite-derived inundation information with observed river water levels. The method integrates Sentinel-1 SAR imagery to identify major flood events and correlates them with temporal variations in water levels at the upstream observation station. Through this relationship, a threshold value of water level is determined to anticipate the onset of flooding several days in advance. This approach provides a practical, data-driven foundation for early flood warning in flat and flood-prone regions, supporting improved preparedness and mitigation strategies for local communities.

Literature Review

a. Flood Characteristics and Spatiotemporal Dynamics

Flooding is a complex hydrometeorological phenomenon resulting from the interaction between precipitation, land surface conditions, drainage capacity, and watershed morphology. In tropical regions such as Indonesia, flood events are primarily triggered by intense and prolonged rainfall during the monsoon season, often amplified by land use change and sedimentation in river channels (Nugroho et al., 2020). The magnitude and duration of floods vary spatially and temporally, influenced by catchment topography, soil characteristics, and human interventions such as deforestation and agricultural expansion (Dasgupta et al., 2021).

Understanding the spatiotemporal dynamics of floods is crucial for assessing hazard patterns and identifying high-risk areas. Spatiotemporal analysis allows for the examination of how flood extent, frequency, and duration evolve over time and space, providing insights into changing hydrological behavior under climate and land-use pressures (Huang et al., 2022). For example, long-term flood pattern studies using satellite observations have shown increasing flood frequencies in lowland areas, particularly where river discharge capacity has been reduced due to siltation or infrastructure development (Ahamed & Bolten, 2017).

Traditional flood assessment has relied heavily on hydrological models that simulate rainfall-runoff processes. However, in data-scarce basins such as the Rokan Watershed, model-based analysis is often constrained by limited and inconsistent hydrometric data. Therefore, integrating remote sensing and hydrological observations offers a more reliable approach to monitor flood events over time and identify critical changes in flood behavior (Haqiqi et al., 2023). Such integration supports the development of spatiotemporal flood characterization frameworks, which can guide the planning of flood mitigation and early warning systems in dynamic tropical basins.

b. Overview of the Rokan Watershed

Almost every year during the rainy season, flooding occurs across various parts of the Rokan River Basin. This phenomenon is partly caused by river shallowing, inadequate drainage system, and the reduction of infiltration areas due to unplanned and poorly regulated land-use changes. The morphological characteristics of the Rokan Watershed also play a central role in shaping these flood dynamics. The watershed physical characteristic is categorized flat with mostly area has slope ranged from 0-2%, which reduces natural drainage capacity and prolongs water retention on the floodplain. Residential areas, oil palm plantations, mining activities, and oil and gas infrastructure are concentrated in flood plain area or low-lying zones adjacent to the river. As a result, flood events in the Rokan Basin not only affect local livelihoods but also pose risks to strategically important industries that support regional and national economies (Ratnaningsih T.K. et al. 2023).

c. Application of Sentinel-1 SAR for Flood Mapping

According to Dhanisa et al. (2024), remote sensing offers great potential as an effective approach for mapping flood distribution, particularly in regions where ground-based data are limited. One of the most commonly used datasets in flood monitoring is Sentinel-1 Synthetic Aperture Radar (SAR) imagery. Sentinel-1 SAR has a significant advantage in that it can operate day and night and is unaffected by cloud cover, smoke, atmospheric water vapor, or hydrometeors (Conde and Munoz., 2019). Flood or water inundation detection in SAR imagery is based on the hypothesis that inundated areas exhibit much lower backscatter intensity (σ^0) compared to dry land, especially under calm wind conditions when the water surface is smooth and specular (Reksten et al., 2019).

Previous studies have successfully utilized Sentinel-1 SAR data for rapid flood mapping and temporal flood monitoring in both tropical and temperate regions, demonstrating its reliability for operational flood assessment. For example, the automated processing chain by Twele et al. (2016) achieved high thematic accuracy (≈ 94-96%) for regions in Greece and Turkey using threshold-based separation of flooded vs. non-flooded areas. Another study, "Monitoring Surface Water Dynamics in the Prairie Pothole Region" by Schlaffer et al. (2022), used dual-polarized Sentinel-1 time series to track seasonal and inter-annual water body changes, highlighting its effectiveness in wetland/flood-prone ecosystems.

d. Water Level Data and Flood Early Warning Framework

Water level data play a crucial role in flood forecasting and early warning systems, as they provide direct and real-time indicators of hydrological conditions in river basins. According to Pahlevi et al. (2021), consistent river water level observations enable early identification of potential flood events, particularly when integrated with rainfall and remote sensing data. However, many watersheds in Indonesia, including the Rokan Basin, face challenges in maintaining continuous hydrological records due to limited monitoring infrastructure and data gaps (Chan et al., 2020).

The development of a flood early warning framework requires defining critical water level thresholds that correspond to inundation conditions on the ground. These thresholds can be established empirically by correlating hydrometric data (e.g., daily or hourly water level measurements) with observed flood extents derived from remote sensing datasets such as Sentinel-1 SAR (Ahamed & Bolten, 2017). Such integration helps identify lead times between rising water levels and flood onset, allowing authorities to disseminate early warnings more effectively.

In many tropical and monsoon-dominated catchments, including Indonesia, the time lag between upstream river level increase and downstream flooding typically ranges from 1-5 days, depending on topography, channel geometry, and rainfall intensity (Li et al., 2022). Establishing this relationship supports the creation of practical, low-cost early warning indicators, particularly in regions where advanced hydrological models cannot be applied due to limited data availability. Recent studies emphasize that data-driven frameworks combining in-situ hydrological monitoring with SAR-based flood mapping can significantly improve disaster preparedness and community response capacity (Schumann et al., 2018; Chini et al., 2021). Such frameworks are especially beneficial for flat, flood-prone watersheds like the Rokan Basin, where conventional modeling is often constrained by sparse data and complex floodplain dynamics.

Methodology

a. Study Area

One of the major river basins in Sumatra Island is Rokan Watershed (). The Rokan watershed spans several province, mostly in Riau, North Sumatra, and West Sumatra with total area of 19.150 km^2. Administratively, area of Rokan watershed mostly placed in Rokan Hulu and Rokan Hilir Regency (Kepmen PU No. 21 2014). The Rokan River strecth approximately 350 kilometers, originating from the Bukit Barisan Mountains and flowing eastward until it empties into the Malacca Strait. The river plays a vital role as a transportation route for local communities as well as a primary source of livelihood and economic activities, particularly for agriculture, fisheries, and plantations. In addition to its economic importance, the watershed also supports various ecological functions, providing water for domestic use, irrigation, and maintaining wetland ecosystems in the lowland and coastal areas. To provide a clearer geographical context, the study area is illustrated in Figure 1 below

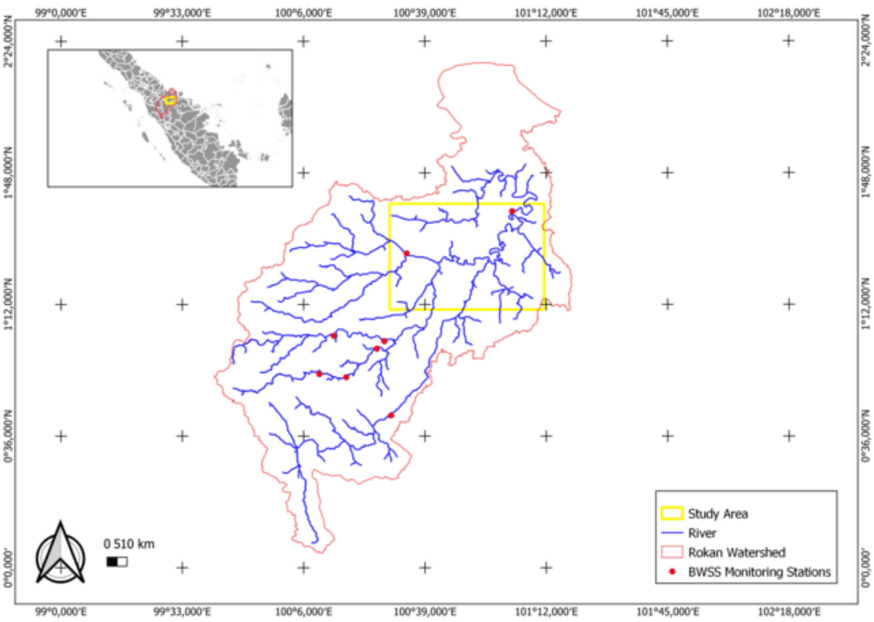

Figure 1: Map of the study area.

b. Hydrological Data Collection

River stage data were obtained from the Sumatera River Region III Office (BWSS III), headquartered in Pekanbaru, which oversees several major river systems including the Rokan, Siak, Kampar, and Indragiri-Akuaman watersheds. According to Presidential Decree No. 12/2012, the Rokan River is classified as an inter-provincial watershed spanning North Sumatra, Riau, and West Sumatra. The dataset used in this study consists of daily water level records measured with Automatic Water Level Recorders (AWLR) from nine river gauging stations along the Rokan River system, namely Koto Bangun, Lubuk Bendahara, Pengaraian, Pekan Tebih, Tangun, Tanjung Medan, Ujung Gurap, and Ujung Tanjung. The hydrological data collection and analysis focused in Ujung Tanjung Station and Lubuk Bendahara Station. The observation period covers the last decade, from 2013 to 2024.

c. Flood Detection

The flood inundation detection in this study was performed using Sentinel-1 SAR imagery, which provides C-band synthetic aperture radar data with dual polarization (VV and VH). VH polarization was selected because it is more sensitive to changes in surface roughness caused by waterlogging and is widely recognized as effective in flood mapping (Manjusree et al. 2012). Data were accessed and processed on the Google Earth Engine (GEE) platform to ensure efficient handling of large datasets without requiring local downloads. The pre-processing steps included application of precise orbit files, radiometric calibration, terrain correction using the SRTM DEM, and conversion of backscatter values into decibels ($\sigma°$). To minimize noise, a Refined Lee filter was applied (Borah et al. 2018). The imagery was then mosaicked and clipped according to the Rokan Basin boundary, and only scenes with Interferometric Wide (IW) swath mode and VH polarization were retained.

Flood detection was conducted using a threshold-based classification approach. Water bodies typically exhibit lower backscatter values compared to other land covers due to specular reflection, with flooded areas falling within a characteristic range of −15 dB to −24 dB in VH polarization (Manjusree et al. 2012; Filipponi, 2019). Pixels with backscatter within this range were classified as inundated, while values above the threshold were categorized as non-flood. To improve classification accuracy, multi-temporal composites were generated to differentiate permanent water bodies from seasonal or event-based inundation. This temporal filtering allowed the identification of anomalous water expansion directly associated with flood events.

The classified inundation extents were then aggregated and analyzed on a temporal scale to identify spatial and seasonal flood patterns across the Rokan Basin. By quantifying the area of inundation for each flood event and linking it with river stage data, trends of extreme flood occurrences were extracted. These temporal patterns were further integrated into a flood monitoring framework that supports the development of an early warning system.

d. Flood Early Warning System Development

The development of a flood early warning system in this study was based on the relationship between observed water level fluctuations and flood inundation dynamics detected from satellite imagery. Historical flood events were first identified using multi-temporal satellite images corresponding to major inundation years. For each identified flood year, the time series of observed water levels was analyzed to determine the peak stage, which represents the highest recorded level during each event. Satellite images were then collected for three distinct periods: before the peak, at the peak, and after the peak. This temporal comparison enabled the visual and quantitative assessment of floodplain expansion and contraction associated with changes in water level. The approach allows for the derivation of threshold-based early warning indicators that can be applied in river systems characterized by a single outlet or without significant tributary inflows. However, the main limitation of this approach lies in the dependency on satellite image availability during critical flood periods, which may restrict temporal continuity of observation.

By integrating in-situ water level observations with satellite-derived inundation information, this method provides a practical framework for flood early warning development in data-scarce regions. The analysis emphasizes the temporal synchronization between hydrological records and remotely sensed imagery to capture the onset, peak, and recession phases of flooding. This integration facilitates the determination of critical water level thresholds that trigger flood warnings, which can subsequently be implemented in automated monitoring systems. Furthermore, the approach supports adaptive calibration, allowing threshold values to be updated as more flood events are observed or as satellite data availability improves over time. Consequently, the system not only enhances real-time flood preparedness but also contributes to long-term flood risk assessment and management.

Results and Discussion

a. Flood Detection Results and Accuracy Evaluation

This study employed a threshold-based backscatter approach to detect inundated areas. A backscatter threshold value of –19 dB was applied to extract water-covered regions, meaning that areas with backscatter values lower than –19 dB were classified as flooded. The selection of the –19 dB threshold was based on an analysis of backscatter intensity characteristics derived from Sentinel-1 SAR imagery over the Rokan Watershed. This threshold was identified as the optimal value to distinguish between flooded and non-flooded areas, providing a balance between the sensitivity of flood detection and the minimization of misclassification errors, such as vegetation or dry land being identified as water. Previous analyses have indicated that floodwater backscatter in VH polarization typically ranges from –15 to –24 dB (Manjusree et al., 2012), thus –19 dB is considered a representative and reliable value for detecting flood inundation in relatively calm water conditions.

Although the Sentinel-1 SAR data proved to be effective in detecting flooded areas, the results still exhibit certain limitations, particularly in identifying inundation beneath oil palm canopies and in small flooded patches. This limitation arises due to the obstruction caused by dense vegetation cover, such as oil palm trees, which prevent most of the radar signals from penetrating to the ground surface. The majority of the radar signals in the C-band frequency used by Sentinel-1 are reflected by the vegetation canopy, thereby reducing the sensor's ability to capture backscattered signals from the water surface underneath. Consequently, flood presence beneath oil palm plantations often remains undetected because the radar signals are not sufficiently strong to penetrate dense vegetation layers.

In addition, the detection of small-scale inundation poses another challenge in this analysis. Small flooded areas often generate backscatter signals that are difficult to distinguish from their surroundings, especially when their size is smaller than the spatial resolution of Sentinel-1 SAR, which is approximately 10 meters. Such small inundations tend to be overshadowed by neighboring pixels with higher backscatter values from non-water elements, making them difficult to accurately identify as flooded areas.

Accuracy evaluation was conducted using the zonal statistics method to analyze the spatial relationship between reported flood points and inundation detection results from Sentinel-1 SAR imagery. The vector data consisted of 439 reported flood locations on January 16, 2024, while the raster data represented flood classification results for the same date (value 1 = inundated, 0 = non-inundated). A 50-meter buffer was created around each flood point to represent the surrounding area potentially affected by flooding. The analysis was performed in QGIS using the zonal statistics function to calculate the number of pixels with a value of 1 within each buffer. A buffer was classified as inundated if it contained at least one pixel with a flood value.

The results showed that 368 out of 439 points were identified as inundated areas, yielding an overall detection accuracy of 83.8%. This indicates that the Sentinel-1 SAR–based method using a −19 dB backscatter threshold effectively identified inundation areas with good agreement to field observations. However, 71 points were not detected, reflecting certain limitations, particularly in areas with dense vegetation cover (e.g., oil palm plantations), small-scale inundation, or shallow water depth, where backscatter values did not meet the detection threshold.

b. Spatiotemporal Variation of Flood Inundation Extent

Observation of flood inundation extent in the Rokan Watershed area using Sentinel-1 SAR imagery was conducted from 2014, the year when the satellite data first became available, until 2024. This data span enables the analysis of annual flood trends, particularly during the peak rainfall periods occurring in December. The continuous availability of data since 2014 facilitates long-term monitoring and analysis of fluctuations in inundated areas each year, as well as the identification of extreme flood patterns over the past decade in the Rokan Watershed.

Based on the detected inundation extent, five major flood events were identified, occurring in 2014, 2018, 2019, 2023, and early 2024 (Figure 2). These years stand out due to the considerably larger inundation areas compared to other years. Meanwhile, years such as 2015, 2016, 2017, 2020, 2021, and 2022 exhibited significantly smaller flood extents, indicating that extreme flooding events occurred only sporadically. The detected inundation extent also shows a strong correspondence with water level data (TMA) recorded at the Ujung Tanjung Station by BBWS, which similarly displayed peak water levels in 2014, 2018, 2019, and early 2024 (Figure 4). The detailed values of flood inundation extent derived from Sentinel-1 SAR detection for the analyzed area are presented in Figure 3.

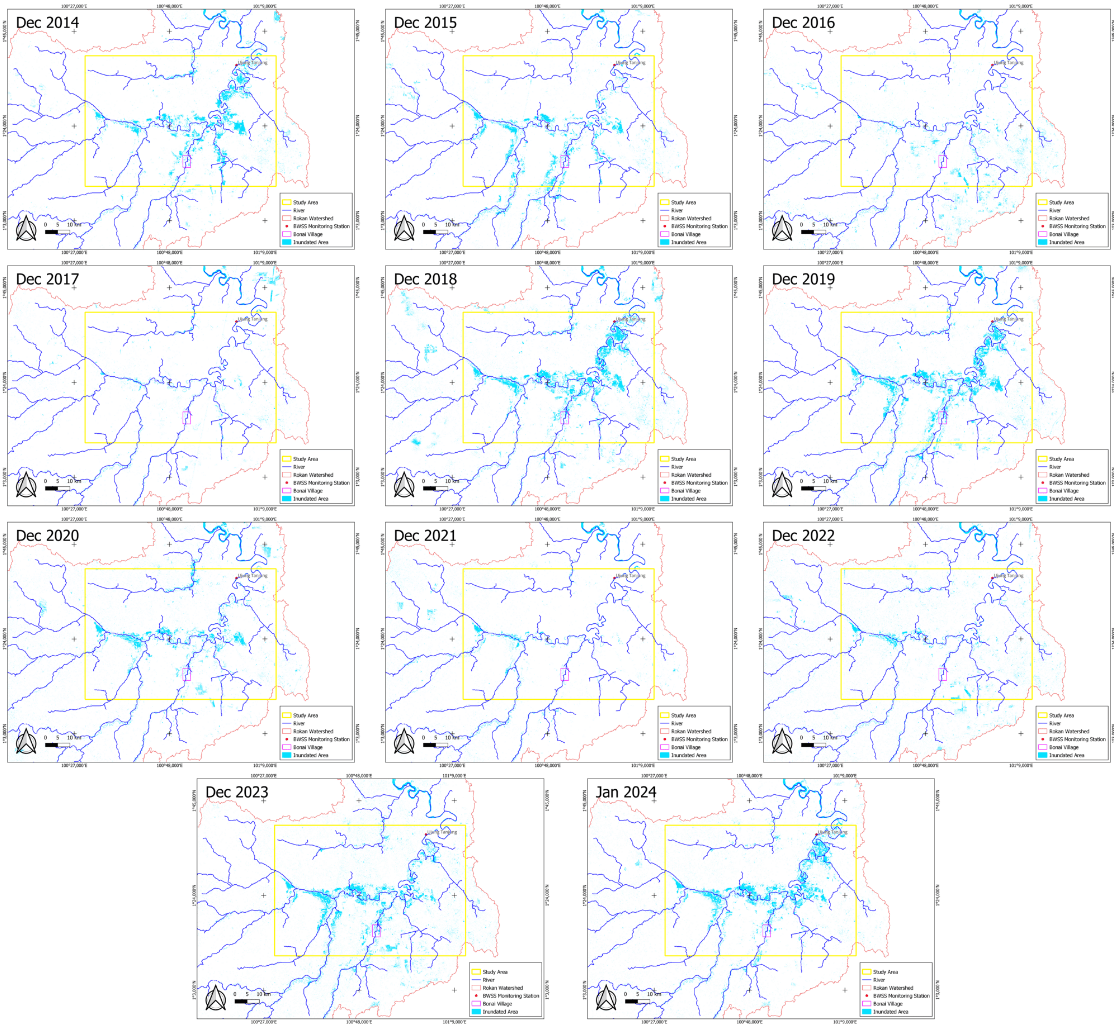

Figure 2: Temporal Variation of Inundated Extent in the Rokan Watershed (2014–2024)

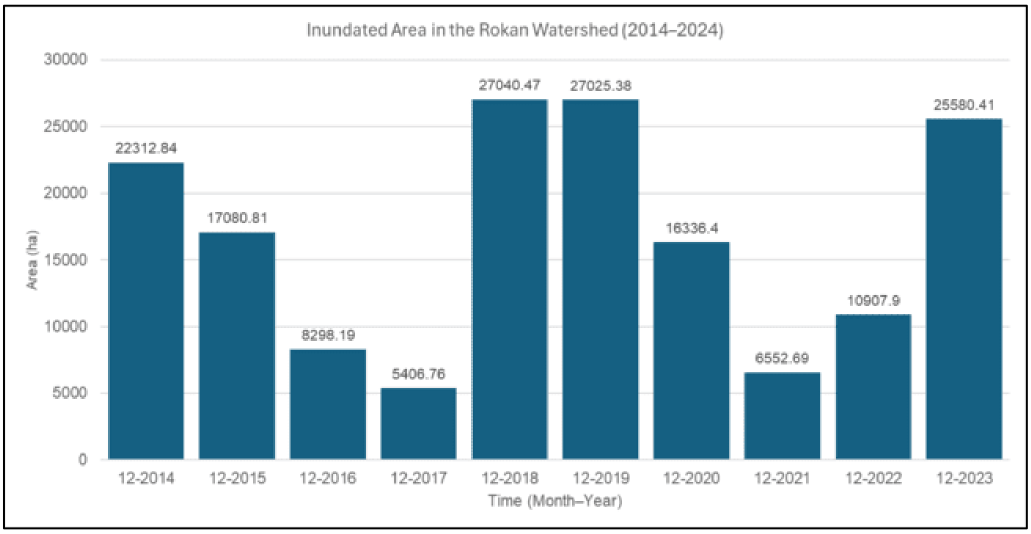

Figure 3: Inundated Area in the Rokan Watershed (2014–2024)

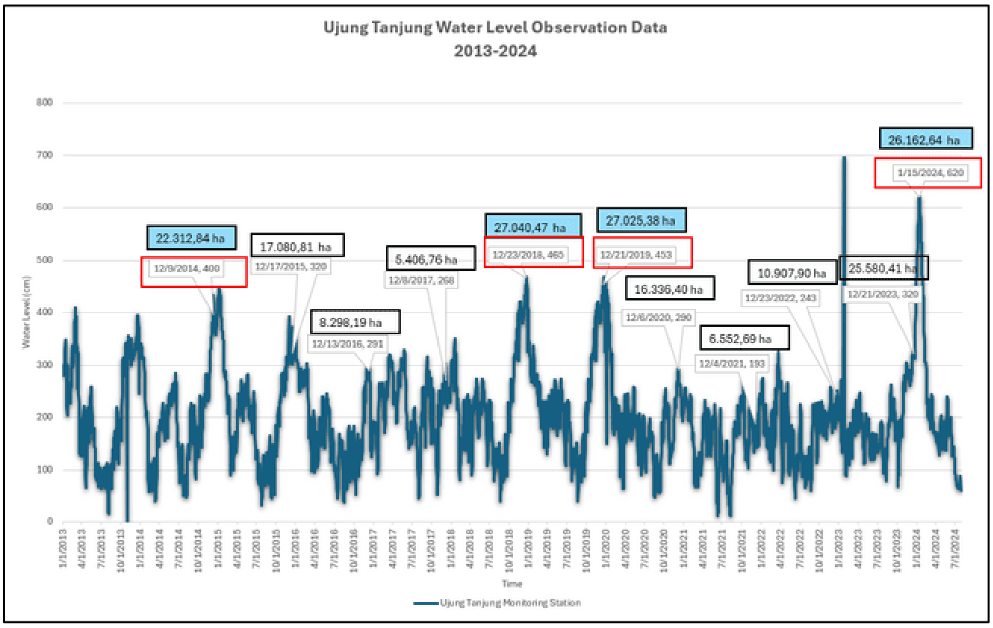

Figure 4: Correlation Between Detected Inundation Extent and Observed Water Level at Ujung Tanjung Station

c. Temporal Dynamics of the Major Flood Event in 2023–2024

Based on the temporal analysis using Sentinel-1 SAR imagery, the major flood event in the Rokan Watershed during late 2023 to early 2024 exhibited highly significant and prolonged inundation dynamics. Flooding was first detected on November 4, 2023, with an inundated area of approximately 16,726.58 hectares, marking the onset of an extensive flood period that continued to develop and reached its peak in mid-January 2024. The extent of inundation increased sharply, particularly during December 2023 and January 2024, with a maximum inundated area of 26,162.64 hectares recorded on January 15–16, 2024.

The increase in flood intensity and inundation extent during this period was likely influenced by high and persistent rainfall during the peak of the wet season. The flat topography in the downstream part of the Rokan Basin exacerbated water accumulation, leading to widespread flooding that extended into agricultural lands, plantations, and residential areas, particularly in low-lying regions such as Bonai Darussalam Sub-district and its surroundings. This pattern indicates a strong interrelation between seasonal rainfall, natural storage capacity of the basin, and a delayed hydrological response in the downstream areas.

Following the mid-January peak, the inundated area gradually decreased. By late February 2024, the flood coverage had reduced to about 14,122.82 hectares, further declining to 7,364.45 hectares in early March. By April 2024, most of the affected areas had dried up, leaving only 6,923.88 hectares of residual water coverage. These findings indicate that the total duration of the major flood in the Rokan Basin lasted approximately three to four months, with the peak phase extending for about one month.

The temporal pattern provides a clear depiction of the annual flood cycle in the Rokan Basin, where increased rainfall toward the end of the year consistently triggers widespread flooding that extends into the early months of the following year. This finding is critical for enhancing flood early warning systems, as it enables the identification of critical periods during which rising water levels can serve as early indicators of flooding in the downstream regions.

d. Flood Early Warning Development

The flood early warning system for Bonai Village can be referenced using the water level data recorded at the BWSS Lubuk Bendahara observation station, as both locations are situated along the same river segment (Figure 5). The relationship between water level (TMA) fluctuations at the Lubuk Bendahara Station and flood occurrences in Bonai Village is illustrated in Figures 6, 7, and 8, which depict the temporal correspondence between hydrological peaks and inundation onset during major flood events.

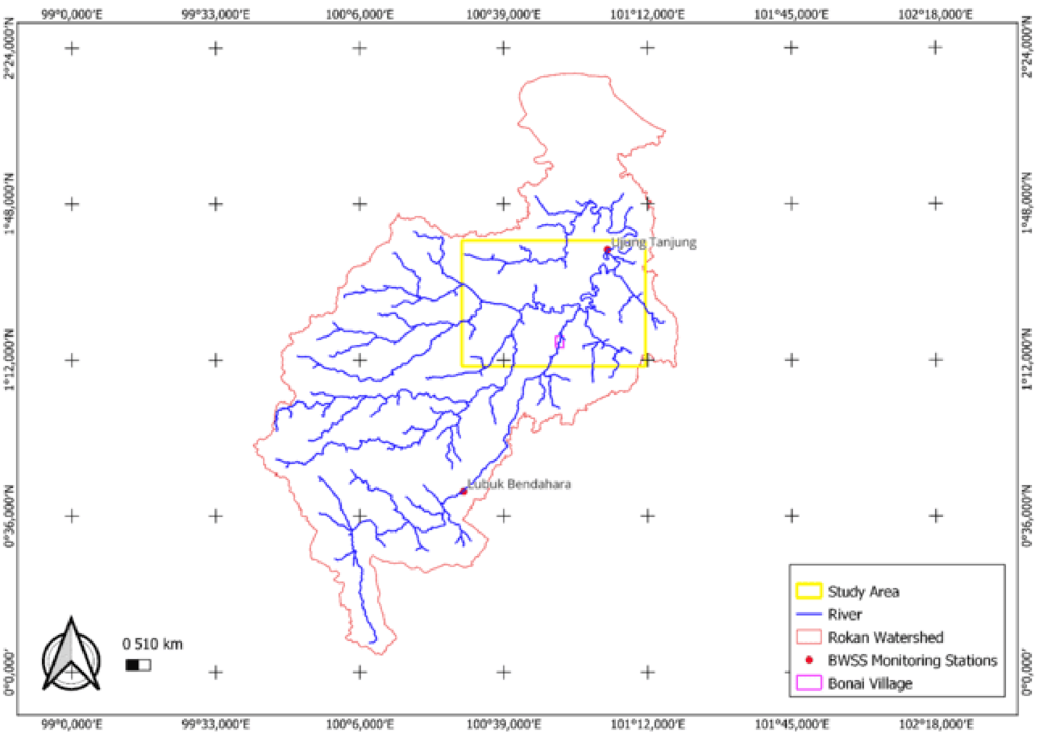

Figure 5: Location of Bonai Village and the BWSS Lubuk Bendahara observation station.

Based on flood detection results derived from Sentinel-1 SAR imagery during the typical flood months (October, November, and December) in 2018, 2019, and 2023, the onset of inundation in Bonai Village was identified. In 2023, flooding was first detected on 4 November 2023, in 2019 on 25 November 2019, and in 2018 on 25 October 2018. These inundation dates were then correlated with the corresponding water level records from the Lubuk Bendahara Station, located approximately 84.79 km from Bonai Village. This comparison aimed to determine the critical water level associated with the onset of flooding and to estimate the time lag between the peak water level and the beginning of inundation.

The analysis results (Table 1) show a temporal delay between the water level peaks at Lubuk Bendahara and the subsequent flood occurrences in Bonai Village. Specifically, in 2023, the peak water level of 221 cm occurred 9 days before the flood; in 2019, a peak of 224 cm occurred 4 days before; and in 2018, a peak of 231 cm occurred 5 days before the observed inundation. These findings indicate that when the water level at Lubuk Bendahara exceeds approximately 220 cm during the typical flood season (October to January), flooding in Bonai Village can be expected to occur within 4 to 9 days afterward. This time lag represents the downstream travel time and accumulation of surface runoff within the same river system.

Furthermore, visual interpretation of Sentinel-1 SAR imagery reinforces these findings. On 5 September 2023, inundation was detected in Bonai Village, corresponding to a recorded water level of 292 cm at Lubuk Bendahara on 28 August 2023, or 7 days prior. Conversely, on 23 October 2023, no inundation was detected since water levels during early October did not exceed the 220 cm threshold. Hence, the 220 cm water level can be regarded as a critical warning threshold for potential flood occurrence in Bonai Village. Nevertheless, this estimation is primarily based on correlations between water level records and satellite-derived inundation detection and does not yet incorporate local rainfall data, which may further refine the accuracy of early warning predictions.

Table 1. Pre-flood peak water level and its temporal relationship with flood onset

Flood Onset Date	Pre-Flood Peak Water Level Date	Pre-Flood Peak Water Level (cm)	Time Difference
4 November 2023	25 October 2023	221	9 Days
25 November 2019	21 November 2019	224	4 Days
25 October 2018	20 October 2018	231	5 Days

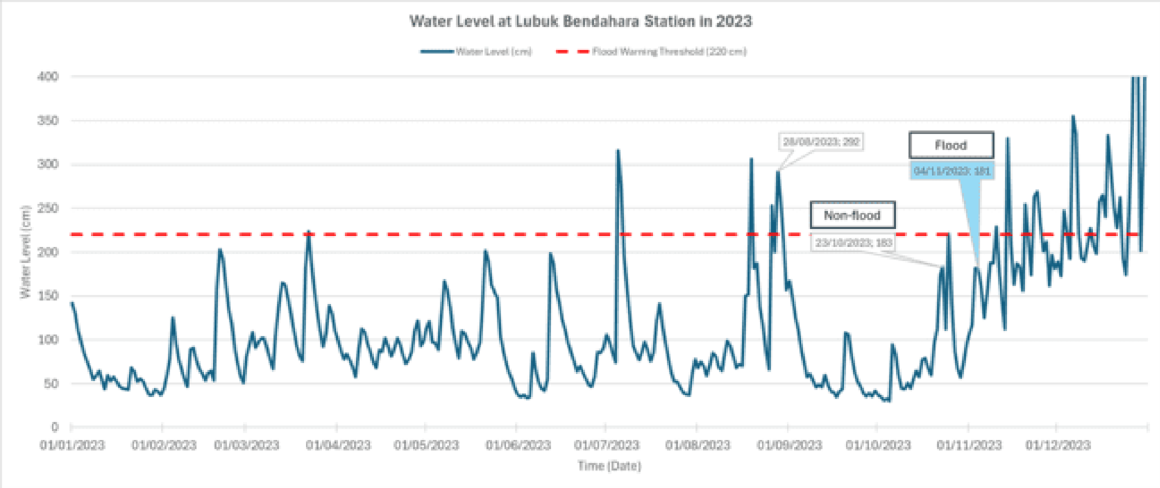

Figure 6: Water level at Lubuk Bendahara Station in 2023

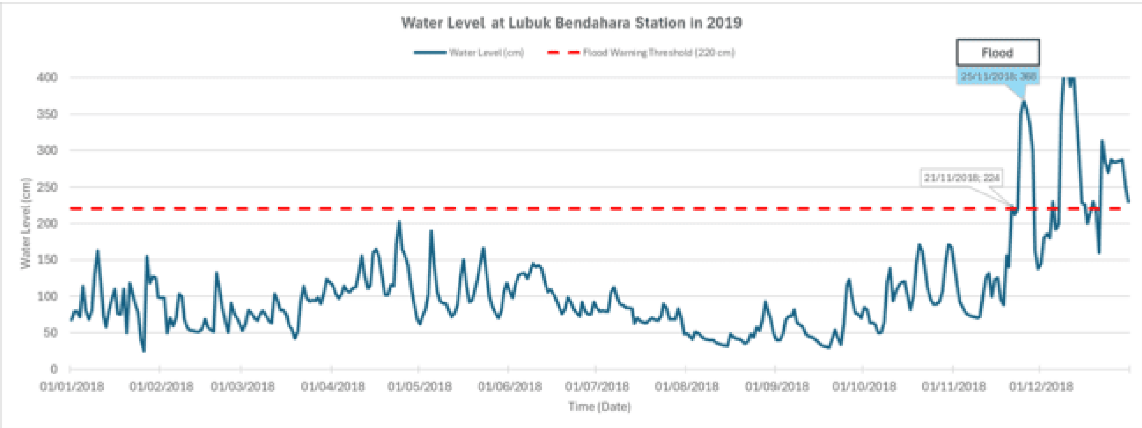

Figure 7: Water level at Lubuk Bendahara Station in 2019

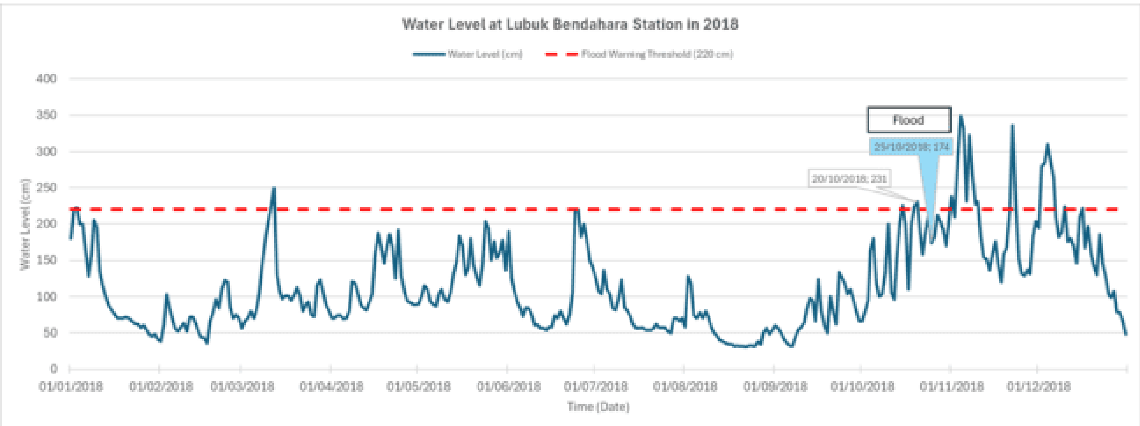

Figure 8: Water level at Lubuk Bendahara Station in 2018

Conclusion and Recommendation

This study successfully demonstrated the capability of Sentinel-1 SAR imagery for detecting and analyzing flood inundation dynamics in the Rokan Watershed over a decade (2014–2024). The analysis revealed five major flood events, with the largest occurring in 2023–2024, where inundation areas reached more than 26,000 hectares during the peak period. The backscatter threshold of −19 dB proved effective for identifying flood extents, achieving an accuracy of 83.8% when validated with ground-based flood reports. However, certain limitations were observed, including difficulties in detecting inundation beneath dense vegetation canopies (e.g., oil palm plantations) and small or shallow flooded areas that fell below the spatial and radiometric sensitivity of Sentinel-1 C-band data.

Based on the relationship between satellite-derived flood detection and observed water levels, this study also developed a preliminary concept for a flood early warning system. The analysis showed that flood events in Bonai Village occurred approximately 4-9 days after water levels at the upstream Lubuk Bendahara station exceeded 220 cm, suggesting that this threshold can serve as an early indicator of potential flooding. Nevertheless, the system's effectiveness remains constrained by the temporal availability of satellite data and the absence of rainfall integration, which limits continuous monitoring. Future research should incorporate multi-sensor satellite observations combined with hydrological and rainfall data to improve temporal resolution, enhance flood prediction accuracy, and establish an operational early warning system for flood-prone regions.

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