A Modern Approach to Land Area Estimation in Sri Lanka Using Sentinel-2 Images and Google Earth Engine

Mafaz M.F.M.
Government Surveyor, Survey Department of Sri Lanka
wearemafaz@gmail.com

ABSTRACT

Accurately determining Sri Lanka's land area has traditionally been a time-consuming and resource-intensive process, heavily reliant on ground surveys. This study introduces a pioneering satellite-based approach for rapidly and precisely estimating land area using Google Earth Engine (GEE). Leveraging high-resolution Sentinel-2 imagery, we employ advanced image processing techniques, including the Normalized Difference Water Index (NDWI) to distinguish between land and water bodies. This methodology involves preprocessing the Sentinel-2 data to remove atmospheric distortions, applying cloud masking, and using Otsu's method to determine an optimal NDWI threshold for land-water differentiation. The binary water mask generated from the NDWI is further refined using the Canny edge detection algorithm to enhance the precision of water body boundaries. Additionally, coastal vectors are extracted from the land-water boundary to improve the accuracy of the land area calculation. To ensure robustness and account for seasonal variations, an annual composite of Sentinel-2 images is used, which mitigates the effects of transient atmospheric conditions and temporal variations. The study considers seasonal monsoons by analyzing data across the North-East (NE) monsoon, South-West (SW) monsoon, and both inter-monsoon periods. Our results were validated against the latest official land area values provided by the Survey Department of Sri Lanka, demonstrating a high degree of accuracy and reliability. Our findings highlight the significant advantages of using satellite-based methods for land area estimation, including large-scale coverage, timely updates, and cost-effectiveness. This approach offers a scalable and efficient solution for dynamic land cover monitoring, which is critical for applications such as urban planning, environmental management, and disaster response. The substantial reduction in estimation time and resources, combined with the accuracy of the results, suggests that this methodology could potentially replace traditional ground surveys for land area estimation in Sri Lanka.

Keywords
Land area estimation, Sentinel-2, Google Earth Engine, NDWI, Monsoon

1. Introduction

Sri Lanka, an island nation in the Indian Ocean, is situated to the southwest of the Bay of Bengal and southeast of the Arabian Sea. According to the United Nations Convention on the Law of the Sea (UNCLOS), an island is a naturally occurring landform surrounded by water and above the high tide line. The territory of Sri Lanka includes its main landmass along with several significant islands, each of which has unique archaeological, social, and economic significance.

The need for accurately calculating Sri Lanka's land area has become increasingly critical due to several factors. Coastal developments, natural hazards such as tsunamis, floods, and cyclones, and the continuous rise in sea levels have all contributed to significant changes in the shoreline. These phenomena highlight the importance of constant monitoring of the coastal areas on a national scale. As land is a scarce and valuable resource, continuous calculations of land extent are essential for understanding the quantitative behavior of the nation's territory. This data enables authorities to make informed decisions and develop policies to protect and manage land resources effectively.

Given Sri Lanka's status as an island nation, the factors mentioned above, combined with anthropogenic activities such as urban development and infrastructure projects, are likely to cause further changes in coastal areas, ultimately affecting the overall land extent. Therefore, the annual, or even more frequent, computation of land area is vital for safeguarding the nation's resources and ensuring sustainable development.

Accurately determining the land area of Sri Lanka has long been a critical task for various applications, including urban planning and environmental management. Traditional methods, which rely on ground surveys and digitizing high-resolution images obtained over time, are not only time-consuming but also resource-intensive. Additionally, acquiring high-resolution commercial satellite images can be costly.

To address these challenges, the proposed method uses reasonably high spatial resolution images (10 meters) and up-to-date imagery, combined with the computational power available in Google Earth Engine (GEE). By applying various algorithms within GEE, this approach enables frequent and accurate calculations of land area whether on an annual, sub annual, or even monthly basis. This method offers a more efficient and cost-effective alternative to traditional techniques, providing timely and scalable coverage for accurate land area assessment.

The study utilizes Google Earth Engine (GEE) and high-resolution Sentinel-2 imagery to estimate Sri Lanka's land area with improved accuracy and efficiency. The use of advanced image processing techniques, including the Normalized Difference Water Index (NDWI), Otsu's method for thresholding, and the Canny edge detection algorithm used in assessing the land extent.

Sea level changes introduce significant complexity to land area determination. While factors such as anthropogenic activities, development, and natural hazards tend to remain relatively constant, sea level fluctuations add variability to the process. Our study incorporates daily tidal changes, which are not typically considered in seasonal or sub-seasonal analyses, into the calculations. Additionally, we address monthly sea level variations and the impact of seasonal monsoon effects.

The monsoon cycle, which significantly influences tidal patterns, has been carefully mapped to account for these variations. Specifically, we analyzed changes during the North-East (NE) monsoon, South-West (SW) monsoon, as well as the first and second inter-monsoons. To refine our analysis, we separated data into the following periods: January, February, November, December, and the respective end-of-year months, reflecting the high amplitude of sea level variations influenced by the monsoon-current system south of Sri Lanka. We also considered associated changes in the wind field, as discussed in "The Seasonal Cycle of Sea Level in Sri Lanka and Southern India" by E.M.S. Wijeratne, P.L. Woodworth, and V. N. Stepanov.

By mapping these different monsoon seasons, we aimed to better understand coastal changes and their impacts on land area determination, providing a more accurate representation of sea level influences throughout the year.

2. Study Area, materials and methods

Sri Lanka, an island located in the Indian Ocean, lies to the southwest of the Bay of Bengal and to the southeast of the Arabian Sea. It spans from 5° 55′ N to 9° 51′ N in latitude and from 79° 41′ E to 81° 53′ E in longitude, covering an estimated land area of 65,610 square kilometers. The country's maritime boundaries are governed by the United Nations Convention on the Law of the Sea (UNCLOS), which delineates the main island along with several key islands that are notable for their archaeological, cultural, and economic significance.

The need for accurate land area calculation in Sri Lanka is increasingly important due to a combination of natural hazards, coastal development, and rising sea levels. Coastal regions are particularly vulnerable to changes caused by tsunamis, floods, and cyclones, which can alter shorelines and affect the overall land area. The study area includes Sri Lanka's entire coastline, encompassing diverse geomorphological features such as bays, estuaries, lagoons, and sandy beaches.

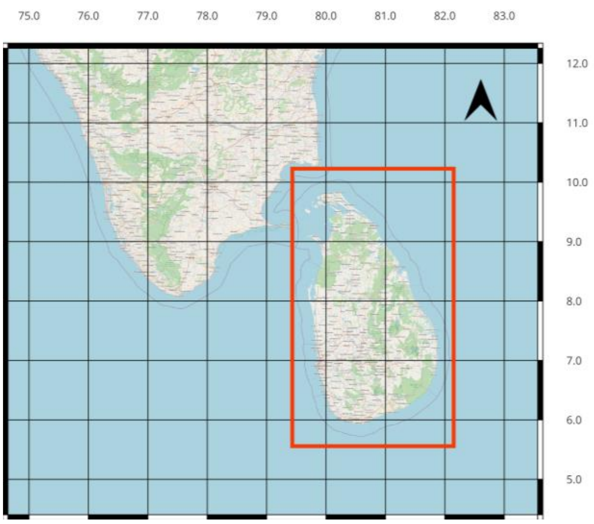


Figure 1 Study Area

Sri Lanka's coastal regions are not only crucial for the country's economy supporting fisheries, tourism, and infrastructure but also represent a significant portion of its population and land area. Approximately 32% of Sri Lanka's total land area is within coastal zones, and these areas are home to around 26% of the population. Given the importance of these regions and the dynamic nature of coastal environments, frequent and accurate calculations of land extent are essential for effective land resource management and policy development.

The study leverages Sentinel-2 imagery and Google Earth Engine (GEE) to accurately estimate the land area of Sri Lanka, accounting for dynamic coastal changes due to seasonal monsoons and sea level fluctuations. The methodology integrates several remote sensing techniques and image processing methods to provide a comprehensive approach to land area extraction, ensuring high precision in coastline delineation and eliminating errors caused by atmospheric disturbances, inland water bodies, and small islands.

The initial phase involves preprocessing Sentinel-2 images from 2023 to ensure data quality. This includes both radiometric and atmospheric corrections. Radiometric correction adjusts the image pixel values to correct sensor-related errors and normalize the data for consistent reflectance values. Atmospheric correction minimizes distortions caused by atmospheric particles, gases, and water vapor, ensuring that the surface reflectance values are representative of the ground conditions. Following these corrections, cloud masking algorithms were applied to remove clouds and shadows, which can obstruct land and water features. The use of algorithms such as the Quality Assessment Band (QA60) in Sentinel-2 ensures that only the clear portions of the image are analyzed. This step significantly enhances the data quality, eliminating potential errors caused by cloud coverage.

The next step involves the calculation of the Normalized Difference Water Index (NDWI). This index uses the reflectance values of the green (band 3) and near-infrared (band 8) wavelengths to distinguish between water bodies and land surfaces. The NDWI helps to clearly differentiate between land and water by enhancing the visibility of water bodies and reducing the influence of vegetation and other land features. It is crucial for distinguishing coastline boundaries, especially in areas where land meets water.

Once the NDWI is computed, the Otsu thresholding method is employed to automate the segmentation of land and water areas. The Otsu method selects the optimal threshold by minimizing the intra-class variance between land and water pixels, ensuring a precise delineation between these two features. This technique is particularly useful in dealing with complex boundaries and varying pixel values across the coastal regions. The automatic thresholding provides a clear demarcation of the coastline, allowing for consistent and accurate extraction across different months and seasons.

One of the unique aspects of the study is its incorporation of seasonal monsoon effects and monthly sea-level variations. The Southwest monsoon, Northeast monsoon, and the two inter-monsoon seasons significantly impact Sri Lanka’s coastal areas, causing fluctuations in the shoreline. To address these variations, Sentinel-2 imagery was analyzed on a monthly basis, and the resulting raster data was categorized by season. For each monsoon season and inter-monsoon period, the NDWI was recalculated, and the coastline was re-extracted to account for sea-level changes.

Following the thresholding process, edge detection algorithms were applied to refine the coastline boundaries. The Canny Edge Detection algorithm, a widely used method in image processing, was particularly effective in enhancing the precision of the extracted coastlines. This algorithm identifies sharp discontinuities in pixel intensity, allowing for more accurate tracing of the water-land interface. It involves noise reduction, gradient calculation, non-maximum suppression, and double thresholding to finalize the detected edges and refine them to the true boundaries of water and land.

To maintain the focus on the coastal boundaries, the study excluded inland water bodies such as lakes, lagoons, and rivers, as well as small islands with an area smaller than 100 square meters. This was achieved using a combination of vector extraction and raster manipulation techniques. All identified inland water bodies and small islands were masked out, allowing for a cleaner and more precise extraction of the coastline, ensuring the study concentrated solely on Sri Lanka's coastal land area.

After extracting the coastline for each month, the raster data was converted into vector format to facilitate further spatial analysis. The extracted coastline vectors for each season and month were compared to determine any shifts or changes in land extent due to the seasonal sea-level variations. This analysis was performed using spatial comparison techniques, overlaying the vectors from the Southwest monsoon, Northeast monsoon, and inter-monsoon periods to analyze coastline changes and their impacts on Sri Lanka's land area.

For final verification, the study cross-checked the extracted coastlines with high-resolution imagery from the Planet Explorer plugin in QGIS. Manual inspection and validation were performed to ensure the accuracy of coastline extractions, and any anomalies were corrected using this high-resolution data. The resulting outputs were used to calculate the land area variations for each season, ensuring that the final estimates reflected real-world changes in the coastline.

Seasonal variations were then analyzed for the North-East (NE) and South-West (SW) monsoons, along with the inter-monsoon periods and the yearly average. For each season, vectors were extracted to represent the coastline changes over time.

Finally, the outputs were validated against the Sri Lanka Survey Department's 2023 recalculation, ensuring the results were both accurate and reliable.

2.2 Data Acquisition

The Sentinel-2 imagery used in this study was acquired from the Copernicus Open Access Hub. The imagery, with a spatial resolution of 10 meters, is currently active and provides detailed information on land and water features. The image collection spans multiple seasons, including the Southwest Monsoon, Northeast Monsoon, and the two Inter-Monsoons. This seasonal approach allows for the analysis of land-water boundaries under varying climatic conditions. The entire year of 2023 is divided into different monthly periods corresponding to the monsoon seasons.

2.4 Adaptive Threshold Detection Otsu Thresholding

The Normalized Difference Water Index (NDWI) was employed in this study to differentiate between land and water, specifically focusing on the accurate delineation of Sri Lanka's shoreline, including its islands. Given the variability in spectral properties of open water across different regions and seasons, traditional fixed-threshold methods can introduce significant local errors. To overcome these challenges, we developed a method that automatically estimates thresholds for different monsoon seasons, leveraging the approach described by Donchyts et al. in their study on surface water mask generation.

We began extracting an area covering Sri Lanka's entire shoreline, incorporating crucial details including islands. The NDWI was calculated using Sentinel-2 imagery, with preprocessing steps such as atmospheric correction and cloud masking to enhance image quality. Instead of applying a single threshold, we employed the methodology outlined by Donchyts et al., which involves automatic threshold estimation for varying environmental conditions.

Calculated NDWI for different Monsoon seasons Following the threshold estimation, the Canny edge filter was applied to the NDWI image to detect sharp transitions between water and land. This was followed by Otsu's thresholding, which automatically determines the optimal threshold by maximizing the variance between the two classes. The combination of these techniques helps to refine the land-water boundary, particularly in areas where water bodies are narrow or fragmented. To focus specifically on the coastline, only the coastal area was extracted, concentrating on the shoreline threshold to ensure accurate representation of the coastal boundaries. Figure 2 depicts the histogram of the NDWI for two periods, where water and land can be clearly identified. The threshold was calculated based on this histogram to differentiate between water and land.

This approach not only improves the accuracy of land area estimation by adapting to local conditions but also provides a robust framework for automated shoreline analysis. The combination of NDWI, adaptive thresholding, and edge

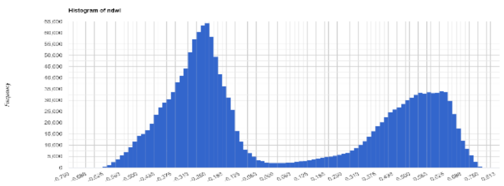


Figure 2 Histograms of NDWI values within Respective Period where (a) Average of 2023 threshold- 0.054

detection techniques offer a scalable solution that can be applied to other regions with similar challenges, significantly reducing the time and resources required for such analyses.

2.5 Edge Detection Algorithm

The binary water mask obtained from the NDWI was refined using the Canny edge detection algorithm, which enhances the precision of the water body boundaries. This process helped in accurately defining the coastline by improving the boundary delineation.

Subsequently, inland water bodies and small islands were removed to focus solely on the coastal boundaries. The refined coastline was then extracted from the land-water boundary and converted into vector format for detailed analysis

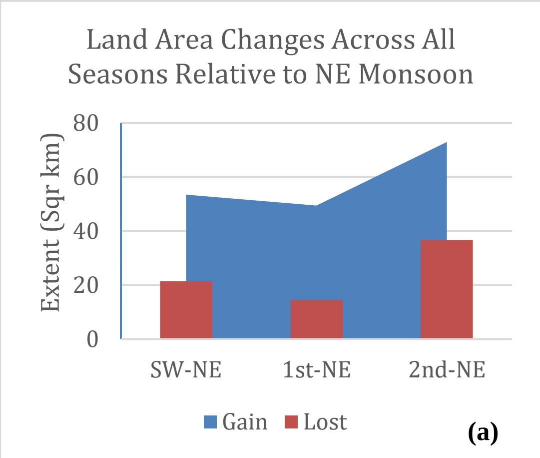
3. Results

The land area of Sri Lanka was estimated using processed Sentinel-2 imagery for different seasons of 2023 through Google Earth Engine (GEE). Variations in the estimates were primarily attributed to seasonal water level changes. The methodology included Otsu's Adaptive Threshold Detection, which enabled automatic thresholding for the land-sea area separation. This approach refined the classification of land and water boundaries, resulting in consistent and repeatable estimates. The results of the land area estimation are as follows, as shown in Figure 10.

- NE Monsoon (January, February, November, December): 65,597 km²
- SW Monsoon: 65,889 km²
- Average Land Area for 2023: 65,903 km²
- Survey Department Recalculated Land Area (excluding water): 65,489 km²

While analyzing the changes in the shoreline due to monsoon patterns, fluctuations in water bodies directly connected to the sea, such as lagoons and estuaries, were observed. Initially, these coastal features were excluded from the shoreline change analysis. A clear land-sea boundary was first extracted to accurately capture the coastline's dynamics. Subsequently, the extent of the country’s land area for both the South-West and North-East monsoons was calculated, incorporating the extracted land-sea boundary. The variation related to the North-East monsoon was then calculated for the South-West monsoon, as well as the 1st and 2nd inter-monsoons. Gains and losses in land area were depicted, providing a comprehensive understanding of the dynamic coastal environment during these seasonal periods. Additionally, the average land area for all 12 months was calculated to identify the overall changes in extent.

In analyzing shoreline changes, a key step involved utilizing a masked buffer along the shoreline of Sri Lanka to accurately delineate the coast. This buffer was applied to mitigate the impact of fluctuations in internal water bodies, such as lagoons and



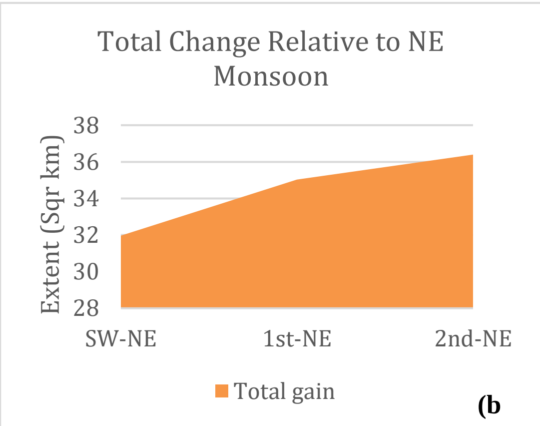


Figure 3: (a) Overall gains and losses in land area and (b) the total gain is shown in Figure 4 relative to the North-East Monsoon extent.

The analysis reveals a general increase in land area during the South-West Monsoon and the inter-monsoon periods, with the 2nd inter-monsoon exhibiting the highest extent. The effects of the monsoon are minimal during the inter-monsoon periods.

District-wise analysis reveals shown in charts that the North-East Monsoon predominantly affects the northern part of

estuaries, which could otherwise affect the analysis due to seasonal monsoon variations. By isolating the coastal areas and excluding these internal water bodies, the buffer ensured a precise representation of the land-sea boundary. The shapefile used for this purpose was obtained from the Survey Department, providing a reliable and authoritative base for the analysis. By employing this buffered mask, we were able to effectively isolate and analyze changes in the shoreline.

Sri Lanka, particularly the Jaffna and Kilinochchi districts. During this monsoon season, there is a noticeable decrease in land area in these northern districts, as the monsoon's influence drives away water from these areas, leading to reduced extent of water bodies.

Conversely, as the monsoon season transitions to the inter-monsoon periods, the land area in these districts shows a steady increase. The 1st inter-monsoon period witnesses a gradual gain, followed by a more pronounced increase during the South-West Monsoon. The 2nd inter-monsoon period exhibits the highest land area extent, highlighting a significant recovery and expansion of land in the northern region.

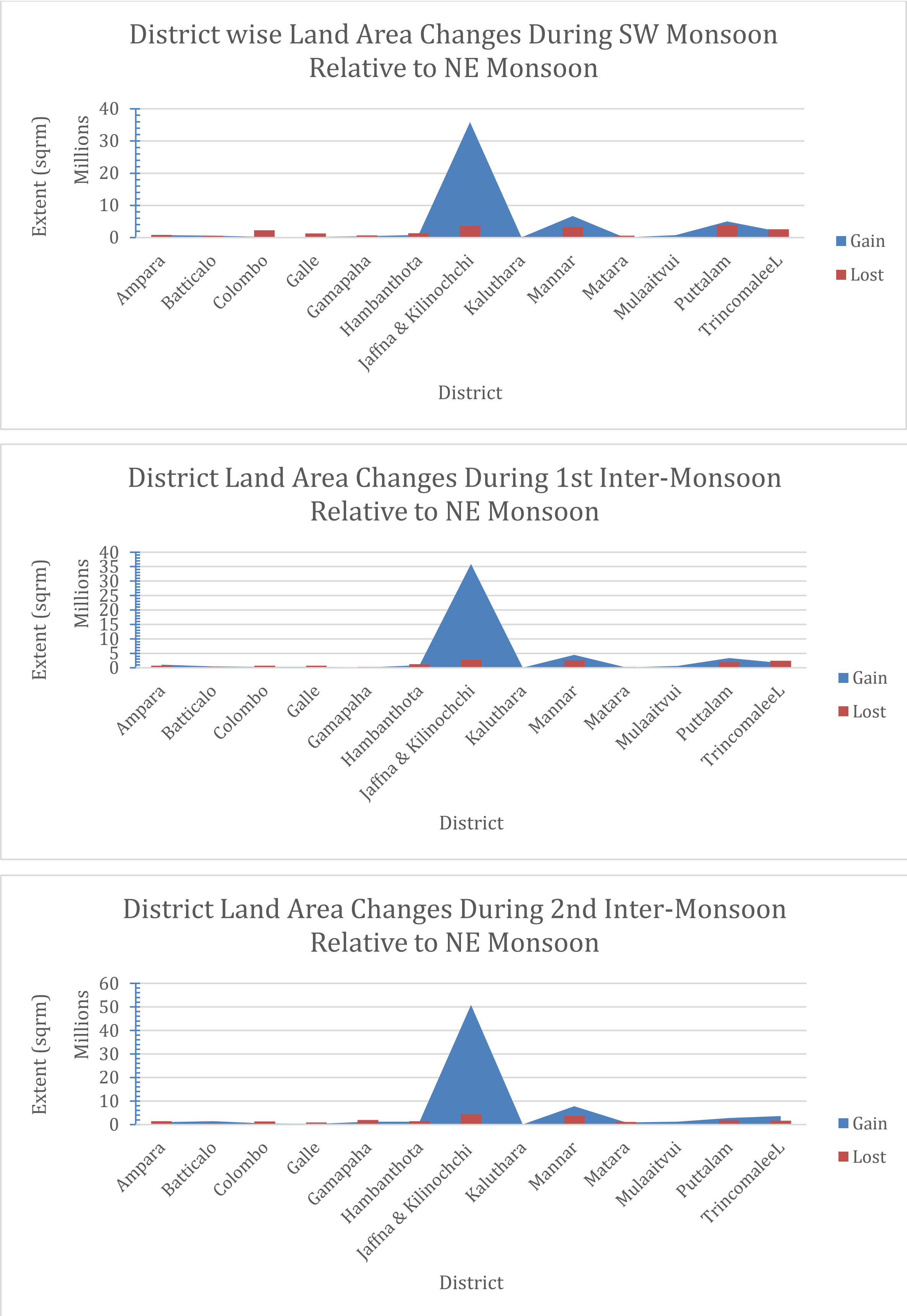


Figure 4: District Wise Land area changes with Seasons

Figure 4 illustrates the overall gain in land extent across the country, showing a clear increase in land area during the South-West Monsoon and the inter-monsoon periods. The charts highlight that the 2nd inter-monsoon period, in particular, shows the highest land extent, reflecting substantial land recovery and expansion. This is consistent with the district-wise observations, in figure 5 where the northern regions experience a notable increase in land area as the monsoon season shifts away from the North-East Monsoon.

The analysis supports that the North-East Monsoon results in the lowest land extent in these northern districts, while the subsequent periods (1st inter-monsoon, South-West Monsoon, and 2nd inter-monsoon) show a progressive increase in land area. The data confirms that the overall land extent increases significantly during the inter-monsoon periods, with the 2nd inter-monsoon achieving the highest extent.

Despite the 2nd inter-monsoon showing the highest extent, it covers only one month, limiting the temporal coverage. The analysis, supplemented by Planet Explorer's monthly composites to address gaps in Sentinel-2 data due to cloud cover, shows that the overall differences between the South-West Monsoon and the annual average land extent are minimal, with only a 0.02% variation.

4. Discussion

The use of Otsu's method for thresholding and the application of the Canny edge detection algorithm significantly improved the accuracy of the land-water boundary delineation. This study also demonstrated the potential of Google Earth Engine as a powerful tool for large-scale spatial analysis, providing a scalable solution for monitoring land cover changes. Future work could explore the integration of additional spectral indices and machine learning algorithms to further refine the

An in-depth district-wise analysis revealed changes in land area across different seasons(figure 6). The land area was examined relative to the North-East monsoon as a baseline, with attention paid to regions where significant variations in land extent were detected, providing insights into the spatial patterns of seasonal land changes.

With all the district-wise charts, it is clear that the two main monsoon seasons—NE and SW Monsoons—have significantly affected districts along the Sri Lankan coastline, resulting in noticeable changes in land extent.

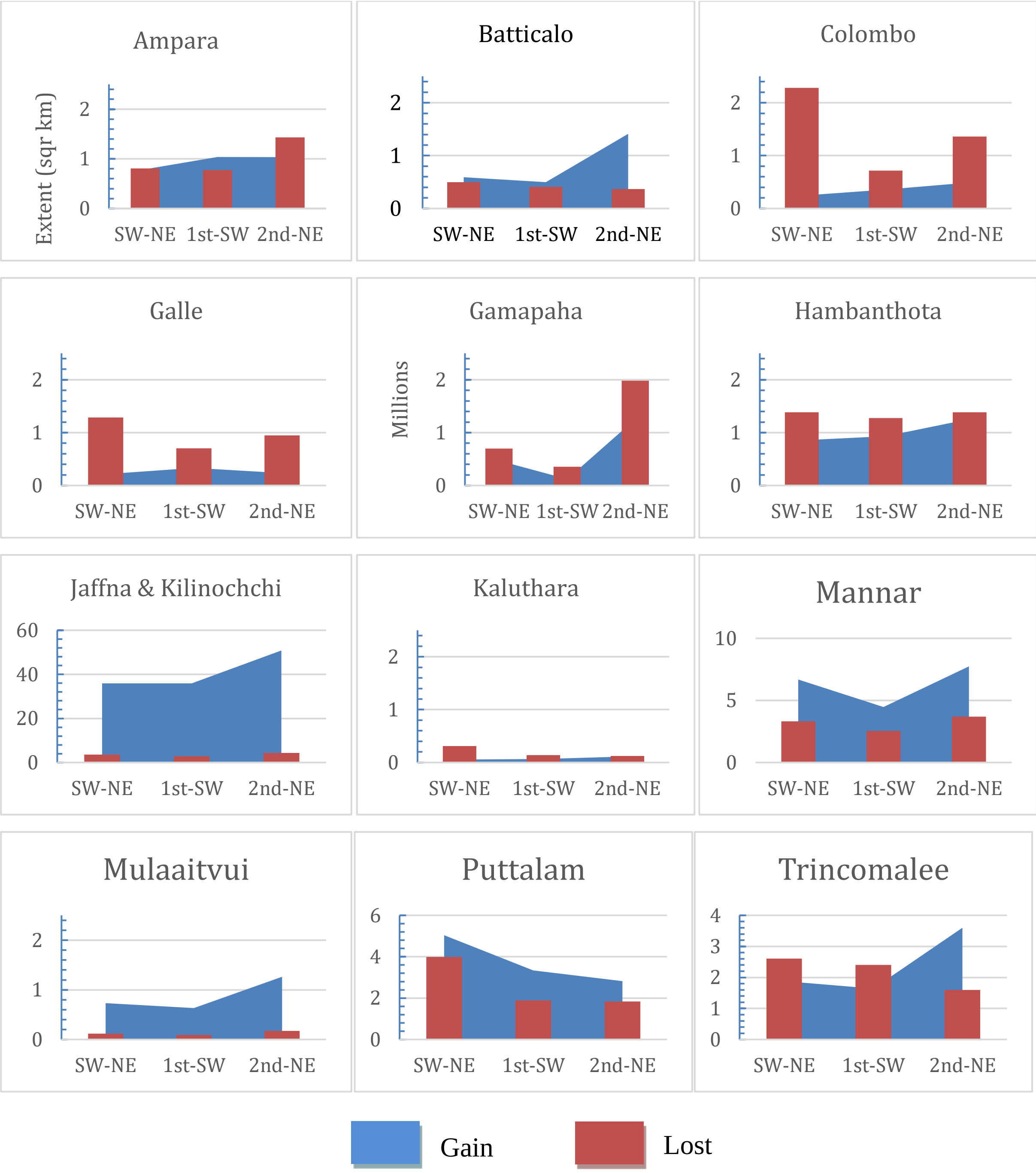


Figure 5:District Wise Land Area Changes Across All Seasons Relative to NE Monsoon

In the SW Monsoon, the districts experiencing the most land loss include:

- Trincomalee
- Kaluthara
- Galle
- Hambanthota
- Colombo

During the NE Monsoon, the districts with significant land loss are:

- Jaffna
- Kilinochchi
- Mannar

Comparing the values, the land extent changes in the NE Monsoon are more pronounced than in the SW Monsoon. This indicates that the NE Monsoon has a more substantial impact on the coastline compared to the SW Monsoon. The districts with the most visible changes are highlighted below, in figure 7,8 and 9 illustrating the varying effects of each monsoon season on coastal land extent.

The statistical measures highlight the overall stability of land area calculations while identifying minor seasonal fluctuations:

4.3 Seasonal Differences

The seasonal land area changes were calculated to understand the impact of monsoon cycles on the extent of Sri Lanka's landmass:

NE Monsoon to SW Monsoon, Percentage Change = 0.44%

SW Monsoon to 2023 Average, Percentage Change = 0.02%

4.4 Comparison with Survey Department Recalculated Value

The accuracy of this study's results was further validated by comparing them to the recalculated land area from the Survey Department. The Survey Department's recalculated land area is 65,489 square kilometers. The comparisons are as follows:

Comparison	Difference (km^2)	Percentage Change (%)
NE Monsoon vs. Survey Department Recalculated Land Area	110.770	0.17%
SW Monsoon vs. Survey Department Recalculated Land Area	400.402	0.61%
2023 Average vs. Survey Department Recalculated Land Area	414.513	0.63%

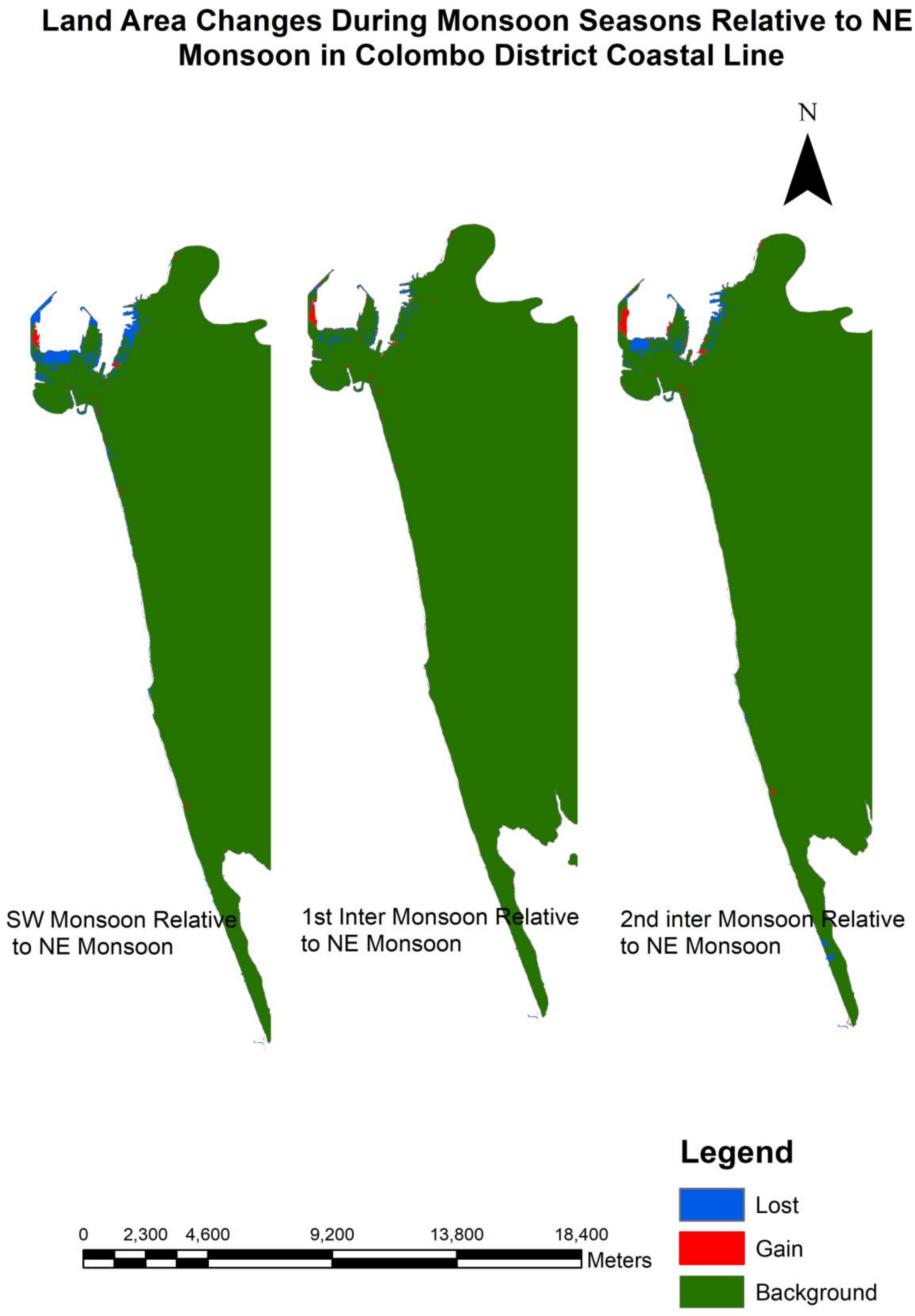


Figure 6 : Colombo Monsoon Variation

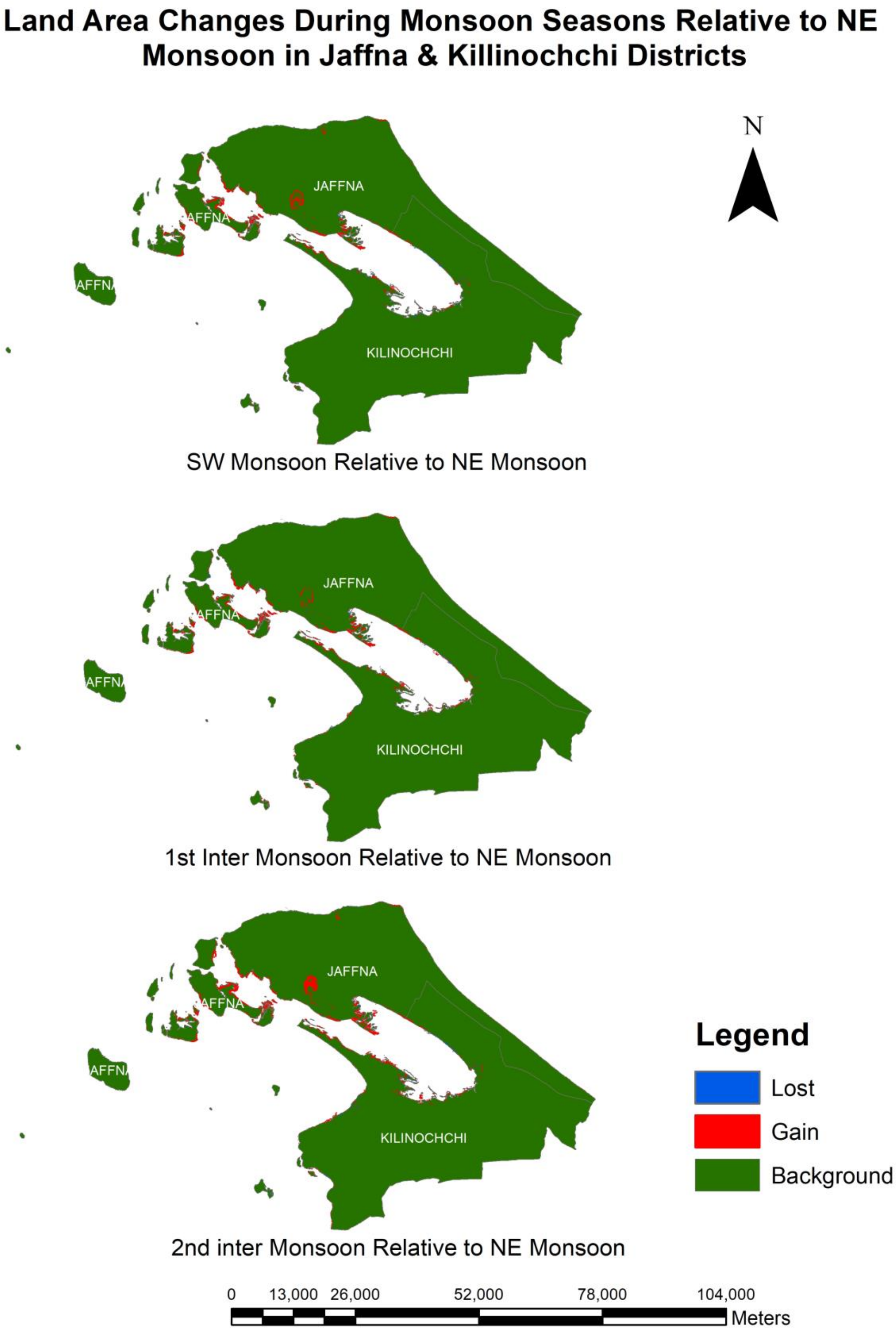


Figure 7:Jaffna and Killinochchi Monsoon Variation

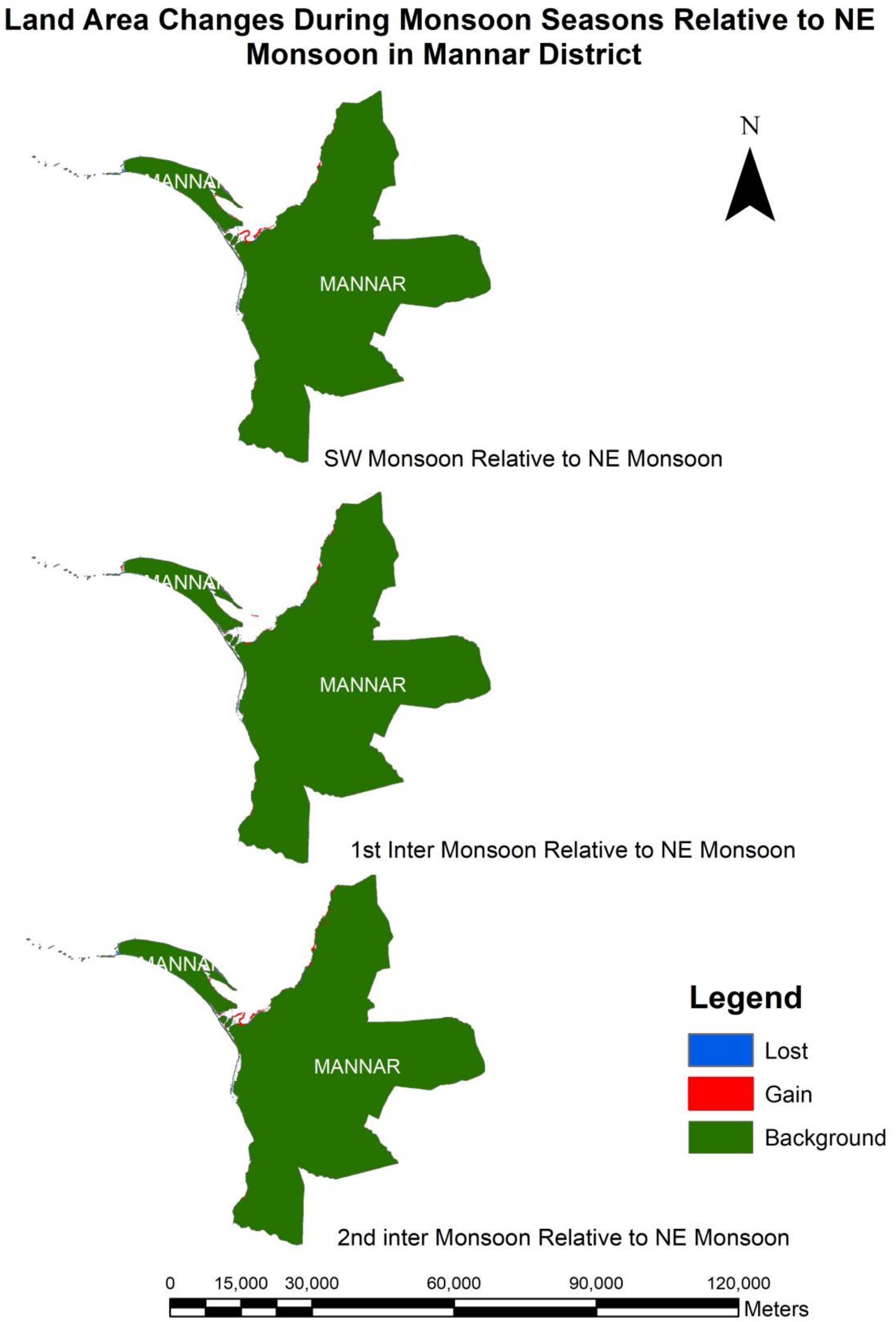


Figure 8:Mannar Monsoon Variation

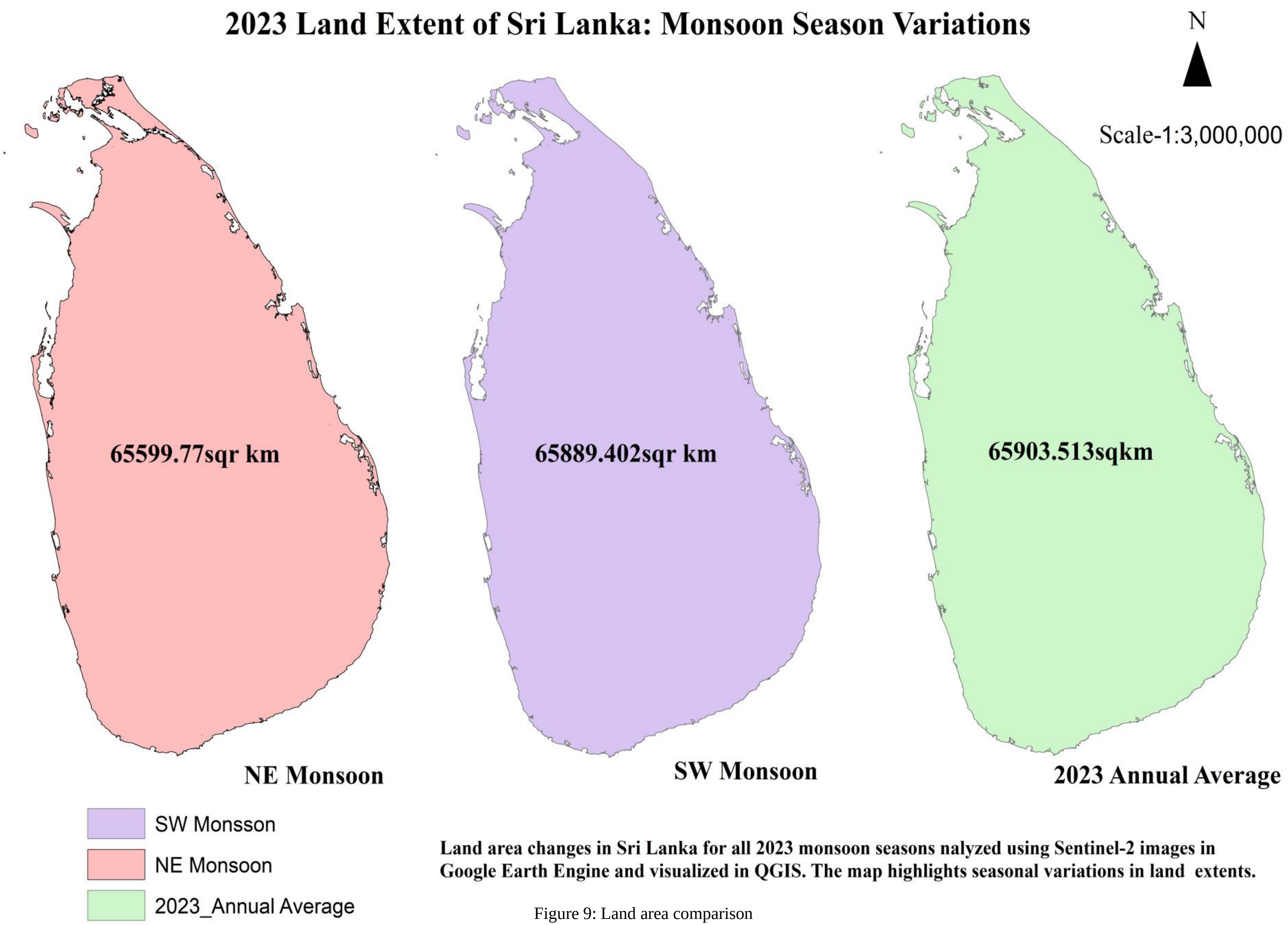


Figure 9: Land area comparison

5. Conclusion

This study introduces a modern approach to land area estimation in Sri Lanka using Sentinel-2 imagery and Google Earth Engine. The findings indicate that satellite-based methodologies can effectively replace traditional ground surveys, offering a more efficient, accurate, and scalable solution. The results underscore the potential of remote sensing technologies to support national-scale land cover monitoring and management efforts.

The statistical analysis presented in this study offers a comprehensive understanding of Sri Lanka’s land area changes, highlighting the efficacy of satellite-based methodologies for accurate land area measurement. The minor seasonal fluctuations identified in the shoreline and land area, particularly during the SW and NE monsoons, underscore the need for continuous monitoring to account for coastal erosion and sea-level changes.

The percentage differences with the official recalculated values were consistently below 1%, showcasing the robustness of this methodology.

However, one limitation was noted in the final determination of water and land areas, mainly due to inland water bodies such as rivers. These inland water bodies influence the accuracy of the shoreline analysis near the coast. Additionally, the inclusion criterion for islands required that only those larger than 100 square meters be considered in the land area calculations.

In conclusion, it is important to note that the buffer used for shoreline analysis may require adjustment to better reflect variations observed in certain districts. The current buffer, while effective overall, does not fully account for the significant changes in shoreline dynamics experienced in some areas. To address these discrepancies, future analyses should consider updating the buffer parameters to enhance accuracy. This adjustment will ensure a more precise representation of coastal changes and provide a clearer understanding of regional variations. Detailed assessments and adjustments to the buffer will be discussed further in the following chapter.

References

1. Canny, J. (1986). A computational approach to edge detection. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *PAMI-8*(6), 679-698. https://doi.org/10.1109/TPAMI.1986.4767851
2. Coppin, P., & Bauer, M. (1996). Digital change detection in forest ecosystems with remote sensing imagery. *Remote Sensing Reviews*, *13*(3-4), 207-234.
3. Donchyts, G., Schellekens, J., Winsemius, H., Eisemann, E., & van de Giesen, N. (2024). A 30 m resolution surface water mask including

estimation of positional and thematic differences using Landsat 8, SRTM and OpenStreetMap: A case study in the Murray-Darling Basin, Australia. [Provide Journal/Publisher Details].

4. Gandhi, U. (2020). Automated coastline detection and extraction using Google Earth Engine. Available at www.spatialthoughts.com.
5. Mafaz, M. F. M. (2024). *A modern approach to land area estimation in Sri Lanka using Sentinel-2 images and Google Earth Engine*. https://code.earthengine.google.com/4325d64e6e1b70e8416ba40d07b1e69d
6. McFeeters, S. K. (1996). The use of the normalized difference water index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, *17*(7), 1425-1432.
7. Otsu, M. (1979). A threshold selection method from gray-level histograms. *IEEE Transactions on Systems, Man, and Cybernetics*, *9*(1), 62-66. https://doi.org/10.1109/TSMC.1979.4310076
8. Samuel, J. (2018). Geospatial techniques for coastal zone management: A study of Sri Lankan coastal regions. *Journal of Coastal Research*, [Provide Volume/Issue Details].
9. Schott, P., & McCreary, J. P. Jr. (1981). Circulation and variability at monsoon seas. *Reviews of Geophysics*, *19*(1), 19–40.
10. Schott, P., & McCreary, J. P. Jr. (2001). The monsoon circulation of the Indian Ocean. *Progress in Oceanography*, *51*(1), 1-123. https://doi.org/10.1016/S0079-6611(01)00083-0
11. Sengupta, D., & Vemuri, V. (2020). Coastline extraction using a multi-resolution approach and Landsat imagery. *Science of the Total Environment*, *139290*. https://doi.org/10.1016/j.scitotenv.2020.139290
12. Woodroffe, C. D. (2002). *Coastal geomorphology: An introduction*. Cambridge University Press.
13. Xu, H. (2006). Modification of normalized difference water index (NDWI) to enhance open water features in remotely sensed imagery. *International Journal of Remote Sensing*, *27*(14), 3025-3033.
14. Zhang, J., et al. (2017). Urban land cover classification with multi-source remote sensing data based on random forest algorithm. *Remote Sensing*, *9*(4), 364.