

Flood Dynamics Evaluation Using Sentinel-1 SAR Intensity and Coherence for Mapping Extent and Depth Estimation

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Abstract

This study investigates the potential of using Sentinel-1 Synthetic Aperture Radar (SAR) Single Look Complex (SLC) imagery to map flood extent and Ground Range Detected in High Resolution (GRDH) datasets to estimate depth maps. Derna, located along Libya's coastline, is prone to flash floods due to its geography and susceptibility to intense rainfall associated with climate change. The catastrophic flood event on September 10 and 11, 2023 emphasized the city's vulnerability, resulting in significant casualties, infrastructure damage, and economic losses. This flood tragically led to the loss of many lives, underscoring the urgent need for effective flood monitoring and response strategies. Conventional flood monitoring methods, reliant on ground measurements or optical imagery, proved inadequate for rapid assessment during this large-scale disaster. To bridge this gap, the study investigates the efficacy of Sentinel-1 SAR data for accurate and timely flood mapping in data-scarce regions like Derna. Leveraging SAR imagery's unique attributes, including all-weather and day-night operability, and analyzing both intensity and coherence values, the research aims to generate accurate flood maps to support post-disaster response and recovery efforts. The study delineates an approach for deriving flood extent maps and depth estimation by analyzing data acquired before and after a flood event, even in the absence of readily available ground truth data. The results highlight the effectiveness of Sentinel-1 SAR coherence in mapping Derna's extensive inundation and SAR intensity for preliminary depth estimation, providing crucial insights for post-disaster response and recovery endeavors.

Keywords: SAR applications, Interferometric SAR, Backscattering analysis, Flood mapping and monitoring, Risk mitigation and assessment.

Introduction

Floods are among the most devastating natural disasters, posing significant threats to human lives, infrastructure, and economies worldwide. They result from various factors such as heavy rainfall, storm surges, rapid snowmelt, or the overflow of rivers and coastal areas. Floods can cause widespread destruction, including loss of life, damage to buildings, roads, bridges, and agricultural land, disruption of essential services such as water supply and sanitation, and displacement of populations. Moreover, they can have long-term socioeconomic impacts, affecting livelihoods, food security, and the environment. Dam failures resulting from heavy rain and floods can exacerbate these risks, leading to catastrophic flooding of surrounding areas. Given their destructive potential and increasing frequency and intensity due to climate change, effective flood monitoring, mapping, and mitigation strategies are essential for minimizing risks and enhancing resilience to future events. Conventional flood monitoring methods, including ground-based observations and the use of optical imagery, have demonstrated limitations in delivering timely and accurate assessments during significant disasters. Optical imagery, while valuable for various Earth observation applications, faces challenges during flood events, such as obstruction by cloud cover or reduced visibility due to

heavy rainfall. These constraints impede real-time data collection and hinder effective monitoring of flood extents and dynamics. Similarly, ground-based observation methods, although useful for long-term monitoring, are hampered by safety concerns and limited spatial coverage during hazardous flood conditions. The dynamic and rapidly evolving nature of floods can pose safety risks to ground observers, making it challenging to collect real-time data in hazardous conditions. Moreover, ground-based methods may lack the spatial coverage needed to assess flood extents over large areas effectively. Consequently, there is a pressing need for alternative approaches that can overcome these challenges and provide comprehensive flood monitoring capabilities, particularly in regions prone to frequent flooding. To address these limitations, advanced remote sensing technologies like Synthetic Aperture Radar (SAR) offer promising solutions. SAR systems, such as Sentinel-1, provide all-weather capabilities and can penetrate cloud cover, operate day or night, and offer unparalleled insights into flood dynamics. Sentinel-1, as an open-source and high-resolution SAR system, offers distinct advantages for various environmental applications, making it a promising tool for flood mapping, especially in adverse weather conditions. Previous research has highlighted the effectiveness of SAR data in flood mapping (Martinez and Le, 2007; Pierdicca et al., 2013; Mason et al., 2014; Martinis et al., 2014; Dasgupta et al., 2018; Bioresita et al., 2018; Hardy et al., 2019). For instance, a recent study (Nasirzadehdizaji et al., 2019) utilized multi-temporal Sentinel-1 SAR data to map flooded areas and changes in water bodies, distinguishing between flooded areas and permanent water bodies. Using Sentinel-1 GRDH images, they extracted backscatter values and generated a color composite image for detecting flooded areas and changes in permanent water bodies. They further validated the extracted flood and surface water using Sentinel-2 multispectral images, focusing on the Short-Wave Infrared (SWIR) multispectral band. In another study, an automated change detection method employing Sentinel-1 SAR data (Bioresita et al., 2018) proposed an algorithm for noise reduction while preserving detailed information. This approach offers a more efficient, flexible, and robust computation method, particularly beneficial for highly unbalanced datasets, thereby improving change detection outcomes.

While previous studies have demonstrated the effectiveness of SAR backscattering for mapping flood extents, the synergistic application of intensity and coherence values derived from SAR data remains relatively unexplored. This study aims to investigate the potential effectiveness of utilizing Sentinel-1 SAR imagery for mapping flood extent and preliminary depth estimation in regions with limited data availability, such as Derna. Through a comprehensive analysis of both intensity and coherence values inherent in Sentinel-1 SAR imagery, this study seeks to produce accurate flood maps to bolster post-disaster response and recovery endeavors.

Data and Method

Derna, situated along Libya's coastline at 32°45'49"N 22°38'10"E, features diverse topographical characteristics, including coastal plains and rugged mountains, making it prone to natural hazards like flash floods. With a Mediterranean climate, the region experiences hot, dry summers and mild, wet winters. Intense rainfall, often associated with climate change, increases the risk of flooding, especially in low-lying areas. The district is intersected by several rivers and wadis, with the Derna River (Wadi Derna) being prominent. Originating in the inland mountainous terrain, the Derna River flows towards the Mediterranean Sea, shaping the local landscape. Settlements and agricultural activities are strategically located along its course. The river's dynamic flow patterns, coupled with seasonal precipitation changes, heighten the region's susceptibility to flooding. The region experienced an intense precipitation event, with approximately 400 mm of rainfall recorded during Storm Daniel on September 10, 2023. This extreme weather event resulted in the collapse of hundreds of buildings and

tragically led to the loss of thousands of lives. Fig. 1 displays the geographic layout of the study area.

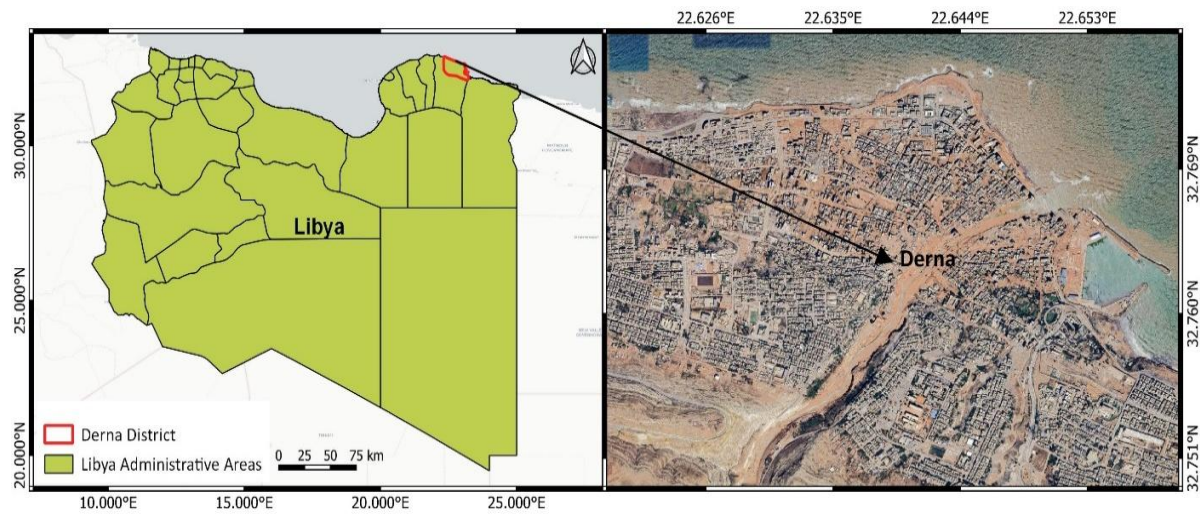


Fig 1. The location maps of study area.

Sentinel-1 SLC SAR data in descending orbit pass, and VV polarization, were collected to evaluate flood dynamics in the Derna region. A total of 3 images in the Interferometric Width (IW) swath acquisition mode, with a relative orbit (track number) of 109, were acquired for interferometric SAR and multitemporal analysis. In the InSAR processing, pairs of Sentinel-1 SAR images acquired from August 27, 2023, to September 8, 2023, were utilized as the pre-flood dataset, while images from September 8, 2023, to September 20, 2023, were used as the post-flood dataset. Additionally, two GRDH datasets were incorporated into the analysis, collected on August 31, 2023 (pre-flood), and September 12, 2023 (post-flood), in ascending orbit pass. These image pairs and GRDH data offer temporal coverage before and after the flood event, enabling the detection of changes in surface characteristics for flood depth estimation. Further details about the characteristics of the Sentinel-1 SLC dataset used in the study and interferograms' information are provided in Table 1.

Table 1. Acquisition dates and characteristics of sentinel-1 SLC C-band dataset and interferograms formation.

Image No.	Absolute Orbit-Frame	Acquisition Date	Temporal Baseline (days)	Perpendicular Baseline (meters)	Interferogram Formation
1	50056-486	27-Agu-2023	-	-	-
2	50231-486	08-Sep-2023	12	32	1+2
3	50406-486	20-Sep-2023	24	6	1+3

The InSAR method, renowned for its capability to monitor ground movements resulting from a spectrum of phenomena such as earthquakes, volcanic activity, land subsidence, and flooding, offers profound insights into surface dynamics across extensive spatial scales. In the specific context of scrutinizing Sentinel-1 SAR data for flood dynamics in the Derna region, the InSAR processing entailed several pivotal stages. Initially, the SAR data underwent meticulous pre-processing to rectify various distortions and artifacts, encompassing radiometric and geometric corrections. Then, interferograms were crafted by computing the phase disparities between pairs of SAR images captured prior to and following the flood occurrence. These interferograms were then meticulously unwrapped to derive absolute phase values and subsequently translated into maps depicting surface deformation. Additionally, coherence images were generated to evaluate the fidelity of interferometric measurements, identifying

regions exhibiting low coherence indicative of alterations in surface characteristics like flooding. Furthermore, intensity (backscattering) values were gleaned from the SAR data to complement the interferometric analysis for flood extent investigation. Intensity values specific for flood depth estimation were obtained from GRDH data collected in ascending pass direction due to the high temporal resolution of the obtained data. Ultimately, through the analysis of coherence and intensity values, flooded areas were demarcated, enabling the estimation of flood extent and depth. Leveraging advanced algorithms and techniques, the InSAR processing workflow facilitated the attainment of accurate and dependable flood mapping outcomes, thereby bolstering effective disaster response and management endeavors in the Derna region. To derive coherence and intensity values, a comprehensive process was implemented. Initially, coherence images were generated from the interferometric SAR data. Coherence assesses the correlation between two SAR images, offering insights into the consistency of backscattered signals. Regions with high coherence denote stable surfaces, while low coherence values imply changes in surface characteristics, such as flooding. Coherence values were computed for each pixel in the SAR images using specialized algorithms, considering factors like temporal and spatial baselines. Similarly, intensity (backscattering) values were extracted from the SAR data. Backscattering intensity gauges the strength of radar signals reflected from the Earth's surface and can vary based on surface roughness, moisture content, and other factors. Intensity values were acquired for each pixel in the SAR images, offering valuable insights into surface conditions and aiding in flood depth estimation. Following the extraction of coherence and intensity values, a thorough analysis was conducted to delineate flooded areas and estimate flood depth. After delineating the flooded areas, further analysis was conducted to estimate the flood depth for selected pixels, considering intensity values. Topographical data related to the area before and after the flood event, as well as information from media reports documenting the flood, were used to estimate the flood depth. Thereby, threshold values were obtained considering these parameters and topographical changes for flood depth estimation.

Results

Coherence values derived from SAR data offer insights into changes in surface characteristics, enabling accurate flood extent mapping. Lower coherence values indicate changes such as flooding. By analyzing coherence values, decision-makers can obtain detailed information on the extent of flooding, facilitating recovery and risk mitigation efforts. Fig. 2 illustrates the flooded area patterns from SAR images, including an optical image, intensity map, and coherence map. The red box in Fig. 2 highlights areas where flooding is visible in both the optical image and coherence map but not in the intensity map obtained from interferometric analysis. This discrepancy highlights the complementary nature of coherence-based flood detection. Similarly, coherence analysis based on the selected pixels also provides valuable information for flood mapping. Coherence values (Digital Number-DN) showed high coherence before the flood event, and after the event, the values decreased according to the surface changes, which were either due to the appearance of water or residuals carried by the flood and deposited elsewhere. The analysis of SAR intensity derived from the GRDH data offered valuable insights into estimating flood depth in the Derna region, underscoring the correlation between intensity values and flood depth for flood assessment. Intensity values, measured in decibels (dB), were grouped into distinct ranges, each corresponding to a probable flood depth. The estimated flood depth based on the intensity threshold values is presented in Table 2.

Table 2. Estimated intensity threshold values and corresponding probable flood depth.

Intensity (dB) Ranges	Probable Flood Depth
Greater than -4.5	0.1 to 0.5
-4.5 to -6.0	0.5 to 1.0
-6.0 to -8.5	1.0 to 2.0
-8.5 to -10.0	2.0 to 5.0
-10.0 to -15.0	5.0 to 8.0
Less than -15.0	Greater than 8.0

A decrease in post-flood intensity values relative to pre-flood levels manifests as darker patterns, indicative of water presence due to signal absorption or attenuation. Post-flood intensity values ranging from -10.0 to -15.0 dB corresponded to deeper flood depths of 5–8 m. Conversely, values exceeding -4.5 dB were associated with shallower flooding (0.1–0.5 m), while those between -4.5 and -6.0 dB indicated probable depths of 0.5–1.0 m; values from -6.0 to -8.5 dB suggested depths of 1.0–2.0 m. Furthermore, intensity values between -8.5 and -10.0 dB aligned with probable depths of 2.0–5.0 m, and those below -15.0 dB denoted flood depths exceeding 8.0 m. Fig. 3 displays the Intensity and coherence analysis for the selected pixels, illustrating the changes in surface characteristics before and after the flood event. While ground measurements were unavailable, reports from news articles, media, and eyewitness accounts claimed that after flood-control dams were destroyed, a massive wall of water inundated the city of Derna, situated directly below the lower dam, and the flood depth reached up to 60 feet (~18 meters) in height while flowing towards the Mediterranean Sea. This discrepancy between reported flood depths and those estimated from SAR intensity values underscores the challenge of accurately assessing inundation levels. Nonetheless, SAR data remains invaluable for disaster management efforts, providing critical information for assessing and responding to flood events. Future research may involve integrating SAR data analysis with hydrological and hydraulic modeling, along with ground measurements, to enhance flood extent mapping and depth estimation accuracy.

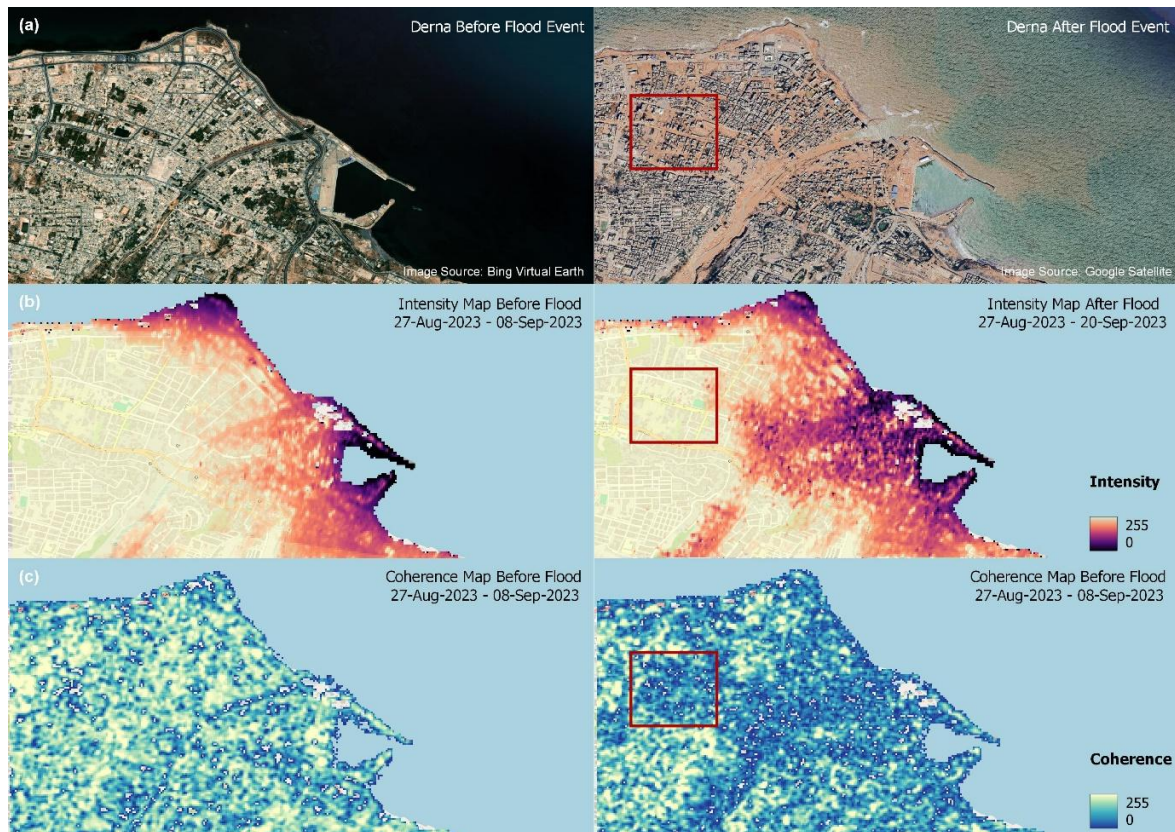


Fig. 2. Flooded area patterns from SAR images: (a) Optical image, (b) Intensity map, and (c) Coherence map. The red box highlights areas where flooding is visible in the optical image and coherence map but not in the intensity map.

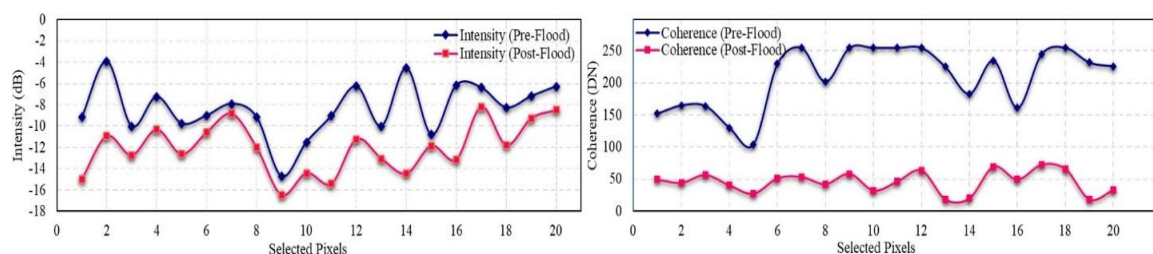


Fig 3. Intensity and coherence analysis for the selected pixels in the Derna region before and after the flood event.

Conclusion

This study underscored the effectiveness of SAR data analysis in assessing flood dynamics, providing critical insights into flood extent mapping and preliminary depth estimation. It also emphasized the vital importance of robust flood monitoring and mitigation strategies to safeguard lives and infrastructure. By examining intensity and coherence data, meaningful correlations were identified between intensity values and flood depths, along with surface feature alterations indicative of potential flooding. SAR data, with its all-weather and day-night operability, offers distinct advantages over other methods, providing valuable insights for post-disaster response and recovery efforts. However, despite the valuable information offered by intensity and coherence values for flood extent mapping and initial flood depth estimation, disparities between reported flood depths and the depth estimated by SAR highlight the challenges of precise inundation level assessments using remote sensing alone. Consequently, further investigations could utilize ground measurements to improve the accuracy of flood extent mapping and depth estimation.

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