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Automated Coastline Mapping Using Sentinel 2-based NDVI on Google Earth Engine: A Decision Support Tool for Diachronic Coastal Monitoring

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Abstract

Coastal zone monitoring requires efficient and reproducible methods for coastline extraction across multiple spatial and temporal scales. In this study, we present NDVICoast, an automated decision-support tool developed on Google Earth Engine (GEE) for diachronic coastline mapping using Sentinel-2 imagery. The method leverages the Normalized Difference Vegetation Index (NDVI) as a proxy for extracting the vegetation boundary, which serves as a reliable indicator of coastline position in vegetated coastal environments. The tool automates the complete workflow from image acquisition and preprocessing to coastline extraction at two different dates. The method was validated at two sites in Québec with distinct coastal geomorphologies. At the Saguenay Fjord, the automated extraction achieved a Root Mean Square Error (RMSE) of 4.20 meters compared to in situ data, while at Baie-Trinité, the RMSE was 5.12 meters when compared to a digitized reference coastline. NDVICoast enables rapid processing of large temporal datasets, facilitating systematic coastal change detection. Results demonstrate the tool's capacity to support coastal management decisions through consistent, repeatable, and cost-effective coastline monitoring across multiple time periods.

1. Introduction

Coastal zones represent dynamic environments subjected to multiple natural and anthropogenic pressures, including sea-level rise, erosion, sedimentation, and human development (Kandrot 2013). Accurate monitoring of coastline position and its temporal evolution is essential for coastal management, hazard assessment, and understanding landscape dynamics. Traditional coastline mapping methods, including field surveys and manual digitization from aerial imagery, are time-consuming, costly, and difficult to replicate consistently across large spatial and temporal scales.

Remote sensing has emerged as a fundamental technology for coastal monitoring, offering synoptic coverage and temporal repeatability. Various approaches have been developed for automated coastline extraction, including water-index thresholding, supervised classification, edge detection, and machine learning (Toure *et al.* 2019). However, many existing methods require significant manual intervention, specialized software, or substantial computational resources, which limit their operational deployment.

The launch of the European Space Agency's Sentinel-2 constellation has provided unprecedented opportunities for coastal monitoring through its combination of high spatial resolution (10 m), high temporal resolution (5-day), and free data access (ESA 2015). Simultaneously, cloud-based platforms such as Google Earth Engine (GEE) have democratized access to satellite imagery analysis by providing integrated data archives and computational infrastructure (Gorelick *et al.* 2017).

In vegetated coastal environments, the boundary between terrestrial vegetation and water or bare substrate serves as a stable, ecologically significant proxy for the coastline (Boak et Turner 2005). The Normalized Difference Vegetation Index (NDVI) provides a robust metric for vegetation detection that is less sensitive to atmospheric and illumination variations than individual spectral bands. While the majority of existing automated coastline extraction tools rely on water indices (such as Normalized Difference Water Index (NDWI) and Modified Normalized Difference Water Index (MNDWI)) to delineate the water-land interface (Vos *et al.* 2019; Almeida *et al.* 2021), these approaches can be sensitive to water turbidity, wave conditions, and tidal variations. In contrast, a vegetation-based approach using NDVI offers enhanced temporal stability by targeting the terrestrial vegetation boundary, which remains more consistent across different environmental conditions (Toure *et al.* 2019). However, there remains a need for operational tools that integrate such automated NDVI-based processing workflows with accessible cloud-based platforms.

This study presents the development and validation of an automated decision-support tool, NDVICoast, implemented within GEE for diachronic coastline mapping using NDVI derived from Sentinel-2 images. The tool addresses three main operational requirements: automating the entire processing workflow, ensuring reproducibility across multiple time periods, and providing accessibility through a cloud-based platform.

2. Material and Methods

2.1 Study sites

To evaluate the performance of NDVICoast, we chose to use it to map coastline in two different sites with different coastal structures (Fig. 1). The first site is located in the Saguenay Fjord, Quebec (48.42536° N, 70.73730° W, (WGS84)). The fjord represents a unique coastal environment characterized by steep terrain, mixed forest vegetation extending to the water's edge, and water depths exceeding 200 m in some locations, creating an abrupt terrestrial-aquatic transition. However, this transition becomes smoother and more gradual near river mouths. The validation site is located at the mouth of the Pelletier River, a tributary flowing into the Saguenay Fjord. The second site is located in the Baie-Trinité Regional County Municipality, to the north of Baie-Comeau (49.51794° N, 67.23524° W (WGS84)). This site has a wide variety of landforms, including rocky shores as well as beaches composed of sand and gravel.

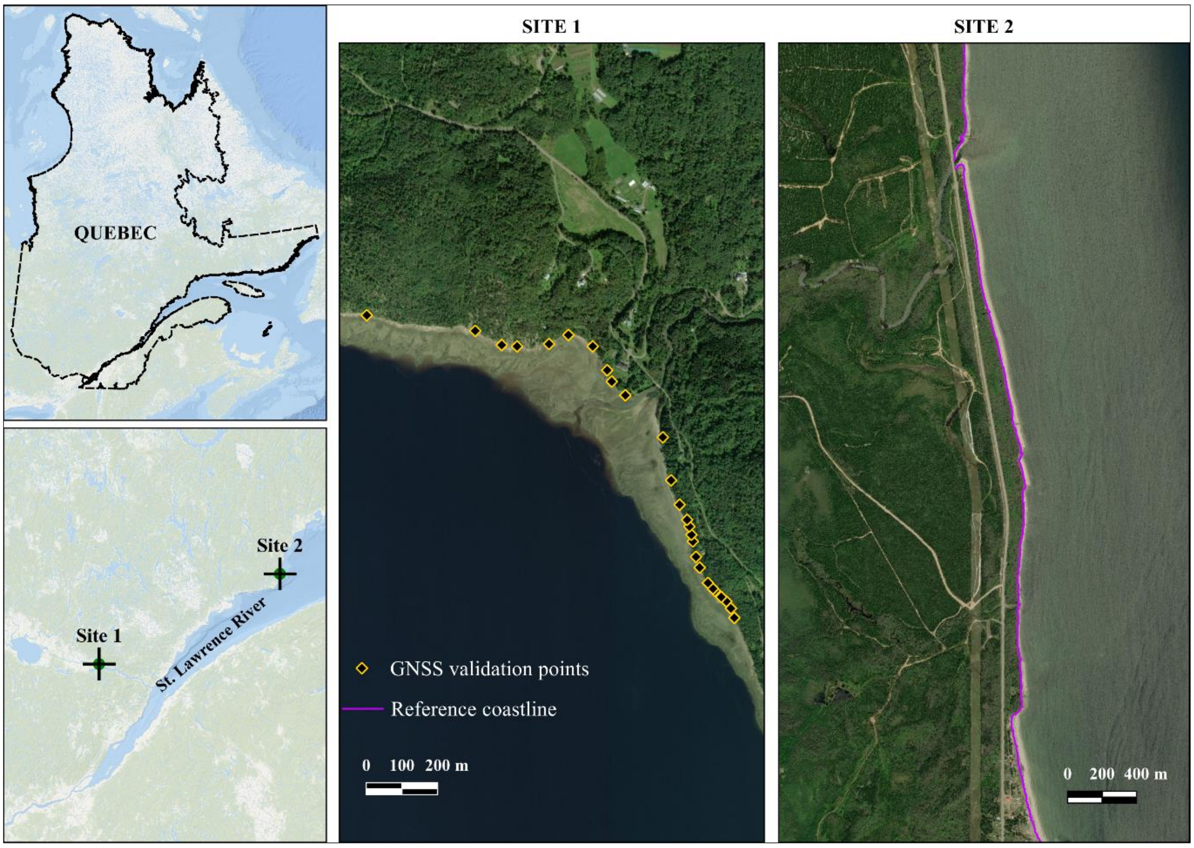

Figure 1: Location map of the validation sites on ESRI Satellite basemap.

2.2 Data and Platform

The analysis used Sentinel-2 Level-2A imagery from the GEE data catalog. Sentinel-2 provides multispectral imagery at 10 m spatial resolution in the red and near-infrared bands required for NDVI calculation.

GEE was selected as the development platform due to its integrated access to the complete Sentinel-2 archives, server-side processing capabilities, and JavaScript API for tool development. The platform eliminates the need for data downloads and local storage while enabling rapid prototyping and deployment of geospatial analysis workflows. Sections 2.3 to 2.5 describes how NDVICoast generally works in GEE, and Section 2.6 addresses how it performed on the study site.

Validation data for site 1 were collected on August 1, 2025 at the mouth of the Pelletier River on the Saguenay Fjord using systematic Global Navigation Satellite System (GNSS) field surveys. These surveys measured the position of the vegetation boundary to serve as a reference for coastline extraction. For Site 2, a reference coastline was digitized from a 2024 aerial image with a spatial resolution of 20 cm.

2.3 Image Preprocessing

Image preprocessing is automated within the GEE framework to ensure consistency across temporal acquisitions. The preprocessing workflow includes:

1. Temporal filtering: Selection of Sentinel-2 cloud-free images within the date ranges specified by the user – two for diachronic analyses. The selected images are then ranked according to their cloud cover over the user-defined area of interest. The acquisition with the lowest cloud coverage for each time range is automatically selected for further processing.

2. Masking: Application of the Sentinel-2 Scene Classification Layer (SCL) to remove pixels classified as cloud, cloud shadow, or snow.

3. Composite generation: spatial mosaics are automatically generated when the user-defined area of interest intersects multiple satellite tiles. Temporal composites are then produced using a median reducer, which helps to minimize residual atmospheric effects and radiometric inconsistencies between tiles, while filling data gaps.

4. Spatial clipping: All selected and preprocessed images are clipped to the user-defined area of interest (AOI). This step ensures that subsequent analyses are strictly limited to the spatial extent specified by the user, reduces data volume, and improves computational efficiency within the GEE environment.

2.4 NDVI Calculation and Thresholding

Still in GEE, the NDVI is automatically calculated following the standard equation:

$$NDVI= (NIR-RED)/(NIR+RED) \quad (1)$$

where NIR represents Band 8, and Red represents Band 4 of Sentinel-2 imagery.

To automatically determine the optimal threshold for separating vegetation from non-vegetation pixels, Otsu's method (Otsu 1979) is implemented in GEE. This automatic thresholding technique analyzes the NDVI histogram and identifies the threshold that minimizes intra-class variance while maximizing inter-class variance between the two groups (vegetation and non-vegetation).

2.5 Coastline Extraction

The previous step produces a binary raster for each time range. In GEE, the rasters are first vectorized to obtain polygons, which are then converted into polylines representing vegetation boundaries. This method delineates all vegetation limits within the area. To isolate the coastal boundary, the user is asked to draw a rough coastline directly in the GEE interface. A buffer is then generated around this drawn coastline using a user-specified distance, and the polylines are clipped to it. This ensures that only vegetation limits along the coastline are retained. These steps are applied to both dates, resulting in two coastlines that the user can download for further analysis in other GIS software.

2.6 Validation

Validation was carried out by comparing the extracted coastlines with reference data: in situ GNSS measurements for Site 1 and a digitized reference coastline for Site 2. The tool generates two multi-date coastlines; however, for each site, only one coastline was validated due to the availability of reference data.

Positional accuracy was assessed by calculating perpendicular distances between the automated NDVI-derived coastline and the GNSS-derived reference coastline. The Root Mean Square Error (RMSE) and the Mean Absolute Distance (MAD) were computed as:

$$RMSE = \sqrt{(\Sigma(d\_i^2) / n)} \quad (2)$$

$$MAD = \Sigma(d\_i^2) / n \quad (3)$$

where d_i represents the perpendicular distance for point i and n is the total number of comparison points.

3. Results

The application features a user-friendly interface that streamlines the coastline extraction workflow. Users can easily select the area of interest, define two temporal ranges, and choose processing parameters such as buffer distances (Appendix 7.1). The interface also allows verification of drawn geometries, including the boundary zone and the reference coastline. Intermediate results, such as the NDVI for the two dates and the generated polylines, can be visualized directly within the interface. Finally, the extracted coastlines can be exported for further analysis in external GIS software. Its intuitive layout enables both expert and non-expert users to perform diachronic coastline mapping efficiently.

NDVICoast demonstrated efficient processing performance enabled by GEE's cloud infrastructure. In each site, the tool successfully delineated two distinct coastline positions corresponding to the selected dates, enabling temporal change analysis (Appendix 7.2). For each analysis period, the automated workflow extracted independent coastline vectors for subsequent comparison to quantify coastal evolution. This dual-date extraction capability allows users to directly assess coastline displacement, identify erosion and accretion zones, and calculate rates of change over the selected time interval.

The evaluation of the extracted coastlines shows a reasonable level of accuracy, with some variation between sites. For Site 1, the RMSE is 4.20 m and the MAD is 3.43 m. For Site 2, the RMSE is 5.12 m and the MAD is 4.13 m (Table 1), suggesting slightly lower accuracy. This difference can be partly explained by the fact that the reference line was digitized manually, which introduces higher error margins compared to the GNSS points used in Site 1. Overall, these results demonstrate that the coastline extraction tool provides reliable outputs, with mean deviations below 5 m, approximately half a pixel of the Sentinel-2 imagery used in this tool.

Table 1: Assessment of the accuracy of the coastlines extracted at the two sites. Errors are expressed in meters.

	Evaluation method	**RMSE**	**MAD**
Site 1	GNSS points	4.20	3.43
Site 2	Reference ligne	5.12	4.13

The results of the multi-temporal mapping are presented in Fig.2 for Site 1 and Fig.3 for Site 2. These maps show the two coastlines extracted at different dates, as well as the validation data, allowing for a visual assessment of the accuracy of the NDVICoast tool. They clearly illustrate NDVICoast’s ability to track spatiotemporal changes in the coastline while highlighting areas of variability. At both sites, the discrepancies between the two coastlines remain small, suggesting a stable coastal environment or one with limited variations during the study period.

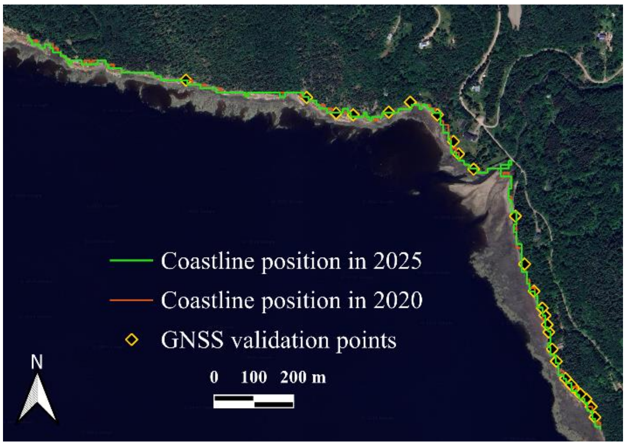

Figure 2: Results of coastline mapping with NDVICoast on site 1, overlaid on ESRI Satellite basemap.

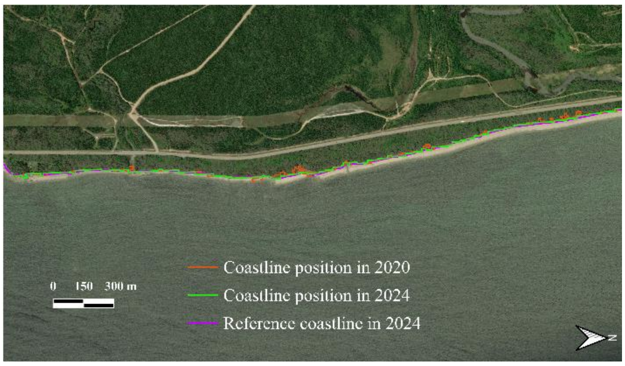

Figure 3: Results of coastline mapping with NDVICoast on site 2, overlaid on ESRI Satellite basemap.

4. Discussion

The workflow achieved sub-pixel accuracy for both sites, with an RMSE of 4.20 m for Site 1 and 5.12 m for Site 2, both below approximately 0.5 Sentinel-2 pixels, highlighting the high spatial precision of NDVICoast for coastline extraction. This accuracy is sufficient for many coastal management applications, including monitoring erosion hotspots, assessing long-term trends, and evaluating coastal restoration projects. It can also help identify areas that need finer-scale monitoring across large areas.

The spatial transferability makes the NDVICoast particularly well-suited for regional-scale coastal monitoring studies. Users can apply the same workflow to extensive coastal segments or multiple disconnected study areas without manual intervention, facilitating systematic assessment of coastline dynamics at regional scales. The ability to process any user-defined area of interest within the GEE platform eliminates traditional constraints related to image acquisition, preprocessing, and computational resources that often limit the spatial extent of coastal monitoring programs.

However, several limitations constrain applicability. The vegetation boundary approach is most appropriate for vegetated coasts where terrestrial vegetation extends consistently to the water's edge. Non-vegetated coasts, including beaches, rocky shores, and artificial structures, may require alternative approaches (Hastuti *et al.* 2024). Additionally, a specific limitation concerns the presence of submerged or partially emerged vegetation during low tide conditions. In areas where aquatic vegetation becomes exposed at low tide, the NDVI signal may incorrectly identify these vegetated zones as part of the terrestrial coastline, leading to seaward bias in the extracted position. User visual validation may thus remain necessary.

Temporal limitations also arise from seasonal factors, including vegetation phenology and snow cover. The method requires cloud-free imagery during periods of maximum vegetation vigor, limiting analysis to growing season months. In northern latitudes, this restricts temporal sampling to approximately 4-5 months per year, precluding year-round monitoring and potentially missing rapid coastal changes occurring outside the growing season, such as during major fall or winter storms.

Finally, a potential source of error stems from the alignment between the two Sentinel-2 images used for multi-temporal analysis (Rengarajan *et al.* 2024). Misregistration or slight geometric shifts between images can introduce small inaccuracies in the extracted coastline positions, which may affect the quantification of coastal change.

5. Conclusion

This study has demonstrated the successful development and validation of an automated decision-support tool for diachronic coastline mapping using Sentinel-2 NDVI in Google Earth Engine. The tool achieved a positional accuracy of 7.52 m (RMSE measure), sufficient for many operational coastal monitoring applications in vegetated coastal environments.

Key contributions include: (1) the automation of the complete processing workflow from image acquisition to coastline vectorization, (2) the implementation on an accessible, free cloud-based platform enabling use by non-expert coastal managers, (3) the validation in a challenging fjord environment demonstrating robustness to complex coastal morphology, and (4) the demonstration of efficient processing enabling rapid analysis of large spatial and temporal datasets.

The tool addresses a critical need for cost-effective, reproducible, and accessible methods for coastal monitoring amid accelerating coastline changes. By using vegetation boundaries as a proxy for coastlines and leveraging freely available satellite data and cloud computing infrastructure, the approach enables systematic monitoring of coastlines at local to regional scales, supporting evidence-based coastal management decisions.

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
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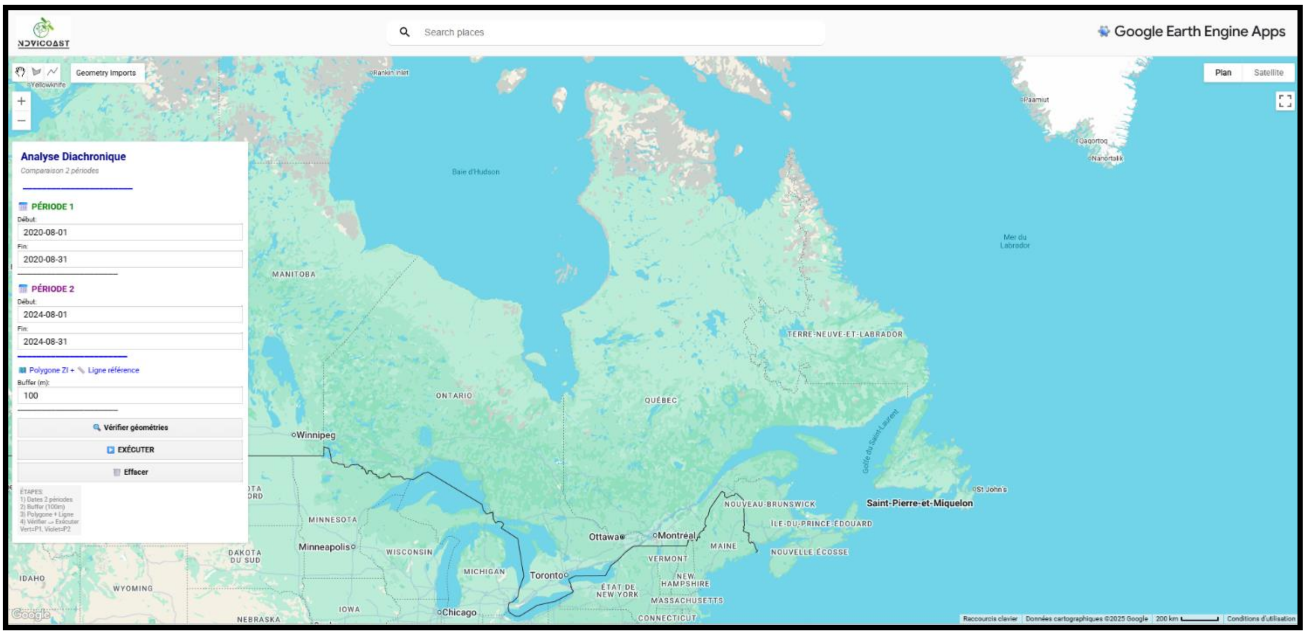
7. Appendices

7.1 NDVICoast interface



7.2 Example of results generated by NDVICoast on site.