

TIDAL FLOOD MAPPING WITH A SIMPLE BATHTUB MODEL IN SUNGAI KAKAP DISTRICT, INDONESIA

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Received 2025-09-24 | **Revision** 2025-10-10 | **Accepted** 2025-12-30
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Abstract: Sungai Kakap District, located in Kubu Raya Regency, West Kalimantan, is a low-lying coastal region highly exposed to tidal dynamics, making it susceptible to recurrent tidal flooding (rob). Accurately mapping spatially explicit flood extents is a vital foundation for vulnerability assessment, disaster preparedness, and mitigation planning. This study aims to map the tidal flood extent during a significant event in December 2024 in Sungai Kakap District using a static inundation approach known as the Simple Bathtub Model. The research methodology integrated historical water level data from the BMKG Pontianak Maritime Station with a Digital Elevation Model (DEM) derived from SRTM data. By setting a maximum water level threshold of 1.8 meters based on peak tidal records, the inundated areas were identified and mapped using the Google Earth Engine (GEE) platform. To ensure reliability, the resulting flood map was validated against field observations using a confusion matrix. Validation results demonstrated an Overall Accuracy (OA) of 0.74 and a Kappa coefficient of 0.43, indicating that the model provides a moderate but acceptable representation of flood patterns in low-lying deltaic plains. Spatial impact analysis revealed significant socioeconomic consequences: the flood inundated approximately 150,000 meters of the road network, submerged between 900 and 1,000 buildings, and affected an estimated 16,000 to 17,000 residents. These findings highlight the high vulnerability of coastal communities in West Kalimantan and demonstrate that the Simple Bathtub Model is a practical and effective tool for supporting local governments in developing data-driven mitigation strategies and enhancing long-term coastal resilience.

Keywords: Flood Mapping, DEM, Simple Bathtub Method, Sungai Kakap District

INTRODUCTION

The Sungai Kakap District in Kubu Raya Regency, West Kalimantan, is a low-lying coastal area directly influenced by tidal dynamics, making it highly susceptible to recurrent tidal flooding. Recently, tidal flood events have occurred with an increasing frequency. Tidal flooding in the region has caused widespread disruption to local communities and infrastructure, resulting in the inundation of roads and bridges, damage to residential areas, and considerable economic losses. These impacts are consistent with broader evidence that tidal flooding represents an escalating hazard in many low-lying coastal regions worldwide (Takagi et al., 2016).

Thus, there is an immediate necessity for precise and geographically detailed flood extent mapping to serve as a basis for vulnerability evaluation, disaster readiness, and mitigation

strategies (Hinkel et al., 2014). To address this need, this study integrated water-level observations with a DEM processed using the Simple Bathtub Model. Coastal flood studies widely apply this approach, which assumes that inundation propagates across topographic depressions and low-elevation areas (Ramirez et al., 2016). In addition, Geographic Information Systems (GIS) are employed to evaluate the spatial extent of flooding and quantify its impacts on exposed populations and critical infrastructure (Schumann & Bates, 2018).

Notwithstanding its straightforwardness, the bathtub method has faced criticism for oversimplifying hydrodynamic phenomena and frequently undervaluing regional discrepancies in flood magnitude (Schuerch et al. 2018). However, in data-scarce regions such as West Kalimantan, preliminary flood hazard assessments remain practical and cost-effective.

Therefore, this study contributes to the growing body of research on coastal flooding by demonstrating the applicability of the Simple Bathtub Model in an Indonesian context, providing empirical evidence of its performance, and delivering impact-based insights that can support the local government in developing more effective mitigation strategies and enhancing long-term coastal resilience.

LITERATURE REVIEW

According to Watrobski et al., (2019), there is Sungai Kakap District, covering an area of approximately 453.1 km² with a population of around 117,402 inhabitants, is located in a low-lying coastal region that is highly exposed to tidal dynamics (BPS Kubu Raya, 2024). Administratively, the district comprises 15 villages and directly borders the Natuna Sea to the west, placing it at considerable risk of recurrent tidal flooding (BPS Kubu Raya, 2024). Its geographic orientation and demographic characteristics make the area particularly vulnerable to tidal inundation, especially under the combined influence of sea level rise and coastal climate variability.

Research on tidal flooding in Indonesia has been extensive, particularly in the urban coastal areas of Java. For instance, Marfaei and King (2008) examined a tidal flood event in Semarang, integrating tidal observations with field surveys to map flood extent and assess the influence of land subsidence. Subsidence exacerbated the widespread inundation they found in the northern coastal zone. Similarly, Okvitasari et al. (2024) conducted a vulnerability assessment in Surabaya, East Java, and found that several coastal districts would be moderately to highly vulnerable to tidal flooding in the future.

Beyond Java, tidal flood studies have also been carried out in Kalimantan and other Indonesian coastal regions. A modeling study in Pontianak applied a coupled approach to generate probabilistic tidal flood maps (Ardianto et al., 2022). This highlights the advantages of integrating hydrodynamic and climatological models over static approaches. Furthermore, Araújo et al. (2021) illustrated the use of spatial modeling for tidal flood hazard and mitigation planning, highlighting the significant influence of topography, tidal range, and shoreline morphology on local vulnerabilities.

In terms of risk assessment and mitigation, Putiaini (2023) introduced a modified Coastal Vulnerability Index (CVI) in Indramayu, West

Java, to assess physical vulnerability to tidal flooding by integrating parameters such as geomorphology, tidal range, shoreline change, and vegetation cover. This framework supplies a numerical way to rank adaptation strategies in coastal areas.

Nonetheless, a significant study void persists in Kalimantan, where investigations into tidal flooding are notably limited in comparison to those conducted in Java. Data constraints, especially in high-resolution topographic and hydrodynamic assessments, hinder the effectiveness of sophisticated flood models. Consequently, there exists an urgent necessity to assess more direct and pragmatic modeling methodologies in environments with limited data. This research tackles the existing deficiency by utilizing the Simple Bathtub Model in the Sungai Kakap District and evaluating its accuracy in depicting real flooding and socioeconomic consequences.

RESEARCH METHODS

This study focused on the tidal flood event that occurred in December 2024 in Sungai Kakap District, Kubu Raya Regency, West Kalimantan, Indonesia. A Region of Interest (ROI) was delineated to define the spatial extent of the study area and to extract the Digital Elevation Model (DEM) derived from the Shuttle Radar Topography Mission (SRTM) dataset. The study area is illustrated in Figure 1, where the shaded region represents the boundaries of the Region of Interest used for subsequent topographic and spatial analyses.

The primary method employed in this study was the Simple Bathtub Model, a widely used static inundation approach for assessing coastal flood extents. Following natural topographic depressions, the model assumes that tidal inundation propagates across low-lying areas below the designated water-level threshold. This approach, although simplified, has proven effective in data-limited regions for preliminary flood hazard mapping.

To create the tidal flood extent map, two essential datasets were employed: (1) a Digital Elevation Model (DEM) depicting the topographical surface of the region and (2) hydrological data from the Kapuas River in Pontianak, collected from the BMKG Maritime Station. The DEM functioned as the elevation standard for pinpointing regions vulnerable to flooding, while the tidal data offered water level indicators for the December 2024 inundation event. Figure 2 illustrates the variations in water

levels of the Kapuas River from December 17 to 23, 2024, which served as the foundation for

establishing the maximum inundation threshold for the river.

Figure 1. Region of Interest

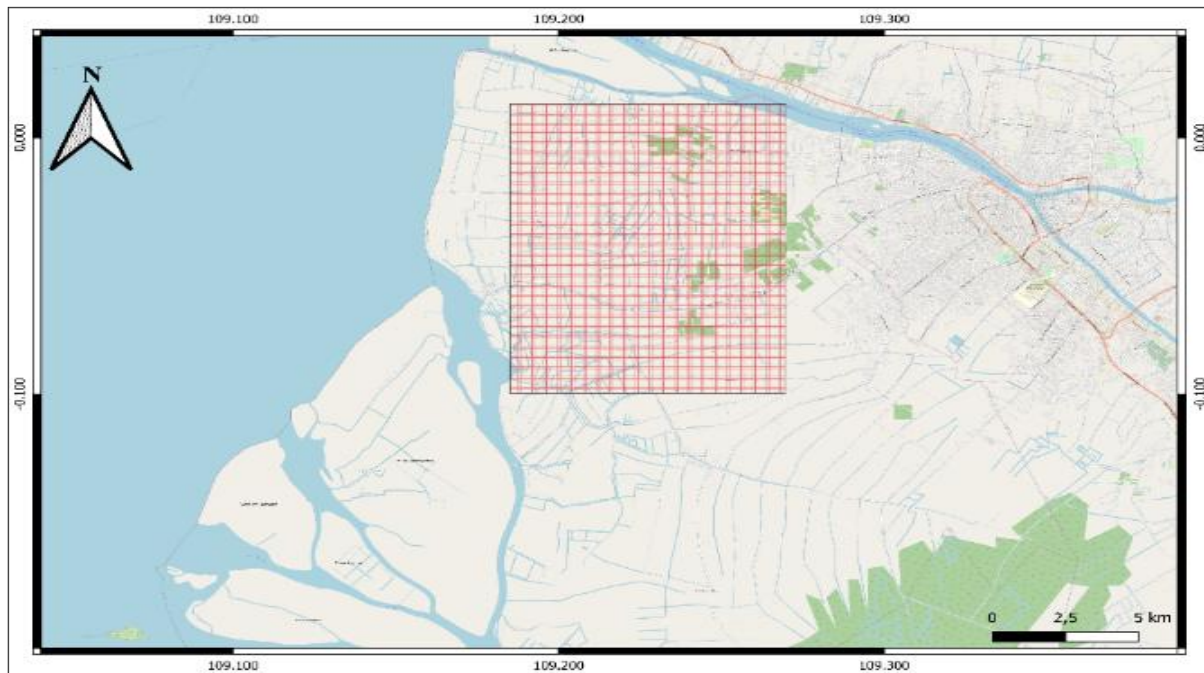
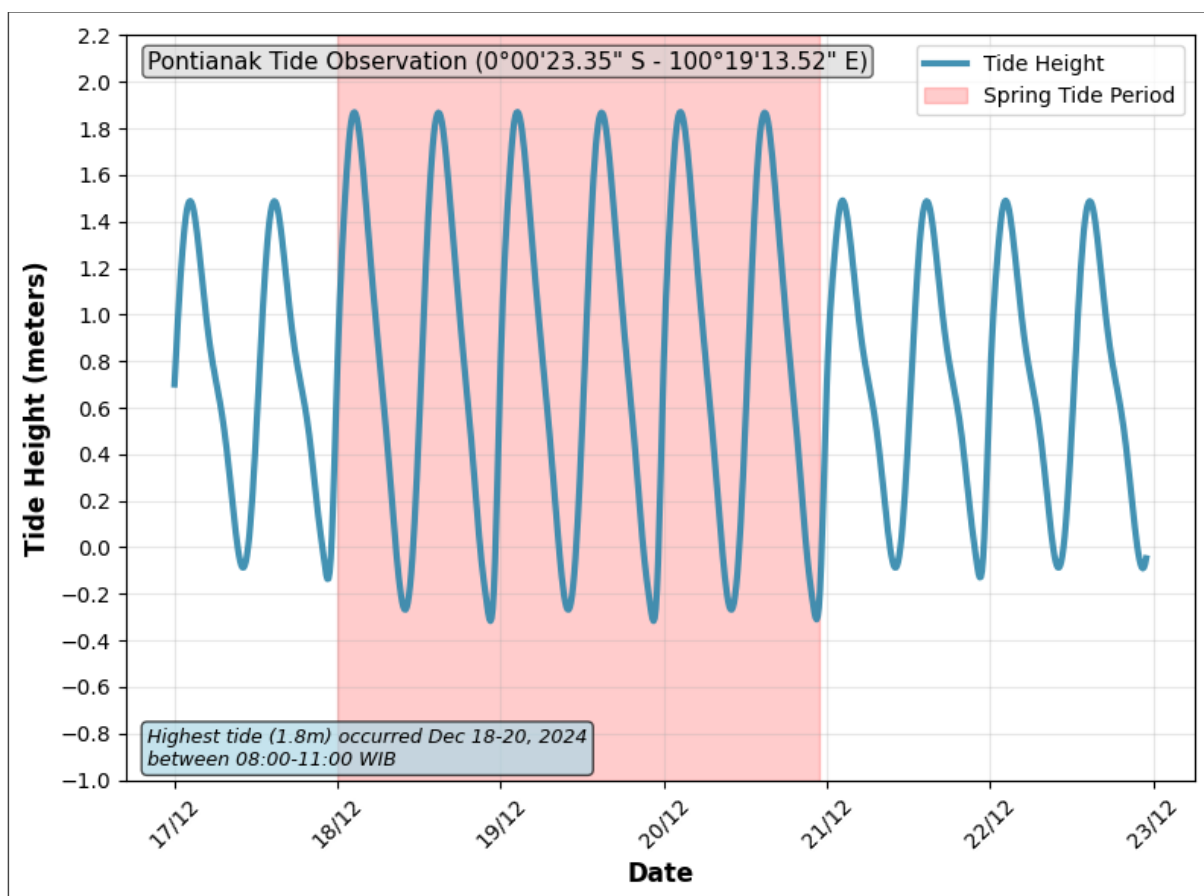


Figure 2. Water level fluctuations of the Kapuas River in Pontianak, adapted from BMKG Maritim Pontianak (2024).



Flood Scenario Development

The tidal flood scenario was developed using a threshold-based approach, whereby all pixels in the DEM with elevations below the maximum observed water level were classified as inundated areas. The first stage involved DEM preparation, which included error correction and clipping to match the study site boundaries. The DEM was derived from Shuttle Radar Topography Mission (SRTM) data, which have been widely applied in flood hazard and inundation studies (Hogg & Holland, 2008). To ensure data reliability, preprocessing steps, such as void filling, hydrological conditioning, and noise removal, were applied following established procedures (Gesch, 2009).

The next step was to determine the floodwater level threshold based on historical tidal records from the BMKG Maritime Station in Pontianak. These observations provided water level fluctuations for the December 2024 event, from which the maximum tide height was identified as 1.8 m (Fig. 2). This elevation was adopted as the threshold, with all DEM cells below this value classified as being inundated (Sampson et al., 2015).

The Google Earth Engine (GEE) platform was employed to identify and map the inundated areas during the final stage. The DEM was reclassified into raster categories representing areas above and below the threshold of the water level. The resulting raster was then converted into a thematic map distinguishing between the inundated and non-inundated zones. This output provides a spatial representation of the December 2024 tidal flood event and supports local authorities' decision-making for future flood risk management and mitigation planning.

Flood Map Validation

Model validation was performed by comparing the raster-derived flooded and non-flooded areas with reference data obtained from field observations. The validation involved both visual interpretation and statistical assessment using a confusion matrix. The confusion matrix evaluates the classification performance through four categories: True Positive (TP), True Negative (TN), False Positive (FP, Type I Error), and False Negative (FN, Type II Error). The overall accuracy (OA) was calculated using Equation (1), which measures the proportion of correctly classified pixels. The interpretation of the OA values is summarized in Table 1 (Gorunescu, 2011).

$$OA = \frac{TP+TN}{TP+TN+FP+FN} \quad (1)$$

Table 1. Accuracy Value Classification

Accuracy Value	Classification
0.90 – 1.00	Very Good
0.80 – 0.90	Good
0.70 – 0.80	Moderate
0.60 – 0.70	Fair
0.50 – 0.60	Poor

Source: Gorunescu, 2011

In addition to OA, the Kappa coefficient was used to assess classification reliability under potential class imbalance. Unlike accuracy, Kappa accounts for the probability of random agreement, providing a more robust evaluation (Chmura Kraemer et al., 2002). It is calculated using Equations (2) and (3).

$$PRE = \frac{(TP+FP) \times (TP+FN) + (TN+FN) \times (TN+FP)}{(TP+TN+FP+FN)^2} \quad (3)$$

$$Kappa = \frac{OA - PRE}{1 - PRE} \quad (2)$$

Table 2. Kappa Coefficient Classification

Kappa Value	Classification
< 0.21	Poor
0.21 – 0.40	Fair
0.41 – 0.60	Moderate
0.61 – 0.80	Good
0.81 – 1.00	Very Good

Source: Chmura Kraemer, et al., 2002

A Kappa value of 0 indicates no agreement, while 1 represents perfect agreement (Ukrainski, 2016). The interpretation scale is presented in Table 2.

Flood Impact Assessment

After the verification of the flood extent map, an overlay analysis was executed to examine the repercussions on infrastructure and the populace. Flood extent rasters were layered atop infrastructure and settlement data acquired from OpenStreetMap with QGIS. This locational overlap detected submerged roadways, edifices, and other vital infrastructures in the Sungai Kakap District.

Population figures in grid format were obtained from the WorldPop Global Project (www.worldpop.org) utilizing GEE to evaluate the impacted populace. The demographic

datasets were subsequently amalgamated with the flood extent map and OpenStreetMap layers utilizing QGIS. The overlay analysis assessed the quantity of residents subjected to flooding, therefore offering an in-depth insight into the socioeconomic repercussions of the December 2024 tidal inundation.

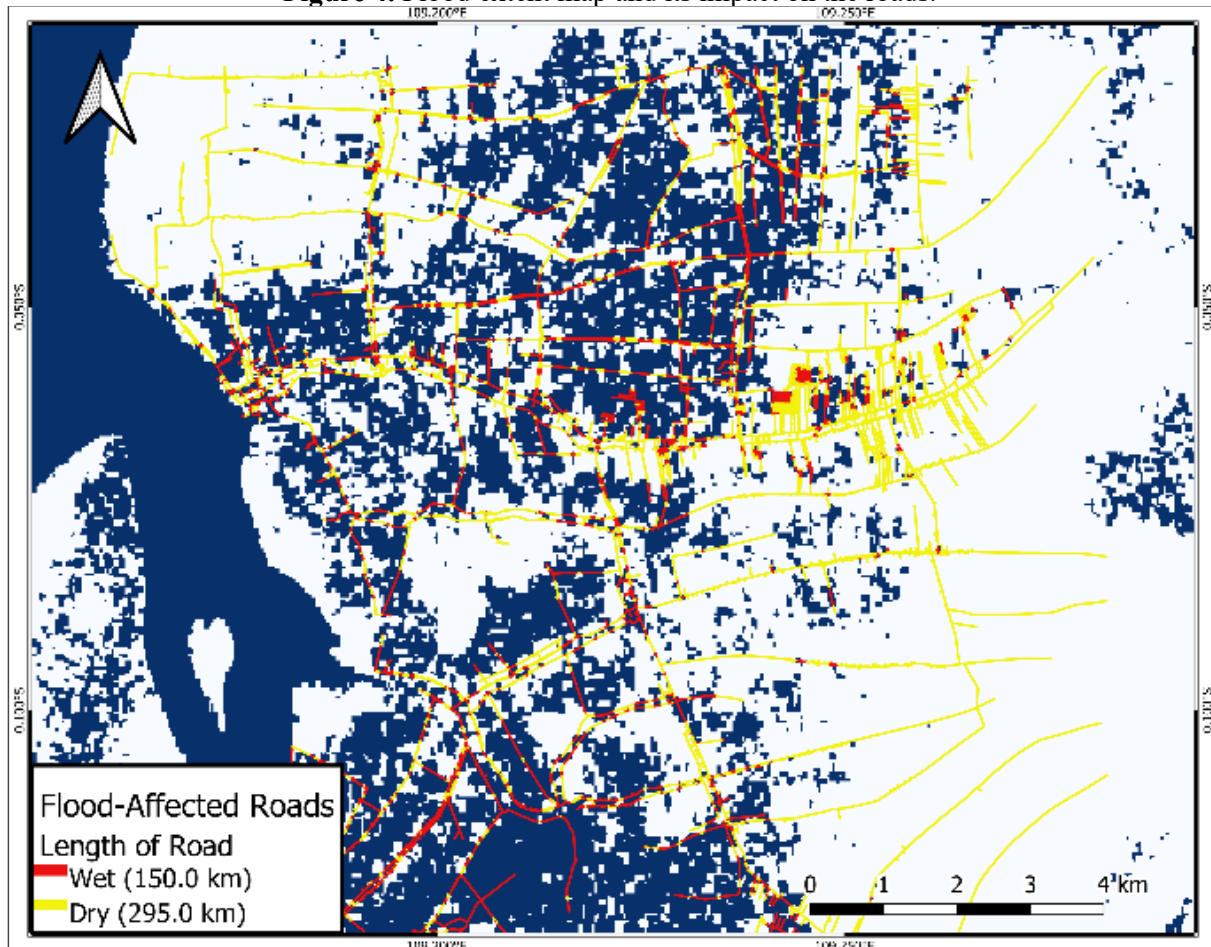
RESULTS AND DISCUSSION

The execution of the Simple Bathtub Model (SBM) necessitates precise river water level data relevant to the timeframe of flooding in the research region. In this research, water level measurements were utilized to depict the hydrodynamic circumstances during the tidal flood event of December 2024, offering a benchmark height for flood inundation assessment. Tidal inundation in the Sungai Kakap District is significantly affected by variations in the Kapuas River, hence combining recorded river levels with topographical information is crucial for pinpointing regions at risk of flooding. The temporal fluctuations of river water levels indicate the interplay between tidal influences and regional hydrological

factors, therefore acting as an essential parameter for assessing the geographical spread of floodwater movement.

The Digital Elevation Model (DEM) is compared to the corresponding river water level in the Simple Bathtub Model to estimate flood inundation. This model assumes that all terrain below the specified water-surface elevation is potentially inundated. This method applies a uniform water-level threshold across the study area to simulate the flood extent that may result from tidal fluctuations, storm surges, or long-term sea-level rise associated with climate change (Cooper et al., 2013). Subsequently, regions with elevations below the designated water-level benchmark are classified as inundated, an analogy to the process of water filling a bathtub until it reaches a predetermined height (Nicholls et al., 2021). The SBM is a widely adopted and efficient method for preliminary flood hazard assessment, particularly in low-relief coastal environments where topography is the dominating factor influencing inundation patterns, despite its conceptual simplicity.

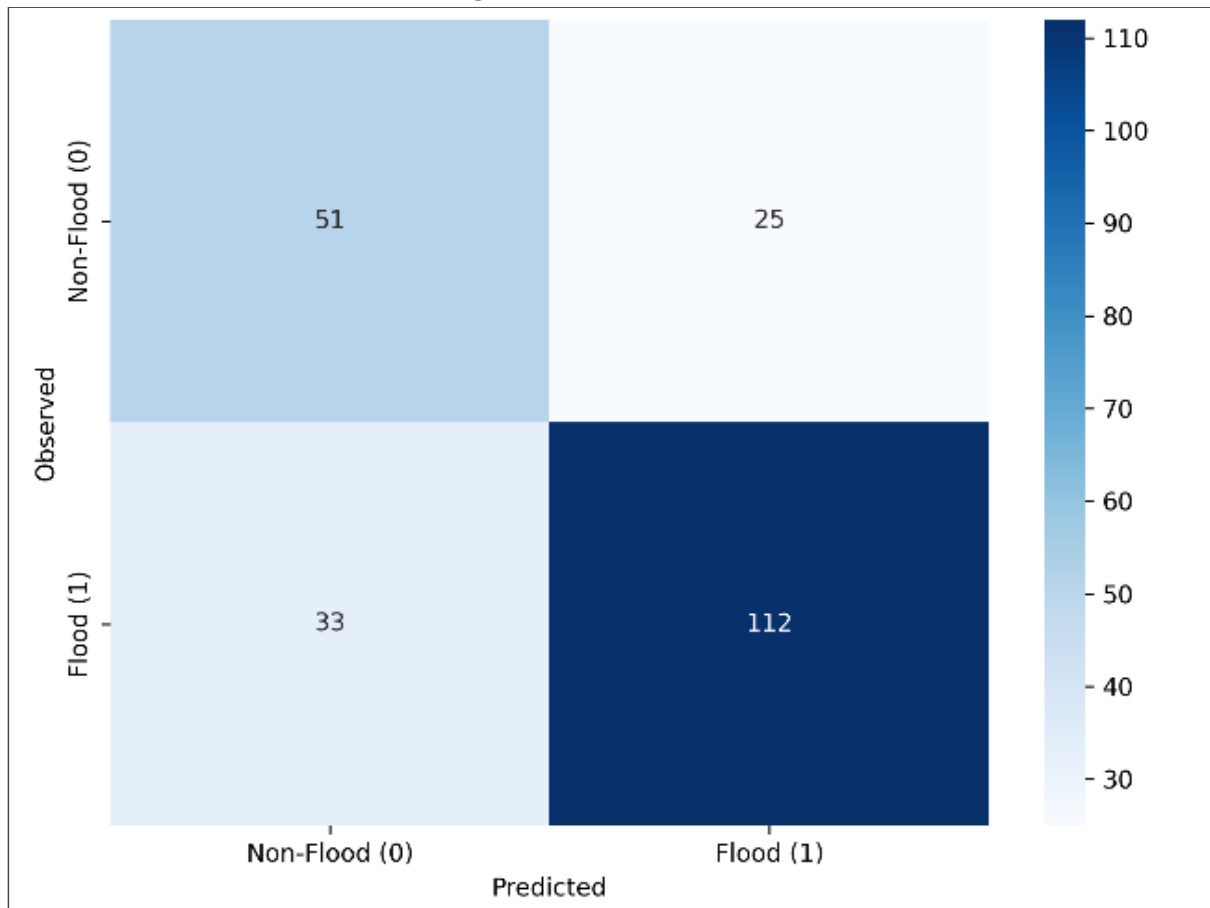
Figure 4. Flood extent map and its impact on the roads.



The validation of the flood extent map using the confusion matrix method yielded an overall accuracy of 0.74 and a Kappa coefficient of 0.43 (Figure 5). This level of accuracy is considered moderate but acceptable compared with similar studies using the bathtub approach, which

generally report accuracies between 0.70 and 0.85 (Narendr et al., 2024; Sanders et al., 2024). This performance indicates that the Simple Bathtub Model can reasonably capture the general spatial pattern of tidal inundation in the low-lying deltaic plains of the study area.

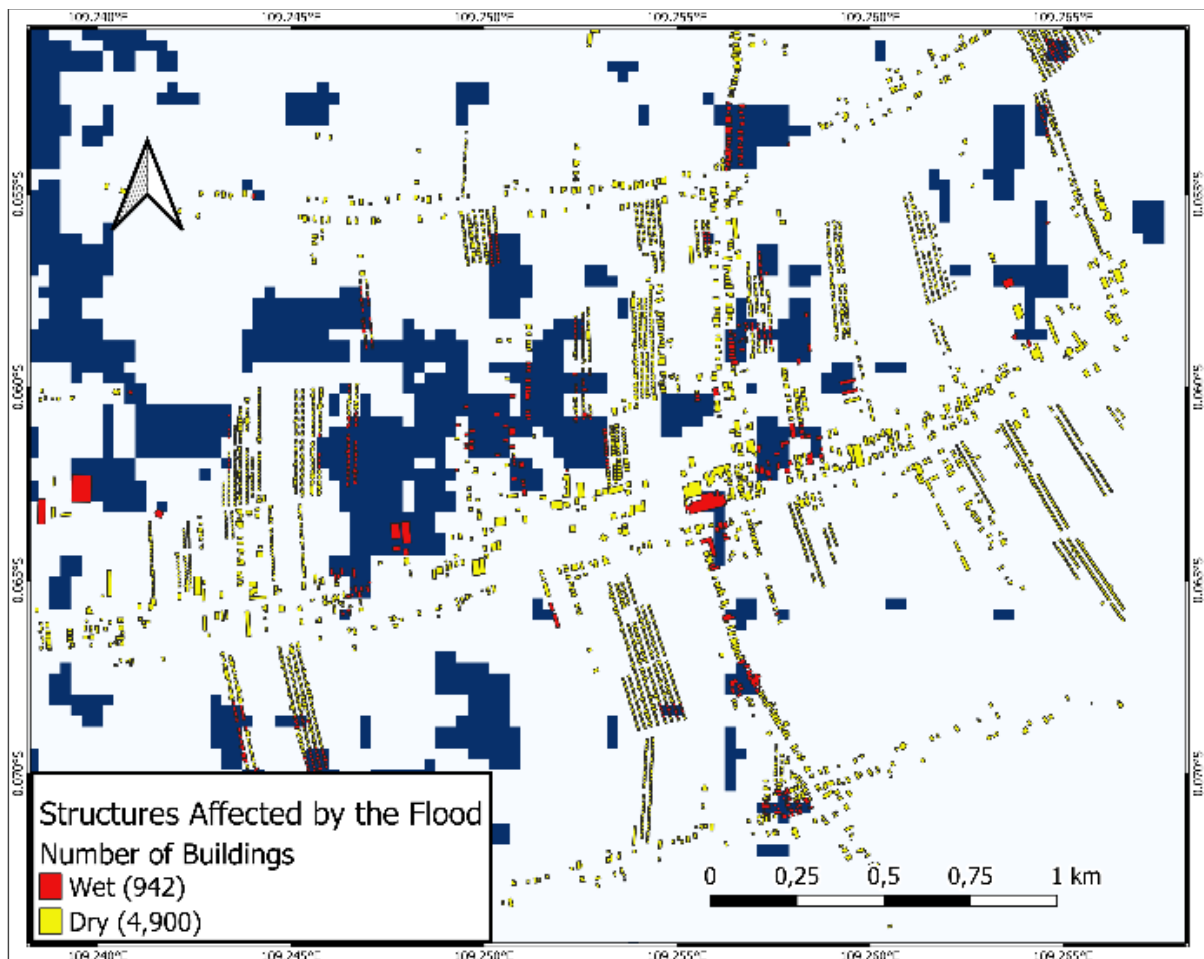
Figure 5. Confusion Matrix



Building upon this validated flood extent, the study proceeded to evaluate the impact of flooding on regional road infrastructure. The road network, obtained from OpenStreetMap (OSM), was used as the exposure dataset. OSM offers freely available and globally updated geospatial data, encompassing roads, buildings, rivers, and additional features, and has been extensively utilized in hazard exposure research (<https://www.openstreetmap.org>). The spatial analysis findings depicted in Figure 4 demonstrate the flood coverage in relation to the road infrastructure. Around 150,000 meters of roadways were submerged, depicted in red to signify damp conditions, whereas roughly

295,000 meters were left unscathed and are illustrated in yellow. This underscores the significant disturbance to regional connections.

Moreover, infrastructure exposure was appraised through the analysis of OSM building data. Figure 6 displays an amalgamation of the inundation area and the structural footprints inside the Sungai Kakap District. The analysis revealed that approximately 900 buildings were inundated during the event. The most affected buildings were in Sungai Kakap Village, the central hub of community and economic activity. Significant impacts were also identified in Punggur Kecil Village, whereas Sungai Itik Village experienced relatively minor impacts.

Figure 6. Flood impact analysis on the buildings

The impact of the December 2024 tidal flood on buildings was evaluated by overlaying the flood inundation map generated using the Simple Bathtub Model (SBM) with the building footprint dataset. This analysis identified 942 buildings as flood-affected (wet) and 4,900 buildings as unaffected (dry), accounting for approximately 16.1% and 83.9%, respectively, of the total 5,842 mapped buildings (Figure X). The affected buildings are primarily concentrated within low-elevation areas where the simulated flood water level exceeds the ground surface elevation, indicating a strong relationship between terrain characteristics and the spatial extent of tidal inundation.

The spatial distribution of inundated buildings reveals that flood impacts are not evenly distributed across the study area but instead occur in distinct clusters. These clusters are predominantly located in areas characterized by relatively flat topography and direct hydraulic connectivity to tidal channels and drainage networks. Conversely, buildings situated on slightly elevated terrain remain largely unaffected, despite being located within the

same general floodplain. This pattern demonstrates that even minor differences in elevation, as represented by the SRTM-derived Digital Elevation Model (DEM), can substantially influence the extent of tidal flood propagation and the exposure of the built environment.

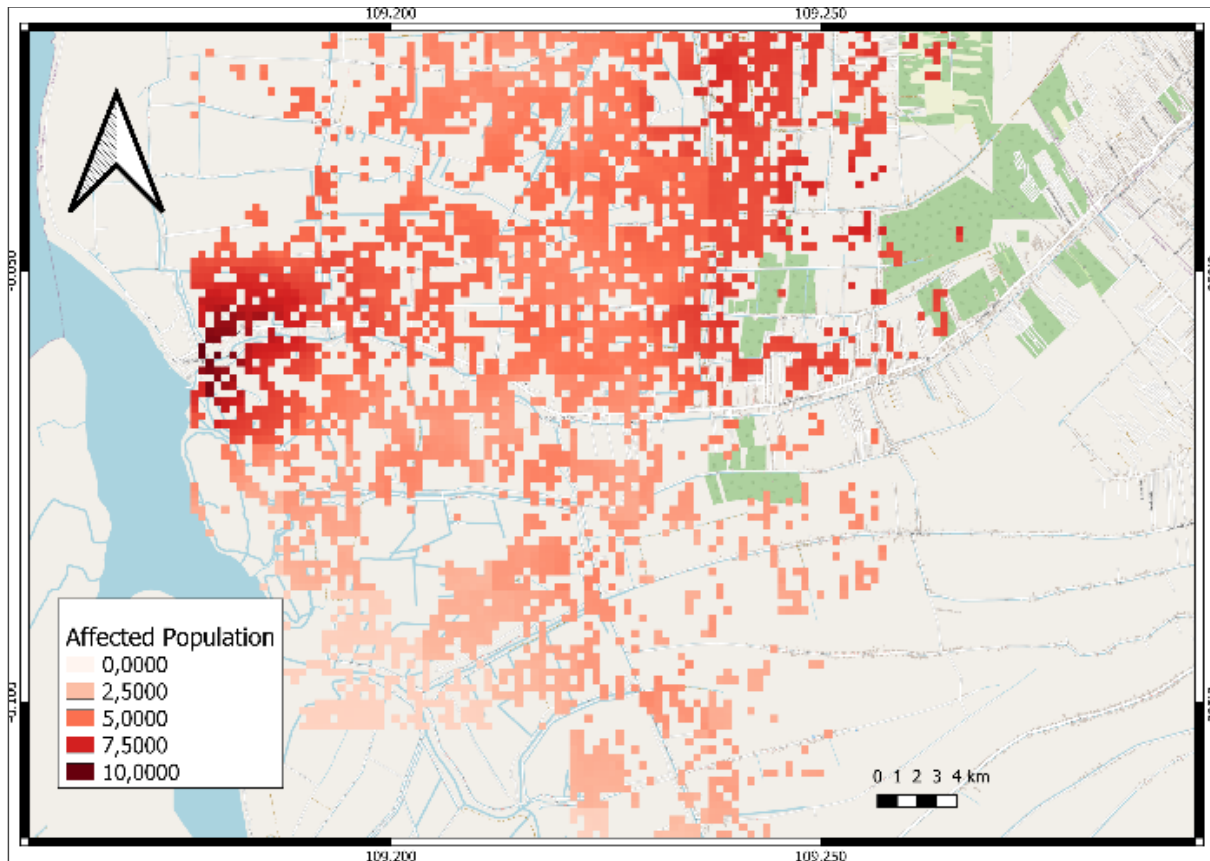
The findings highlight the effectiveness of integrating the Simple Bathtub Model with SRTM-derived DEM and building footprint data to rapidly assess flood exposure in low-lying coastal environments. The resulting building exposure map provides valuable spatial information for identifying areas requiring priority interventions, particularly in settlements with a high concentration of flood-affected structures. Such information can support evidence-based decision-making for land-use planning, infrastructure improvement, flood mitigation measures, and disaster risk reduction strategies aimed at enhancing community resilience against future tidal flood events.

Finally, population statistics in grid format from the WorldPop Project (Gaughan et al., 2013) were superimposed on the flood extent

map to assess population vulnerability (Figure 7). The intensity of the effects is depicted by a red gradient, with deeper hues indicating a greater number of impacted residents. The assessment approximated that around 16,000 to

17,000 individuals were impacted by the tidal flooding incident in December 2024. This degree of exposure offers essential understanding for prioritizing emergency responses and long-term mitigation strategies.

Figure 7. Flood impact analysis on the population.



CONCLUSION

This study successfully mapped the tidal flood extent during the December 2024 event in Sungai Kakap District, West Kalimantan, providing a spatially explicit assessment of its socioeconomic impacts. By employing the Simple Bathtub Model, the research identified that the flood reached a maximum inundation threshold of 1.8 meters, driven by peak tidal fluctuations. The validation outcomes demonstrated an overall accuracy of 0.74 and a Kappa coefficient of 0.43, indicating that this static modeling technique offers a moderate but dependable depiction of flood dynamics in low-lying deltaic regions.

The spatial analysis revealed significant disruption to the region's infrastructure and population: approximately 150,000 meters of road networks were inundated, nearly 1,000 buildings were submerged (centered primarily in Sungai Kakap Village), and an estimated 16,000 to 17,000 residents were directly affected. These

findings highlight the acute vulnerability of coastal communities in West Kalimantan to recurrent tidal hazards and emphasize the urgent need for data-driven disaster risk reduction strategies.

Furthermore, the study demonstrates that in data-scarce regions, the integration of tidal observations with freely available DEMs via platforms like Google Earth Engine (GEE) offers a cost-effective and practical tool for preliminary hazard mapping. Although the bathtub model possesses intrinsic constraints in accurately representing intricate hydrodynamic phenomena, its efficacy in this scenario offers a significant basis for local authorities to emphasize emergency preparedness and develop enduring coastal resilience strategies. Subsequent investigations ought to emphasize the integration of enhanced topographic data and land subsidence factors to improve the precision of flood forecasting in this swiftly evolving coastal environment.

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