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Mapping and Mitigating Flood Extent in Keta Municipality Using Sentinel-1 SAR: A Remote Sensing Approach for Disaster Management

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Abstract:** Floods constitute a pervasive and destructive natural disaster worldwide, with increasing frequency and severity necessitating innovative approaches for monitoring, management, and mitigation. Traditional flood assessment methods, reliant on labour-intensive field inspections during flood events, are constrained by time-consuming processes and limited accessibility to affected areas. The emergence of satellite remote sensing, offering synoptic views at unprecedented spatial resolutions and accuracies, presents an opportunity to address these limitations effectively. This research harnesses satellite remote sensing, specifically the Sentinel-1 Synthetic Aperture Radar (SAR), to map the extent of the November 07, 2021 floods within the Keta Municipality. Analyzing three strategically chosen SAR data sets acquired before, during, and after the flood event, this study not only provides precise flood extent mapping but also gains valuable insights into the dynamic nature of floods in the Keta Municipality. The investigation of this study focuses on the Keta Lagoon, revealing an inundated area of 7044.3 km^2 during the November 07, 2021 floods. Beyond technical methodology, this study holds critical implications for flood mitigation and urban planning. This study presents recommendations to the Keta Municipal Assembly, emphasizing the urgency of flood mitigation measures and the necessity for relocating communities near the lagoon. In an era of climate unpredictability, this research underscores the pivotal role of remote sensing in flood disaster response and proactive urban development. By synthesizing spatial data and offering a comprehensive assessment of flood dynamics, this study highlights the potential of remote sensing as an indispensable tool for disaster management and environmental monitoring. Ultimately, it contributes to the global endeavour of enhancing resilience to an escalating flood threat.

***Keywords** Satellite Remote Sensing, Flood Mapping, Climate Change, Sentinel-1 SAR, Disaster Management.*

1. INTRODUCTION

Increasingly severe and frequent floods, potentially linked to anthropogenic activities, have heightened the need for innovative flood monitoring and mitigation. Traditional assessment methods are becoming inadequate, with global floods causing extensive damage. Field inspections, though valuable, are constrained by time and access limitations. Real-time, comprehensive flood information is now crucial [1] [2] [3]. The advent of satellite remote sensing technology has revolutionized the capacity to map and monitor flood events effectively. The inherent advantage of remote sensing lies in its ability to provide a synoptic view of vast geographic areas at spatial resolutions and accuracies that were once unattainable through traditional means [4]. Keta Municipality in Ghana has been experiencing flooding over the years. The causes of these floods have been attributed to many factors, but the most significant amongst them is the fact that Keta lies in the lowland and that it is affected by the rise in sea level. Flooding in Keta has had a severe impact on the socioeconomic life of the people. About 2,000 residents were displaced following tidal flooding resulting from the attacks of the wave on about 300 households [5].

There have been a lot of studies on flood mapping and inundation using remotely sensed data. Dhanabalan et al. [6] used Sentinel-1 SAR data to monitor floods in southern Kerala, India, during a 2018 event. Their study identified flooded areas and assessed damages, showcasing SAR technology's value in disaster management. Yet, data gaps and the need for socio-economic integration require further research to enhance flood mitigation and resilience strategies. Parajuli et al. [7] did a study in Nepal, specifically the Siraha Municipality, focusing on flood susceptibility mapping and optimizing evacuation routes. Using GIS and the Analytical Hierarchy Process, the research identifies 47% of the area as highly susceptible to floods, aids in evacuation planning, and early warning system development. However, the study lacks comprehensive mapping and route planning, indicating a need for further research to enhance flood risk assessment, early warning systems, and efficient evacuation planning.
Uddin et al. [8] did a study on operational Flood Mapping Using Multi-Temporal Sentinel-1 SAR Images: A Case Study from Bangladesh. This study addresses the pressing issue of flood impact in Bangladesh by developing a rapid flood inundation and potential flood-damaged area mapping methodology. Utilizing Sentinel-1 and Landsat-8 imagery, the research achieved high accuracy in mapping flood extents and identifying cropland damage for various months in 2017. The results of their study provide valuable data for effective flood response efforts and can serve as a replicable model for annual flood mapping in Bangladesh. The gap in their study is the absence of a detailed discussion on the practical application and utilization of flood inundation maps in actual flood response and disaster management efforts. While their study successfully develops an operational methodology for flood mapping, it does not delve into how these maps were used or disseminated to support on-ground response actions, evacuation planning, or damage assessment. Further insights into the real-world applications and impacts of flood inundation maps would provide a more comprehensive understanding of their effectiveness in aiding flood response efforts in Bangladesh.

Lin et al. [9] also did a study on rapid urban flood risk mapping for data-scarce environments using social sensing and region-stable deep neural networks. Their paper introduces an innovative approach to near real-time flood risk mapping tailored for data-scarce environments in urban settings. Departing from traditional physically-based and empirical modelling, the method leverages social sensing and region-stable deep neural networks (RS-DNN) to extract disaster information and risk distribution factors for rapid flood risk assessment. This approach offers a promising solution for fast and adaptable flood risk mapping across various disaster scenarios and cities, addressing the challenges posed by data limitations in disaster-prone areas. The gap in their paper is the need for a more comprehensive discussion on the validation and real-world application of the proposed near-real-time flood risk mapping method. While the study introduces an innovative approach leveraging social sensing and deep neural networks, it does not provide details on how well the method performs in practice or how it has been applied in actual urban flood risk management scenarios.

Mohammadi et al. [10] also did a study on flood Detection and Susceptibility Mapping Using Sentinel-1 Time Series, Alternating Decision Trees, and Bag-ADTree Models. Their study addresses the pressing issue of floods in Iran by employing time series satellite data analysis and a novel ensemble-based model, bag-ADTree, for flood detection and susceptibility mapping. Using Sentinel-1 data and twelve conditioning parameters, it accurately identifies flood locations and areas prone to flooding. The rigorous validation measures of the study, including root mean square error and area under the ROC curve, confirm the effectiveness of the bag-ADTree model, making it a valuable resource for crisis management and flood risk mitigation in the region. The gap in this study lies in the limited discussion regarding the practical applications and implications of flood detection and susceptibility mapping results for crisis management and flood risk mitigation in Iran. While the study successfully introduces a novel model (bag-ADTree) and validates its accuracy, their study lacks insights into how these findings can be utilized in real-world flood response and management scenarios. Further exploration of how the generated flood maps and susceptibility assessments can inform decision-making, evacuation planning, and disaster preparedness in the study area would enhance the practical relevance and utility of the study.

From the prior studies discussed on flood mapping, this study has the potential to contribute to the field of flood monitoring and disaster management. This study offers fresh insights from a different geographical context, addressing gaps in temporal coverage. It also integrates the socio-economic factors, emphasizing practical applications, and promoting scalability and adaptability of SAR-based flood mapping techniques. These contributions will enhance the understanding of how remote sensing can be effectively utilized for flood mitigation and disaster resilience in various regions. In this context, this study leverages the potential of satellite remote sensing, specifically the Sentinel-1 Synthetic Aperture Radar (SAR), to map the extent of the November 07, 2021 floods within the Keta Municipality. The significance of this study extends beyond its technical methodology. By examining three strategically chosen SAR data sets acquired before, during, and after the flood event, this study aims to comprehensively assess the dynamics of the flooding event and its aftermath. The synthesis of this information not only allows for the precise mapping of flood extent but also contributes to a deeper understanding of the evolving nature of floods in the Keta Municipality. The focal point of the investigation is the Keta Lagoon, where the area was inundated by floodwaters on November 07, 2021. The findings and insights derived from this research hold implications for future flood mitigation strategies and urban planning in the Keta Municipality. As a result, this study culminates in a set of recommendations to the Keta Municipal Assembly, emphasizing the urgency of flood mitigation measures and the thoughtful relocation of communities situated in proximity to the lagoon. In this era of increasing climate variability and unpredictability, harnessing the capabilities of remote sensing technology not only enhances the ability to respond effectively to flood disasters but also paves the way for proactive and resilient urban development [11]. This study serves as a testament to the potential of remote sensing as an indispensable tool in the domain of disaster management and environmental monitoring.

2. MATERIAL AND METHODS

2.1. Study Area

Keta Municipality in the Volta Region of Ghana was selected as the study area for this work. Geographically, Keta Municipality is located between latitudes 5.450 ° N and 6.005 ° N and longitudes 0.300 ° E and 1.050 ° E. It lies 160 kilometres East of Accra, near the Volta Estuary. The Municipality has a total area of 753.1 km^2. The largest lagoon in Ghana is the Keta Lagoon and it has the potential for extensive commercial aquaculture farming while also facilitating water transportation to neighbouring communities. The Keta Municipality is situated within a 1200 km^2 protected wetland area [5].

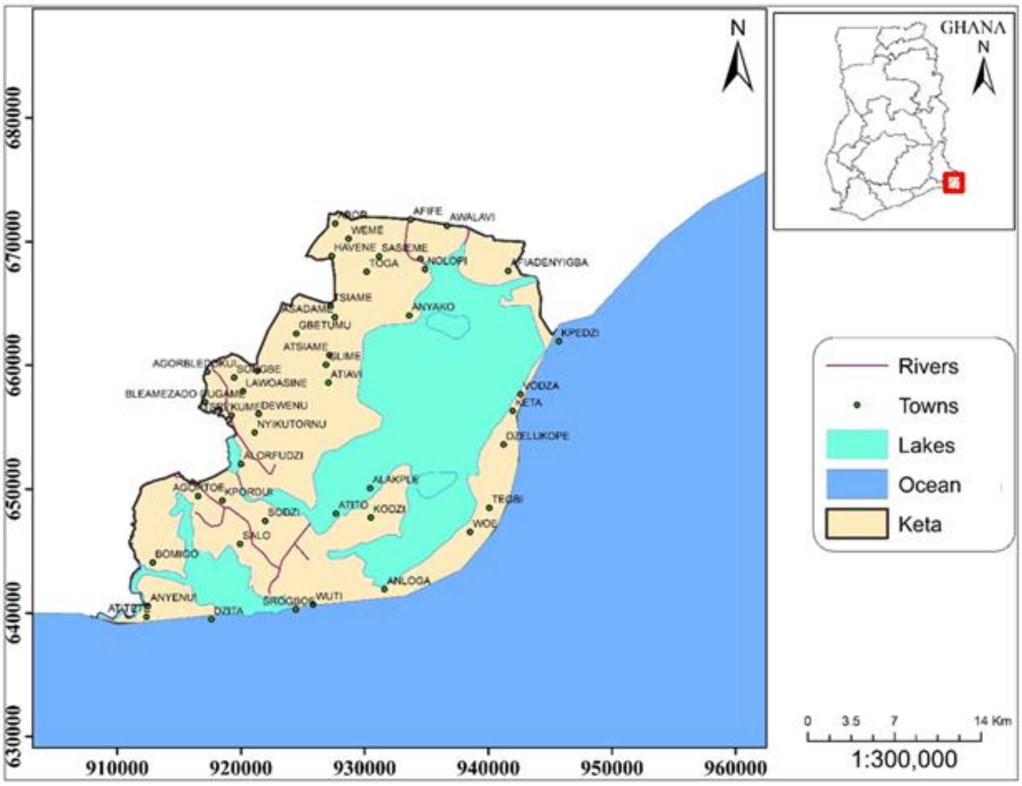

Figure 1. A Map of Keta Municipality in Ghana

2.2. Materials Used

2.2.1. Sentinel-1 Satellite SAR Data

Ground Range Detected High-Resolution (GRDH) Sentinel-1 SAR data acquired over Keta Municipality were downloaded freely from the Copernicus Open Access Hub website. SAR data were used because of the ability of SAR to capture data in all weather conditions and it can penetrate through clouds [12]. As the study seeks to map the extent of the 07, 2021 floods in Keta, three (3) SAR data sets were strategically selected in such a way that analyses could be performed on images acquired before the day of the flood (pre-flooding), during the flooding period (flooding) and after the flooding period (post-flooding). Table 1 presents information about the data used for the study.

Table 1. Sentinel-1 Dataset used for the study

SAR Data	**Remarks**
S1B_IW_GRDH_1SDV_20211027T180928_20211027T180953_029325_037FFF_8BA8_Orb_NR_Cal_Spk_TC	Pre-flooding
S1B_IW_GRDH_1SDV_20211108T180927_20211108T180952_029500_038554_2A06_Orb_NR_Cal_Spk_TC	During Flooding
S1B_IW_GRDH_1SDV_20211120T180927_20211120T180952_029675_038AB2_D1A3_Orb_NR_Cal_Spk_TC	Post-flooding

2.2.2. Software Used

The Sentinel-1 SAR data was processed using Sentinel Application Platform (SNAP) version 8.0 and QGIS 3.22 software for analysis and visualization. Sentinel Application Platform (SNAP) is a common software architecture on which several open sources, and free toolboxes for utilizing Earth observation missions for science are available [13]. Environmental scientists, businesses that generate value, students, and teachers are all targeted by SNAP. SNAP includes a desktop application (SNAP Desktop) for working interactively with Earth Observation data, the Graph Processing Framework to build and run recurring workflows, a command line interface, as well as Python and Java programming interfaces [14]. As a result, SNAP can be utilized for interactive picture analysis and visualization, and processing chain automation. The SNAP software was used in this study for the processing of Sentinel-1 SAR data.

2.2.3. The Quantum Geographic Information System (QGIS)

A Geographic Information System (GIS) is a system for the management, analysis, and display of geographic information. Previously known as Quantum GIS, QGIS is a free and open-source desktop GIS program that enables users to create, edit, and export graphical maps as well as analyze and modify geographical data. Both raster and vector layers are supported by QGIS [15]. In addition to creating maps, QGIS offers users the ability to study and update spatial data. Raster and vector layers are also supported by QGIS; vector data is saved as either point, line, or polygon features. The software can georeferenced images and supports a variety of raster image formats [15].

2.3. Methods

2.3.1. Data Pre-processing

Data preprocessing is a critical step in ensuring the accuracy and reliability of synthetic aperture radar (SAR) imagery for further analysis. In this study, several essential preprocessing operations were conducted to prepare and enhance the quality of the SAR images obtained from the Copernicus hub. The goal was to remove geometric and radiometric distortions, calibrate the data, and prepare it for subsequent analysis.

1. Data Acquisition and Loading

The initial phase involved downloading satellite imagery data from the Copernicus hub. These SAR images, often acquired from spaceborne sensors, contain valuable information about the surface of the earth. Subsequently, the acquired data was loaded into the Sentinel Application Platform (SNAP), a powerful software tool designed for SAR data processing and analysis.

2. Graph Building

To facilitate an organized and automated workflow, a graphical representation of data processing steps was created using the graph builder tool in SNAP. This graph outlined a sequence of operations aimed at improving the quality and utility of SAR data.

3. Subset Operation

The first step in the processing sequence was the "Subset" operation. This operation involved defining and extracting a specific area of interest from the SAR data, effectively reducing the dataset to the region under investigation. This subset operation focused processing resources on the relevant geographical area, optimizing subsequent analyses.

4. Apply File Orbit

Accurate geolocation information is essential for SAR data calibration and interpretation. To achieve this, the "Apply File Orbit" operation was performed. This operation utilized orbit ancillary data to precisely determine the position of the satellite during SAR data acquisition. This information is crucial for georeferencing and removing geometric distortions from the imagery.

5. Thermal Noise Removal

Radiometric calibration is a fundamental step in ensuring the accuracy of SAR data. The "Thermal Noise Removal" operation was employed to correct radiometric distortions and enhance the quality of the imagery. This step contributes to more accurate and consistent radiometric information.

6. Calibration

Radiometric calibration, the next operation, accounted for sensor-specific features and incidence angles, translating raw backscatter intensity into normalized radar cross-section (Sigma0) values. This step ensures that the data is standardized and suitable for quantitative analysis.

7. Speckle Filtering

SAR imagery often contains speckle noise, which can reduce image quality. The "Speckle Filter" operation was applied to mitigate this noise without compromising spatial resolution. It enhanced the visual quality of the imagery while preserving critical spatial information.

8. Terrain Correction

Lastly, "Terrain Correction" was performed to correct geometric distortions caused by variations in terrain elevation. By utilizing a digital elevation model (DEM), this operation geocoded the SAR imagery and generated map-projected outputs. This step ensured that the data could be accurately aligned with geographical coordinates and terrain features.

The data preprocessing methodology outlined in this study effectively addressed geometric and radiometric distortions, calibrated the data, and prepared it for further analysis. These preprocessing steps were essential for ensuring the accuracy and reliability of the SAR imagery, laying the foundation for subsequent investigations and applications. The flow of this process is shown in Figure 3.

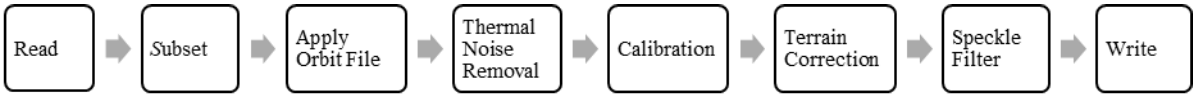

Figure 3. Conceptual framework of SAR image preprocessing in the SNAP software

2.3.2. Binarization and Data Exportation to QGIS for Analysis

Binarization Process

Binarization is a fundamental image processing technique used to separate specific features or objects from an image by assigning pixel values to either 0 or 1, typically representing "non-presence" or "presence" of the target feature, respectively. In this study, binarization was employed to delineate water bodies from non-water areas within the synthetic aperture radar (SAR) imagery.

1. Adding a dB Virtual Band

To enhance the distinguishability between water and other surfaces, a new virtual band was created in the SAR imagery. This virtual band was based on the decibel (dB) scale, which is commonly used in radar data processing due to its logarithmic nature. The dB transformation helps to emphasize variations in pixel values, making it easier to differentiate water bodies from surrounding terrain.

2. Defining the Binarization Expression

The critical step in the binarization process involved specifying the conditions under which a pixel would be classified as "water" or "non-water." This was achieved using a conditional expression in the Band Maths tool. The expression used was: "If Sigma0_VH_db -25.0 then 1 else 0."

Breaking down the Expression: "Sigma0_VH_db" represents the pixel values in the virtual dB band, specifically for the VH polarization. "-25.0" is the threshold value chosen to differentiate between water and non-water. Pixels with values greater than or equal to -25.0 dB were classified as water (assigned a value of 1), while those below -25.0 dB were considered non-water (assigned a value of 0). This expression effectively acted as a decision rule, marking pixels with a dB value indicative of water presence as "1" and others as "0."

Exporting the Water Mask

Once the binarization process was completed, a new band, often referred to as a "water mask" or "binary mask," was generated, with pixel values of 1 representing water bodies and 0 representing non-water areas. This water mask band was then exported as a GeoTIFF file.

Data Exportation to QGIS for Analysis

To conduct further spatial analysis, the water mask GeoTIFF, containing the binary classification of water and non-water areas, was exported to QGIS, a popular Geographic Information System (GIS) software. QGIS provides a versatile platform for geospatial analysis, visualization, and mapping. In QGIS, researchers can utilize a wide range of spatial analysis tools and techniques to study the distribution, characteristics, and dynamics of water bodies identified in the SAR imagery. This integration between SAR preprocessing and GIS analysis allows for comprehensive investigation and interpretation of water-related phenomena, supporting the objectives of the study. The binarization process involved transforming SAR imagery into a binary representation of water and non-water areas using a specified threshold value. This water mask was then exported to QGIS for subsequent geospatial analysis and visualization, enabling a deeper understanding of water-related phenomena in the study area.

2.3.3. Flood extent mapping using GIS

Water masks representing pre-flooding, during-flooding, and post-flooding periods were initially prepared as raster layers and subsequently converted into vector format to create polygon features denoting water presence. The overlay analysis, facilitated by QGIS software, was pivotal in identifying the dynamic changes in water extent during the flood event. By employing the "Union" tool, overlapping areas between the water polygons from different periods were identified. To precisely determine the extent of flooding during the flood event, polygons present exclusively during the during-flooding period, and absent in both the pre-flooding and post-flooding periods were singled out. These polygons effectively represented the flooded areas. The subsequent calculation of their areas provided quantified information on the extent of flooding in the municipal area during the specified event. The findings, accompanied by spatial visualizations and mapping, offered crucial insights for flood assessment and disaster management, ultimately contributing to informed decision-making in the region.

3. RESULTS AND DISCUSSIONS

3.1. Results

3.1.1. Production of Water Masks for Flood Scenarios

The SAR data obtained from Copernicus (Figure 4) after pre-processed (Figure 5) and stacked (Figure 6) was able to extract Water masks for three significant flood scenarios in the Keta Municipality: October 27th, 2021 (Pre-Flooding), November 8th, 2021 (Flooding), and

November 20th, 2021 (Post-Flooding) as shown in Figure 7. These water masks were essential in delineating the extent of flooding during the critical period of November 07, 2021 (Figures 11 and 12).

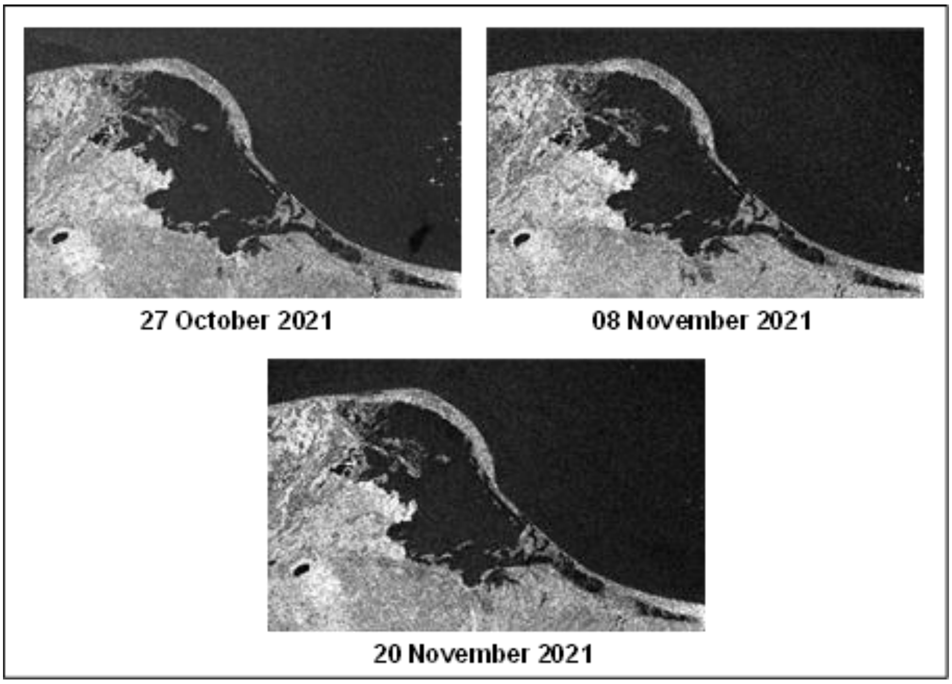

Figure 4. Unprocessed Sentinel-1 SAR GRDH images covering Keta Municipality

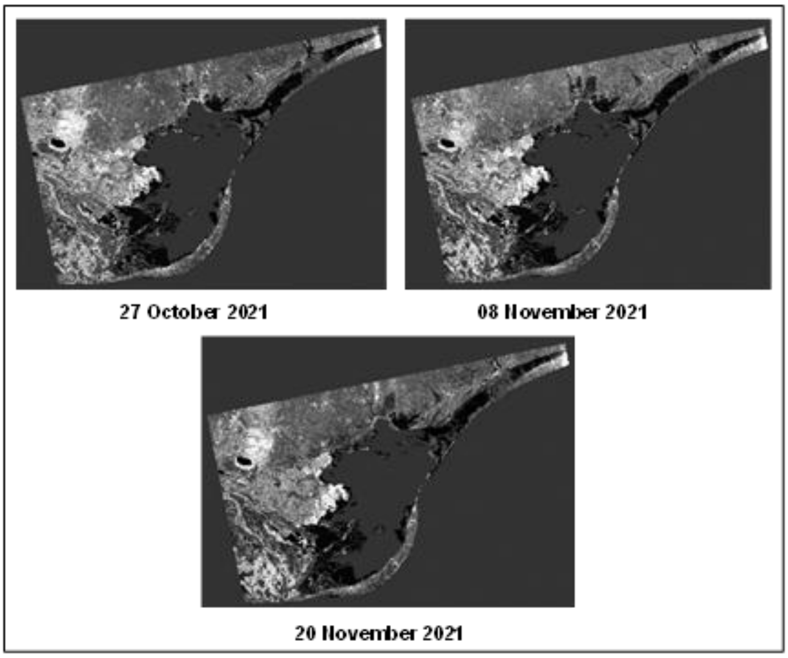

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Figure 5. Radiometric and Geometric corrected subset of Sentinel-1 SAR GRDH data for this study

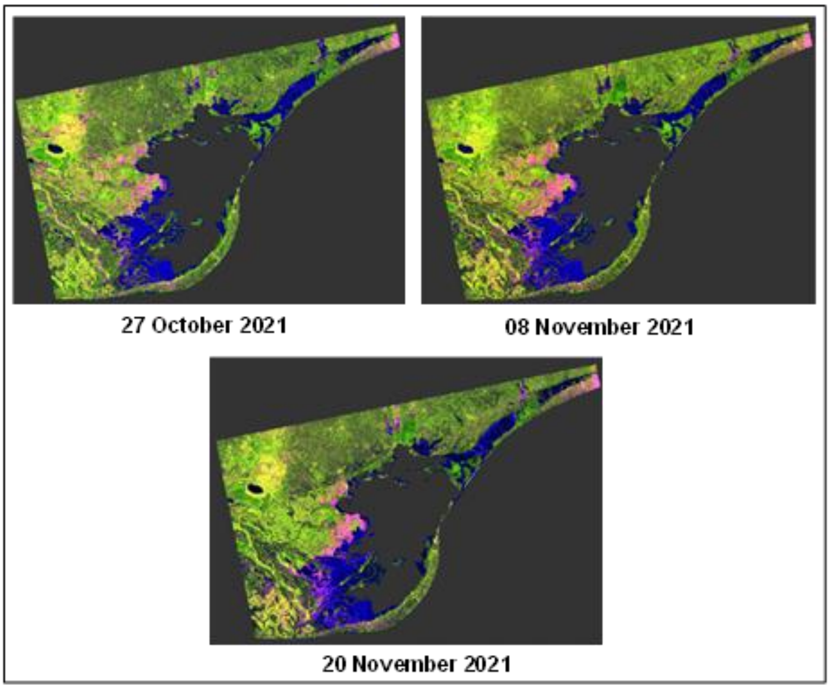
27 October 2021
08 November 2021
20 November 2021

Figure 6. RGB Composite Sentinel-1 SAR data for the study

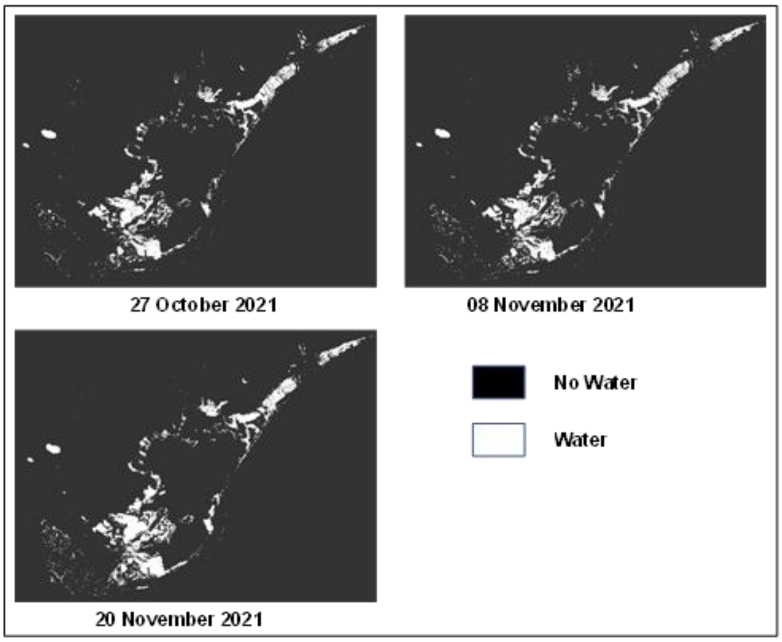
27 October 2021
08 November 2021
20 November 2021

Figure 7. Water masks of Keta for October 27th, 2021 (Pre-Flooding), November 8th, 2021 (Flooding), and November 20th, 2021 (Post-Flooding)

3.1.2. Extent of the November 07, 2021, Flood

The water boundary of the Keta Lagoon within the Keta Municipality before, during, and after the flood in the municipal is shown in Figures 8, 9, and 10. The analysis of water masks for the specific date of November 07, 2021, revealed a substantial area of 7044.3 km^2 being inundated within the Keta Municipality as shown in Figures 11 and 12. This extensive flood event had significant implications for the region, affecting both urban and rural areas, as well as infrastructure, agriculture, and the livelihoods of the local population.

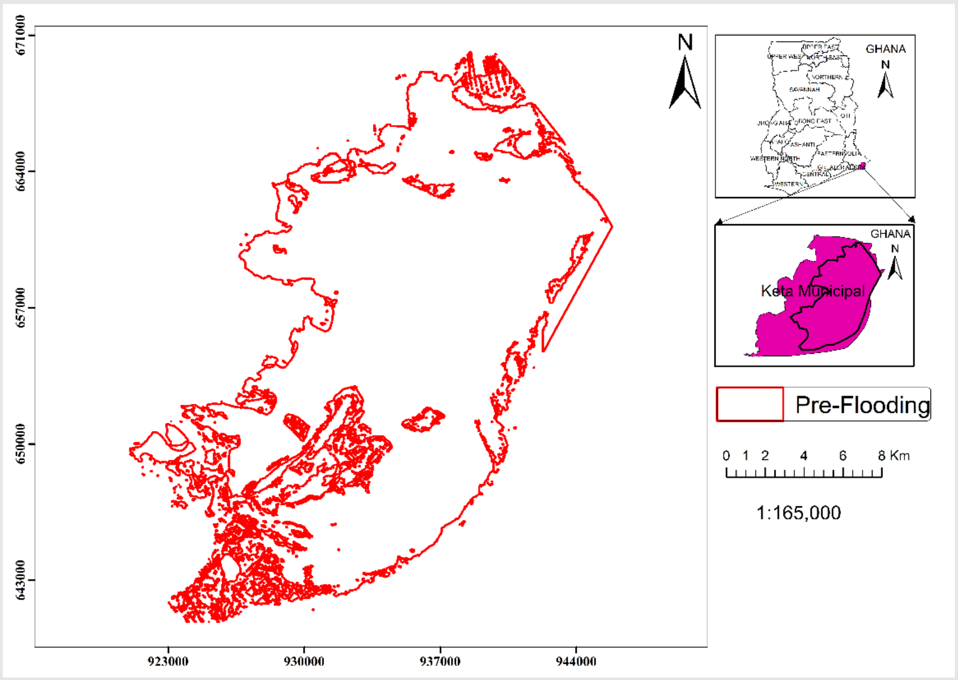

Figure 8. Water boundary for Pre-Flooding

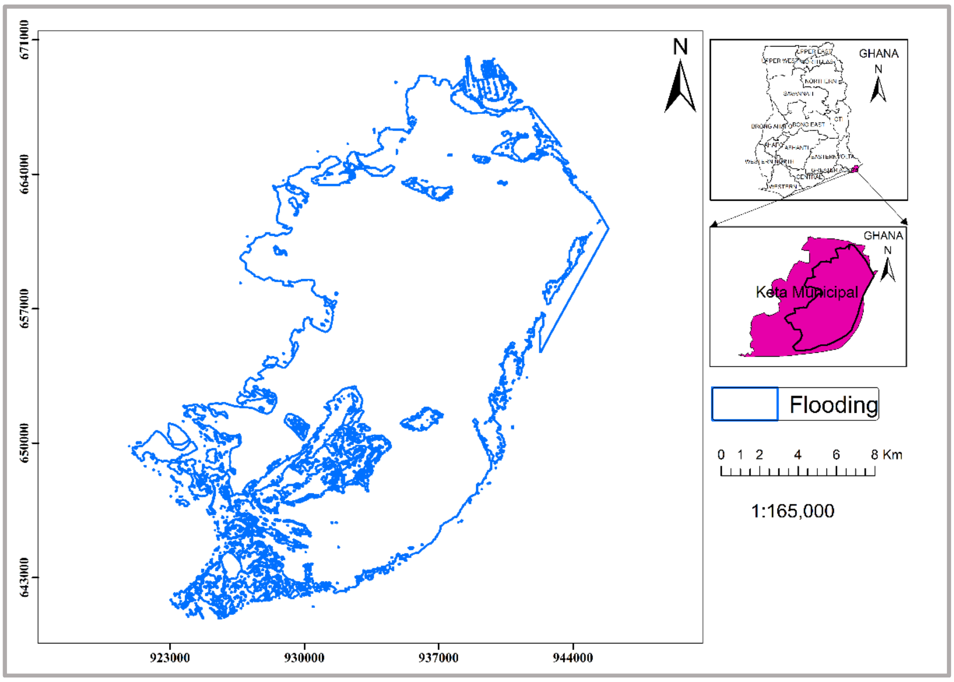

Figure 9. Water boundary for flooding

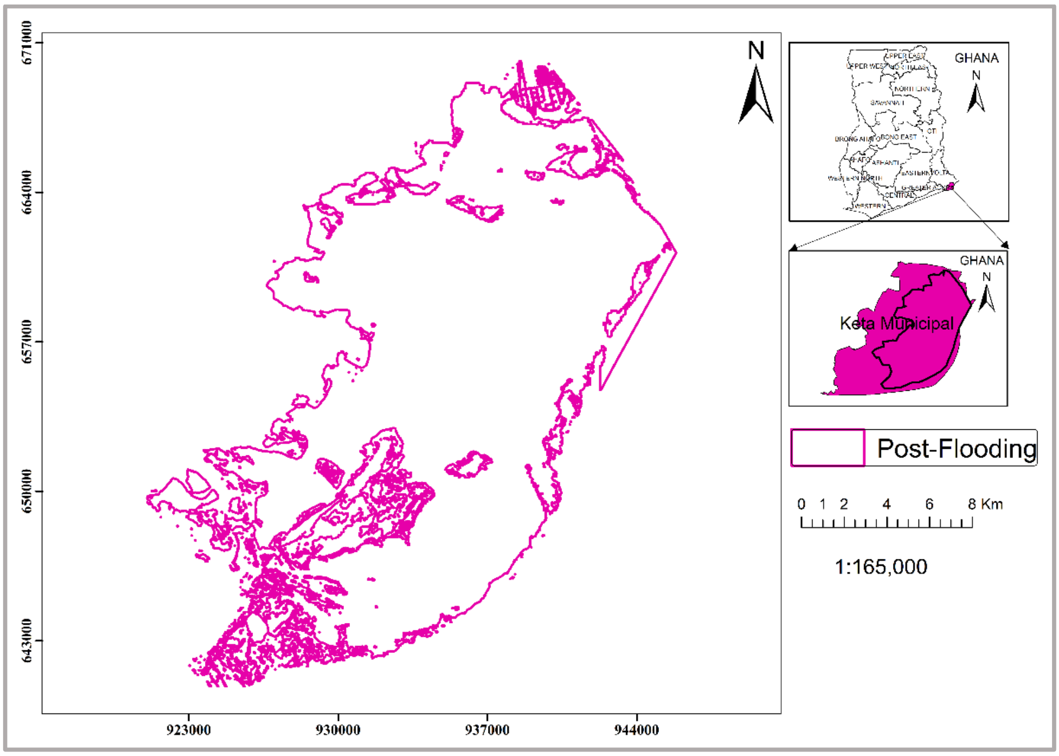

Figure 10. Water Boundary for Post-Flooding

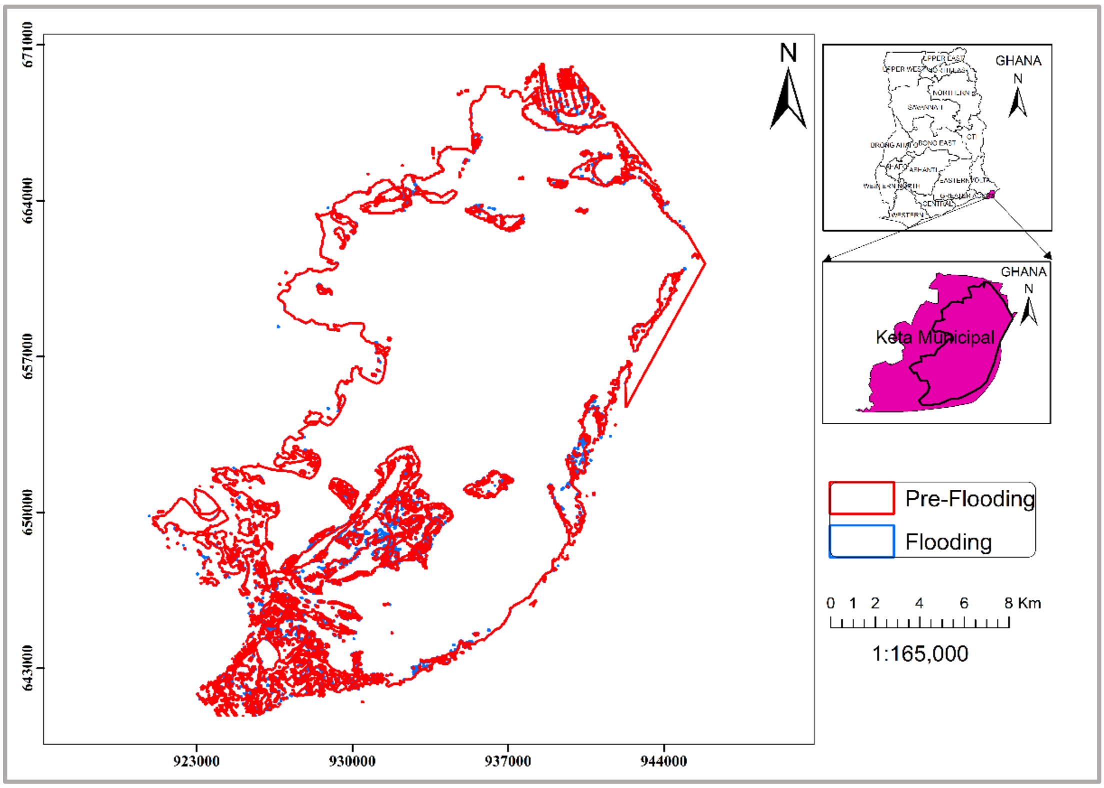

Figure 11. Composite Map of the Water Boundaries for Pre-Flooding and Post-Flooding

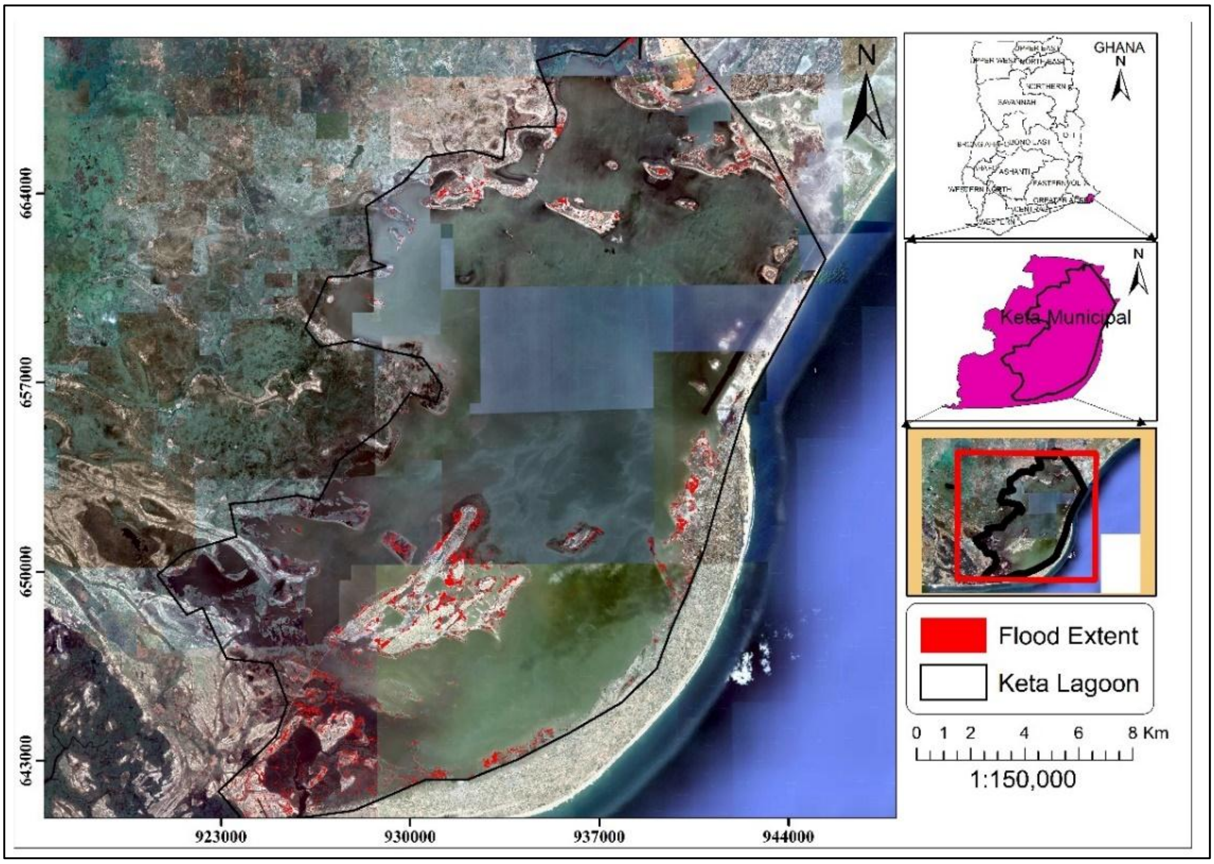

Figure 12. Extent of 07 November 2021 Flood within the Keta Municipality

3.2. Discussions

The results of this study illuminate the significant impact of the November 07, 2021 flood event within the Keta Municipality, underscoring the critical role of remote sensing and spatial analysis in flood assessment and disaster management. This discussion delves deeper into the implications of the findings, their relevance for both short-term response and long-term planning, as well as the broader context of climate change adaptation.

3.2.1. Magnitude of the Flood

The extensive inundation area of 7044.3 km^2 during the November 07, 2021 flood event demonstrates the magnitude of the disaster. Such a vast affected area signifies a substantial natural disaster with far-reaching socio-economic implications. The scale of the flood highlights the urgency of effective disaster management and mitigation strategies to safeguard lives and property in the future.

3.2.2. Identifying Vulnerable Areas

The water masks not only delineated the flood extent but also identified specific areas within the Keta Municipality that were most vulnerable to flooding. This knowledge is invaluable for disaster preparedness and response efforts. Targeted interventions, such as early warning systems, evacuation plans, and infrastructure improvements, can be prioritized in these vulnerable zones to enhance resilience.

3.2.3. Assessing Impact

Accurate mapping of the flood extent allows for a comprehensive impact assessment. Understanding how communities, infrastructure, agriculture, and ecosystems were affected is vital for guiding recovery and reconstruction efforts. The data generated in this study can assist decision-makers and disaster management authorities in allocating resources effectively.

3.2.4. Long-Term Planning and Mitigation

The findings emphasize the importance of integrating flood risk reduction measures into long-term urban planning. Sustainable land use practices, such as zoning regulations and flood-resistant construction, can mitigate future flood impacts. Additionally, investments in flood control infrastructure and improved drainage systems are essential for minimizing vulnerabilities.

3.2.5. Climate Change Adaptation

Considering the implications of climate change, understanding the spatial and temporal patterns of flooding is critical. The extent of the November 07, 2021 flood event may be indicative of changing precipitation patterns and rising sea levels, both linked to climate change. This underscores the need for proactive climate change adaptation strategies at the local and regional levels. The results from this study highlight the multifaceted significance of accurately mapping flood extents using remote sensing and spatial analysis. Beyond providing a visual representation of the flood event, these findings inform disaster management, urban planning, and climate resilience efforts. The extensive area affected by the flood event on November 07, 2021, serves as a stark reminder of the pressing need for proactive measures to mitigate the impact of future flood events and adapt to the challenges posed by a changing climate.

3.2.6. Addressing the Gabs

This study in the Keta Municipality addresses temporal coverage gaps, enriching the understanding of flood dynamics and emphasizing the need for event-specific assessments. It enhances practical utility by demonstrating how flood extent maps inform real-world responses, aiding decision-making, evacuation planning, and damage assessment. Integrating socioeconomic factors highlights the broader impact on communities, infrastructure, and agriculture, vital for tailored mitigation and resilience strategies. The methodology's scalability and adaptability enable its use in regions with similar data constraints and disasters. This holistic approach combines flood extent and socio-economic impact, empowering stakeholders for proactive risk mitigation and disaster resilience, locally and globally.

Recommendations

The Municipality should ensure the following points for sustainable flood management:

1. Strengthen Flood Preparedness and Response
2. Improve Urban Planning and Regulations
3. Invest in Flood Control Infrastructure

4. Promote Climate-Resilient Agriculture
5. Develop Climate Change Adaptation Strategies

4. CONCLUSION

In conclusion, this study employed remote sensing technology and spatial analysis to provide a comprehensive assessment of a significant flood event within the Keta Municipality, particularly on November 07, 2021. The generation of water masks for pre-flooding, during-flooding, and post-flooding scenarios allowed for a detailed delineation of the flood extent, revealing an extensive inundated area of 7044.30 km^2. This finding underscores the magnitude of the disaster and its far-reaching socio-economic implications.

The implications of this study extend beyond a mere depiction of flood extent. It identifies vulnerable areas, assesses the impact on communities and infrastructure, and emphasizes the importance of integrating flood risk reduction measures into urban planning. Moreover, in the context of climate change, the study serves as a reminder of the need for proactive climate adaptation strategies at the local and regional levels.

Day in and day out, it is imperative that the Keta Municipality and relevant stakeholders heed the recommendations outlined in this study. Strengthening flood preparedness, improving urban planning, investing in flood control infrastructure, promoting climate-resilient agricultural practices, and formulating long-term climate adaptation strategies are essential steps toward reducing the risk and impact of future flood events.

Ultimately, this research contributes not only to the understanding of the dynamics of flooding but also to the imperative of proactive measures to mitigate the impact of such events. In a world where climate variability and environmental challenges continue to evolve, the lessons learned from this study are valuable not only for the Keta Municipality but also for communities worldwide facing similar threats. By embracing these lessons and taking decisive action, a more resilient, adaptive, and sustainable society in the face of a changing climate and increasing flood risks can be built.

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Conflicts of Interest

The authors declare no conflicts of interest in relevance to this manuscript.

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