Coastline Detection from Remotely Sensed Imagery: Development of a Methodology Based on Advanced Smoothing Techniques and the Canny Edge Detector

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Abstract. Coastline extraction is a task of fundamental importance for coastal zone management and its accurate detection has greatly concerned the scientific community for more than a decade. In this paper an algorithm for the semi-automatic coastline detection from remote sensing data was designed and developed. The algorithm consists of three processing steps. In the first step, certain edge-preserving filters were applied for data enhancement, smoothing and simplification. Then, image edges were detected based on the Canny edge detector and resulted pseudo-edges or undesirable ones were eliminated based on certain processing techniques, namely measurements of entropy, K-means clustering and thresholding. In the final step, a post-processing scheme was implemented in order to deal with the connectivity of the detected coastline based on mathematical morphology operators. The developed methodology was applied on six high resolution QuickBird and WorldView-2 images, one medium resolution ASTER image and two high resolution TerraSAR-X radar data. A quantitative and qualitative evaluation was performed using the standard measures of completeness, correctness and quality. The comparison with the ground truth data from photo-interpretation demonstrated the effectiveness of the developed algorithm.

Keywords. Edge preserving smoothing, anisotropic diffusion, morphological levelings, K-means clustering, entropy.

1. Introduction

Following the definition of the European Environment Agency (EEA), a coastline is a *'line that separates a land surface from an ocean or a sea'* and constitutes one of the most important linear characteristics of the Earth's surface. It refers to a spatially continuous line of contact between the land and a body of water [1]. Coastline mapping and change detection are essential for safe navigation, environmental protection, resource management and sustainable coastal development and planning. Knowledge of coastline is the basis for measuring and characterizing land and water resources [2].

The development of geographical information systems in combination with availability of more and more accurate data in digital format, allow for the development of automated systems in order to extract certain elements, such as coastlines. At the same time, since a large amount of data can be available in real time and it is important to be managed systematically and in a short time, research and realisation of semi-automatic and automatic procedures of processing and extraction of geoinformation are essential for environmental monitoring [3].

On this demand and according to the trends of the literature, many algorithms have been developed by geographers, geologists, geophysicists, mathematicians, foresters, engineers (such as geomatic, electrical, civil, cartographers and surveyors), computer scientists, oceanographers and others. The algorithms used come under the fields of Image Processing and Computer Vision in approximately 80%, as opposed to software packages. It was observed that segmentation is by far the most commonly applied technique for coastline detection, due to its utility to reduce spatial redundancy. Classification, edge detectors and other techniques, e.g. mathematical morphology, measurements of texture, rational functions, snakes, level sets, calculation of the first and the second derivative, Markov Random Fields, have been used, as well [3].

Segmentation in three processing steps was used by Liu and Jezek (2004) [2], as well. Pre-segmentation tasks were noise removal and edge enhancement by using isotropic and anisotropic diffusion filters. Their segmentation algorithm included a locally adaptive thresholding routine taking into account the local characteristics of land and water bodies. After removing some left over isolated pixels, the closing operator from mathematical morphology was applied during a post-segmentation step in order to smooth the detected coastline.

Armenakis and Savopol (2004) [4] presented a semi-automatic methodology based on object-based analysis. They used image processing and GIS tools, combined with a spatial constraint. Therefore, water masses detection and extraction was based on thresholds, spectral, spatial and Boolean ‘AND’ operators. The spatial constraint was the notion that water bodies are located in areas with zero or minimum terrain slope.

Karantzalos (2007) [5] applied three basic steps in his approach. Initially, image enhancement and smoothing took place, applying both classical, e.g. Gaussian filter and advanced techniques, e.g. anisotropic diffusion. The goals were noise removal, image simplification, enhancement of its contrast and retaining only features at certain desirable scales. Following, an edge detector was applied in order to extract the coastline edges. However, the objective was to retain only the coastline edges, since all edges were detected. This was achieved by analyzing the texture of the image, using two-dimensional Gabor filtering. Final position of coastline resulted from the fusion of both edge detection and texture analysis information.

Puissant et al. (2008) [6] proposed an approach in two steps, based on the hit-or-miss transform and according to the geomorphologic context of the coastline. After performing two detections of possible coastline pixels (respectively without false positive and without false negative), they combined the results through a double thresholding procedure followed by a final marker-based watershed to locate the exact coastline.

Inspired by diffusion snake, the work of Li et al. (2009) [7] was based on B-spline function, curve evolution and the cartoon model of Mumford-Shah functional. The results showed that comparing to the classical snake method, their work was robust to noise and the initial curve position, less control points were used and no pre-processing and post-processing of the image was needed. However, when the curves vary very sharply, their boundaries cannot be accurately detected.

In this paper, the main goal was the development of a methodology for high resolution data. At the same time, the possibility of its extension in medium resolution as well as SAR data was investigated. Other objectives were the application of the Canny edge detector and various pre-processing, main-processing and post-processing techniques to a wide range of data. Similar to Liu and Jezek [2] and Karantzalos [5], pre-processing techniques such as the anisotropic diffusion algorithms of Perona & Malik [8] and Alvarez, Lions & Morel [9], alternating sequential filtering and morphological levelings were applied. Extending the work of Karantzalos [5], alternative formulations were developed to retain only the coastline edges, such as K-means clustering. Post-processing techniques included various mathematical morphology tools [2]. Final objectives were the quantitative and qualitative evaluation of the results and the mapping scales simulated.

2. Methodology

The developed approach was composed by three basic processing steps: pre-processing, main-processing and post-processing. The structure of the methodology is presented in Figure 1.

The developed methodology was applied on six high resolution pan-sharpened QuickBird and WorldView-2 images (0.7m and 0.5m, respectively), one medium resolution ASTER image (15m) and two high resolution TerraSAR-X data (3m).

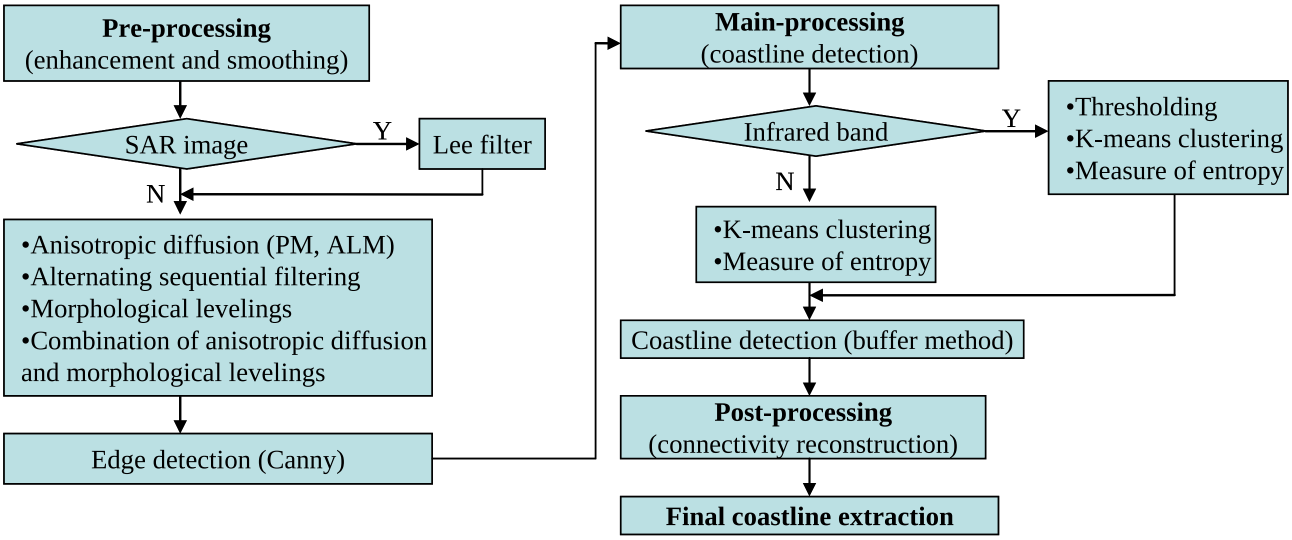

Figure 1: The methodology for coastline detection from remotely sensed imagery, based on advanced smoothing techniques and the Canny edge detector.

2.1. Pre-processing

Data pre-processing involves a number of filtering types with the following objectives: (a) enhancement of elements of interest and in particular contrast enhancement of neighboring pixel intensities, (b) smoothing and simplification of the image, (c) noise removal, (d) element removal in certain scales whereas preservation of others in certain desirable scales. Final goal of pre-processing is, on one hand, the improvement of the image and its interpretation and, on the other hand, the improvement of the detection of its elements of interest, which lies in the 'facility' of processing techniques to detect them [3], [5].

Since in most circumstances an object of interest is present at several scales, scale-space representations have been developed in order to simplify the image while preserving its edges. The recognition of the objects uses a series of coarser representations of the initial image [10]. A variety of multiscale transformations, both classical and advanced, have been developed for that cause. Classical techniques are Gaussian filtering, isotropic diffusion and morphological filters, e.g. dilation, erosion, closing, opening. Their main drawback is that they do not 'respect' the natural boundaries of objects, permitting global blurring. Simultaneously, the morphological dilation and erosion displace the edges through level-shifting [11], while openings displace the horizontal edges [10]. However, openings and closings do not create spurious extrema [10]. A more powerful class of morphological filters that can preserve the horizontal contours is the openings and closings by reconstruction [12]. However, one of their disadvantages is that they treat asymmetrically the image foreground (peaks) and background (valleys) [10].

Therefore, the advanced non-linear techniques of anisotropic diffusion, alternating sequential filtering and morphological levelings have been developed for smoothing and enhancing. In this paper, the *anisotropic diffusion* algorithms of Perona & Malik [8] and Alvarez, Lions & Morel [9] were applied. A symmetric treatment of peaks and valleys was obtained using *alternating sequential filters* (ASF) [13], [14], [15], [16]. However, they are very complex computationally [10], [17], leading to a huge number of operations. A recent solution to the asymmetry problem mentioned above came from the development of a more general powerful class of morphological filters, the *levelings*, introduced by Meyer [10]. Levelings have very interesting properties including contour preservation and the fact that no spurious extrema appear [10].

In this paper, apart from the PM, ALM anisotropic diffusion algorithms, the ASFs and MLs, the combination of anisotropic diffusion and MLs were applied, as well. The goal was to enhance smoothing through a low number of ML iterations – after the implementation of anisotropic diffusion. Moreover, Lee filter was applied to SAR data before enhancement and smoothing, for speckle removal [2]. Figures 2, 3 and 4 show cross-sections from the results of pre-processing techniques applied on a Quickbird image. ALM algorithm converged after intense filtering, enhancing the edges whereas preserving their location. Contrary to ALM, PM preserved only the strong edges since the main drawback of the method is the small objects elimination (300 iterations). Furthermore, morphological levelings preserved more accurately the edges than ASF, with regard to their intensity changes and spatial accuracy (4 levelings). However, since MLs remain intensely contingent on the Gaussian markers, some objects were not visible after a certain number of iterations or their contours were displayed. Hence, a low number of levelings was used to enhance ALM smoothing.

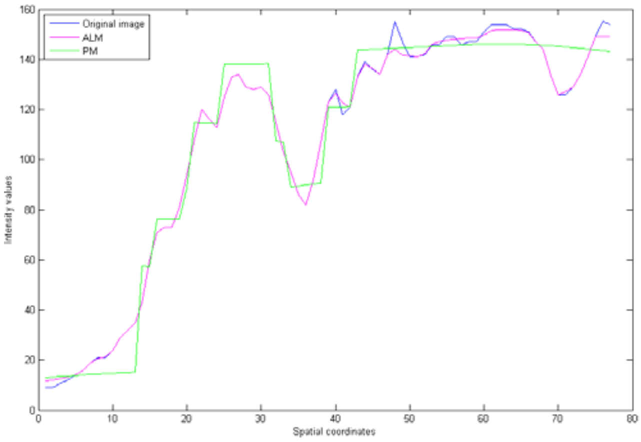

Figure 2: Cross-sections from different filtering types.

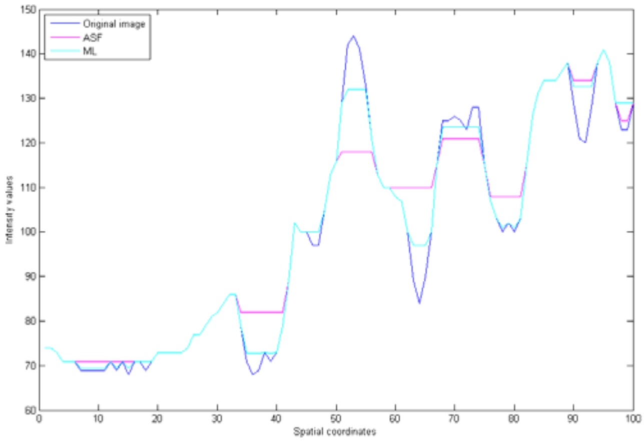

Figure 3: Cross-sections from different filtering types.

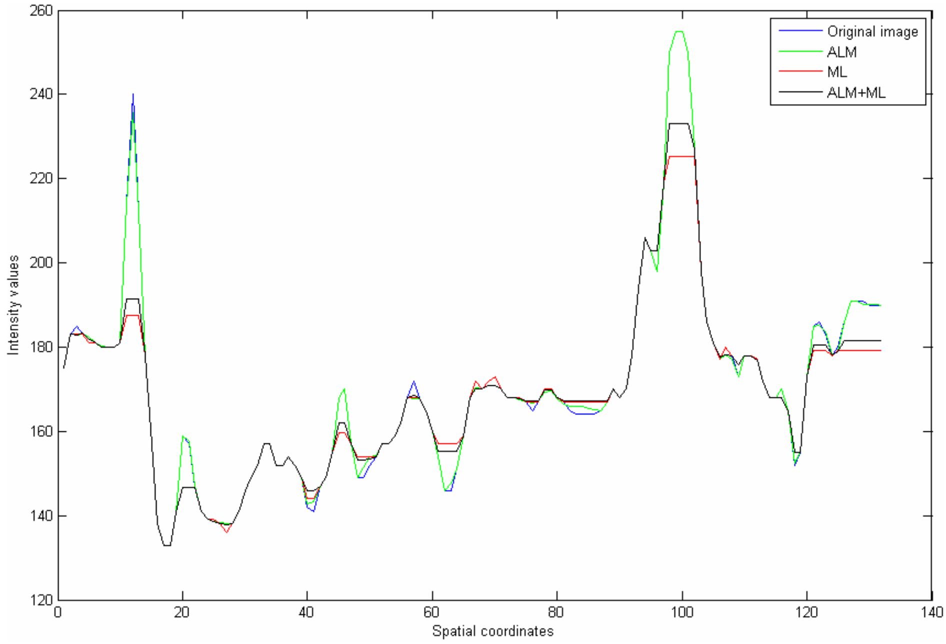

Figure 4: Cross-sections from different filtering types.

Coastline extraction from digital images refers to *boundary detection*; a fundamental problem in many Computer Vision and Image Processing tasks. In these fields, edge detection is a usual approach of boundary detection. Therefore, after enhancement and smoothing, the edges were detected by the Canny edge detector [18].

2.2. Main-processing

Since all edge detectors are sensitive to all intensity value changes, undesirable or pseudo-edges are detected, as well. In order to retain only the coastline edges the measurements of texture variations, K-means clustering and thresholding were applied. By clustering the data into two super classes, land and sea, a first approximation of the coastline is performed. These techniques were applied on the initial data and not on the smoothed ones.

2.2.1. Thresholding

It is known that in infrared bands the water masses absorb the electromagnetic radiance; hence, they appear black in the images. Based on the histogram of an image, one can identify the distribution of the intensity values of the land and water surfaces, appearing by two 'bells'. The proper threshold was estimated based on the limit values of the water surface 'bell'. However, this choice is a very time-consuming procedure. Furthermore, the implementation depends on the availability of infrared bands. In the case studies where infrared bands were not available, the red bands were used instead.

2.2.2. K-means clustering

The Matlab K-means algorithm was used, available in the Image Processing toolbox. The number of clusters developed was related to the data size. In general, the basic problem of K-means is the randomness of clusters, which are dependent on the choice of initial centers. This led to different clusters each time applied, meaning a different label for the same cluster. Therefore, an alternative formulation was developed. The hypothesis made was that the sea would be the cluster with most of pixels, regardless the iterations of the algorithm, the cluster numbers and labels. This statement was based on the almost single intensity values of sea, near to zero. Therefore, all other clusters constituted the land surface and a two-cluster binary image was developed.

2.2.3. Measurements of entropy

A different solution to the problem of non-desirable edges detection is the measurements of texture variations. In this paper, the statistical method of entropy was used, applying the equivalent Matlab algorithm. The measurable exploitation of entropy was possible through multilevel thresholding. Followed by morphological reconstruction, the final binary image of land-water surfaces was developed.

The coastline detected by thresholding, K-means clustering and entropy, was not its final location. A buffer zone of 3 to 25 pixels was applied to it, depending on the main-processing techniques outcome – including the edge detection by Canny. Since the output of Canny, thresholding, K-means and entropy were binary images (0: background, 1: edge), the final edges that formed the coastline would be the pixels of sum 2 (1: edge detected by Canny + 1: edge detected by the processing techniques). Hence, every pixel detected in the buffer zone implemented, would be a coastline pixel.

2.3. Post-processing

When pre-processing and processing techniques fail to perform ideally due to texture complexity, the output edges usually are not connected and micro pseudo-edges may appear [3]. Another problem was that edges detected in the buffer zone did not belong to the coastline. *Morphological reconstruction* can restore connectivity appreciatively. The transformations used were available in the Matlab Image Processing toolbox. The combinations adopted according to situation, based on the pre-processing and processing outcome. Hence, it was not possible to form a single scheme. The tools used were the following: '*bwareaopen*' performes a morphological opening of a binary image, '*imfill*' fills 'holes', where 'hole' is a set of background pixels enclosed by foreground pixels, '*bwmorph/ clean*' eliminates isolated pixels, '*bwmorph/ bridge*' transforms a set of background pixels to a set of foreground pixels if they have two non-zero neighbors that are not connected, and '*bwmorph/ thin*' thins objects to lines. Furthermore, the morphological operators of erosion, opening and closing were used.

3. Results

Photo-interpretation alone is not sufficient for the evaluation of the results. Therefore, the procedure included quantitative and qualitative evaluation of the outcome using completeness, correctness and quality criteria [19], [20]. Three coastline extraction results were compared to the manually digitized coastlines, specifically the Canny detected, the thresholding/ K-means/ entropy detected as the boundary of the two classes of land and sea, and the final extracted one by the developed methodology. The comparison was implemented using three different buffer zones of one, three and five pixels respectively, fitting the reference data to the extraction outcome. Their use was considered necessary since the reference data can contain errors, as well, caused by the data quality, the photo-interpreter's experience and the digitization procedure of the manually extracted coastlines.

The following figures (5 to 15) show the extracted coastlines on the original images, after the developed methodology was applied. The results obtained are promising. Figure 5 shows a QuicBird image (0.7m ground resolution) after enhancement and smoothing (ALM of 200 iterations), Canny, measurements of entropy, four levels of thresholding and morphological reconstruction. For a buffer zone of three pixels the evaluation was as follows: completeness 79,34%, correctness 80,31% and quality 66,42%. The method was applied on the four Quickbird images. The results from a quantitative perspective can simulate coastline mapping in scales of 1:7000 to 1:13000 and for operational purposes.

Figure 6 shows a WorldView-2 image (0.5m ground resolution) after enhancement and smoothing (ALM of 200 iterations followed by 5 MLs), Canny, K-means clustering (two clusters) and morphological reconstruction. For a buffer zone of three pixels the evaluation was as follows: completeness 83,13%, correctness 84,06% and quality 71,81%. The method was applied on two WorldView-2 images. The results from a quantitative perspective can simulate coastline mapping in scales of 1:5000 to 1:9000.

Figure 7 shows a TerraSAR-X data (3m ground resolution) after enhancement and smoothing (Lee filter, ALM of 300 iterations followed by 5 MLs), Canny, measurements of entropy, four levels of thresholding and morphological reconstruction. For a buffer zone of three pixels the evaluation was as follows: completeness 72,73%, correctness 74,94% and quality 58,5%. In general, processing SAR data requires special attention and professional knowledge. The main dilemma refers to the use of methods that relate to grey intensity values. Since water masses are not necessarily characterized by single intensity values, these methods are not always useful. These variances, including the shadows in this type of images, often complicated the detection of the true coastline locations. However, the problems that emerged were the same as in multispectral imagery. The method was applied on two TerraSAR-X data. The results from a quantitative perspective can simulate coastline mapping in a scale of 1:54000.

Figures 8, 9 and 10 show the coastline extraction in more detail. A promising detection has been performed. However, some connectivity issues remain. Some pseudo-edges appeared which did not belong to the coastline.

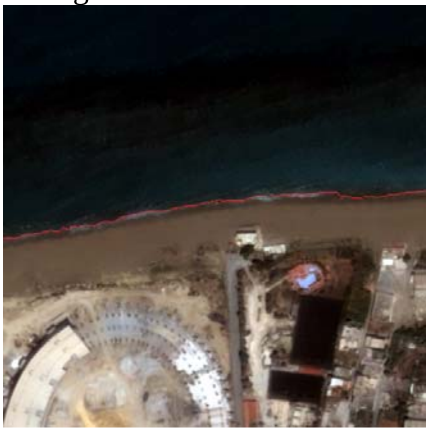

Figure 5: Quickbird image (0.7m).

Figure 6: Worldview-2 image (0.5m).

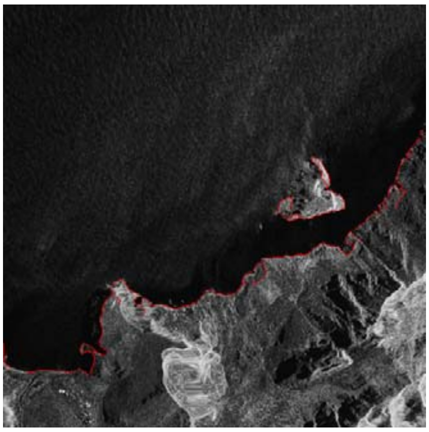

Figure 7: Terrasar-X data (3m).

Figure 8: Subset of Figure 5 Quickbird image (0.7m).

Figure 9. Subset of Figure 6. Worldview-2 image (0.5m).

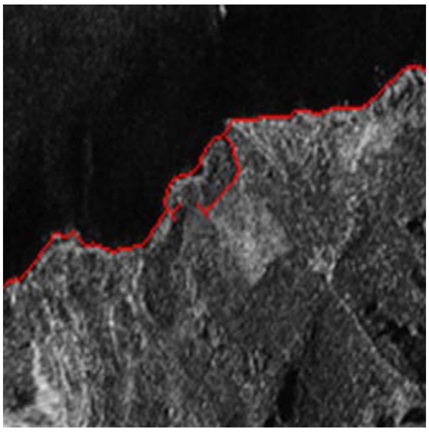

Figure 10. Subset of Figure 7. Terrasar-X data (3m).

Figure 11: Aster image (15m).

Figure 11 shows an ASTER image (15m ground resolution) after enhancement and smoothing (ALM of 50 iterations followed by 5 MLs), Canny, thresholding and morphological reconstruction. For a buffer zone of three pixels the evaluation was as follows: completeness 84,61%, correctness 83,7% and quality 72,64%. The results from a quantitative perspective can simulate coastline mapping in a scale of 1:150000.

Figures 12 and 13 show the coastline extraction in more detail. The developed algorithm performed effectively. The same connectivity problems are presented in this case, as well. In general, restoration of this problem is a demanding procedure to estimate, even in a coarse approximation.

Figure 12 : Subset of Figure 11
Aster image (15m).

Figure 13: Subset of Figure 11
Aster image (15m).

The data quality and difficulties, such as noise, rocky areas, shallow water surfaces and ports, can affect the results. The main-processing techniques and the ground truth affect the extraction outcome, as well. In the case of ports, the main problem was the separation of land surfaces from ships, and not the separation of 'sea' from 'non-sea' surfaces, since the true coastline location was the boundary of ports and not ships. In Figure 14 a QuickBird image and the corresponding final output are shown, pointing up this task (ALM of 200 iterations, K-means in four clusters). In Figure 15 the true coastline location (ground truth) is shown.

Figure 14 : Quickbird image (0.7m), coastline extraction.

Figure 15: Quickbird image (0.7m), ground truth.

The developed methodology based on the Canny operator resulted to better coastline detection than processing techniques which clustered the data into land and sea. The use of thresholding and

K-means in the developed methodology led to similar results. Nevertheless, the measurements of entropy was applied successfully only in three cases; possibly due to multilevel thresholding. ALM led to more complete and qualitative edge detection compared to ALM+ML which led to more correct detection. However, the main-processing and post-processing techniques applied, affected the outcome. For example, ALM led to more complete and correct results for thresholding, whereas ALM+ML led to more correct and qualitative results for K-means. In general, edge detection by the Canny operator performed best, due to the difficulties concerning the thresholding and homogenization criteria and the connectivity restoration. Therefore, the development of a single methodology remains a crucial but challenging task, caused by the varieties of coastal environment.

4. Conclusions

A coastline detection methodology from remotely sensed data was developed and evaluated. A wide range of data was used for that purpose. Based on the quantitative and qualitative evaluation, the developed methodology can deliver promising results. Even if, in some cases, we processed data that were not the raw ones the results were acceptable. Taking into account that the methodology was based only on techniques that do not incorporate knowledge about the spatial relations between every extracted pixel/segment and its neighbours, the proposed approach proved a challenging one. Further topics of research include the restoration of coastline connectivity especially near man-made construction like in ports and the application of the methodology in more data types in order to tune further algorithm parameters.

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