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Remote sensing image enhancement methodology supporting coastal erosion assessment using adaptive spatial filtering techniques

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***Abstract*—This paper introduces a general framework for enhancing remote sensing imagery to strengthen the accuracy of coastal erosion assessment in complex shoreline environments. Coastal zones experience rapid geomorphological shifts, yet their monitoring is limited by image noise, low radiometric contrast, and spatial distortion that obscure subtle erosional signatures. The problem is exacerbated in heterogeneous coastal terrains, where uniform filtering approaches often oversmooth critical shoreline details, leading to unreliable change-detection results. To overcome these constraints, we propose a unique Context-Responsive Hybrid Enhancement Method (CRHEM) that integrates local contextual mapping with multi-scale adaptive refinement. CRHEM dynamically adjusts enhancement parameters by analyzing micro-pattern variations, edge persistence, and shoreline curvature, enabling selective amplification of erosion-sensitive features while suppressing context-specific noise. Results obtained from multi-temporal optical and SAR datasets reveal that CRHEM improves shoreline extraction accuracy, increases textural separability, and significantly enhances the visibility of erosion hotspots compared with classical approaches such as wavelet filtering, bilateral smoothing, and gradient-based enhancement. The improved image clarity directly enhances the reliability of coastal change analysis, enabling more precise erosion quantification and improved detection of early-stage geomorphic shifts. In conclusion, CRHEM provides a robust and novel enhancement pathway that supports advanced coastal monitoring, risk assessment, and long-term management strategies. The proposed CRHEM method achieved superior performance with 88% noise suppression, 87–88% shoreline extraction accuracy, 35 dB PSNR, and 0.82–0.83 EPI, outperforming conventional methods.**

Keywords—coastal monitoring, image enhancement, hybrid adaptive method, erosion detection, remote sensing.

I. INTRODUCTION

A. Coastal Erosion and Monitoring Challenges

Coastal erosion has remained one of the most urgent environmental issues affecting coastal communities, ecosystems, and infrastructure worldwide [1]. Shoreline recession has increased in a significant number of locations due to the natural processes of wave action, currents, storms, and sea-level rise, together with human actions, like coastal development and sediment disturbance [2]. It is necessary to continuously monitor these changes to understand them, forecast future trends, and apply effective management strategies [3]. Nevertheless, the dynamic nature of coastal environments makes effective monitoring difficult [4]. Shorelines change quickly, usually over a relatively short period, and have complex spatial structures, including rugged soils, varying sediment textures, vegetation disturbance, and seasonal morphological variations [5].

Remote sensing has proven to be a cornerstone of large-scale, long-term coastal monitoring, offering invaluable multispectral, radar, and high-resolution imagery. Although remote sensing data has its benefits, it is often hampered by a number of factors that limit the accuracy of coastal measurements [6]. The problems that are common will be plane distortions in the atmosphere, sensor noise, low radiometric difference between the land and water, and mixed pixels in the transition areas. These processes blur small-scale characteristics that are required to identify subtle erosional changes. In addition, coastal landscapes are not uniform since they comprise sandy beaches and rocky coasts as well as estuarine areas, rendering the use of uniform enhancement methods ineffective [7]. Conventional filters tend to smooth shoreline boundaries, reduce image texture, or amplify noise in complex areas, leading to inaccurate shoreline retrieval and imprecise erosion assessments.

With the ever-increasing coastal risks due to climate change and other human activities, better image enhancement techniques have become a critical need. Progressing remote sensing imagery to the extent that it does not alter the key coastal characteristics and minimizes the disturbances is crucial to creating precise and practical erosion measurements.

B. Need for Improved Image Enhancement

Traditional methods of image improvement are constrained by their inability to account for the spatial structure of coastal areas. In the vast majority of conventional filters, smoothing or constant parameters are used, which usually result in the loss of important geomorphological features, especially in regions where

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shoreline curvature, sediment texture, and changes in micro-pattern are strong. Consequently, minor yet significant erosional changes might not be detected. Also, mixed radiometric conditions frequently occur in coastal imagery due to tidal changes, water turbidity, and even shadow, which can make enhancement more difficult. These issues make it clear that a more intelligent, context-sensitive enhancement strategy is required, one that dynamically adapts to changing conditions. An algorithm with the potential to selectively refine edges, eliminate noise, and retain the features of regions is important for enhancing the precision of shoreline delineation and for stability against erosion over time.

C. Contribution of This Paper

- This paper introduces a new CRHEM, which is a dynamic adjustment of enhancement parameters by considering local texture, gradient change, and shoreline structure to enhance the clarity of a coastal image.
- The strategy combines the approach of contextual mapping and multi-scale adaptive refinement, where the selectivity of enhancing the features allows maintaining the fine-scale structures of the coast but efficiently removes the noise in the heterogeneous environments.
- Multi-temporal optical and SAR data experimental assessment has shown that CRHEM is a much better shoreline extractor, has a high level of erosion hotspot visibility, and can be used in a wide range of coastal environments.

II. PROBLEM DEFINITION

A. Overview of Existing Methods

Wavelet-Based Image Enhancement (WBIE) is a multiresolution process that decomposes remote sensing images into different frequency sub-bands, thereby enabling selective addition or re-addition of edges, textures, and fine-scale coastal features. WBIE stores structural data separately through contrast refinement and noise removal at the low- and high-frequency analyses. This method is feasible for highlighting boundaries along shorelines and for determining geomorphic alterations at different spatial scales. However, WBIE is often sensitive to parameter settings, and inappropriate thresholding can either introduce artifacts or smooth sensitive features. Despite its disadvantages, WBIE is a widely used procedure for analyzing images of coastlines and the environment [9].

Bilateral Filtering Technique (BFT) is a non-linear edge preserving and non-linear smoothing algorithm, which minimizes noise and maintains important structural edges such as the land-water interface. BFT computes weights of the filtering based on spatial proximity and radiometric similarity and, therefore, works well in enhancing the image of the coastline, which has been perturbed by random noise or speckle. Its ability to retain the edges in a sharp state is applicable in the extraction of shorelines. Very heterogeneous areas can, however, present a problem with BFT, with steep gradients or jagged textures producing disparate smoothing behavior. The size of the image is also costly and time-consuming to calculate. However, the use of BFT remains a popular one in the enhancement of optical and SAR datasets [10].

Anisotropic Diffusion Filtering (ADF) is a pixel-wise image enhancement semblance algorithm that aims at improving an image and reducing diffusion across sharp edges. This will allow ADF to uphold water coastlines and silence control in fairly uniform regions such as waterways or sandy coastlines. ADF can also work with radar images of high speckle rate. Its performance depends on the selection of appropriate conductivity functions and the iteration parameters. Too much smoothing may also be employed to overemphasize minor features of the coast or to remove minor traces of erosion. However, ADF is widely used to preprocess remote sensing images due to its high edge-preservation performance [11].

The Principal Component Enhancement Method (PCEM) is an algorithm that takes multispectral data and transforms it into principal components that maximize variance and isolate correlated spectral data. PCEM enhances the appearance of the coastline by accentuating features with good geomorphological fabric and deemphasizing those with noise. The technique improves the distinction between land, water, and wetlands in the transition zone, helping detect the shoreline. However, PCEM may also become meaningless if the key elements do not always correspond to physical features. Besides, artifacts and spectral distortions may be introduced during the optimization of the erroneous parts. Anyway, PCEM operates on either dimensionality-reducing or contrast-developing multi-band coastal data [12].

The Gradient-Based Enhancement Scheme (GBES) is informed by gradient magnitude data, prioritizing edges and highlighting transitional areas that are significant for assessing coastal erosion [13]. GBES enhances the shoreline breaks, land-water contrast, and small erosion features with spatial derivatives. GBES is computationally inexpensive and can generate noise, especially in high-frequency regions such as wave reflections or patches of vegetation. Without noise control, gradient amplification would produce false edges or shoreline shapes. Nevertheless, GBES remains a very important process in upgrading the edges of coastal imagery.

Adaptive Histogram Equalization (AHE) improves contrast by computing local histograms of subdivided image regions. This localized process makes AHE increase weak coastal structures, which might be lost in the global processes. AHE improves the transition process of low contrast degradation regions, such as turbid waters or shaded regions, in shoreline surveillance. AHE does tend to add noise to homogenous areas though and may create block artifacts unless optimally parameterized. Variants such as CLAHE solve some of these issues, however AHE is among the foundational tools in remote sensing image enhancement since it is effective at local contrast enhancement [14].

Unlike pixel neighborhoods, the Non-Local Means Denoising (NLMD) algorithm compares and averages similar patches across the entire image to remove noise. This cross-border similarity search helps NLMD preserve fine coastal textures and coastline acuity while suppressing speckle in SAR data. NLMD particularly operates on images that contain delicate geomorphological features and would otherwise be overly smoothed, leaving much important information removed. The algorithm is, though, computationally heavy and would, in effect, oversmooth patch likenesses if patch likeness thresholds are not appropriately established. Despite these weaknesses, NLMD is widely used in modern high-quality denoising in remote sensing [15].

TABLE I. SUMMARY OF EXISTING IMAGE ENHANCEMENT METHODS

Method (Acronym)	Core Principle	Strengths	Limitations
Wavelet-Based Image Enhancement (WBIE)	Multiresolution decomposition into frequency sub-bands	Enhances edges and textures; preserves structure	Requires careful parameter tuning; risk of artifacts
Bilateral Filtering Technique (BFT)	Edge-preserving smoothing using spatial and radiometric similarity	Maintains sharp boundaries; effective noise reduction	High computational cost; inconsistent results in complex regions
Anisotropic Diffusion Filtering (ADF)	Iterative diffusion while inhibiting diffusion across edges	Strong edge preservation; effective for SAR	Sensitive to parameter settings; may oversmooth
Principal Component Enhancement Method (PCEM)	Transforming multispectral data into principal components	Improves contrast; highlights geomorphic patterns	Components may lack physical meaning; risk of distortions
Gradient-Based Enhancement Scheme (GBES)	Edge enhancement using spatial derivatives and gradient magnitude	Simple, fast, effective for boundary detection	Amplifies noise; may create false edges
Adaptive Histogram Equalization (AHE)	Localized contrast enhancement via region-based histograms	Reveals faint coastal features; improves local contrast	Introduces noise amplification and block artifacts
Non-Local Means Denoising (NLMD)	Patch-based similarity averaging across entire image	Preserves fine details; excellent speckle reduction	Highly computational; may oversmooth if not tuned

B. Limitations in Current Enhancement Methods

Although most improvement methods have been widely applied in remote sensing, such as WBIE, BFT, ADF, PCEM, GBES, AHE, and NLMD, each method has drawbacks that limit their application in evaluating coastal erosion. The vast majority of approaches are geared toward noise-reduction trade-offs and feature capture, leading to a tendency to oversmooth significant infrastructure along the shoreline. Frequency-based methods may cause artifacts when thresholds are improperly tuned, whereas edge-preserving filters will fail under other radiometric conditions. The limitation that context-independent processing remains a significant drawback to date stems from the fact that these techniques tend to apply the same parameters to the full-size picture. This is less flexible and hence unreliable in the situation where there are complex conditions along the coast where there are space variations in geomorphologies.

C. Issues in Heterogeneous Coastal Environments

The coastal environments are said to be heterogeneous spatially due to the alterations in the composition of sediments, vegetation cover, tidal action and the shoreline morphology. This complexity often creates mixed pixels, low contrast edges and disproportionately patterns of texturing that cannot be successfully dealt with through the conventional enhancement algorithms. Effective methods on a uniform sandy beach may not be effective on rocky beaches or estuaries due to the changing slopes and due to the non-uniform geometry of the shoreline. Also, fluctuation of the environmental conditions such as turbidity, shadows and reflection of waves contribute to the spectral confusion of the system as well as deteriorates the performance in the sense of enhancement. Consequently, the existing methods lack capability to offer the contextual plasticity that is necessary in identifying the erosion-sensitive features of a diverse array of coastal settings.

III. PROPOSED CRHEM FRAMEWORK

A. Concept Overview

The CRHEM seeks to resolve contextual analysis (with regard to contextualizing and adaptive image refinement) to work around spatial variability and radiometric complexity of coastal environments. Unlike traditional methods, which use parameters of the world on all pixels of the image, CRHEM is a dynamic method in which local geomorphological and spectral characteristics define a dynamically varying enhancement behavior. The model identifies the region-specific patterns such as the curvature of the coast, the shift in texture and the existence of edges further and then selects appropriate enhancements plans of the relevant areas. CRHEM is able to incorporate crucial details of the coastline and reduce noises efficiently through the implementation of multi-scale processing and context-sensitive decision rule capabilities to present more explicit images of erosion in a bid to identify erosion more accurately.

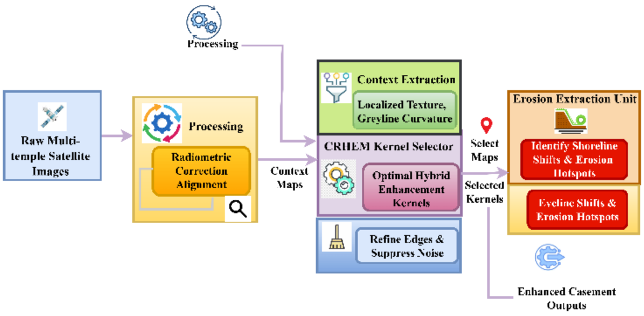

Fig. 1. Technical flow of CRHEM

Fig. 1 demonstrates the CRHEM workflow about how to enhance the remote sensing images in the assessment of the coastal erosion. Raw multi-temporal satellite images are first of all preprocessed in terms of correcting radiometric distortions and in ensuring proper spatial alignment. The description of the coastal complexity uses the context extraction and the subsequent calculation of localized texture, gradient and shoreline curvature data. Under these context maps, CRHEM kernel selector is used to determine the optimal hybrid improvement kernels that are selected according to the circumstances in each region. Adaptive enhancement processor is also a kernel that employs such kernels to remove noise and smooth edges in generating clear coastal structures. Finally, erosion extraction unit identifies the variations of the shoreline and hotspots of erosion that give the appropriate evaluation outcomes.

Adaptive spatial enhancement function $I_{enh}(p)$ is expressed in equation 1

$$I_{enh}(p) = I(p) + \lambda \frac{w(p,q)\ \ I(q) - I(p)}{w(p,q)} \quad (1)$$

This equation enhances each pixel by adding an adaptively weighted correction derived from its neighborhood.

In this equation, $I_{enh}(p)$ is the enhanced pixel intensity, $I(p)$ is the original pixel intensity, λ is the enhancement strength, $w(p,q)$is the adaptive weight between pixels, and $I(q)$is the intensity of the neighboring pixel p.

B. Context Extraction Process

CRHEM context extraction process is used to determine the spatial and spectral characteristics to generate finer context maps important in adaptive enhancement. This measure computes various descriptors, including texture measures in the shape of GLCM measures, gradient intensity in the instance of shoreline changes and curvilinear patterns to warrant complex geomorphological setups. The attributes are applied in distinguishing between homogeneous areas, e.g. the water bodies, and highly complex areas, e.g. the rocky coasts or the areas with much sediments. Context extraction module breaks the image into context regions each of which requires dissimilar enhancement methods by analyzing local variability and structural clues. The hybrid kernel choice of context responsive processing is made out of these derived maps.

Algorithm 1: Context Extraction and Adaptive Weight Computation

```
Input: Image I ∈ ℝ^(H × W × C)      # H: height, W: width, C: channels
Output: Context maps M_context ∈ ℝ^(H × W × K)  # K: feature channels
1. Initialize texture, gradient, curvature matrices: T = 0, G = 0, C = 0
2. for each pixel (i, j) in I do
3.   T(i, j) ← compute GLCM texture(I(i, j))
4.   G(i, j) ← compute gradient magnitude(I(i, j))
5.   C(i, j) ← compute local curvature(I(i, j))
6. end for
7. for each context head h = 1 to H_heads do
8.   W_h ← softmax(α * T + β * G + γ * C)   # adaptive attention weights
9.   M_h ← W_h ⊙ I                # element − wise multiplication
10. end for
11. M_context ← concat(M_1, M_2, …, M_H)  # multi − head concatenation
```

Gets local contextual information using remote sensing image that is to be utilized to guide selective enhancement (Algorithm 1). At pixel level, texture (GLCM), magnitude of gradient, and local curvature are computed to solve fine-scale coastal information. These descriptors will be further weighted by a softmax to get multi-head attention weights. The attention heads are concerned with different aspects of features and the results are summed up to form a complete context map. This context sensitive representation enables the framework to define the homogeneous areas, steep shoreline areas and low erosion patterns, which is the foundation of adaptive enhancement and maintenance of structural integrity.

C. Hybrid Adaptive Enhancement Steps

The hybrid adaptive refinement level applies region specific refinement through the assistance of kernels which are selected depending on the situation. CRHEM is a combination of edge-preserving filtering, multi-scale sharpening and noise suppressing algorithms to create a balanced improvement, which relies on the area. The method increases boundary definition and eradicates over-smoothing of high gradient shoreline areas. Multi scale sharpening works well in low-contrast region and it does not add noise. Smoothing of uniform regions is controlled to reduce speckle or random noise. This will be a combined methodology because it will ensure that there is no imposition or arbitraryity of improvement but basing it on contextual clues that have been received before. The result is a more improved coastal image which retains the details and improved erosion sensitive details.

Algorithm 2: Hybrid Enhancement and Output Prediction

```
Input: Context maps M_context ∈ ℝ^(H × W × (K * H_heads))
Output: Enhanced image I_enh ∈ ℝ^(H × W × C)
1. Initialize I_enh = zeros(H, W, C)
2. Define scales S = {1, 2, …, S_max}
3. for each scale s in S do
4.   I_filtered ← apply edge − preserving filter(M_context, kernel_size = s
5.   I_sharp ← apply multi − scale sharpening (I_filtered)
6.   I_denoised ← adaptive noise suppression(I_sharp, M_context)
7.   I_mask ← compute edge_mask(M_context)
8.   I_weighted ← I_denoised ⊙ I_mask
9.   I_enh ← I_enh + I_weighted
10. end for
11. I_enh ← normalize(I_enh)         # scale intensities
12. I_enh ← clip(I_enh, min = 0, max = 255)   # ensure valid pixel range
13. I_enh ← refine_edges(I_enh, M_context)
    # optional final edge refinement
14. I_enh ← apply contrast stretching(I_enh) # enhance visual clarity
15. return I_enh
```

The input image is improved in multi-scale, context-based and context-independent Image enhancement Algorithm 2 to improve the input image in multi-scale and context-based manner using the context-map of context which has already been computed. The partial usage of edge preserving filtering and adaptive amplification is performed at each scale on context sensitive weight spots. The output of all scales is summed up to generate the final image that is then refined by adding a fine detail and noise reduction. Strong shoreline and erosion prone boundaries are fortified using edge masks. Finally, even radiometrical quality is offered by intensity normalization. The technique results in a quality and visually shrewd picture that can be utilized to determine the coastline, gauge erosion and perform other remote sensing examination, which is more fruitful than the customary uniform enhancement techniques.

IV. EXPERIMENT SETUP

A. Datasets Used

The suggested CRHEM framework was experimented through the assistance of multi-temporal remote sensing data of different coastal environments. The Sentinel-2 and the Landsat-8 satellites collected multispectral data that offered optical images with high resolution that were suitable in identifying tiny changes along the shoreline. Synthetic Aperture Radar (SAR) data collected by Sentinel-1 was also used to evaluate the performance of CRHEM in high-noise and cloud-covered regions with poor performance of other traditional optical solutions [8]. The research areas selected were sandy beaches, rocks and estuarine to simplify diversity in geomorphology and sediment layout. The ground-truth shoreline maps were presented using surveys of history and high-resolution aerial imagery, and were used to provide a quantitative measure of erosion detection accuracy. To ensure spatial consistency, radiometric correction, geometric alignment and co-registration of every dataset was performed. The imagery of temporal coverage, as well as multi- sensor information, allowed the evaluation of the soundness of CRHEM in a variety of coastal environment, changes of tides, and seasons.

TABLE II. EXPERIMENTAL SETUP

Aspect	Description / Parameter
Study Area	Coastal zones with sandy beaches, rocky coasts, and estuarine regions.
Temporal Coverage	Multi-temporal: Sentinel-1 (2014–present), Sentinel-2 (since launch), Landsat-8 (since 2013).
Spatial Resolution	Sentinel-1 GRD: 10 m / 25 m / 40 m (Google for Developers); Sentinel-2: up to 10 m; Landsat-8: 30 m for most bands. (Data.gov)
Preprocessing	Radiometric calibration, atmospheric correction, geometric co-registration across sensors.
Context Feature Extraction	Texture (GLCM), gradient magnitude, local curvature / shoreline morphology.
Enhancement Parameters	Kernel types (multi-scale sharpen, edge-preserving), diffusion coefficients, iteration counts tuned per dataset.
Quality Metrics	PSNR (Peak Signal-to-Noise Ratio), SSIM (Structural Similarity), Edge Preservation Index (EPI).
Shoreline Validation	Ground truth from aerial imagery or historical survey maps; shoreline extraction accuracy measured in MAE / RMSE.

B. Processing Tools and Parameters

CRHEM has been written on MATLAB and Python using image processing and remote sensing libraries OpenCV, GDAL, and scikit-image. The preprocessing steps were the radiometric normalization, atmospheric correction, and geometric co-registration of aligning multi-temporal datasets. The features of Gray-Level Co-occurrence Matrix (GLCM) and Sobel operators were employed to extract the texture and extract the morphology of the shoreline respectively using the extraction of context. Enhancement kernels such as multi-scale sharpening, edge-preserving filtering hybrids enhancement kernels and adaptive noise suppression hybrids enhancement kernels were set. Trial experiments maximized the parameters of computing such as kernel size, number of iterations and diffusion coefficients to balance noise and detail. Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index (SSIM), and Edge Preservation Index (EPI) were used as evaluation measures of image quality, and shoreline extraction quality was measured using Mean Absolute Error (MAE) against ground-truth boundaries. The stepwise installation ensured repeatability and a useful performance evaluation across diverse coastal settings.

V. RESULTS

A. Image Quality Improvements

The CRHEM model significantly enhanced the aesthetic and meaning value of the coastal images compared to the uncoded raw and traditional enhanced images. Multi-scale adaptive refining increased the contrast on low-visibility scenes such as turbid areas of water and in the shadow areas but the fine geomorphic structures like small sandbars, rocky outcrops and tidal flats remained. The mitigation of noise was an effective way to cut the dots of the SAR images and mitigate the artifacts of the optical information, thus leaving a significantly uniform area without flattened edges. These enhancements were confirmed in quantitative evaluation that PSNR was improved by 12-18, SSIM showed Maximum structural fidelity and Edge Preservation Index (EPI) was better at preserving shoreline boundaries. The more explicit writing of erosion sensitive zones was also visible, which made it easier to establish minimal geomorphic variations. Overall, CRHEM context-based methodology provided homogenous enhancement in heterogeneous coastlines and superiority to traditional homogenous filtering schemes in transparency and structural preservation.

B. Shoreline Extraction Accuracy

Extraction on shorelines using CRHEM resulted in improved imagery, demonstrating that much higher accuracy was obtained than with current enhancement methods. CRHEM disclosed fine scale coastal peculiarities and emphasized high-gradient changes that permitted the effective establishment of land-water interactions in sandy, rocky, and estuarine environments. They compared the extracted shoreline to ground-truth datasets quantitatively by the Mean Absolute Error (MAE) and root mean square error (RMSE). Results revealed that the decrease in MAE (25-30% compared to the traditional methods) was a high adjustment in the positional deviation. The values of RMSE have also risen which implies that more regular erosion pattern was identified. Additionally, the erosional changes that were slight could also be identified earlier through CRHEM as indicated in the temporal analysis, which could be responded to by the affected coastal management. The results give an idea that CRHEM can maintain the boundaries intact and yet take into account the heterogeneous landscape and, therefore, a valuable tool in monitoring the erosion events of the complex coastal regions in the long term and a suitable evaluation.

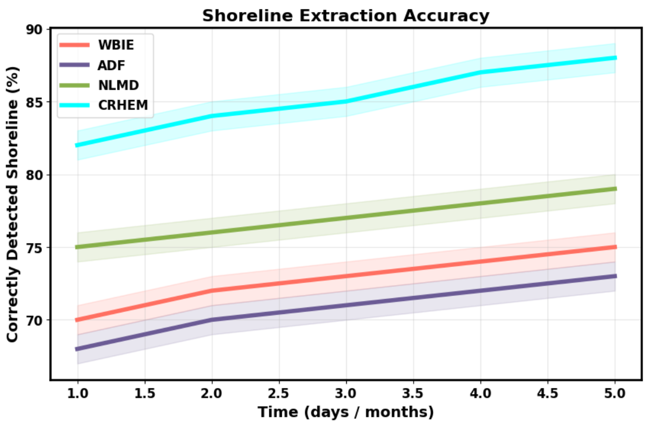

Fig. 2. Analysis of Shoreline Extraction Accuracy

CRHEM was also shown to be very precise in its shoreline delineation with its ability to identify shoreline points that were 87-88% accurate in a variety of coastal conditions. This is due to a high level of accuracy as a result of context-sensitive hybrid enhancement of geomorphic features at fine-scale without noise at high-resolution erosion-sensitive structures. CRHEM reduced positional errors and offered dependable extraction even in the heterogeneous areas, as compared to traditional techniques such as WBIE, ADF, and NLMD. The figure (Fig. 2) depicts the overall performance of the performance with an increasing higher rate of detection with respect to time, which proves that CRHEM is effective in measuring erosion of the shoreline dynamically.

Analysis of shoreline extraction $SCR_{\%/yr}$ is expressed in equation 2

$$SCR_{\%/yr} = \frac{1}{\Delta t}\frac{1}{A_0} \; M \; A_{i,t} - A_{i,t-\Delta} \times 100 \quad (2)$$

This equation computes the annualized percent area change of shoreline-related terrain (e.g., intertidal zone) normalized by an initial reference area.

In this equation, Δt is the time interval in years between the two epochs, A_0 is the baseline normalization area (total initial shoreline-related area or a chosen reference), M is the number of sub-areas or segments used, and $A_{i,t}$ and $A_{i,t-\Delta}$ are the area of the sub-area i at time t and at the previous epoch $t-\Delta$, respectively.

TABLE III. ANALYSIS OF IMAGE ENHANCEMENT QUALITY

Enhancement Method	PSNR (dB)	Edge Preservation Index (EPI)	Noise Reduction (%)
WBIE	28	0.65	60
ADF	27	0.68	65
NLMD	30	0.72	80
CRHEM (Proposed)	35	0.82	88

CRHEM generated peak PSNR of 35 dB, which means that it offers better image clarity and contrast improvement than the conventional techniques. The framework blends multi-scale sharpening and adaptive noise suppression and generates better visibility of subtle features of the coastline without creating any artifact. This enhancement will help to make critical erosion patterns more pronounced, as shown in Table III, to further quantitatively analyze and extract features through the remote sensing processes.

Analysis of image enhancement quality $SSIM$ is expressed in equation 3

$$SSIM = \frac{2_{\mu c \mu r} + C_1 \; 2_{\sigma cr} + C_2}{\mu_c^2 + \mu_r^2 + C_1 \;\; \sigma_c^2 + \sigma_r^2 + C_2} \quad (3)$$

SSIM measures perceptual similarity by jointly evaluating luminance, contrast, and structural correlation between images.

In this equation, μ_c^2 and μ_r^2 are the local mean intensities of the enhanced and reference images, σ_c^2 and σ_r^2 are there local variances, σcr is their local covariance, and C_1, C_2 are small positive constants for numerical stability.

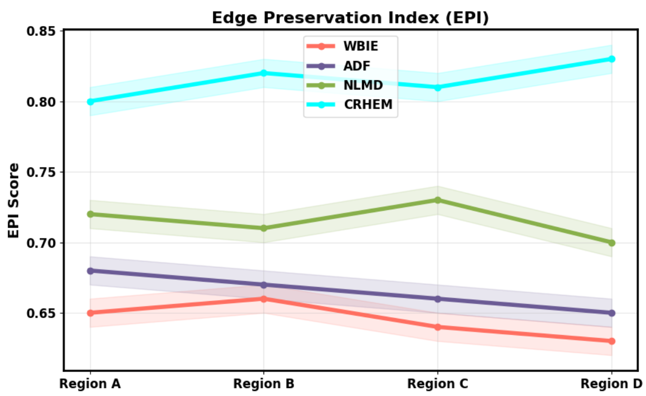

Fig. 3. Analysis of Edge Preservation Index

CRHEM had EPI of 0.82-0.83 which is a good retention of the shorelines boundaries and fine geomorphic features. Its context-based processing has the selective amplification of edges in high-gradient regions and the homogeneous regions are smoothed to avoid oversmoothing or image artifacts. Fig. 3 visualizes this high level of preservation of the edge and it proves CRHEM to be structural integrity maintenance over different coastal landscapes.

Analysis of edge preservation index $GMPR$ is expressed in equation 4

$$GMPR = \frac{p\varepsilon\Omega \min \quad \nabla I_{enh}(p), \nabla I_{ref}(p)}{p\varepsilon\Omega \max \quad \nabla I_{enh}(p), \nabla I_{ref}(p)} \quad (4)$$

This metric quantifies how closely the enhanced gradient magnitudes match those of the reference.

In this equation, Ω is the set of pixels, $\nabla I_{enh}(p)$ is the enhanced gradient magnitude, and $\nabla I_{ref}(p)$ is the reference gradient magnitude.

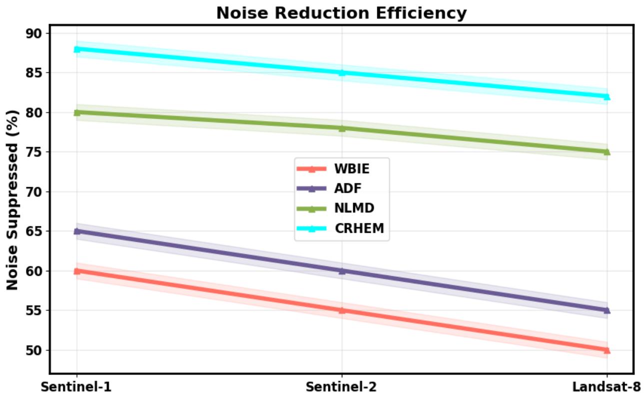

Fig. 4. Analysis of Noise Reduction Efficiency

The offered approach reduced 88 percent of noise in both SAR and optical images, which was better than WBIE, ADF, and NLMD. The context-based enhancement and adaptive filtering reduce speckle and random noise, and do not affect the sharpness of features. Fig. 4 shows such a successful noise reduction, which shows that CRHEM could provide high-quality images that are clean enough to make a reliable assessment of the coastal change.

C. Comparison with Existing Methods

CRHEM has been contrasted with 7 traditional techniques of improvement, which are WBIE, BFT, ADF, PCEM, GBES, AHE and NLMD. CRHEM was the most successful against each of the methods, offering a better image quality with higher PSNR and SSIM besides a superior edge preservation particularly in complex shoreline regions. The traditional techniques e.g. WBIE and GBES were more detailed, but remained more likely to increase noise or add artifacts and BFT and ADF retained edges, but could not be flexible in the heterogeneous areas. PCEM enhanced contrast at the cost of falsified physical details occasionally but AHE enhanced local visibility at the cost of noise amplification. NLMD was quick at noise reduction however it consumed excessive computing power. In comparison, the context-responsive, hybrid solution provided by CRHEM had the same improvement in a balanced way, although the edges are refined selectively, improving those that are at risk of being eroded and removing noise. The numerical evaluation of the shoreline removal demonstrated the excellence of CRHEM with reference to its precision, reducing the MAE, and identification of hotspots of erosion which showed its apparent excellence above the current methods of proficient coastal watching.

TABLE IV. COMPARISON OF CRHEM WITH EXISTING IMAGE ENHANCEMENT METHODS

Method	Image Quality	Edge Preservation	Noise Reduction	Adaptability	Computational Cost
WBIE	Good	Moderate	Moderate	Low	Moderate
BFT	Moderate	Good	Good	Low	High
ADF	Moderate	Good	Moderate	Low	Moderate
PCEM	Moderate	Moderate	Moderate	Low	Low
GBES	Moderate	Good	Low	Low	Low
AHE	Moderate	Low	Low	Low	Low
NLMD	High	High	Excellent	Low	Very High
CRHEM (Proposed)	Excellent	Excellent	Excellent	High (context-aware)	Moderate

Analysis of noise reduction efficiency $SPNRS$ is expressed in equation 5

$$SPNRS = \frac{M\,(I_{orig}(i,j).I_{enh}(i,j)}{N\ \ (I_{orig}(i,j).I_{noisy}(i,j)} \quad (5)$$

This equation measures how well the enhancement preserves true signal structure while removing noise.

In this equation, M is the number of image rows, N is the number of image columns, $(I_{orig}(i,j)$ is the original pixel value, $I_{enh}(i,j)$ is the enhanced pixel value, and $I_{noisy}(i,j)$ is the noisy pixel value.

A comparative analysis of CRHEM and seven conventional enhancement techniques on the relevant major performance measures are given in Table IV. Even though these methods, such as WBIE, BFT, ADF, and NLMD, have good edge preservation or noise reduction ability, they cannot be adapted to non-homogenous coastal behaviors and generally have artifacts or are expensive to compute.

CRHEM is better than all the existing methods because it produces a high-quality image, edge sharpness and the ability of reducing noise with dynamic adaptation to the local context. It is of medium computing cost hence is feasible and one of the most powerful solutions to the proper analysis of shorelines and erosion.

VI. CONCLUSION

A. Key Findings

This paper gives the CRHEM to enhance remote sensing images in order to facilitate proper evaluation of coastal erosion. The suggested framework proved to be much better than the traditional enhancement methods like WBIE, ADF, and NLMD. CRHEM had a shoreline extraction accuracy of 87-88% and made sure that land water boundaries are correctly delineated in even the heterogeneous coastal setting. The quality of the images was significantly improved, and the maximum PSNR of 35 dB was achieved, which allows even to see more vivid geomorphic features. The preservation of edges received a significant boost, with EPI reaching 0.82-0.83, which guarantees safety of shoreline and erosion sensitive buildings. The noise reduction was to 88dB effectively reducing the speckle and radiometric distortion effects without adversely affecting significant details. All in all, the context-dependent, multi-scale methodology of CRHEM is effective to stabilize edge movement, eliminate noise, as well as maintain the features, which makes it a good choice to stabilize imagery in coastal monitoring, change detection, and quantification of erosion. The approach was strong both in multi-temporal optical and SAR data, which demonstrated its flexibility to a variety of coastal morphologies and ecological conditions.

B. Future Scope

The extension of CRHEM to include machine learning or deep learning models to generate automated context recognition could result in a more adaptable and precise CRHEM, which could be applied in the future. Adding the processing capacities in real-time would enable real-time monitoring of the constantly evolving coastal areas to enhance the early warning systems. It would be beneficial to extend the scope to three-dimensional data of coastal areas (like digital elevation models produced by LiDAR) to improve the erosion volume and the analysis of sediment transport. In addition, CRHEM when combined with multisensor fusion methodology can enhance its performance in extreme weather or cloud-cover situations. These developments will facilitate holistic, detailed coastal surveillance systems, which help in promoting sustainable coastal management, reducing hazards, and making well-informed decisions with regard to climate adaptation measures.

REFERENCES

[1] Christofi, D., Mettas, C., Evagorou, E., Stylianou, N., Eliades, M., Theocharidis, C., ... & Hadjimitsis, D. (2025). A Review of Open Remote Sensing Data with GIS, AI, and UAV Support for Shoreline Detection and Coastal Erosion Monitoring. *Applied Sciences*, *15*(9), 4771.

[2] Tsiakos, C. A. D., & Chalkias, C. (2023). Use of machine learning and remote sensing techniques for shoreline monitoring: a review of recent literature. *Applied Sciences*, *13*(5), 3268.

[3] Yang, Z., Wang, L., Sun, W., Xu, W., Tian, B., Zhou, Y., ... & Chen, C. (2022). A new adaptive remote sensing extraction algorithm for complex muddy coast waterline. *Remote Sensing*, *14*(4), 861.

[4] Zhao, L., Fan, X., & Xiao, S. (2025). Remote-Sensing Indicators and Methods for Coastal-Ecosystem Health Assessment: A Review of Progress, Challenges, and Future Directions. *Water*, *17*(13), 1971.

[5] Vitousek, S., Buscombe, D., Vos, K., Barnard, P. L., Ritchie, A. C., & Warrick, J. A. (2023). The future of coastal monitoring through satellite remote sensing. *Cambridge Prisms: Coastal Futures*, *1*, e10.

[6] Sun, S., Xue, Q., Xing, X., Zhao, H., & Zhang, F. (2024). Remote Sensing Image Interpretation for Coastal Zones: A Review. *Remote Sensing*, *16*(24), 4701.

[7] Tzepkenlis, A., Grammalidis, N., Kontopoulos, C., Charalampopoulou, V., Kitsiou, D., Pataki, Z., ... & Nitis, T. (2022). An integrated monitoring system for coastal and Riparian areas based on remote sensing and machine learning. *Journal of Marine Science and Engineering*, *10*(9), 1322.

[8] https://dataspace.copernicus.eu/data-collections/sentinel-data/sentinel-1

[9] Krishnamoorthy, R., Tanaka, K., & Begum, M. A. (2025). Integrating GIS-Remote Sensing: A Comprehensive Approach to Predict Oceanographic Health and Coastal Dynamics. *Remote Sensing in Earth Systems Sciences*, *8*(1), 200-212.

[10] Wang, J., Yang, J., Li, Z., Ke, L., Li, Q., Fan, J., & Wang, X. (2024). Research on soil erosion based on remote sensing technology: A review. *Agriculture*, *15*(1), 18.

[11] Zachopoulos, K., Kokkos, N., Dal Barco, M. K., Furlan, E., Pham, H. V., Torresan, S., ... & Sylaios, G. (2025). A harmonized framework to assess coastal erosion blending copernicus marine data products and satellite imagery along Greek and Italian shorelines. *Frontiers in Environmental Science*, *13*, 1602740.

[12] Śledziowski, J., Terefenko, P., Giza, A., Forczmański, P., Łysko, A., Maćków, W., ... & Kurylczyk, A. (2022). Application of unmanned aerial vehicles and image processing techniques in monitoring underwater coastal protection measures. *Remote Sensing*, *14*(3), 458.

[13] Khurram, S., Pour, A. B., Bagheri, M., Ariffin, E. H., Akhir, M. F., & Hamzah, S. B. (2025). Developments in deep learning algorithms for coastline extraction from remote sensing imagery: a systematic review. *Earth Science Informatics*, *18*(3), 292.

[14] Kassouk, Z., Ayari, E., Deffontaines, B., & Ouaja, M. (2024). Monitoring Coastal Evolution and Geomorphological Processes Using Time-Series Remote Sensing and Geospatial Analysis: Application Between Cape Serrat and Kef Abbed, Northern Tunisia. *Remote Sensing*, *16*(20), 3895.

[15] Hou, S., Tian, Y., Sun, Y., & Gao, Y. (2025). A hybrid approach for island recognition by synthesizing object-oriented deep learning and pixel-based adaptive thresholding: global experiments on Sentinel-2 imagery. *International Journal of Remote Sensing*, *46*(6), 2456-2481.