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ANALYSIS OF THE SUPER TYPHOON RAI-INDUCED INFRASTRUCTURE DAMAGE IN SEVERELY AFFECTED AREAS OF CARAGA REGION, PHILIPPINES USING SENTINEL-1 SAR IMAGERIES

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KEY WORDS: Sentinel-1 SAR, Coherence Change Detection (CCD), Normalized Difference Built-Up Index (NDBI), Damage Assessment, Typhoon Rai

ABSTRACT:

The Philippines is prone to typhoons because of how it is geographically located around the globe. A recent event that devastated many parts of Mindanao and Visayas was super typhoon Odette with the international name “Rai.” It was estimated that damage to infrastructures equates to over P17.71 billion as of January 10, 2022, and that Caraga Region has suffered the most significant loss totalling more than P12.82 billion. Due to the large-scale incurred damages, the number of people who were affected and suffered heavy economic loss, it is necessary to find ways that would provide spatial information to help decision-makers, stakeholders, and emergency respondents to prioritize areas which need the utmost concern. Over the past years, damage assessment maps were derived from optical images, which are weather-dependent and free. However, appropriate satellite images are hard to come by, especially during typhoons where clouds are prominent. Sentinel-1 SAR imagery was used because of its unique characteristics. It is not weather-dependent, before and after images from the event are available, and it is an open-source data. Damage maps were generated by detecting the change in the complex coherence between pre-and co-typhoon stacked images. Results were validated using high-resolution satellite images from reliable sources, finding out that there is good correspondence between the coherence-based change images and ground data depicted from high-resolution satellite images. It is concluded that Sentinel-1 SAR imagery could capture the extent of damages and help provide timely and accurate geospatial information during catastrophic events.

1. INTRODUCTION

The Philippines is prone to typhoons and tropical cyclones because of how it is geographically located, which typically brings torrential rainfall and flooding over large areas. The strong winds and heavy rain generally result in numerous human deaths and the destruction of property (PAGASA, 2022). It can destroy vehicles, buildings, bridges, roads, and other external structures, transforming loose material into destructive flying projectiles. Super typhoon Odette (Rai) was the recent typhoon that hit and left the Visayas and Mindanao Islands devastated. According to the national disaster management agency’s collated reports, damage to public infrastructure has reached over P17.71 billion as of January 10, 2022. Schools and other government buildings and facilities account for over half of the 667 damaged structures identified since the typhoon hit on December 16, 2021. Others include roads, bridges, flood control structures, health care facilities, and utility service facilities. Furthermore, in the northeastern section of Mindanao, Caraga Region suffered the most damage, totalling more than P12.82 billion (BusinessWorld, 2022).

Caraga region encompasses Dinagat and Siargao's island provinces and Surigao City, three of the hardest impacted places by the country's biggest typhoon last year (BusinessWorld, 2022). These three areas were known for their different tourist sites, structures, and landmarks, prior to the devastation. Given the magnitude of the typhoon’s destruction, it is crucial to investigate how it affected the infrastructures and the damage it caused to afflicted areas. Rapid, detailed, and accurate structural assessments and change detection are necessary and very effective in capturing the full and clear image of the damage (Massarra, 2012).

In the study, Sentinel-1 SAR images are utilized to map the potentially damaged areas in the reported severely affected areas in Caraga Region. Pre-typhoon and post-typhoon images were collected and coregistered to one master image, and the coherence of the stacked image was determined. The coherence images were then differentiated through change detection, and possible areas with a high degree of change were shown. The results of the study would like to prove that using Sentinel-1 SAR imageries would be practical in rapid damage assessment since it is not dependent on weather conditions like cloud cover, which is prominent before and after typhoons.

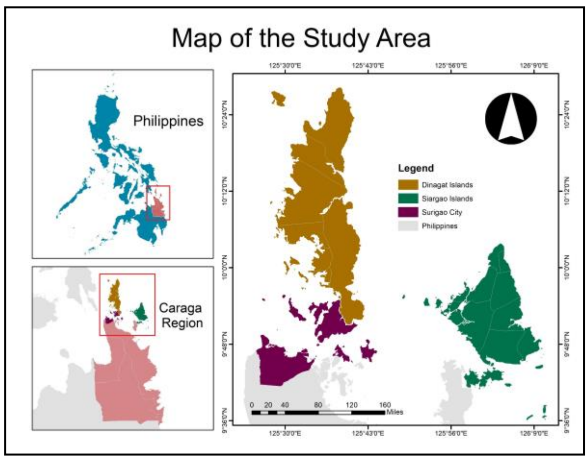

Figure 1. Location map of Dinagat Islands, Surigao City and Siargao Islands

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2. METHODOLOGY

2.1 Methodological Framework

Figure 2 shows the diagram that encapsulates the steps that have been done in this research and the expected outputs of the study. Detailed discussion of these processes is further indicated in the subsequent subsections.

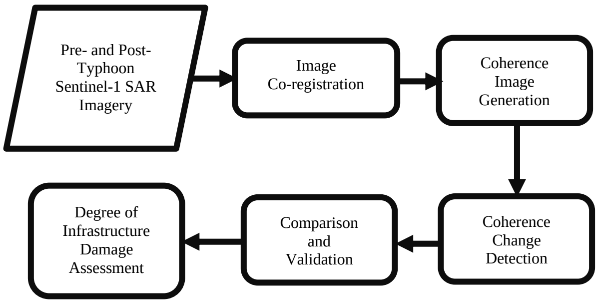

Figure 2. Flowchart for the generation of a coherence change layers from Sentinel-1 images through Coherence Change Detection as basis for analyzing the infrastructure damage

2.2 Sentinel-1 Image Initial Processing

Three (3) Sentinel-1 satellite images representing the dates December 2, 14, and 21, 2021, were acquired from the Copernicus Open Access Hub. These images underwent initial processing using the SNAP (Sentinel Application Platform) software which was available for free download on the European Space Agency website. All the images were split, as the study only used the sub swath and burst where the area of interest is located. Through this, the swaths and bursts outside the study area were deleted, which helped in lessening the processing time. Precise orbits were applied to Sentinel-1 satellite images, giving better orbit information, which improves the geometric correction and co-registration of the images.

2.3 Generation of Pre- and Co-typhoon Coherence Image

Using three SAR images in each study area, the researchers generated pre- and co-disaster image pairs. The pre-disaster image pair used two images, with the shortest temporal baseline away from each other, taken shortly before typhoon Odette had ravaged the study areas. One from pre-typhoon and the other from post-typhoon were also utilized for the co-disaster image pair. Each image pair has undergone co-registration using the back-geocoding process, followed by enhanced spectral diversity. The process resulted in two images containing the stacked bands for the pre-and co-typhoon image pairs. Coherence estimation was employed for the two stacked images in each study to estimate the coherence between each pair of SAR images. The following coherence estimated images have then been debursted, which refers to stitching the bursts together, multilooking that creates square pixels, which reduces the speckle to some degree because it averages out the pixels in one dimension, geometric/terrain correction, which corrects distortions caused by topography and subset. This process has resulted in two (pre-typhoon and co-typhoon) coherence images.

2.4 Coherence-based Change Detection

Using the two coherence images generated from the earlier processes, the researchers have created a stack of the two coherence images using the Stack tool in the Sentinel Application Program (SNAP). The resulting image has been processed to generate a coherence-based change image using the stacked images of pre-typhoon and co-typhoon images. It was done through the SNAP SAR Applications "Change Detection." To depict the extent of damages in the possible areas of destruction, the average coherence index table from Hoffmann (2007), where the ratio of complex coherence was used to estimate if an area is severely damaged (i.e. $\rho \geq 2.5$), significantly damaged ($2.5 > \rho \geq 2.0$), or lightly damaged ($2.0 > \rho \geq 1.5$).

2.5 Generation of Normalized Difference Built-up Index (NDBI)

The researchers used a Landsat satellite image, i.e., Landsat 8 OLI for October 12, 2021 and Landsat 9 for March 9, 2022 image scenes to generate Normalized Difference Built-up Index (NDBI). It uses the fifth (NIR) and sixth (SWIR) bands of Landsat 8 and Landsat 9 used in the study. NDBI emphasizes built-up areas in a location (Zha et al., 2003). NDBI values range from -1 to 1, whereas lower values represent water bodies and higher values represent built-up areas. Value for vegetation lies in between (Kshetri, 2018). The results generated in the NDBI were then used to correlate with the coherence estimation of the pre-typhoon and co-typhoon Sentinel-1 satellite images. A difference NDBI was also generated with the pre-and post-typhoon NDBI and correlated with the Coherence change map.

3. RESULTS AND DISCUSSIONS

3.1 Pre-typhoon and Co-typhoon Coherence Estimation

Figures 3 to 5 show the coherence layers in Surigao City, Siargao Islands, Dinagat Islands before and after typhoon Odette (Rai) had ravaged these lands. Higher values closer to one (1) identify a high correlation between image pairs. A dark color presents decorrelation between two image pairs. There is a significant change in appearance between the pre-typhoon and co-typhoon coherence estimated images. Places that are very light in the first set of images (a) have mostly softened out in the second set of images (b). Lighter areas can be seen mainly in the outer edges of the study area, which might be because most concentrated buildings or man-made structures were centered in these areas since their primary source of living revolved mostly around aquatic resources.

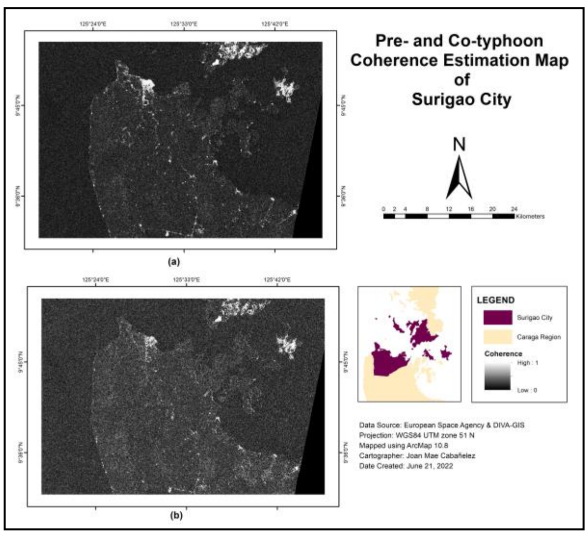

Figure 3. Pre-typhoon and Co-typhoon Coherence map of Surigao City

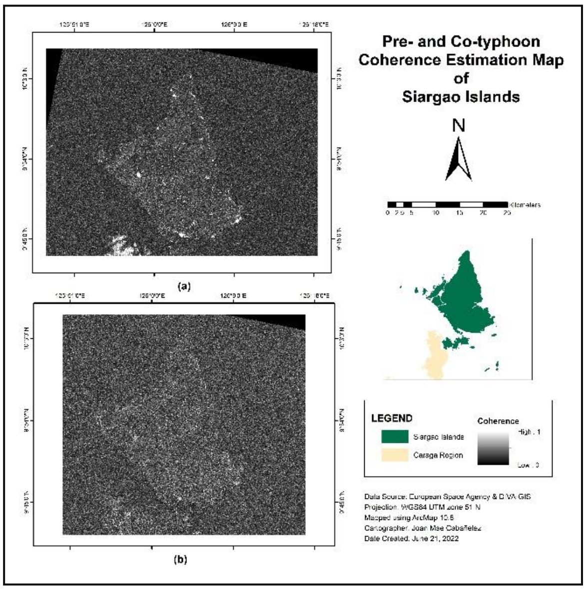

Figure 4. Pre-typhoon and Co-typhoon Coherence map of Siargao Islands

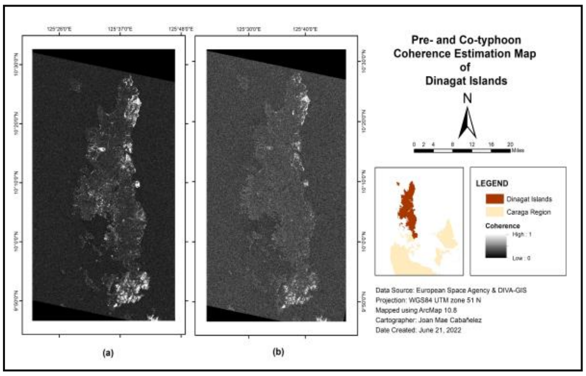

Figure 5. Pre-typhoon and Co-typhoon Coherence map of Dinagat Islands

3.2 Coherence-based Change Image Generation Using Pre- and Co-typhoon Coherence Images

Figures 6 to 8 depict the coherence change between the pre-typhoon and co-typhoon coherence images. A building footprint of each study area taken and updated from OpenStreetMap (OSM) was shown beside each coherence change image to exhibit the ability of Sentinel-1 SAR imageries in identifying potentially damaged areas, especially where infrastructures like buildings are concentrated. Unlike in the coherence estimated images, higher values with light appearance mean a significant difference between the coherence estimated images (pre-typhoon and co-typhoon images). In the Dinagat Islands coherence-based change image, there are many areas where there is a substantial change between the pre-typhoon and co-typhoon coherence images presented by white colors, as seen in Figure 8. Not only did it quantify the changes for built-up areas, but it can also be seen that there is a significant change in the vegetative areas. However, it is not included in this research. Figure 6 shows a very significant change in the center of Surigao City; it is also depicted on the right side of the coherence change image, which is a building footprint of Surigao City that the highlighted part does correspond to built-up areas or an area where there is a concentrated number of buildings. The same trend can be seen in Figure 7, where the highlighted areas of change correspond to areas of the concentrated building footprint.

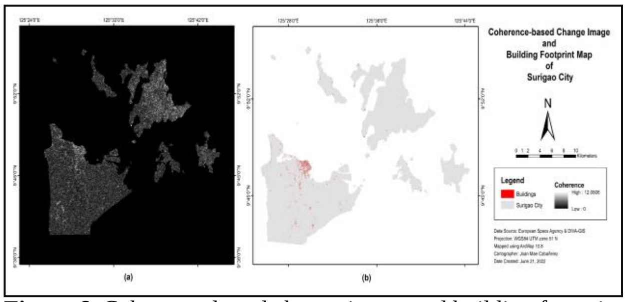

Figure 6. Coherence-based change image and building footprint of Surigao City

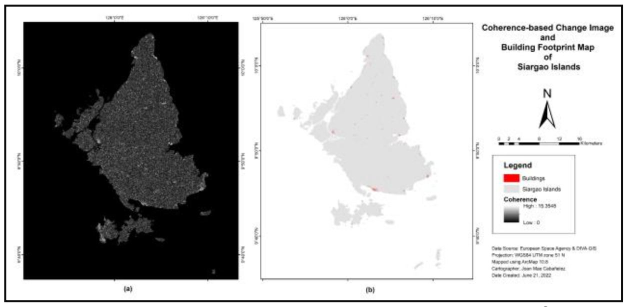

Figure 7. Coherence-based change image and building footprint of Siargao Islands

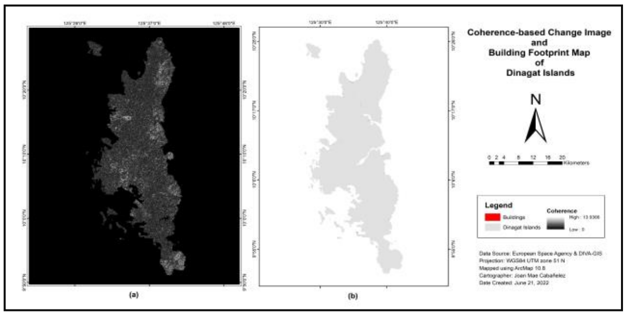

Figure 8. Coherence-based change image and building footprint of Dinagat Islands

3.3 Normalized Difference Built-up Index (NDBI)

Figures 9 to 14 show the pre-and post-typhoon NDBI results for each area and the reclassified non- and built-up areas using Landsat images. Regarding the NDBI results, warm tones such as orange to red represent higher values. In comparison, green to blue represents lower values. The generated NDBI values were then extracted to reclassify non-built-up and built-up areas in Dinagat Islands, Siargao Islands, and Surigao City. Here, negative pixel values were equated as non-built-up areas, while positive pixel values correspond to the built-up areas. Built-up and non-built-up areas are represented with red points and gray boundaries, respectively. As seen in Figures 9, 11 and 13, pre-typhoon-built ups are generally lessened after the typhoon, which can be implied as changes in the infrastructure of the areas. Those masked portions of the NDBI images were the cloud-contaminated scenes of Landsat images. The delineation of urban areas was referenced from the building footprints obtained from OpenStreetMap platform and ESRI's 2021 LULC map.

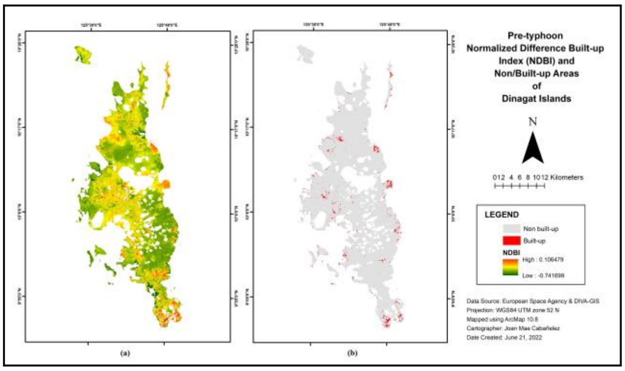

Figure 9. NDBI and built-up layers of Dinagat Islands during pre-typhoon condition.

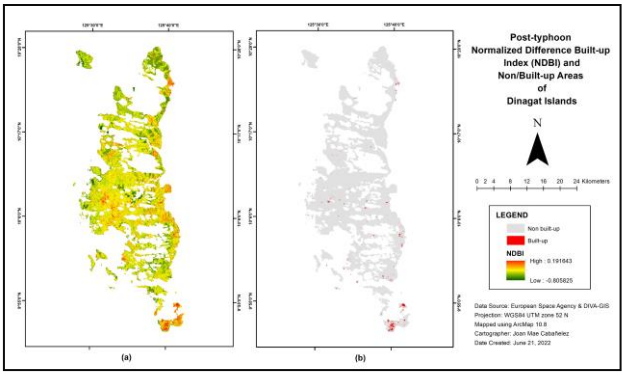

Figure 10. NDBI and built-up layers of Dinagat Islands during post-typhoon condition.

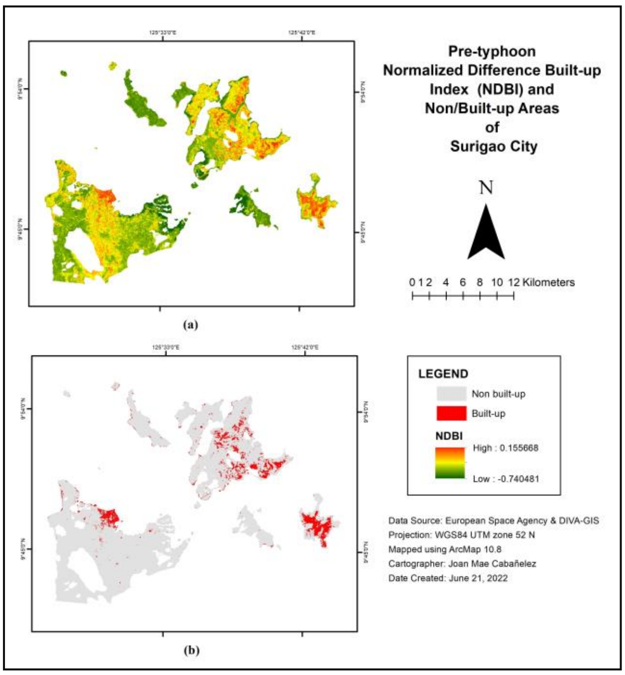

Figure 11. NDBI and built-up layers of Surigao City during pre-typhoon condition.

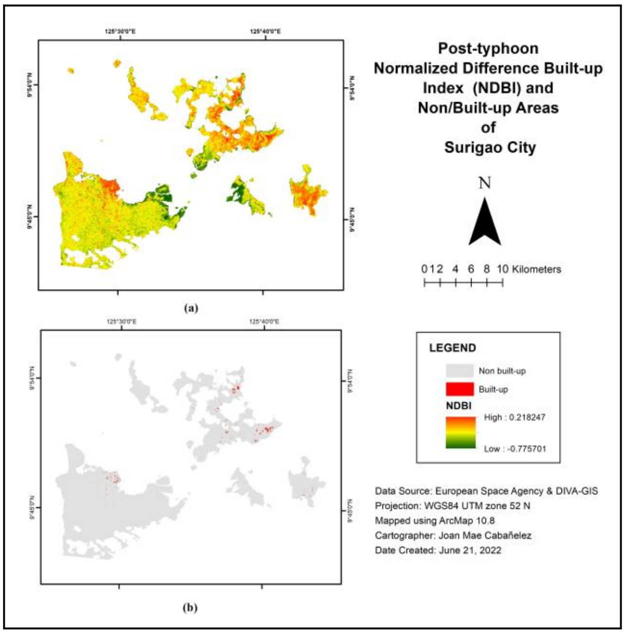

Figure 12. NDBI and built-up layers of Surigao City during post-typhoon condition.

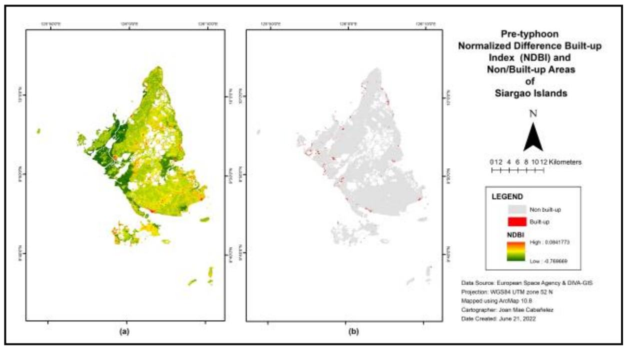

Figure 13. NDBI and built-up layers of Siargao Islands during pre-typhoon condition.

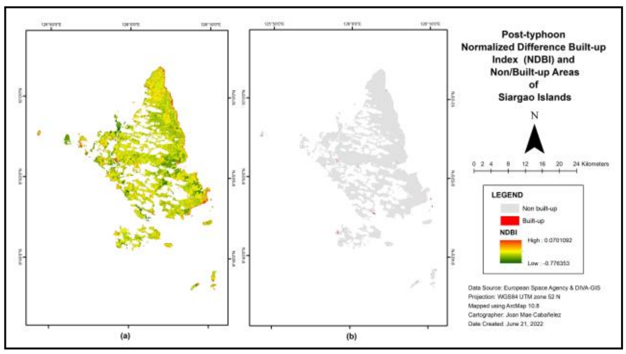

Figure 14. NDBI and built-up layers of Siargao Islands during post-typhoon condition.

3.4 Correlation of Coherence-based images and NDBI values

The correlation of coherence and NDBI layers were included in the analysis. Sampling points were generated within the built-up layers with 100 random points.

A simple comparison of the relationship between the pre-typhoon and post-typhoon NDBI with the pre-typhoon and co-typhoon coherence showed that the variables do not have a strong and linear relationship. In Dinagat Islands, the pre-typhoon values for both NDBI and coherence estimated images have a positive relationship, yielding an R^2 value of 0.1128 for pre-typhoon values; while for the post-typhoon values, R^2 equates to 0.0012. For Surigao City and Siargao Island, R^2 value goes from 0.4103 to 0.1588 and 0.0673 to 0.0015, respectively. The pre-typhoon correlation graph of Surigao City had garnered the highest correlation coefficient, which is r = 0.63.

The researchers found limitations regarding the correlation between the two data derivatives in analyzing damages to building infrastructures. The spatial resolution of the radar image (i.e., Sentinel-1 data) and optical image (i.e., Landsat 8 data) is different in that the latter will not fully capture the spectral detail of a particular pixel dimension corresponding to the former. No single optical image sufficiently covered the study area near the date of the event, both before and after the typhoon scenario, since the place experienced a La Niña condition wherein clouds were prevalent in the atmosphere for that particular timeframe. Since the mosaics for pre- and post-typhoon were collected within six months, three months before, and three months after, there was a non-uniformity of values for NDBI. Some extent depicted a gradual recovery for built-up areas, especially from those optical images acquired during February and March. The same goes for the regeneration of vegetative surfaces.

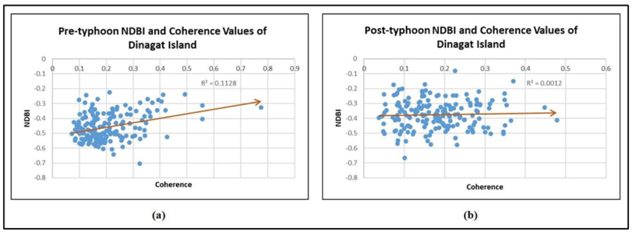

Figure 15. Graph showing the relationship between NDBI and coherence values of Dinagat Islands

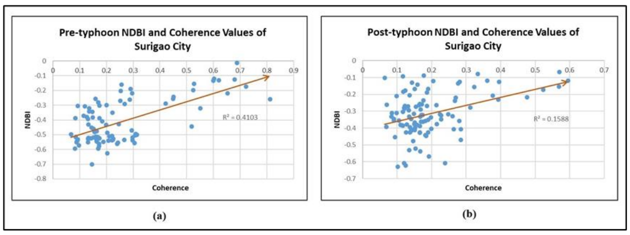

Figure 16. Graph showing the relationship between NDBI and coherence values of Surigao City

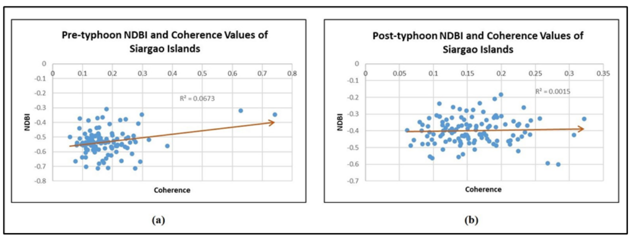

Figure 17. Graph showing the relationship between NDBI and coherence values of Siargao Islands

3.5 Qualitative Assessment, DOST-ASTI Maps, and Published Article from Reliable Source

Visual comparison of the images/maps from published articles taken from DOST-ASTI and PhilStar and the derived damage map from coherence images are shown in Figure 18. The damage maps using Sentinel-1 SAR imagery were able to capture the intensity of the damage caused by super typhoon Odette (Rai) in the study areas, namely Dinagat Islands, Surigao City, and Siargao Islands. The optical images that DOST-ASTI optimized were from Ronnicque (2022) and PhilStar was from their news article (PhilStar, 2021).

It can be summarized that damage maps derived from detecting changes in the pre-typhoon and co-typhoon coherence images were able to positively determine potentially damaged areas that were also visually identified as disastrous locations by optical images used by agencies cited above. For example, Figure 18 shows a part of Dinagat Islands where typhoons damaged houses and buildings in the high-resolution optical image from the agencies mentioned. By looking at the coherence-derived damage map, the same portion was also red, which depicts that Sentinel-1 SAR imagery-derived damage map was able to capture the changes in these areas. It also shows that some damaged vegetated areas were detected by SAR imagery. Though it is not the focus of this study, it would be suitable for topics about this to be taken in the future. Moreover, there is a good correspondence between the optical images for validation and the SAR-derived damage map.

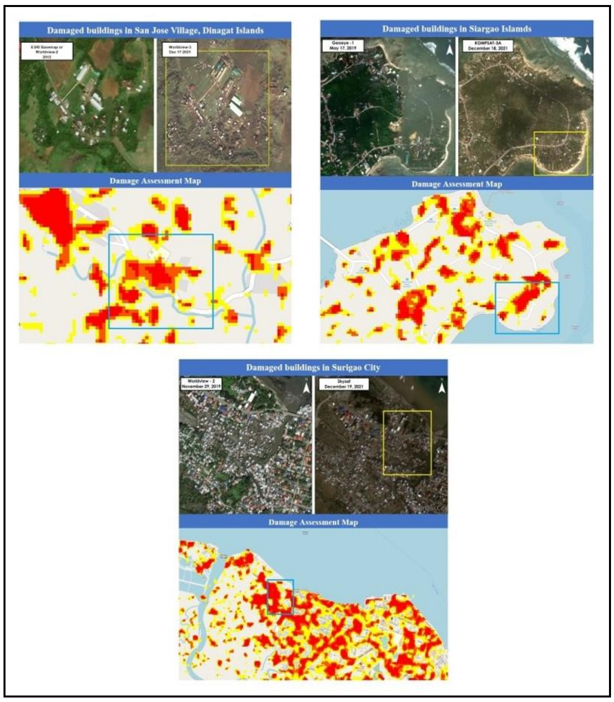

Figure 18. Comparison of CCD result with high resolution images from reliable sources

3.6 Generation of Damage Assessment Maps

Using the average coherence index table from Hoffman (2007), a damage map of the study areas was generated (see Figures 12). Coherence values 0 - 1.5 was identified as No Damage, 1.5 - 2.0 were identified as Lightly Damaged, 2.0 - 2.5 as Moderately Damaged, and values higher than 2.5 was identified as Severely Damaged. Damage assessment maps are important in assessing areas of concern to help decision-makers and stakeholders provide aid to areas in desperate need of help. Areas of severe damage could be observed mostly on the boundaries near the sea in the study sites and were highlighted in the maps of Surigao City and Siargao Islands. These places are also identified as areas with concentrated buildings based on the building footprint available in OpenStreetMap (OSM). It was useful in validating those areas identified as potentially damaged correspond to areas with infrastructures like buildings.

Moreover, even though this study focuses on identifying damage to infrastructures, SAR-derived damage assessment maps were also able to capture the changes in vegetated areas. However, most of them were identified as Lightly Damaged category because of their low backscatter values as well as their dynamic changes even in a very short period. Thus, changes in vegetative areas are not identified as sudden changes between pre-typhoon and co-typhoon coherence images and are not depicted as severely damaged.

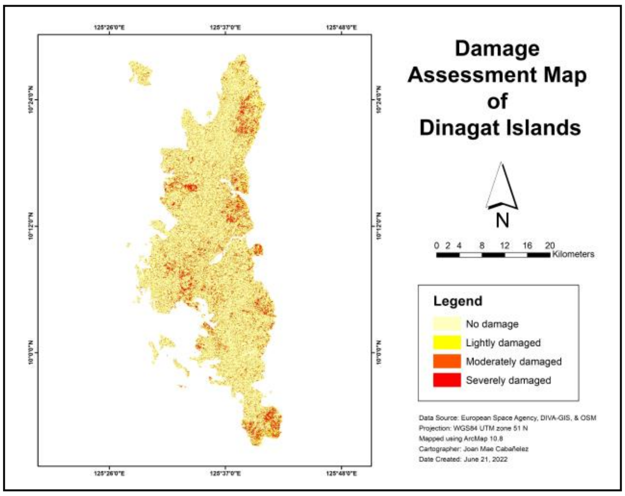

Figure 19. Coherence-based derived damage assessment map for Dinagat Islands using Sentinel-1 SAR image

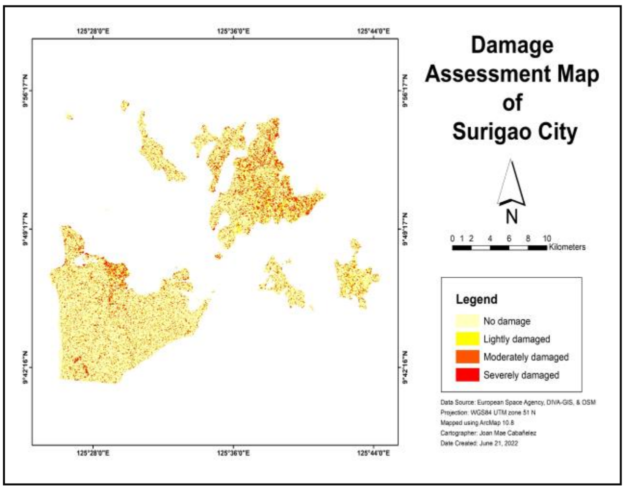

Figure 20. Coherence-based derived damage assessment map for Surigao City using Sentinel-1 SAR image

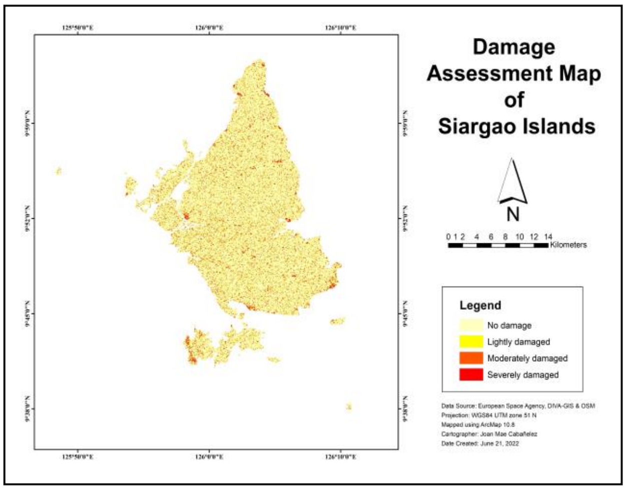

Figure 21. Coherence-based derived damage assessment map for Siargao Islands using Sentinel-1 SAR image

4. CONCLUSIONS AND RECOMMENDATIONS

Rapid damage assessment and mapping is one of the most critical factors of disaster response and management. Maps are generally one of the most traditional and used ways to provide efficient disaster response and recovery after disastrous events like hurricanes, explosions, landslides, typhoons, etc. In this study, Sentinel-1 SAR imageries were utilized to generate a damage map based on the changes in the complex coherence between pairs of images. Through the qualitative analysis presented in this research, it can be concluded that Sentinel-1 SAR imagery-based change map could give relevant and timely information to decision-makers and stakeholders in disaster response and management after a disastrous event like a typhoon. It accurately showed the extent and possible locations of building damages in the study areas. It was also validated through optical images taken from reliable sources and found to correspond well with the assessment maps shown in these sources.

Moreover, using the building footprint that was collected from OpenStreetMap, it was positively shown that the areas with high coherence correspond to areas with concentrated infrastructure. Same with NDBI, areas of built-up depicted correspond to areas with high coherence in the coherence images. However, barren lands are more pronounced in NDBI images because of their proximity to the spectral signature emitted by infrastructures.

To further refine the result of the study, it is recommended to include other infrastructures (e.g., bridges, road networks) in the damage assessment of the areas and using other ancillary data like actual ground photos as another source of in situ validation. It is also suggested to explore the capability of SAR intensity maps in rapid damage assessment apart from the coherence-based images.

ACKNOWLEDGEMENTS

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