

RESEARCH ARTICLE

Sentinel-1 Estimated Maximum Flood Extent for Sub-District Flood Exposure Mapping in Makassar City, Indonesia

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Abstract

Sub-district level information on flood exposure is basic requirement for disaster mitigation and spatial planning, yet it is rarely available for Indonesian cities because satellite imagery seldom captures the inundation peak. The February 2023 flood in Makassar City is a clear case: with only Sentinel-1A operating on 12 day repeat cycle, the peak of 13-17 February was never imaged and nearest acquisition on 21 February recorded receded condition. This study reconstructs the Estimated Maximum Flood Extent (EMFE) for that unobserved peak using surrogate variables and compares two reconstruction pathways: EMFE-GRD, in which backscatter thresholding is corrected to peak conditions using external hydrological data and EMFE-SLC in which interferometric coherence change carries the peak information inherently and receives only a partial correction. The novelty of this study is the explicit use of surrogate variables to reconstruct an unobserved flood peak, combined with paired sample significance testing to select between reconstruction pathways. Both products were validated against 90 paired field points. EMFE-GRD was the more accurate pathway (overall accuracy 62.2%, 95% CI 52.2-72.2%, Kappa 0.25), and the paired difference against EMFE-SLC was statistically significant (McNemar $p = 0.028$), although both products remain only moderate agreement and EMFE-SLC was not distinguishable from chance. EMFE-GRD indicates that about 41.6 % of the mainland area is potentially inundated, concentrated in the low-lying eastern and northern expansion zones. The results are presented as a two tier screening instrument, in which a core zone of inter method agreement guides evacuation and resource placement while an anticipatory zone supports worst case planning, giving BPBD Makassar a field validated basis for mitigation priorities and for integration into the city spatial plan.

Keywords: Estimated Maximum Flood Extent, Surrogate Variable, Sentinel-1, Flood Exposure, Disaster Mitigation

1. Introduction

Floods are the most frequent hydrometeorological disaster in Indonesia and urban flood vulnerability continues to rise through the combination of extreme rainfall, low lying topography and the conversion of infiltration land (Priyambodoho et al., 2022; Reihan Haezer et al., 2023). Impacts are unevenly distributed and concentrate on low income communities in lowland areas with limited infrastructure (Escobar Carias et al., 2022). For disaster management, spatial information on the distribution of affected areas down to the smallest administrative unit is therefore a prerequisite for well targeted mitigation.

Makassar City illustrates the problem acutely. On 13-17 february 2023 a major flood struck 12 sub districts with inundation depths of 50-100 cm and displaced 1,869 people (BPBD Kota Makassar, 2023). Neither BPBD city government currently holds a validated, up to date map of flood exposure at sub district level: the available event data consist of incident report points, which do not represent inundation extent and have never been tested for accuracy.

1.1 Limitations of previous flood mapping studies

Synthetic Aperture Radar (SAR) offers an all weather alternative to optical mapping (Amitrano et al., 2024), and two pathways dominate the literature. Backscatter intensity in the Ground Range Detected (GRD) product, separated by automatic thresholding, has become standard for rapid mapping (Jain et al., 2022; Twele et al., 2016; Bauer Marschallinger et al., 2022). Interferometric coherence in the

Single Look Complex (SLC) product is regarded as more reliable in dense urban areas, because it captures the loss of scattering stability over inundated surfaces (Chini et al., 2019; Li et al., 2019; Zhao et al., 2022), and recent work fuses both signals within deep learning frameworks (Zhao et al., 2024).

Three limitations recur across this body of work. First, almost all studies assume that an acquisition coinciding with the inundation peak is available, so that is mapped is the actual extent, the case in which the peak is simply not imaged is treated as a data gap rather than as a problem to be solved. Second, comparative studies typically report overall accuracy without testing whether the observed difference between two methods is statistically meaningful, even though the two maps are usually validated on the same reference points and therefore violate the independence assumption of the conventional Kappa Z-test (Foody, 2004; Congalton, 1991). Third, the reported superiority of coherence in urban setting has been established mainly under short revisit conditions, in which an image pair can tightly bracket the event, whether that superiority survives a long revisit interval has not been examined explicitly.

The limitations are directly consequential for Makassar. Since Sentinel-1B ceased operating in December 2021, only Sentinel-1A has remained active with a 12 day repeat cycle over the study area, so the February 2023 peak was never recorded. Under this constraint the actual extent cannot be mapped by any direct method, and the question becomes which reconstruction strategy performs best when the peak is unobserved.

1.2 Justification of the surrogate variable approach

Three alternatives were considered before adopting a surrogate variable approach. Hydrodynamic modelling can reconstruct a peak from rainfall and discharge, but requires drainage network geometry, roughness and boundary conditions that are not available for Makassar at city scale, and its calibration would in any case depend on the same sparse depth observations used here. Optical or very high resolution imagery is unusable because the event occurred under continuous monsoon cloud cover. Multi temporal SAR compositing over a longer window can widen coverage, but cannot recover a water level that no acquisition observed.

The Estimated Maximum Flood Extent (EMFE) approach avoids these obstacles by reconstructing the peak water surface elevation from substitute variables and propagating it across the terrain, and it is the only one of the four that operates on data already held by the responsible agencies. Two variants are compared. The GRD pathway uses a full external surrogate field depth reports, a rainfall ratio and a tidal correction and is expected to behave as an upper bound prone to false positives. The SLC pathway uses coherence change detection as an inherent surrogate, since the interferometric pair spans the flood period, and receives only a partial external correction, it is expected to behave conservatively and to be prone to false negatives.

1.3 Objective and novelty

The study aims to compile and analyse the spatial distribution of potential flood affected areas at sub district level in Makassar City, Using whichever EMFE pathway proves the more accurate under formal statistical testing, as a basis for recommendations BPBD and the Makassar City Government.

The novelty of the study is its explicit reconstruction of an unobserved flood peak through contrasting surrogate variable mechanisms, selected between by paired sample significance testing rather than by unverified accuracy comparison, and delivered as a field validated sub district exposure map that did not previously exist for the study area.

2. Research Method

2.1 Study Area

The study was conducted in the mainland area of Makassar City covering 17,445.6 ha and comprising 14 sub-districts, located approximately between 199°18' and 199°32' E and 5°00' and 5°14' S. The Kepulauan Sangkarrang sub-district was excluded because it consists of small islands with geographical characteristics and inundation patterns that differ from the urban mainland.

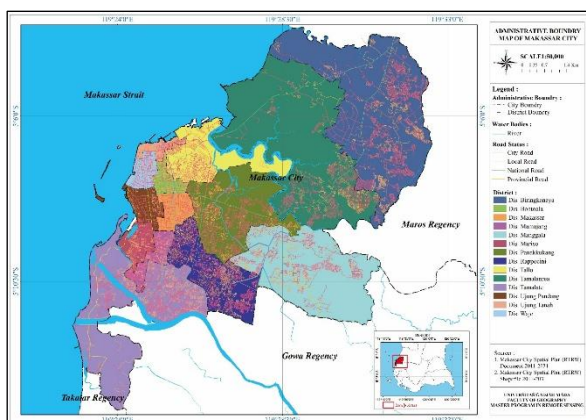


Fig. 1. Map of the study area, Makassar City

The city is flanked by two estuaries, the Tallo River in the north and the Jeneberang River in the south, and is dominated

by lowlands at elevations of 1-8 m above sea level. DEMNAS analysis shows that 79.52% of the area has slopes of 0-8%, classified as flat, so surface runoff is slow and water tends to form long-lasting static inundation. The study area is presented in Fig. 1.

2.2 Data and Data Sources

The main data used in this study are Sentinel-1A images in Interferometric Wide swath mode, ascending orbit, for both GRD and SLC products, covering the periods before and after the February 2023 flood event. Supporting data include the sub-district administrative boundaries of Makassar City from the Makassar City Spatial Plan (RTRW) 2011-2031, DEMNAS at 8.1 m resolution resampled to 10 m in the UTM Zone 50S projection system (EPSG:32750), 45 inundation depth and flood incident points from BPBD Makassar City, rainfall and tidal data from BMKG, and the JRC Global Surface Water dataset for permanent water body masking. Field validation used 90 paired sample points consisting of 45 points in areas predicted to be inundated and 45 points in areas predicted not to be inundated. Field reference labels were established independently of the EMFE maps through tracing of flood watermarks, inspection of BPBD depth points and structured interviews with residents.

2.3 EMFE Reconstruction and Selection of the Most Accurate Method

Processing was carried out on the Google Earth Engine platform and in ArcGIS Pro. In the GRD pathway, initial inundation detection was obtained through Otsu thresholding on the VV and VH polarisations, which were subsequently combined by union. Inundation edges were extracted using focal max and focal min morphological operations, and the DEMNAS elevation values at those edges were assumed to represent the estimated water surface elevation (WSE) under observed conditions. The WSE values were then corrected to peak conditions using an external surrogate variable following the equation $WSE_{max} = WSE_{SAR_interp} + (dh_{BPBD} \times R_{CH}) + dh_{tidal}$, where dh_{BPBD} is the inundation depth interpolated from 45 BPBD points, R_{CH} is the ratio of cumulative peak rainfall to rainfall at the time of acquisition, and dh_{tidal} is the difference in sea level height. Reconstruction of the peak extent was obtained through a flood fill simulation based on a cumulative cost algorithm on DEMNAS, which is mathematically equivalent to an 8-connected neighbourhood flood fill.

In the SLC pathway, initial detection was obtained through coherence change detection on the image pair of 9 and 21 February 2023, whose interval brackets the flood period, so that temporal information on the flood peak is inherently contained in the data. For that reason, the external correction applied was only partial, namely the addition of a constant depth of 0.5 m without a rainfall ratio multiplier or tidal correction, followed by a flood fill simulation based on a modified bathtub model principle.

The determination of the EMFE method to be used as the basis for the affected-area distribution map was carried out in two stages. First, a confusion matrix was computed for each method against the 90 field points, yielding overall accuracy (OA), producer's accuracy (PA), user's accuracy (UA) and the Kappa coefficient, interpreted following the categories of Landis and Koch (1977) as also applied by Rostami and Fathizad (2022). Second, the McNemar test (McNemar, 1947) was applied to the same paired samples with a chi-square statistic of $(b - c)^2 / (b + c)$ at a significance level of alpha 0.05 with a critical value of 3.841 at one degree of freedom. The McNemar test was chosen because it is more appropriate than the Z test of the Kappa coefficient when two maps are validated using the same samples, since the assumption of independence between samples is not met

(Foody, 2004). As a robustness check, the Yates continuity correction and the exact binomial test were also computed.

2.4 Sub-District Spatial Distribution Analysis

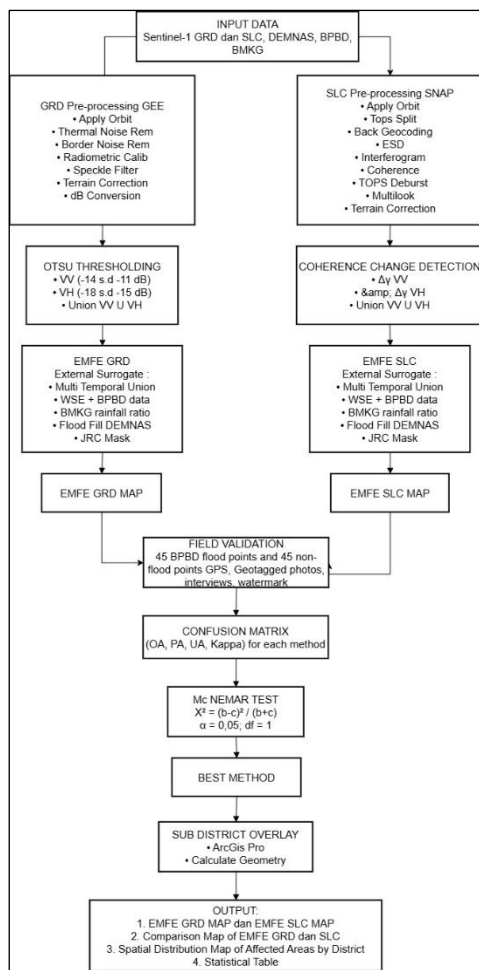


Fig. 2. Research flowchart

The selected EMFE map was overlaid with the administrative boundaries of the 14 mainland sub-districts of Makassar City using ArcGIS Pro. The inundated area in each sub-district was computed in hectares using the Calculate Geometry function in the UTM Zone 50S projection system to ensure accurate area computation, and the percentage of inundated territory was then calculated as the ratio of inundated area to the administrative area of the sub-district multiplied by one hundred per cent. The results were grouped into three classification classes. A two-tier priority scheme was then developed, consisting of a core zone comprising the intersection of areas detected by both methods and an anticipatory zone comprising the additional areas detected only by the selected method. The research workflow is summarised in Fig. 2.

3. Results and Discussion

3.1 Initial Inundation Detection and Coherence Change

Filtering the Sentinel-1 GRD ascending orbit collection over the event period showed that only two scenes were available during February 2023, namely the acquisitions of 9 and 21 February 2023. The multi-temporal union design originally prepared to widen the temporal coverage of detection could therefore not be fully implemented, because the 9 February image recorded pre-event conditions while the 21 February image recorded conditions after the inundation had receded. This situation confirms that the February 2023 flood was effectively a single-scene event for intensity

analysis, and provides the main justification for applying the surrogate variable approach.

The Otsu thresholding algorithm was applied separately to the VV and VH polarisations using a backscatter histogram with 255 bins at 0.1 dB resolution. Based on a literature review, the threshold search range was restricted to -14 to -11 dB for VV and -18 to -15 dB for VH so that the algorithm would not select a threshold in a part of the distribution irrelevant to water characteristics. The computation placed the optimal threshold at -11 dB for VV and -15 dB for VH, both exactly at the upper bound of the prescribed range. This finding is important to report transparently, because it shows that in practice the thresholds used were determined more by the literature constraint than by the Otsu algorithm alone. The reason is evident from the shape of the histogram, in which the VV distribution is highly asymmetric with a frequency peak in the range of -5 to -8 dB and a long tail towards low values, reflecting the dominance of non-water pixels such as buildings and rough surfaces that characterise Makassar City as a densely built urban area.

Table 1. Initial inundation detection area from Sentinel-1 GRD classification

No	Classification result	Area (ha)	Percentage (%)
1	Flood VV (threshold -11 dB)	1,304	13.31
2	Flood VH (threshold -15 dB)	3,334	34.05
3	Union (Flood VV and Flood VH)	4,214	43.03
4	After permanent water masking (JRC GSW > 50%)	941	9.61

Source: Computation on Google Earth Engine, 2026

Applying these two thresholds produced three binary classification maps, summarised in Table 1. The VV polarisation produced relatively limited detection concentrated on open water bodies around the Tallo River estuary, the aquaculture ponds in the north of the city and the ponds in the south-east, consistent with the sensitivity of VV to calm water surfaces through specular scattering. In contrast, the VH polarisation produced far broader coverage extending into the settlement matrix in the central and eastern parts of the city, because cross-polarisation is more robust to volume scattering and double-bounce effects in urban areas. The union of the two polarisations was chosen so that pixels identified as water in either polarisation would be retained, thereby suppressing the risk of false negatives from the earliest stage.

In the SLC pathway, interferometric coherence was computed for the pre-flood pair of 28 January and 9 February 2023 and for the event pair of 9 and 21 February 2023, with coherence change formulated as the difference between pre-flood coherence and event coherence. Positive values indicate a decrease in coherence during the event period, as theoretically expected. The computation results at the reference points are presented in Table 2.

Table 2. Mean interferometric coherence and coherence change at flood and non-flood points

Class	Pre VV	Event VV	Delta VV	Pre VH	Event VH	Delta VH
Flood	0.576	0.623	-0.062	0.582	0.621	-0.037
Non-flood	0.565	0.597	-0.031	0.555	0.571	-0.029

Source: Processed with SNAP Desktop, 2025

The mean coherence values in both classes lie in the moderate to high range, approximately 0.555 to 0.623, and the coherence change at flood points is in fact negative,

namely -0.062 for VV and -0.037 for VH. This means that, on average, flood points did not experience a decrease in coherence from the pre-flood pair to the event pair, and even tended to increase slightly. The difference between the flood and non-flood classes is also very small. Nonetheless, the change at flood points tends to be more negative than at non-flood points, particularly for VV, so the interpretation cannot rest on point-based mean statistics alone and must also consider the spatial pattern of coherence change. Using a coherence change threshold of more than 0.30 and the union of the two polarisations, a candidate change area of 643.64 ha was obtained, which was subsequently positioned as an inherent surrogate, that is, the use of change information already contained in the event coherence pair to represent the initial indication of inundation impact.

3.2 Extent Characteristics of EMFE-GRD and EMFE-SLC

The EMFE reconstruction produced two products with markedly different extent characteristics. EMFE-GRD yielded a potential inundation area of 7,265.2 ha, or 41.65% of the study area, representing an expansion of approximately 7.7 times relative to the post-masking initial detection area of 941 ha. In contrast, EMFE-SLC yielded only 2,018.6 ha, or 11.57% of the study area, an expansion of approximately 3.1 times relative to the initial coherence change detection candidate area of 643.64 ha. The GRD pathway estimate is therefore about 3.6 times larger than the SLC pathway estimate. A concise comparison of the two products is presented in Table 3.

The difference in extent can be explained by the surrogate mechanism of each pathway. In the GRD pathway, the R_{CH} component has a value of 3.125, derived from the ratio of the average peak rainfall of 250 mm to the rainfall of 80 mm at the time of acquisition. This component acts as a multiplier of the BPBD observed depth, so that a depth of only one metre adds about 3.1 m to WSE_{max} . In a city where elevations are predominantly 1-8 m above sea level and slopes are 0-8%, such an increase in water surface height causes the flood fill simulation to spread laterally with little topographic resistance. EMFE-GRD is therefore positioned as an upper bound, or worst-case envelope, and tends to over-estimate. In contrast, the SLC pathway received only a constant increment of 0.5 m and started from a specific coherence change area, so the flood fill spread is more spatially limited and the estimate tends to under-estimate.

Table 3. Comparison of the characteristics of the EMFE-GRD and EMFE-SLC results

No	Aspect of comparison	EMFE-GRD	EMFE-SLC
1	Inundation area (ha)	7,265.2	2,018.6
2	Percentage of study area (%)	41.65	11.57
3	Ratio to initial detection	7.7x (from 941 ha)	3.1x (from 643.64 ha)
4	Surrogate mechanism	Full external	Inherent + partial external
5	WSE correction	$WSE_{SAR} + (dh_{BPBD} \times R_{CH} = 3.125) + dh_{tidal}$	$WSE_{SAR} + dh_{BPBD}$ (0.5 m constant)
6	Distribution pattern	Uniform across the lowlands	Selective and concentrated
7	Position of the estimate	Upper bound (worst-case envelope)	Conservative (lower bound)
8	Error orientation	Few false negatives, prone to false positives	Few false positives, prone to false negatives

Source: Authors' analysis, 2026

3.3 Accuracy and Selection of the EMFE Method

Field validation at 90 sample points confirmed 48 inundated points and 42 non-inundated points. The confusion matrix results for both methods are presented in Table 4. EMFE-GRD correctly detected 28 of 48 inundated points and 28 of 42 non-inundated points, whereas EMFE-SLC correctly detected only 13 of 48 inundated points although it successfully identified 32 of 42 non-inundated points.

Table 4. Confusion matrix of EMFE-GRD and EMFE-SLC against 90 field validation points

Prediction	GRD: Actual flooded	GRD: Actual not flooded	SLC: Actual flooded	SLC: Actual not flooded	Total predicted
Flooded	TP = 28	FP = 14	TP = 13	FP = 10	42 / 23
Not flooded	FN = 20	TN = 28	FN = 35	TN = 32	48 / 67
Total actual	48	42	48	42	90

Source: Field validation, 2025

The accuracy metrics derived from the two matrices are presented in Table 5. EMFE-GRD achieved an overall accuracy of 62.22% with a Kappa of 0.248, classified as fair according to Landis and Koch (1977), whereas EMFE-SLC achieved an overall accuracy of 50.00% with a Kappa of 0.032, classified as poor and practically equivalent to random guessing.

The largest difference occurs in the producer's accuracy of the flood class, at 31.25 percentage points, indicating that the main advantage of EMFE-GRD lies in its ability to capture genuinely inundated areas. This is consistent with the position of the GRD pathway as an upper bound, in which the full WSE correction and the union of two polarisations widen the detection coverage and thereby suppress false negatives. Conversely, the producer's accuracy of EMFE-SLC of only 27.08% shows that this method failed to detect almost three quarters of the areas that were actually inundated, with 35 of 48 points becoming false negatives.

Table 5. Comparison of accuracy metrics and McNemar test results

No	Metric	EMFE-GRD	EMFE-SLC	Difference
1	Overall Accuracy (%)	62.22	50.00	12.22
2	Producer's Accuracy, flood class (%)	58.33	27.08	31.25
3	User's Accuracy, flood class (%)	66.67	56.52	10.15
4	Kappa coefficient	0.248 (fair)	0.032 (poor)	0.216
5	McNemar chi-square	-	-	4.84
6	p-value	-	-	0.028

Source: Confusion matrix and McNemar test computation, 2025

The McNemar test was applied to a 2x2 contingency table with cell a = 38 points correct in both methods, b = 18 points correct in GRD but incorrect in SLC, c = 7 points incorrect in GRD but correct in SLC, and d = 27 points incorrect in both methods. The computation yielded a chi-square of 4.84, greater than the critical value of 3.841 at one degree of freedom, with a p-value of 0.028. The null hypothesis of no difference in accuracy is therefore rejected. Because the number of disagreements lies exactly at the boundary of $b + c = 25$, additional checks were performed, yielding a Yates chi-square of 4.00 with p of approximately 0.046 and an exact binomial test with p of 0.043. All three approaches lead to the same conclusion, so the superiority of EMFE-GRD proves robust to the choice of test variant and is not merely a statistical coincidence.

This finding is notable because it contradicts the theoretical expectation in the literature, which generally regards interferometric coherence as the superior approach

for flood mapping in dense urban areas (Chini et al., 2019; Zhao et al., 2022). Coherence analysis at the 45 reference flood points shows that mean coherence did not decrease during the event period, with a change of only -0.062 for VV and -0.037 for VH, and even a slight increase. The basic assumption of coherence change detection, that inundation reduces coherence, is therefore not satisfied in this case study. The cause is structural: the co-event image of 21 February 2023 was acquired after the inundation had receded, so the coherence pair does not tightly bracket the peak moment, compounded by the characteristics of dense urban areas that maintain high coherence through double-bounce scattering from building walls. The advantage of coherence is thus conditional and strongly dependent on the availability of an appropriate image pair, rather than being an absolute advantage.

It should be emphasised that the accuracy achieved is moderate rather than high. Previous studies reporting accuracies above 90% generally worked with imagery that directly captured the flood peak (Jain et al., 2022; Verdyansyah and Lin, 2025). This difference is a direct consequence of the temporal gap that forms the premise of this study, not an indication of weakness in the processing procedure. The results should therefore be understood within a framework of relative comparison between methods and as a screening instrument, rather than as a claim of absolute accuracy. Based on all these considerations, EMFE-GRD was selected as the basis for compiling the map of affected-area distribution per sub-district.

3.4 Why the coherence pathway underperformed

This outcome contradicts the theoretical expectation that interferometric coherence is superior for flood mapping in dense urban areas (Chini et al., 2019; Li et al., 2019; Zhao et al., 2022). Three factors explain the discrepancy and their combination is instructive for the wider literature. The first is temporal, the co-event image of 21 February was acquired after the water had receded, so the coherence pair does not tightly bracket the peak, the surface had already returned to stability by second acquisition and the decorrelation signal had largely dissipated. (Chini et al., 2019) mapped urban flooding in Houston successfully using a 6 day repeat interval available while both Sentinel-1 satellites were operating, which allowed the pair to straddle the event closely. The difference in outcome is therefore consistent with, rather than

contrary to the published evidence it delimits the conditions under which that evidence holds.

The second is structural. Dense urban surfaces maintain high coherence through double bounce scattering from building walls, which persists even when shallow water is present at ground level (Tsyganskaya et al., 2018). In Makassar's building dense districts this stabilizing effect works directly against the decorrelation the method relies on. The third is that C-Band coherence over a 12-day baseline is itself vulnerable to temporal decorrelation from vegetation and ordinary surface activity unrelated to flooding, which adds noise to the change signal (Olen and Bookhagen, 2018). The result is a change mask in which the flood signal is neither strong nor cleanly separated from background change.

The general lesson is that the advantage of coherence in urban flood mapping is conditional on acquisition geometry in time, not intrinsic to the observable. Where a pair can bracket the peak, coherence supplies information that intensity cannot, where it cannot, the inherent surrogate on which the SLC pathway depends is simply absent and no amount of downstream correction recovers it. This has a practical corollary for agencies in Indonesia: the choice between intensity and coherence pathways should be made after checking the available acquisition dates against the event window, not on basis of general methodological preference. It should also be acknowledged that the accuracy achieved here is moderate rather than high and lower than studies reporting above 90% (Verdyansyah and Lin, 2025; Li et al., 2019). Those studies worked with imagery that captured the flood directly. The difference is a consequence of the temporal gap that forms the premise of this study, not an indication of weakness in the processing chain, but neither does that framing make a moderate map more accurate than it is. On the basis of the evidence above, EMFE-GRD was selected for the affected area map, with the qualifications set out in section 3.3 carried forward

3.5 Sub-District Spatial Distribution of Affected Areas

The tabulation of potential flood-affected areas per sub-district is presented in Table 6 and mapped in Fig. 3. The total potential inundation area contained within the boundaries of the 14 sub-districts reaches 7,262.2 ha, or 41.63% of the study area. The difference of approximately three hectares relative to the EMFE-GRD raster area of 7,265.2 ha arises from the clipping of edge pixels during the overlay with administrative boundaries.

Table 6. Area and percentage of potential flood-affected territory per sub-district based on EMFE-GRD

No	Sub-district	Sub-district area (ha)	Inundated area (ha)	Percentage (%)	Exposure level
1	Panakkukang	1,567.6	884.8	56.44	High
2	Tamalanrea	3,854.1	1,901.0	49.32	High
3	Manggala	2,290.8	1,066.6	46.56	High
4	Biringkanaya	3,675.9	1,607.2	43.72	High
5	Tamalate	2,413.6	1,026.3	42.52	High
6	Rappocini	1,096.3	405.1	36.95	High
7	Mariso	281.2	50.6	17.99	Moderate
8	Tallo	961.5	164.8	17.14	Moderate
9	Mamajang	250.9	42.9	17.10	Moderate
10	Makassar	265.4	36.2	13.64	Moderate
11	Ujung Pandang	267.6	33.6	12.56	Moderate
12	Bontoala	175.0	18.7	10.69	Low
13	Wajo	206.7	15.0	7.26	Low
14	Ujung Tanah	139.9	9.4	6.72	Low
Total		17,445.6	7,262.2	41.63	-

Source: Overlay of EMFE-GRD with sub-district administrative boundaries in ArcGIS Pro, 2026

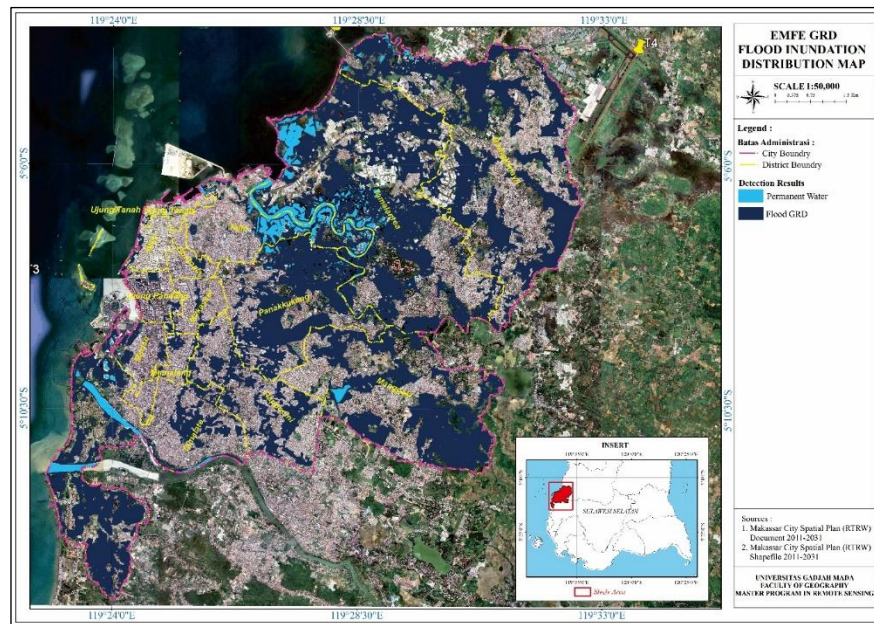


Fig. 3. Map of the distribution of potential flood-affected areas per sub-district, Makassar City

The classification divides the 14 sub-districts into three classes. The high class comprises six sub-districts, namely Panakkukang, Tamalanrea, Manggala, Biringkanaya, Tamalate and Rappocini, in which almost half to more than half of the territory is potentially inundated. The moderate class comprises five sub-districts, namely Mariso, Tallo, Mamajang, Makassar and Ujung Pandang, with inundation proportions of about 12-18%. The low class comprises the three old city-core sub-districts, namely Bontoala, Wajo and Ujung Tanah, with proportions below 11%.

Spatially, the distribution of affected areas displays an uneven pattern strongly correlated with topographic characteristics and the direction of urban development. The six high-class sub-districts are topographically located in the lowlands of the northern, eastern and south-eastern parts of the city, dominated by slopes of 0-8%, so water spreads laterally over an almost flat surface and tends to form long-lasting static inundation. These sub-districts are also relatively new urban expansion zones, with rapid conversion of infiltration land into built-up areas and drainage capacity that remains inadequate. This pattern is consistent with the findings of Djameluddin et al. (2020) regarding the limitations of the gravity drainage system in Makassar City and with the flood resilience analysis of Thoban and Hizbaron (2020).

The largest concentration of inundation follows the Tallo watershed corridor in the northern to central parts of the city, crossing Tamalanrea, Biringkanaya and Manggala, together with an inundation pocket in Antang Village, Manggala Sub-district, in the south-east. This pattern corresponds with the historical record of chronic flood-prone areas in Makassar City and, more importantly, these areas were identified as inundated by both EMFE-GRD and EMFE-SLC. Agreement between two methods resting on different principles, namely backscatter intensity and interferometric coherence, strengthens confidence that these areas are indeed at high risk of inundation.

Conversely, the low inundation proportion in the three old city-core sub-districts must be interpreted with caution. Bontoala, Wajo and Ujung Tanah have small administrative areas of less than 210 ha with very high building density. A small percentage does not mean freedom from risk; it is partly caused by the dominance of impervious surfaces and dense buildings that suppress the proportion of inundated pixels,

and by radar reflection characteristics in dense urban areas that tend to produce false negatives due to layover, shadow and double-bounce effects (Tsyganskaya et al., 2018). Thus, although the proportion of area is low, the city-core sub-districts still require attention to long-lasting local inundation that directly affects economic activity.

It should also be emphasised that the percentages in Table 6 represent the proportion of potentially inundated area relative to the administrative area of each sub-district, and are not indicators of inundation depth or of the number of exposed inhabitants. Because the base map derives from EMFE-GRD, positioned as an upper bound, these figures are maximum estimates that tend to over-estimate. This classification is therefore more appropriately used as a tool for screening mitigation priorities than as a determination of definitive actual inundation extent.

3.6 Two-Tier Priority Scheme and Its Implications

To support operational decision making, the results of both EMFE pathways are presented in a two-tier priority scheme. The core zone is the intersection of areas detected as inundated by both EMFE-SLC and EMFE-GRD, namely the estuary area and the Tallo River corridor, the Manggala-Antang pocket and part of the western coastal belt. This zone has the highest level of agreement between methods and is prioritised for the preparation of evacuation routes and the placement of emergency response resources. The anticipatory zone comprises the additional areas detected only by EMFE-GRD, and is used for worst-case scenario planning and early vigilance. This division translates the complementary characteristics of the two methods into an operational instrument for BPBD.

The scheme must be used with one important caveat. Because EMFE-SLC achieved a Kappa of only 0.032, the core zone cannot be claimed to be an area of high statistical certainty on the basis of SLC performance alone. The strength of the core zone derives from the convergence of three mutually independent sources of information, namely intensity detection, coherence detection and the historical flood records of BPBD, rather than from the accuracy of any single method. This interpretation is important so that the resulting recommendations do not exceed the strength of the available evidence.

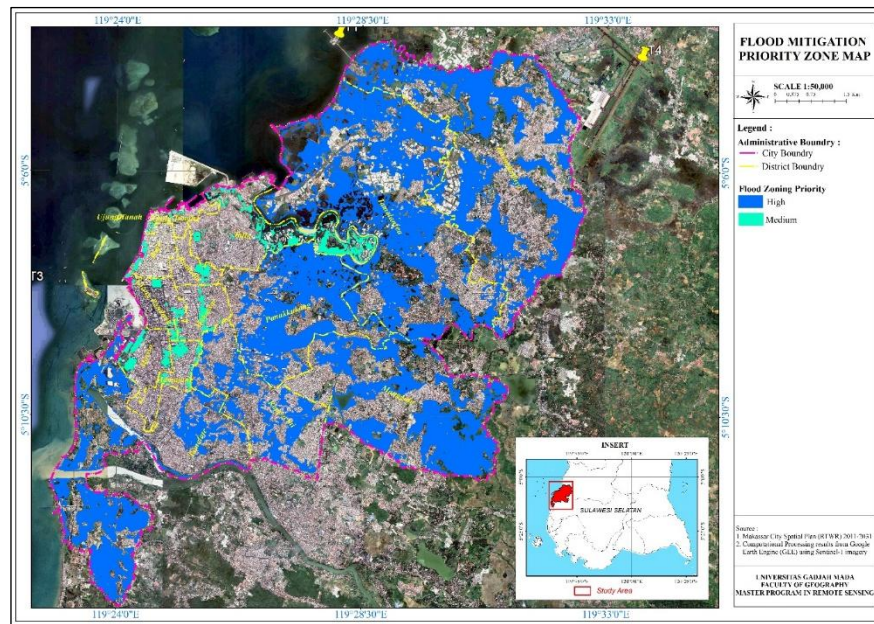


Fig. 4. Map of the two-tier priority scheme (core zone and anticipatory zone)

Based on the exposure classification and the spatial pattern described above, a tiered set of mitigation recommendations is proposed. In the six high-class sub-districts, structural measures are recommended as the top priority, comprising normalisation and capacity improvement of primary drainage along the Tallo watershed corridor, construction of retention ponds and pumping systems to address the limitations of gravity drainage as identified by Djameluddin et al. (2020), and strict control of the conversion of infiltration land in urban expansion zones. These sub-districts should be designated as priority areas in the city flood control master plan. In the five moderate-class sub-districts, a combination of structural and non-structural measures is recommended, comprising routine maintenance of drainage channels, management of river buffer zones and enhancement of local storage capacity, given that these areas function as transition zones. In the three low-class sub-districts in the old city core, non-structural measures focused on local inundation are recommended, including drainage maintenance, waste management to prevent channel blockage, and an early warning system for long-lasting inundation.

Presenting the information at the sub-district level facilitates coordination because it aligns with the administrative authority structure of the city government. This map of potential inundation distribution is recommended for integration into the RTRW document and the Disaster Risk Assessment of Makassar City as a remote sensing-based information layer that has been field validated and statistically tested for significance, while keeping in mind its nature as an upper-bound estimate.

The contribution of this study to the literature lies in two aspects. First, unlike studies that assume the availability of imagery at the flood peak (Jain et al., 2022; Refice et al., 2020; Verdyansyah and Lin, 2025), this study shows that information on affected areas per sub-district can still be derived through a surrogate variable-based EMFE approach even when the inundation peak is not captured by satellite imagery. Second, the application of the McNemar test on paired samples fills the gap left by previous studies, most of which report accuracy values only, without significance testing (Foody, 2004; Congalton and Green, 2019). A limitation that must be acknowledged openly is the asymmetry of the correction treatment between the two pathways, in which the GRD pathway received a full WSE

correction while the SLC pathway received only a constant increment, so that part of the difference in extent arises from differences in parameterisation rather than from sensor capability alone.

3.7 Contribution and limitations

The contribution of this study to SAR-based flood mapping methodology is threefold. It formalises reconstruction of an unobserved flood peak through explicitly tuped surrogate variables, distinguishing an external surrogate that supplies temporal information from outside the imagery from an inherent surrogate that draws it from the interferometric interval it self a distinction that clarifies why the two pathways fail differently and that is applicable wherever revisit intervals do not align with event timing. It supplies empirical evidence that the documented advantage of coherence in urban flood mapping is conditional on revisit interval rather than intrinsic, which qualifies a body of results conditional on revisit interval rather than intrinsic, which qualifies a body of results obtained under two satellite conditions and is directly relevant to the period between the loss of Sentinel-1B and the full operation of Sentinel-1C, And it demonstrates paired sample significance testing as a routine step in method comparison, addressing the gap identified by Foody (2004) and Congalton (1991), including the instructive case in which independent confidence intervals overlap while the paired test rejects the null.

Four limitations qualify these contributions. The asymmetric correction is the most consequential: the GRD dan SLC pathways received WSE increments differing by a factor of about 4.7 and different permanent water thresholds, so the observed difference in extent conflates parameterization with sensor pathway and the accuracy comparison although the paired test is valid for the two maps as produced is comparison of two complete workflows rather than of two sensors. A symmetric correction experiment is needed before any general statement about GRD versus SLC capability can be drawn from these results

Second, the surrogate approach carries assumptions that are not independently verified here. The rainfall ratio assumes depth scales with cumulative rainfall; the flood fill assumes a hydrostatic water surface propagating over terrain, which neglects flow resistance, storage and the drainage network, so it will over-predict in compartments with functioning outfall and under-predict where blockage causes local ponding and

DEMNAS at 8.1 m resampled to 10 m does not resolve the micro-topography or urban drainage. A formal sensitivity analysis over R_{CH} and the flood fill parameters was not performed and should accompany any future application.

Third, the reference data are limited, forty five BPBD points unevenly distributed and responder reported underpin the external correction and 90 validation points give binomial precision of about ± 10 percentage points, sufficient for the comparison drawn here but not for precise characterisation of either map. Fourth, the results are specific to one event in one city and the moderate accuracy achieved means that all downstream products the sub district table, the exposure classes and the two tier scheme inherit that uncertainty and should be used as screening instruments only

4. Conclusions

Where a flood peak escapes satellite observation, its extent can still be reconstructed and this study shows that the choice between reconstruction strategies is an empirical question that can be settled by formal testing rather than assumed from method reputation. Reconstructing the February 2023 peak in Makassar City through external surrogate variables applied to Sentinel-1 GRD proved significantly more accurate than reconstruction through interferometric coherence as an inherent surrogate, and the sub-district exposure map derived from it is the first field validated instrument of its kind available for the city, showing that impact concentrates in the low lying urban expansion zones along the Tallo watershed corridor

The scientific significance of this results lies less in which pathway won than in why. The coherence pathway underperformed not because coherence is uninformative in urban settings but because a 12-day single satellite revisit could not deliver an image pair that brackets the peak. The advantage of coherence reported in the urban flood mapping literature is therefore conditional on acquisition timing rather than intrinsic to the observable and method selection should follow from the available acquisition dates relative to the event window.

Methodologically, the study contributes a framework in which surrogate variables for an unobserved peak are explicitly typed as external or inherent, which explains why the two pathways fail in opposite direction and it demonstrates paired sample significance testing as the correct instrument when two maps are validated on identical reference points including the case, encountered here, in which independent confidence intervals overlap while the paired test rejects the null.

These conclusions carry a necessary qualification. Both products achieved only moderate agreement with field observation and the coherence product was not statistically distinguishable from chance. The resulting maps are accordingly valid as comparative screening instruments that identify where attention and further investigation should be directed and are not valid as determinations of actual inundation extent at any specific location.

5. Recommendations

For methodological development future work should exploit the restored Sentinel-1 constellation following Sentinel-1C so that image pairs can bracket the flood peak and the assumption underlying coherence change detection can be satisfied apply symmetric correction treatments and identical masking thresholds across pathways so that the sensor contribution can be isolated from the parameterization contribution, conduct formal sensitivity analysis over the rainfall ratio and flood fill parameters and integrate higher resolution terrain data or hydrodynamic modelling to relax the hydrostatic assumption.

For validation practice, sample sizes should be increased beyond the approximately 50 perclass convention and depth based validation added, so that exposure classes can reflect severity rather than areal proportion alone.

For operational use, BPBD and the Makassar City Government are advised to adopt the sub-district map as a screening layer within the RTRW and the Disaster Risk Assessment to use the core zone for prepositioning and first response reconnaissance and the anticipatory zone for worst case contingency to record future flood events as inundation polygons zone for worst case contingency, to record future flood events as inundation polygons rather than incident points so that subsequent validation is stronger and to re-derive the scheme after each major event rather than treating it as a fixed product.

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