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Assessing Tsunami Impacts and Enhancing Disaster Response in Tirtayasa Banten through High-Resolution Satellite Imagery

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Abstract: In December 2018, the coastal town of Tirtayasa, Banten, suffered severe damage from a tsunami, leaving the area highly vulnerable to future disasters. This research assesses the tsunami's impact, thoroughly evaluating damage to infrastructure and vegetation using high-resolution satellite imagery. By comparing pre- and post-tsunami images, we quantitatively measure resilience and devastation, documenting significant landscape changes to better understand the extent of damage and identify resilient areas. These insights are critical for developing effective disaster response plans. The study employs advanced geospatial analytic techniques, demonstrating how satellite imagery enhances disaster preparedness and management by enabling prompt and accurate assessments, which are essential for both emergency response and long-term recovery planning. Integrating satellite-based remote monitoring into standard disaster management practices offers substantial advantages, improving the preparedness and response capabilities of vulnerable areas. This research highlights the importance of advanced change detection techniques to improve the accuracy of impact assessments and foster the development of targeted measures to mitigate the effects of future natural disasters.

Keywords: Satellite Imagery, Tsunami Impact, Change Detection, Disaster Management, Resilience

INTRODUCTION

Coastal regions worldwide are among the most vulnerable to natural disasters, particularly tsunamis, which are widely regarded as some of the most unpredictable and destructive natural catastrophes. These massive sea waves, primarily caused by underwater seismic activities such as earthquakes, volcanic eruptions, or landslides, can strike with little to no warning. When they do, the impacts on human settlements, infrastructure, and ecosystems are often catastrophic (Igigabel et al., 2024). The inherent unpredictability of tsunamis, coupled with their potential for widespread destruction, underscores the necessity for sophisticated and reliable impact assessment methodologies to guide emergency response, relief efforts, and long-term recovery planning. In recent years, technological advancements have revolutionized these assessment methods, significantly improving the speed, precision, and comprehensiveness of disaster impact analyses (Bosma et al., 2023).

A stark example of coastal vulnerability to tsunamis was seen during the devastating Sunda Strait tsunami of 2018, which struck coastal villages such as Tirtayasa in Banten, Indonesia (Heriati et al., 2024). The tsunami, triggered by volcanic activity from Anak Krakatau, caused widespread destruction, displacing residents and resulting in a tragic loss of life. The event exposed the limitations of existing disaster assessment protocols, highlighting significant gaps in early warning systems and the critical need for robust disaster preparedness and response infrastructures (Karima et al., 2024). This catastrophe further reinforced the importance of integrating modern technological solutions into disaster management frameworks, particularly in vulnerable regions like coastal Indonesia, where communities face ongoing threats from both geological and hydrological hazards.

One of the most transformative advancements in recent disaster management strategies is the use of satellite imaging technology. Satellite imagery provides rapid and comprehensive coverage of affected areas, allowing for near real-time assessment of the damage (Said et al., 2019). Unlike traditional ground-based surveys, which can be time-consuming and difficult to deploy in the immediate aftermath of a disaster, remote sensing technologies offer critical advantages. They enable disaster response teams to assess the extent of damage with greater speed and accuracy, providing essential data needed for coordinating relief operations and initiating recovery processes (Gholami et al., 2022). In particular, the ability to capture high-resolution satellite images of affected areas shortly after a tsunami strikes enables a far more efficient allocation of resources, ensuring that aid reaches the most severely impacted areas as quickly as possible.

Remote sensing techniques, such as change detection analysis, have become a cornerstone of modern disaster assessment. By comparing pre- and post-tsunami satellite images, researchers can identify changes in land cover, quantify vegetation loss, and assess structural damage to buildings and infrastructure (Mastro et al., 2022). These analyses not only provide a clear picture of the immediate impact but also offer valuable insights into the long-term resilience and vulnerability of landscapes to future disasters. The data gathered from satellite imagery and spatial analysis can inform disaster preparedness strategies, enabling local governments and disaster management agencies to improve early warning systems, strengthen infrastructure, and better protect vulnerable communities (Zhang et al., 2023). Moreover, these tools are essential for understanding the ecological impact of tsunamis, as they allow for the assessment of coastal ecosystems, such as mangroves and coral reefs, which play a vital role in protecting coastal areas from future events.

Building on these advanced geospatial techniques, this study emphasizes the importance of precise damage mapping, which is critical for efficient disaster response. Accurate mapping enables targeted aid delivery, optimizes resource allocation, and improves the overall coordination of relief efforts during the chaotic aftermath of a tsunami (Olavarría, 2009). Furthermore, integrating disaster preparedness and mitigation strategies into urban and regional planning is key to strengthening the resilience of vulnerable coastal communities (Jitt-Aer et al., 2022). By incorporating lessons learned from previous disasters, planners can design cities and infrastructure that are better equipped to withstand the destructive forces of future tsunamis.

This study focuses on assessing the impact of the 2018 tsunami on the coastal region of Tirtayasa, Banten, Indonesia, using high-resolution satellite imagery and advanced geospatial analysis. The novelty of our approach lies in the integration of multiple satellite datasets and sophisticated change detection algorithms, which together provide a more detailed and accurate assessment of the damage compared to earlier studies (Sakamoto, 2023). Through this methodology, our analysis offers critical insights into both the immediate and long-term impacts of the tsunami, highlighting the essential role that satellite imagery and spatial data analysis play in modern disaster management. These insights are crucial not only for addressing the challenges posed by the 2018 tsunami but also for informing future disaster preparedness and response strategies in tsunami-prone regions like Tirtayasa (Wibowo et al., 2023).

In addition to assessing damage, the study aims to contribute to the broader understanding of how geospatial technologies can be leveraged to enhance disaster resilience. The findings from this research provide a blueprint for integrating satellite imagery into disaster response workflows, ensuring that future efforts to mitigate the impact of tsunamis are both timely and effective. The integration of spatial data analysis into disaster management frameworks will be critical in shaping adaptive strategies that address the challenges of climate change, sea-level rise, and increasing coastal populations in Indonesia and beyond.

METHOD

Study Area and Subjects

The primary focus of this investigation is Tirtayasa, a coastal area in Banten, Indonesia, which experienced significant damage during the 2018 tsunami that traversed the Sunda Strait (Figure 1). Given its vulnerable coastal position, combined with its socioeconomic conditions, Tirtayasa is particularly susceptible to the devastating effects of tsunamis. The community's dependence on coastal resources and its proximity to the active volcanic system of Anak Krakatau exacerbate the area's vulnerability. Thus, conducting a thorough impact assessment of the 2018 tsunami is critical for supporting effective disaster management strategies and resilience planning, both for recovery from this event and for preparedness against future tsunamis (Prihartanto et al., 2023).

Figure 1. The figure illustrates the study area of Tirtayasa, Banten, Indonesia, focusing on its location within Java. The inset map highlights Tirtayasa and surrounding areas, including Serang and Cilegon, which are outlined in red to delineate the region assessed for tsunami impact. This visual representation is essential for contextualizing the spatial extent of the research area and for understanding the geographical relationship between the impacted communities and the broader coastal zone.

Data Collection

This study relies on satellite imagery from two key sources, Landsat 8 and Sentinel-2, which were chosen for their capability to capture detailed post-tsunami landscape changes. Both datasets provide high spatial resolution and frequent temporal coverage, which are essential for documenting the immediate and long-term changes in terrain and land cover following a disaster.

- *Sentinel-2:* This optical sensor provides high-resolution images with a spatial resolution of 10 meters, making it ideal for detailed studies of vegetation and land cover changes. The fine resolution allows for more precise detection of structural damage and environmental shifts, which are critical for disaster response efforts.
- *Landsat 8:* Offering multispectral imagery at a spatial resolution of 30 meters, Landsat 8 is particularly useful for broader environmental monitoring and identifying landscape changes over extended periods. It plays a complementary role to Sentinel-2 in this study, enabling the capture of longer-term effects and more subtle changes in land cover.

Preprocessing

To ensure the accuracy and reliability of the satellite imagery, several essential preprocessing steps were conducted. These steps were critical for eliminating potential errors introduced by atmospheric conditions, sensor noise, and differences in acquisition times.

1. *Radiometric Correction:* Adjusts the pixel values of the imagery to account for atmospheric conditions, such as haze or cloud cover, and sensor-specific noise, ensuring that the images accurately reflect ground conditions.
2. *Geometric Correction:* Aligns the satellite images to a common coordinate system, correcting for distortions caused by the sensor's perspective or movement. This step ensures precise overlay and comparison between images taken at different times.

3. *Normalization:* Standardizes the pixel values across different images, accounting for variations in lighting conditions and sensor differences. This ensures consistency in the imagery used for change detection analysis, minimizing discrepancies that could arise from factors unrelated to the tsunami.

Change Detection Techniques

The change detection analysis employed advanced algorithms to identify land cover and land use changes caused by the 2018 tsunami. The following techniques were used:

1. **Algorithm Selection**:
   - *Support Vector Machine (SVM):* A supervised learning algorithm was chosen for its robust performance in land cover classification, particularly in high-dimensional data sets. SVM's resilience to overfitting makes it well-suited for complex classification tasks, where distinguishing between different land cover types (such as vegetation, water bodies, and built-up areas) is essential.
   - *Random Forest (RF):* This ensemble learning method was selected for its capacity to handle large datasets with numerous variables while maintaining high classification accuracy. RF's ability to manage noisy data and its robustness against overfitting make it an effective tool for assessing post-disaster impacts across varied landscapes.
2. **Training and Validation**:
   - *Training Datasets:* Representative samples of various land cover types (e.g., vegetation, water bodies, built-up areas) were selected from both pre-tsunami and post-tsunami satellite images. These samples were used to train the SVM and RF algorithms to distinguish between different land cover classes.
   - *Validation:* Ground truth data collected from field surveys, as well as high-resolution imagery, were used to validate the performance of the algorithms. Validation ensured the accuracy of the classification results, providing confidence in the change detection analysis.
3. **Change Detection Analysis**:
   - *Post-Classification Comparison:* This method compares classified images from different time periods to identify significant changes in land cover. By overlaying pre-tsunami and post-tsunami images, the analysis highlights areas of vegetation loss, infrastructure damage, and land use alterations, offering a detailed and interpretable view of the tsunami's impact on the region.

Data Limitations

While the use of Sentinel-2 and Landsat 8 imagery provides numerous advantages for disaster impact assessments, certain limitations must be acknowledged:

1. *Resolution Constraints:* Despite the high spatial resolution of these sensors, some small-scale features and subtle changes—such as minor structural damages or the loss of individual trees—may not be captured accurately. This limitation can affect the granularity of the analysis and potentially overlook some localized impacts of the tsunami.
2. *Temporal Coverage:* The availability of satellite imagery at specific intervals may limit the ability to capture the full timeline of post-tsunami impacts and recovery phases. In some cases, critical changes that occur immediately following the tsunami, or during early recovery efforts, might not be adequately documented due to the timing of satellite overpasses.

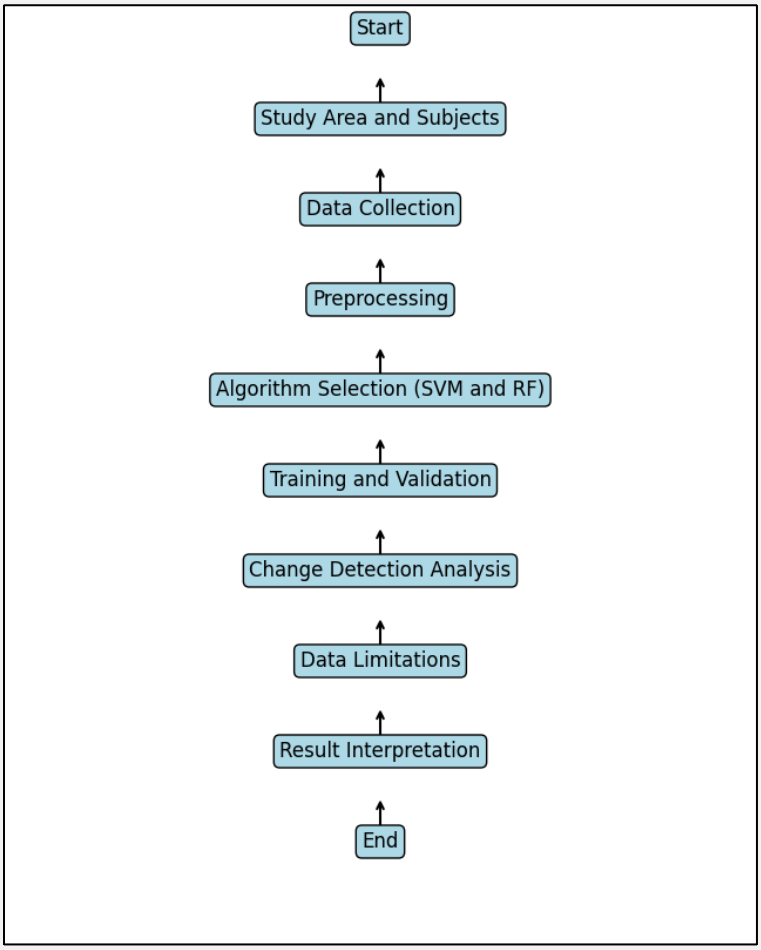

Figure 2. The figure provides a flowchart outlining the research methodology, with a focus on the change detection analysis process. It illustrates the key steps involved, including data collection, preprocessing, algorithm selection (SVM and RF), training, validation, and final change detection analysis.

RESULTS & DISCUSSION

This study employs high-resolution satellite imagery to conduct an in-depth analysis of the tsunami's impact on the Tirtayasa area. Through a systematic comparative analysis between pre- and post-tsunami images, significant transformations within the landscape are meticulously documented. The pre-event imagery provides a clear representation of the natural and built environment, illustrating a baseline of vegetation, infrastructure, and landforms (Moya et al., 2020). In contrast, the post-disaster images reveal extensive damage, including widespread vegetation displacement, infrastructure destruction, and significant alterations to the landscape. This precise visual comparison underscores the magnitude of the disaster's impact and serves as a foundational tool for disaster response and recovery planning. Satellite-based assessments are indispensable for not only mapping the immediate effects of the disaster but also for strategizing long-term recovery and resilience efforts (Koshimura et al., 2020).

Visual Presentation of Data

Pre-Tsunami Conditions

The pre-tsunami satellite imagery of Tirtayasa offers a vivid baseline for understanding the region's environmental and infrastructural conditions before the disaster (Figures 3 & 4). These images, captured using advanced satellite technology, vividly depict the distribution of vegetation, urban structures, and natural features across the region. This baseline is critical for assessing the full scope of damage post-disaster, providing a reference point for understanding the extent of environmental degradation and infrastructure loss.

Figure 3. Depicts the Tirtayasa region before the tsunami, highlighting the natural landscape and infrastructure in place before the disaster.

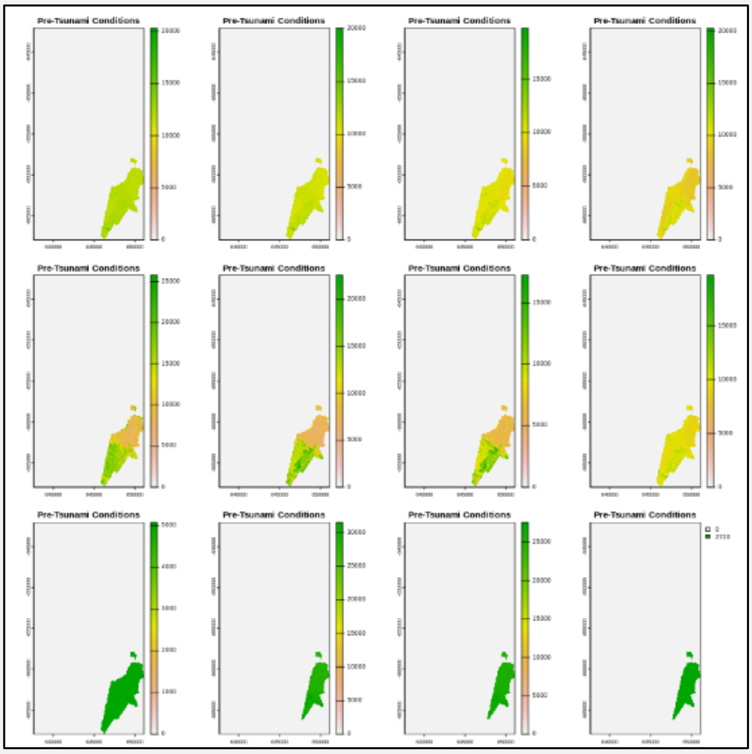

Figure 4. A series of maps illustrating varying stages of vegetation coverage, color-coded to depict differences in vegetation density before the tsunami.

In these images, different land cover types are represented using distinct color codes. For instance, varying shades of green represent regions with dense vegetation, while yellow areas indicate moderate vegetation coverage. White regions signify little to no vegetation, typically representing urban structures or bare land. This level of detail is essential for conducting a precise damage assessment after the tsunami.

By comparing pre-tsunami conditions with post-tsunami data, researchers can accurately quantify changes in land cover, assess the extent of vegetation loss, and evaluate the severity of infrastructural damage. This approach not only facilitates a targeted and efficient disaster response but also supports long-term recovery and planning. The spatial distribution of natural resources, habitats, and human settlements is crucial for both environmental management and urban planning before and after such disasters.

- Green areas: Likely represent regions with dense vegetation, crucial for ecosystem health and coastal protection.
- Yellow areas: Indicate regions with moderate vegetation, often transitional zones that play an essential role in the local ecosystem.
- White areas: Typically signify urban structures or regions with minimal vegetation, where infrastructure development is more concentrated.

The baseline maps provide a comprehensive visual representation of the spatial distribution and condition of vegetation and built-up areas, serving as an invaluable tool for assessing environmental conditions before the tsunami struck.

Post-Tsunami Conditions

Post-tsunami satellite imagery offers a stark contrast to the pre-tsunami conditions, vividly capturing the extensive alterations in the Tirtayasa landscape following the catastrophic event (Figures 5 & 6). These high-resolution images show significant shifts in coloration and texture, which indicate severe environmental and infrastructural damage. Areas that were once lush with vegetation have been drastically altered, with regions appearing muted and disrupted due to the tsunami's force.

Each quadrant in the imagery highlights specific changes in vegetation cover, soil moisture, and the condition of built-up areas. Using a color-coded scheme, the images provide a clear representation of the severity of damage across different regions:

- Green: Indicates regions with minimal or no change, preserving their pre-tsunami state.
- Yellow and orange: Represent areas with moderate alterations, potentially due to waterlogging, soil displacement, or partial destruction of vegetation.
- Bright orange and red: Highlight zones of severe to complete devastation, where infrastructure has been destroyed or severely impaired.

Figure 5. Shows the Tirtayasa region after the tsunami, illustrating the significant alterations to the landscape and environment.

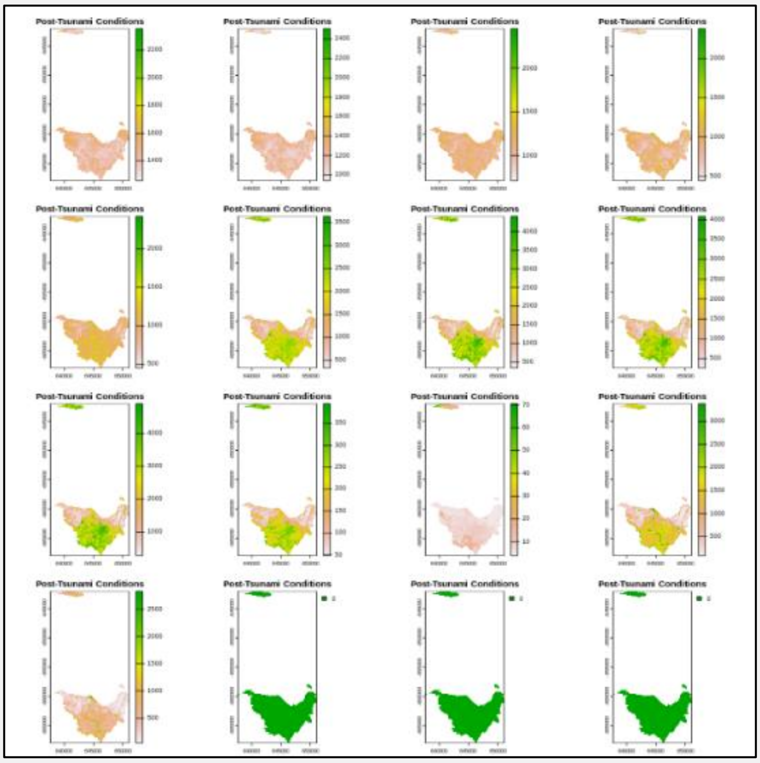

Figure 6. Depicts post-tsunami conditions in Tirtayasa, focusing on changes in vegetation and land cover across different years. The color gradations from green to yellow and orange represent varying levels of vegetation density and land cover damage, providing insight into both the immediate and long-term impacts of the tsunami.

This detailed and methodical breakdown provides disaster response teams with a clear visual representation of the spatial distribution of damage. Such data is critical for effectively targeting recovery efforts and allocating resources where they are needed most. The visuals not only aid in understanding the immediate impact of the tsunami but also help in planning long-term rehabilitation and rebuilding strategies that are essential for the resilience of affected communities.

Change Detection Analysis

The change detection maps presented in this study offer a comprehensive visual assessment of the areas affected by the tsunami (Figures 7 & 8). These maps are categorized into several levels of damage, making it easier to understand the spatial distribution and severity of the tsunami's impact.

- Severe Damage (Bright Red): These zones, marked in bright red, indicate areas where the destruction is almost total. This classification is crucial for prioritizing emergency response and reconstruction efforts, as these regions likely require immediate attention due to the extent of damage.
- Moderate Damage (Orange): The orange areas represent moderate damage. While these regions may not have been completely destroyed, they have experienced significant changes that could affect both infrastructure and ecosystems. Recovery efforts in these areas may be complex, involving repair and restoration initiatives.
- Minor Changes (Yellow): These zones have encountered less severe changes, potentially including minor alterations to the landscape or infrastructure. While these areas may not require extensive recovery efforts, ongoing monitoring and minor interventions could be necessary.

- No Significant Change (Green): Green areas represent regions that remained largely unaffected by the tsunami. These areas are critical for providing insights into factors that contributed to their resilience, such as effective mitigation measures or natural protective features like mangroves.

These change detection maps are an invaluable tool for disaster response planning. By visualizing the damage and quantifying the extent of change, they enable more informed decision-making regarding resource allocation and infrastructure rebuilding. Furthermore, these visuals are crucial for long-term disaster preparedness, helping communities build more robust infrastructure and improve their resilience against future tsunami events.

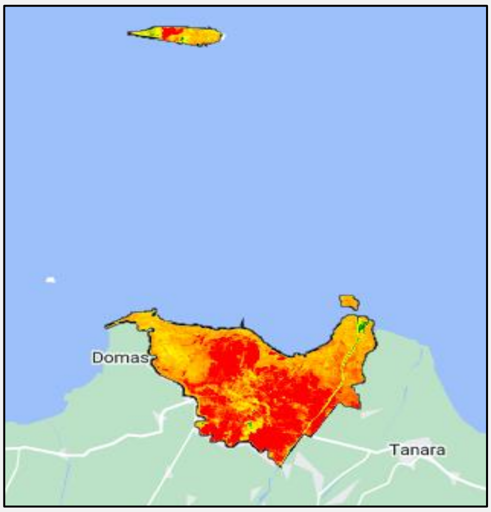

Figure 7. Illustrates a change detection analysis of Tirtayasa, highlighting variations in land cover before and after the tsunami. The color gradient, from yellow to deep red, indicates the intensity of change, with the most affected areas in deep red.

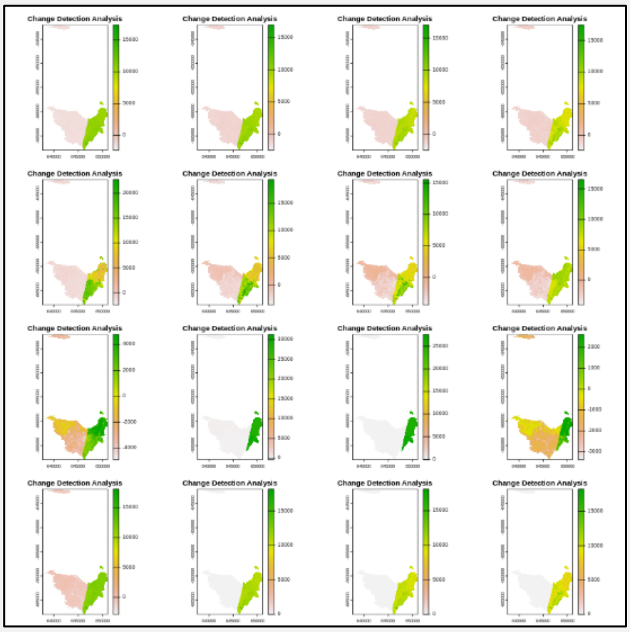

Figure 8. Shows a series of change detection analyses for the Tirtayasa area, using remote sensing techniques. Each panel reflects variations in land cover over different years, illustrating changes such as vegetation loss, land degradation, or recovery over time.

Quantitative Analysis of Changes

The quantitative analysis conducted in this study provides a detailed assessment of the tsunami's impact on Tirtayasa by calculating the total affected area and the extent of damage. Using Google Earth Engine's ee.Image.pixelArea() in combination with the change detection layer, the analysis precisely measures the extent of land cover changes, offering a clear understanding of the spatial distribution of damage. Approximately 24,404.67 square kilometers were impacted by the tsunami, covering both coastal and inland regions. This wide-ranging effect underscores the scale of destruction, affecting not only natural ecosystems but also human settlements.

The mean change observed was -411.56, indicating a widespread decrease in the reflective properties associated with healthy vegetation. This suggests substantial ecological damage, including deforestation, vegetation loss, and the degradation of land cover. The median change, recorded at -223.28, reveals that while the average level of damage is significant, a substantial portion of the region experienced less severe damage than the mean. This suggests that the tsunami's impact was unevenly distributed, with certain areas potentially shielded by natural barriers or subjected to less intense forces. Additionally, the standard deviation of 731.23 highlights the variability in the extent of damage, with some areas facing more extreme changes, such as complete destruction of infrastructure or severe erosion, while others experienced more moderate shifts in land cover.

These statistical measures, combined with visual aids such as maps and charts, provide a comprehensive overview of the tsunami's devastating effects on Tirtayasa. The results serve as essential tools for understanding the scope of destruction and are crucial for informing effective recovery and rehabilitation strategies. The visual aids—consisting of detailed maps and change detection charts—further enhance the clarity and effectiveness of the results by visually representing the spatial extent of the tsunami's impact. These tools make it easier to identify the most affected areas, allowing for more targeted disaster response and future planning.

The results from the change detection analysis offer critical insights into Tirtayasa's resilience and vulnerability to tsunamis. The varying degrees of damage documented in this study highlight areas most at risk, particularly those suffering from significant vegetation loss and severe infrastructural damage. These findings emphasize the need to prioritize recovery efforts in the most severely affected regions, where environmental degradation and the loss of vital resources may pose long-term challenges to rebuilding efforts.

Comparing these findings with research on previous tsunamis, such as the 2004 Indian Ocean tsunami and the 2011 Tohoku tsunami in Japan, reveals a consistent pattern of ecological and infrastructural vulnerability. Both of these earlier events resulted in extensive coastal damage, significant changes in land cover, and major disruptions to local economies. This pattern reinforces the importance of improving coastal management practices and disaster preparedness strategies in regions vulnerable to tsunamis. The similarities in vegetation loss and structural damage between Tirtayasa and other affected regions underscore the need for international cooperation and knowledge sharing to enhance disaster resilience in coastal communities worldwide.

The implications of this research are significant for local policymakers and planners. The detailed mapping of damage levels across different areas provides critical information for prioritizing recovery efforts and efficiently allocating resources. In response to these findings, local governments can take steps to reduce future tsunami damage by strengthening construction regulations, improving early warning systems, and investing in coastal defenses. Enforcing stricter building codes, especially in vulnerable coastal areas, can help minimize the risk of infrastructure collapse during future tsunamis. Similarly, enhanced early warning systems can provide critical lead time for evacuation efforts, helping to reduce loss of life. Moreover, boosting coastal defenses, such as seawalls, mangrove restoration, and dune reinforcement, can mitigate the force of incoming waves and protect inland areas from flooding and erosion.

This research also highlights the need to bolster local disaster response capacities. Sustainable reconstruction initiatives, which incorporate climate-adaptive infrastructure and environmental restoration, will be essential not only for repairing damage but also for increasing the community's resilience to future disasters. Integrating these findings into local and regional planning frameworks can significantly reduce the long-term economic and social costs of future tsunamis.

In addition to informing recovery efforts, the findings from this study are vital for refining disaster preparedness strategies. Communities in tsunami-prone areas must be equipped with knowledge of safe evacuation routes, designated refuge areas, and clear emergency protocols. These measures, coupled with effective communication strategies, can help save lives and minimize damage during future tsunamis. Policymakers should leverage the insights from this research to update existing regulations or develop new strategies that address the weaknesses revealed in this analysis. For example, integrating satellite data and geospatial analysis into disaster management workflows offers a proactive approach to disaster risk reduction. By using data-driven methods to inform response plans, communities can dramatically reduce the financial and human costs of future tsunamis.

CONCLUSION

This study employs advanced geospatial analytics to meticulously map and assess the tsunami's impact on the Tirtayasa region, providing a detailed visualization of damage across various terrains. The findings underscore the severe vulnerability of coastal areas to natural disasters, emphasizing the urgent need for enhanced disaster preparedness and resilience measures. The analysis reveals significant infrastructure damage and widespread vegetation loss, particularly in coastal zones, highlighting the devastating effects of the 2018 tsunami.

The use of sophisticated geospatial data analysis has proven to be highly effective, offering precise and actionable insights that can greatly inform both emergency response strategies and long-term recovery planning. The ability to systematically visualize disaster impacts through satellite imagery and change detection techniques not only deepens our understanding of the extent of damage but also improves the overall efficiency of disaster management and future preventive measures.

Future research holds promising potential. Longitudinal studies could shed light on recovery patterns and assess the effectiveness of different reconstruction approaches over time. Furthermore, the integration of emerging data sources, such as high-resolution drone imagery, could enable even more granular damage assessments at a micro level. Combining socioeconomic data with geospatial analysis could also provide a more comprehensive understanding of the human dimensions of tsunamis, leading to more targeted and community-specific recovery plans.

To enhance our capacity to prepare for and respond to natural disasters, it is essential to continue advancing our analytical methods and expanding the range of data sources. By doing so, we can better mitigate the impacts of future disasters, particularly on the most vulnerable populations.

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