The Evolution of the South-Eastern Baltic Sea Coastline Between 1988 and 2018 by Remote Sensing

Sébastien Gadal[1,2][a] and Thomas Gloaguen[1,3][b]
[1]Aix-Marseille Université, Université Côte-d'Azur, Avignon Université, CNRS, ESPACE UMR 7300, 84000 Avignon, France
[2]Department of Ecology and Geography, Institute of Natural Sciences, North-Eastern Federal University, 670007 Yakutsk, Republic of Sakha Yakutia
[3]Cultural and Spatial Environment Research Group, Faculty of Civil Engineering and Architecture, Kaunas University of Technology, 44249 Kaunas, Lithuania

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Abstract: This article aims to define and explain the evolution of the coastline in Latvia, Lithuania, and Russia since the late 1980s. Coastal erosion is a critical issue for public authorities and is considered as one of the main environmental problems in the south-eastern Baltic region. The political, economic, and social changes associated with the collapse of the Soviet Union have created new pressures in recent decades in previously relatively undeveloped coastal regions. The geomorphology of the latter is the result of various natural morpho-dynamic processes: swells, tides, tectonic movements, etc. Landsat 4-5 TM, Landsat 8 OLI satellite images series between 1988 and 2018 are used to estimate the position of the coastline. The spatial accuracy of the shoreline automatic recognition based on the combination of minimum noise fraction and Laplacian convolution operators is compared with the manual methods of photo interpretation. The results showed a global change of –0.21 m/year with local and temporal disparities. It can be explained by a variety of natural and anthropogenic factors that disrupt the sedimentary stock and the hydrodynamic forces controlling coastal evolution.

1 INTRODUCTION

Among the different methods for extracting the shoreline and analysing its evolution dynamics, such as field, airborne, aerial measurements, spatial imagery presents many advantages.

First of all, it makes it possible to cover territories of several tens to several thousand kilometres. Secondly, it has an incomparable historical perspective, thanks in particular to the Landsat archives that are available since the 1970s and are managed jointly by the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS). Finally, the archives and measurements are standardised, allowing long-term monitoring of coastal evolution.

This research focuses on the analysis of coastal dynamics in the south-eastern Baltic Sea between 1988 and 2018. The study area includes the coastlines of Russia (Kaliningrad Oblast), Lithuania, and Latvia, from Cape Taran to Cape Kolka, i.e. approximately 415 kilometres (Figure 1).

The multi-year shoreline analysis is based on Landsat 4-5 TM and Landsat 8 OLI archives. Two remote sensing methods of shoreline extraction are tested and compared: the first manual, based on photo-interpretation of colour composition, and the second, automatic, based on the extraction of ontological landscape morphology and structure from Laplacian filter and Minimum Noise Fraction (MNF) transformations.

[a] https://orcid.org/0000-0002-6472-9955
[b] https://orcid.org/0000-0003-1849-9615

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Figure 1: Location of the study area.

The results are discussed by comparing spatial and temporal variations in the coastline and highlighted in relation to existing coastal zone management and different review studies.

2 BACKGROUND

Coastal erosion is identified as one of the main environmental problems in the Baltic Sea (Olenin and Olenina, 2002; Harff *et al.*, 2017). This statement reflects both the vulnerable nature of the coastal region and its profound transformation over the last decades since the collapse of the Soviet Union in the 1990s (Gadal and Gloaguen, 2021).

2.1 A Rapid Anthropisation of the Coastal Region

During the Soviet occupation, from the Second World War until the 1990s, the development of the coastal region of the south-eastern Baltic Sea was severely limited. As the external border of the Soviet Union, the coastal regions are militarised because of their strategic interest during the Cold War. As a result, access to the coast is mostly controlled and, except for the main cities, population densities have remained among the lowest around the Baltic Sea (Pranzini and Williams, 2013; Spiriajevas, 2014).

The independence of the former Soviet republic in the 1990s is associated with a rapid transition to a liberal economic system (Brunina *et al.*, 2011; Fedorov *et al.*, 2017). The greater openness to foreign markets gave a strong impulse to the naval and port industries, as well as to tourism (Eaglet, 1999; Spiriajevas, 2014; Fedorov *et al.*, 2017). Economic development is combined with land artificialisation through the creation of new infrastructure to ensure the competitiveness of these activities.

Urban areas are not exempted. The land use class is characterised by the highest land category growth with an evolution of 14% in Lithuania, 55% in Latvia, and 98% in Russia between 1995 and 2015 (European Space Agency, 2017). In addition, the 0-25 km coastal band concentrates more urbanised areas than the rest of each country (European Space Agency, 2017).

2.2 Geomorphological Characteristics of the Coast

The south-eastern Baltic Sea coastline is the result of successive processes of transgression and regression of the ancient Littorina Sea onto Pleistocene and Tertiary glacial deposits. Their erosion has resulted in the formation of sand and gravel beaches and dunes present on the Curonian Spit, the Lithuanian mainland coast as far as Liepaja and the northern coast of Kurzeme Peninsula (Bird, 2010; Łabuz, 2015). The width of the beaches can be up to 100 metres, while the width of the dunes is between 50 and 150 metres. Their height generally varies from 5 to 15 metres but some of them can reach up to 50 metres. Offshore, there is a series of sandy barriers that reduce the force of the swells (Bitinas *et al.*, 2005; Armaitienė *et al.*, 2007; Gulbinskas, 2009; Burnashov, 2011; Pranzini and Williams, 2013; Spiriajevas, 2014). On the Sambian Peninsula and part of the Latvian coast from Liepaja to the north of Ventspils, the coast is occupied by sandy and gravelly beaches of smaller width and cliffs of glacial deposits. They reach up to twenty metres in height (Bird, 2010; Łabuz, 2015).

The average direction of the swell over the period 1999-2018 is predominantly west–east except for the coast near the capes of Taran and Kolka where the direction is northwest-southeast (Björkqvist *et al.*, 2018). During the summer period — June, July, and August — the swell height is less than 0.5 m on average: the most exposed areas are the northern Sambian Peninsula and the Lithuanian mainland coast. In winter — December, January, and February — with storm events, swell heights reach up to 0.8 m on average. The exposed areas remain the same and also include part of the Latvian coast up to Ventspils (Björkqvist *et al.*, 2018).

Sediment transport is provided by longshore drift from south to north with a decreasing volume from the Taran cape to Liepaja — from 500,000-750,000 to 140,000-250,000 m^3/year — before increasing again to the Kolka cape to reaching a transported volume of 1 million m^3/year (Bird, 2010; Weisse *et al.*, 2021).

Tectonic movements create subsidence of 1 mm/year on the Russian coast and between 0 and 1 mm/year from Liepaja to the Curonian Spit. The coastline rises between 0 and 1 mm/year on the rest of the Latvian coast (Bird, 2010; Weisse *et al.*, 2021).

Vertical tidal movements with a semi-diurnal current are approximately 5 to 10 cm (Pranzini and Williams, 2013).

The effects of climate variability will modify the current morphodynamical processes through (1) the increase in sea level — +3 to +5 mm per year between 1995 and 2019 compared to +0.4 mm/year between 1899 and 1975 (Jarmalavičius *et al.*, 2001; Weisse *et al.*, 2021), — (2) the increase in the duration and frequency of storms — with a return period of 6-8 years reduced to 2-3 years for extreme events — and, (3) the reduction in the number of days of ice and snow that protect the coastline from erosion during winter (Žilinskas, 2008).

3 METHODS

3.1 Data Acquisition

Landsat satellite archives, freely provided by the USGS on the Earth Explorer platform (https://earthexplorer.usgs.gov/), were used in this study.

Landsat 4-5 TM and Landsat 8 OLI images composed of spectral bands covering the visible — red, green, blue — and infrared — near-infrared and SWIR — domains with a resolution of 30 m by 30 m have been selected, in addition to thermal bands with a resolution of 120 m by 120 m and 100 m by 100 m respectively, resampled to 30 m by 30 m.

Their selection is justified by: (1) the availability of the data since the 1970s in free access, (2) the possibility of defining criteria such as cloud cover, date, level of image processing, and (3) a spectral resolution allowing to exploit a large diversity of the electromagnetic measurement.

However, with a limited spatial resolution of 30 m by 30 m, the detection of swell or tidal variations is complex. Nevertheless, as the analysis focuses mainly on significant long-term changes in the coastline, this resolution is considered satisfactory. No images older than 1980 were selected due to a spatial resolution of 80 m.

The spatial coverage of the images includes an area from the Russian-Polish border to the western edge of the Gulf of Riga.

The satellite images are selected between the months of May and June when the monthly average wave heights are among the lowest in Klaipeda between 1993 and 2018 (Jakimavičius *et al.*, 2018), and in Ventspils and Liepaja between 1954 and 2012 (Soomere, 2013). This period also avoids snow and ice cover, which can cover up to 75% of the sea surface in the Gulf of Riga on 1st March, for example, making it difficult to identify the coastline (Lépy, 2012).

A maximum threshold of 25% cloud cover is set when selecting images. In total, the dataset consists of 12 satellite images, i.e., 3 images required to cover the whole study area over 4 different decades at regular intervals: 1988, 1999, 2009, and 2018.

3.2 Methods for Analysing the Historical Variation of the Coastline

Two methods of coastline extraction by remote sensing are experimented in this research.

The first one is based on the photo interpretation of colour compositions. The manual digitalisation of the shoreline is based on the operator's knowledge of the terrain and experience in spatial imagery processing.

The second method allows a simple and fast extraction with the automation of a processing chain based on the transformation of satellite images by the MNF algorithm, and their enhancement by a 7x7 pixel windowed Laplacian filter.

3.2.1 Shoreline Extraction by Photointerpretation

According to Faye *et al.* (2011), up to twenty shoreline definitions are possible based on different criteria such as vegetation or topography.

In this study, the wetting limit of the sands is used as a coastline. Colour compositions from the blue, SWIR, and near-infrared spectral bands highlighted this limit by discriminating between water surfaces, sandy surfaces, and vegetated surfaces respectively.

Each coastline is vectorised at a scale of 1:30000. A global margin of error (m) is calculated for each coastline vectorised manually (Equation 1).

$$E_M = \sqrt{{E_{MC}}^2 + {E_{MG}}^2} \tag{1}$$

It includes:

(1) Uncertainties related to the experience and the interpretation of the digitalisation operator and data resolution (E_{MC}). The margin of error depends on the visibility between wet and dry sand. If the limit can be correctly identified on a single pixel, the recorded value will be 30m (60 m if the identification is done on two pixels for example).

(2) Uncertainties related to the georeferencing of images (E_{MG}). These values are provided directly by the USGS in the satellite image metadata.

3.2.2 Shoreline Extraction by Transformation and Enhancement of Satellite Images

The satellite images are transformed with the MNF image transformation (Figure 2-A). The MNF decomposes the satellite images to minimise noise. It reconstructs them into components by identifying groups of pixels based on their variation in surface reflectivity, from the spectral information of all bands. The components are ordered to show decreasing image quality (Vermillion and Sader, 1999; Syarif and Kumara, 2018). This algorithm allows the identification of distinct geographical objects (Libeesh *et al.*, 2022). In our case, components 3 for Landsat 4-5 TM images and 6 for Landsat 8 OLI images clearly identify sandy surfaces.

These components are then processed with a Laplacian filter (Figure 2-B). It creates new images whose pixel values are recalculated using a kernel convolution operator of 7 pixels by 7 pixels. For each pixel in the centre of the kernel and its neighbours, the original values are multiplied by the values of the filter kernel (Figure 3). The sum of these products is assigned to the pixel in the centre of the kernel. The operation is repeated until all the values in the image are recalculated. The Laplacian filter highlights areas with a high intensity of change.

They are relevant to our study because they use contrast to "enhance linear features" and the edges of an image (Fisher *et al.,* 2000; Safaval *et al.,* 2018).

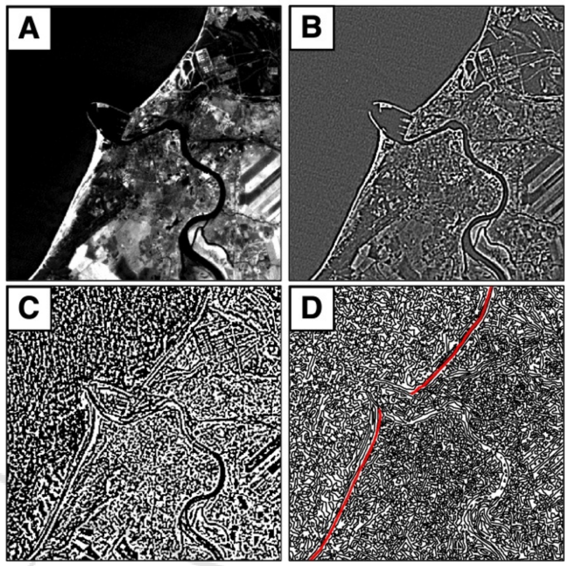

Figure 2: Outputs of different processing steps for automatic coastline extraction: (a) MNF component highligthing the sandy surfaces, (b) Laplacian filter with a 7 x 7 pixel kernel applied to the MNF image transformation, (c) selection by raster calculator of border areas highlighted by the filter, and (d) conversion to vector lines and selection of the border representing the coastline (in red).

The outputs are processed on Geographic Information System (GIS): for each image, the values greater than 0 are selected to keep only the border areas highlighted by the filter (Figure 2-C). These areas are converted into vector polygons and then into simplified lines. The file is finally cleaned to keep only the line corresponding to the coastline (Figure 2-D).

0	0	-1	-1	-1	0	0
0	-1	-3	-3	-3	-1	0
-1	-3	0	7	0	-3	-1
-1	-3	7	24	7	-3	-1
-1	-3	0	7	0	-3	-1
0	-1	-3	-3	-3	-1	0
0	0	-1	-1	-1	0	0

Figure 3: Values of the Laplacian kernel filter.

A global margin of error (m) is calculated for each coastline vectorised automatically (Equation 2).

$$E_A = \sqrt{{E_{AG}}^2 + {E_{AE}}^2} \quad (2)$$

It includes:

(1) Uncertainties related to the georeferencing of images (E_{AG}). These values are provided directly by the USGS in the satellite image metadata.

(2) Uncertainties related to the accuracy of coastline extraction (E_{AE}). The calculation of this margin of error is based on the root-mean-square deviation (RMSE) of the distances between the manually and the automatically extracted coastlines (Equations 3, 4 and 5). The RMSE is calculated for each satellite image, from 5 randomly positioned points on the coastline extracted manually and automatically (120 points in total).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta E_i^2 + \Delta N_i^2)} \quad (3)$$

$$\Delta E_i^2 = x_M - x_A \quad (4)$$

$$\Delta N_i^2 = y_M - y_A \quad (5)$$

Where,

ΔE_i^2 is the distance between the x-coordinates of the points on the manual coastline (x_M) and the points on the automatic coastline (x_A).

ΔN_i^2 is the distance between the y-coordinates of the points of the manual coastline (y_M) and the points of the automatic coastline (y_A).

i represents each pair of control points used for the calculation of the margin of error of the coastline extraction.

n is the set of control points used to calculate the margin of error of the coastline extraction.

3.3 Statistical Analysis of Historical Shoreline Variation

The DSAS (Digital Shoreline Analysis System) extension on ArcGIS is used to calculate the quantitative evolution of the coastline (Faye *et al.*, 2011; Bagdanavičiutė *et al.*, 2012; Thieler *et al.*, 2018).

A terrestrial reference line is drawn on which perpendicular transects at 50 m intervals intersect the extracted coastlines. The points of intersection are used for the calculation of the changes. A transect is ignored in the calculations if all the coastlines (digitised automatically or manually) are not intersected. Finally, a 95.5% confidence interval was defined for calculations.

(1) The End Point Rate (EPR) is the calculation of the average annual rate of change by dividing the net change — the distance between the intersection points of most recent and old coastlines — by the number of year difference. Here, the EPR is used to calculate the annual rate of change for each decade, i.e., 1988-1999, 1999-2009, and 2009-2018.

This calculation highlights the main trends in terms of coastal accretion or retreat. However, the fact that only two dates can be considered is not significant for the intermediate and sometimes important evolutions of the shoreline, hence the interest in using the following two calculations for the period 1988-2018.

(2) The Linear Regression Rate (LRR) provides, for each transect, the annual rate of change of the coastline position from a least-squares regression line "[…] placed so that the sum of squared residuals is minimised" (Thieler *et al.*, 2018).

(3) The Weight Linear Progression (WLR) is based on the same principle as the LRR with the exception that the linear regression model is weighted by the global error margins (E_M and E_A): "more importance or weight is given to more reliable data to determine the most appropriate line" (Thieler *et al.*, 2018).

Using the coefficients of determination of LRR and WLR — LR2 and WR2 — it is possible to measure the variability of the coastline values in a linear regression model.

4 RESULTS

4.1 An Intra-Period Evolution Characterised by a Great Stability of the Coastline Between 1988 and 2018

Between 1988 and 2018, the evolution of the south-east Baltic Sea coast is characterised by overall stability (Figure 4). The annual rates of change are almost identical between the manual (–0.21 m/year) and automatic methods (–0.23 m/year).

With the consideration of intra-period variability and the weight of the most reliable data, the evolution does not exceed –0.3 m/year of coastline retreat. The values obtained with the manual method are more dependent on the margins of error due to a greater difference in the mean values of variations between the two methods with the calculation without weighting (–0.28 m/year against –0.21 m/year with the automatic method).

For these calculations, more than a third of the coefficient of determination values are above 0.75. This means that 30% of the coastline presents a significantly regular evolution trend in time and space, whatever the extraction method of the coastline.

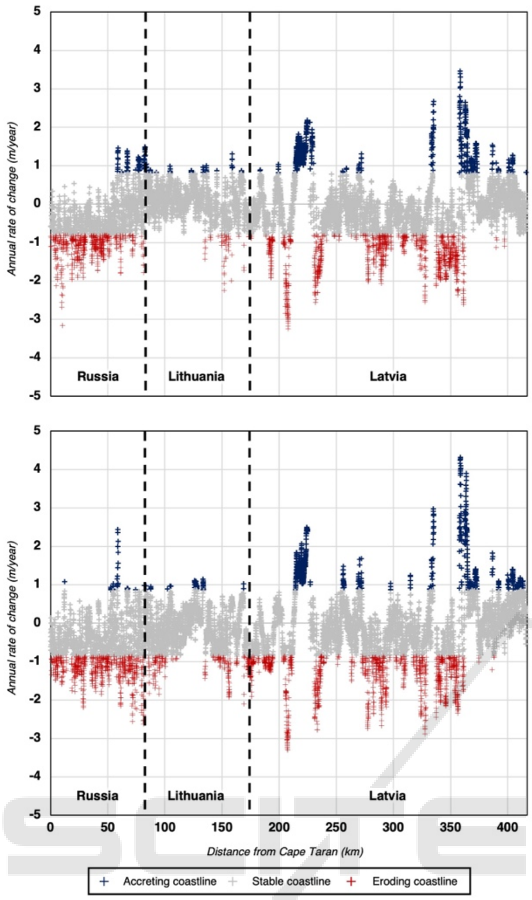

Figure 4: Annual rate of shoreline change with weighting data for the period 1988-2018 for automatic (top) and manual (bottom) methods of extraction of the coastline.

The difference between the values of variation calculations with reliable data weighting is only 0.37 m/year between the two methods and 0.36 m/year for the calculations without weighting.

Considering intra-period variability, we observe differences in the multi-annual rate of change over the period 1988-2018 between countries (Figure 4).

The results of both methods of coastline extraction show a retreat in Russia of about half a metre per year, independently of the weighting or not in the calculation. However, these results are not significant. For the automatic method, the margin of error is measured at 0.83 m/year (unweighted calculation) and 0.80 m/year (weighted calculation). For the manual method, 0.98 m/year and 0.86 m/year respectively. Any variations above these thresholds are considered as accretion. Below the negative values of these thresholds, erosion can be observed. Nevertheless, more than one-third of the Russian coastline is considered eroded according to the calculations. Only the measure without weighting of the manual extraction of the coastline does not show the same proportion (17%).

The multi-annual variations calculated for the Latvian coast also show a retreat of about –0.20 m/year between 1988 and 2018. With a standard deviation of the annual variation rates of 1 m/year, the coastal variation values are more dispersed on the Latvian coast. This dispersion can be explained by a greater proportion of accreting and eroding areas (about 10% and 20% of the Latvian coastline) than in other countries. The results obtained with the automatic extraction of the coastline are constant independently of the weighting or not.

In Lithuania, we observe a large part of the coast (more than 80%) is considered "stable”. Over the period 1988-2018, the annual variations of the Lithuanian coastline are different depending on the methods of extraction of the shoreline. The photo-interpretation digitalisation shows a coastal retreat of –0.14 to –0.18 m/year while the automatic processing shows an accretion of 0.07 m/year.

4.2 Inter-Period Analysis of Annual Variations

4.2.1 A Regular Alternation Between Accretion and Erosion Zones Disturbed over Time

When the evolution of the coastline is analysed by decade, the same trend towards a retreat of the south-eastern Baltic coastline can be observed over time for both methods of coastline extraction. The strongest variations are observed for the period 2009-2018 with an annual variation rate of –0.88 m/year for the manual method and –0.71 m/year for the automatic extraction method. The results are not significant enough to consider this variation as ‘erosion’.

The results calculated with automatic and manual shoreline extraction present a certain alternation between eroded and accreted areas in the period 1988-1999 (Figure 5). Nevertheless, differences appear spatially when analysing the periods 1999-2009 and 2009-2018.

The results obtained with the manual extraction method show that shoreline erosion is increasing over time. The multi-year variations measures between 2009 and 2018 in Russia (–1.54 m/year) and Lithuania (–0.95 m/year) are significant.

We observe a change in spatial dynamics of coastal evolution with the automatic method of extraction of the coastline. During the period 1988-1999, the Russian coastline retreated by –0.58 m/year, while the Latvian coastline grew by 0.02 m/year. For the period 2009-2018, the situation has been reversed. The Russian coast is accreting by 0.28 m/year while the Latvian coast is eroding with an annual variation rate of –1.31 m/year. The Lithuanian coast shows relative stability over time (–0.09 m/year for the period 1988-1999 and 0.10 m/year for the period 2009-2018).

4.2.2 Spatial Accuracy Analysis of the Results

The analysis of the coastline extraction methods' spatial accuracy allows for observing the spatial divergence of the results (Figure 5). For each decade, we calculated a moving average trend chart with the annual variations of the two coastline extraction methods. To smooth the results and show significant fluctuations, the average threshold is defined on 200 values.

For the period 1988-1999, the largest differences between the annual shoreline variations of the two methods of shoreline extraction are located on the coast of the Curonian Spit. In the rest of the study area, both charts follow the same evolution trends (Figure 5).

For the period 1999-2009, the differences in annual shoreline variation between the coastline extraction methods are small with the exception of the Sambian and Curonian coasts. The manual method of extraction models a retreat of the Lithuanian part of the Curonian Spit, while the automatic method of extraction shows an accretion for example (Figure 5).

There is also a clear divergence in the modelling of shoreline evolution in the proximity of the Latvian port of Pavilosta (270 km), with an accretion of the coast for the automatic method and a significant retreat for the manual method.

The differences in annual variation between the extraction methods are the most significant in the period 2009-2018. The spatial modelling is less accurate because of the cloud cover, which implies potentially larger margins of error.

For Russia and the Lithuanian mainland, the results of the manual method show a clear erosion (–1.29 m/year and –1.16 m/year), whereas the results of the automatic method indicate overall stability (0.24 m/year and 0.03 m/year). A very strong retreat of the Latvian coast can be observed using the automatic coastline (–1.31 m/year). The erosion rate is more modest for the calculations performed with the manual coastlines (–0.62 m/year). The trend remains identical for both spatial modelling methods (Figure 5).

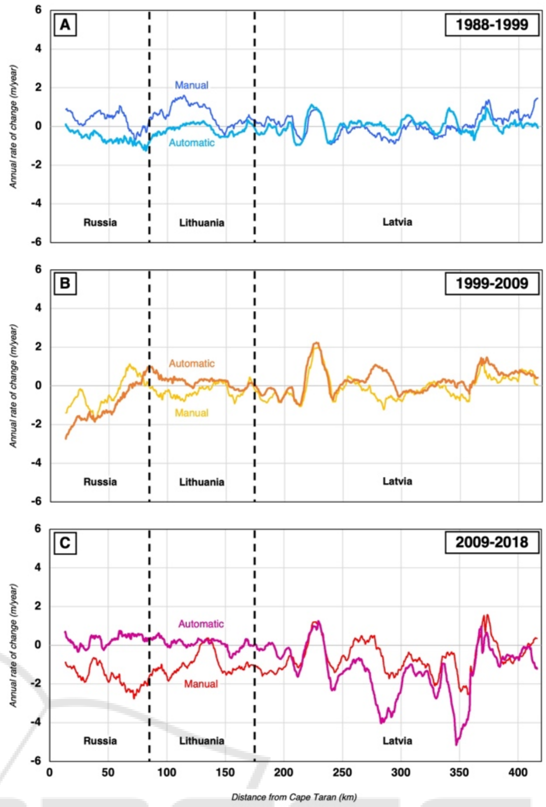

Figure 5: Averaged trend charts of annual inter-period variations for automatic and manual methods of extraction of the coastline for the periods (a) 1988-1999, (b) 1999-2009, and (c) 2009-2018.

Cyclical dynamics are also observed over time and regardless of the extraction method. These variations are most often characterised by rapid peaks of variation which correspond in their location to the presence of port areas: Sventoji (170 km), Liepaja (225 km), Pavilosta (270 km), and Ventspils (335 km).

5 DISCUSSIONS

5.1 Natural and Anthropogenic Factors Explaining the Evolution of the Coastline

In this research, we highlighted an alternation between eroding and accreting areas during the period 1988-1999 regardless of the extraction method used (Figure 5). These coastal dynamics are representative of the spatial redistribution of sediments conditioned by the inflow and outflow of longshore drift along the southeast coast of the Baltic Sea.

During the periods 1999-2009 and 2009-2018, this alternation is disturbed either in favour of more intense erosion (manual method) or changes in pre-existing spatial dynamics (automatic method).

The rise in sea level and the increase in extreme storm events are "natural" processes that can explain the current evolution of the coastline. They are responsible for the weakening of the foredunes which protects against erosion. A large part of the coastline is vulnerable because it is formed by sandy beaches. In addition, there is a limited human intervention for coastal protection in these same areas. Coastal management consists mainly of beach nourishment, dune ridge reinforcement and natural fences to fix vegetation in the dune and capture sand. Many protected areas have also the objective of protecting the natural coastal heritage (Gulbinskas et al., 2009; Nitavska and Zigmunde, 2013; Pranzini, and Williams, 2013; Spiriajevas, 2014). A weakening of dune activity can impact sediment supply (Armaitienė *et al.,* 2007).

This evolution could also reflect the more sensitive anthropogenic pressures and degradations on the coast. They manifest themselves in the form of disturbances to sediment supply and stocks.

Recreational activities are the cause of a weakening of the dunes when tourists walk off the signposted paths and damage the dune ridge for example (Žilinskas, 2008; Pranzini et Williams, 2013). Greater deterioration is observed in areas of high residential development with houses built behind the dunes to take advantage of the sea view.

The sedimentary stocks are seriously altered by sand and gravel extraction activities, which are used in particular to extend the ports or for construction activities (Pranzini and Williams, 2013; Žilinskas *et al.*, 2020).

Changes in coastal dynamics can also be explained by a disruption of the natural forces that control the evolution of the coast. The most relevant examples are ports (Figure 6) where coastal defence structures (groins, dykes) capture part of the sediment transport through longshore drift (Bagdanavičiūtė et al., 2012; Jarmalavičius *et al.,* 2012; Pranzini and Williams, 2013). Sand captures in these structures generally cause local erosion and accretion downstream and upstream respectively. These structures are also found along the coast of the Sambian Peninsula (Karmanov *et al.*, 2018).

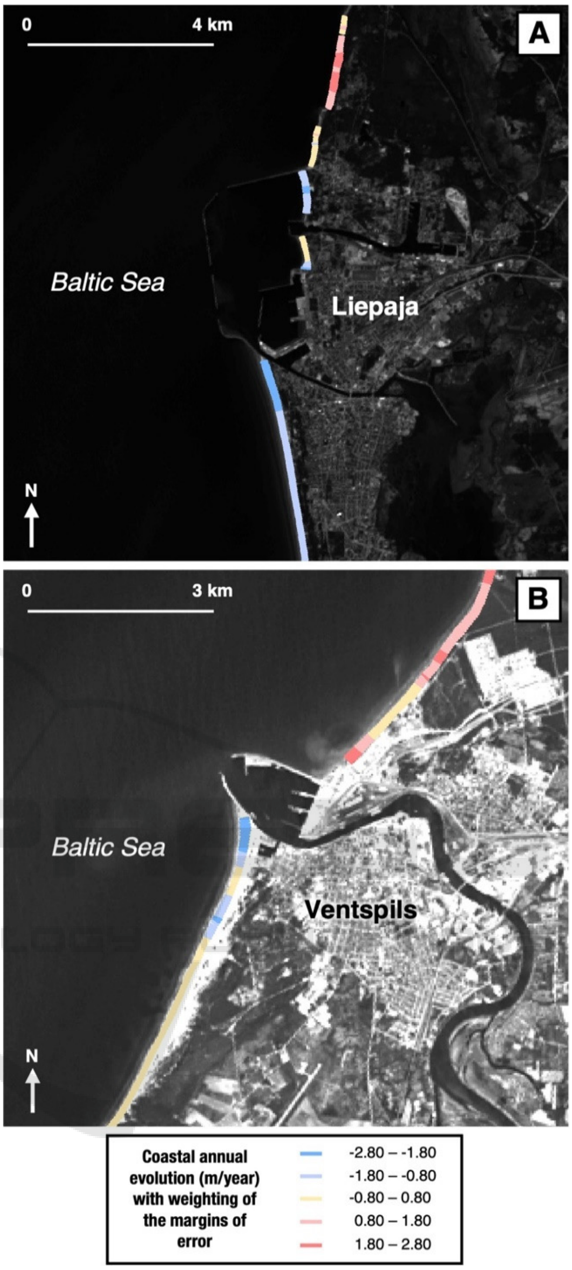

Figure 6: Evolution of the coastline between 1988 and 2018 in the ports of (a) Liepaja and (b) Ventspils, Latvia.

5.2 Critical Analysis of the Methodology

5.2.1 Time-Processing

This research provided an opportunity to compare two remote-sensing coastline extraction methods. The automatic method represents a significant time processing advantage over the manual method in terms of the digitalisation process. This 'time benefit' increases with the size of the area studied due to the automation of the processing chain.

5.2.2 Accuracy of the Shoreline Recognition

The extraction of the coastline with the automatic method is not directly associated with terrain criteria such as topography, presence of vegetation, sand humidity, etc. It depends primarily on the spectral calibration of the bands, the spectral range covered, and the spatial resolution. Some limitations of the automatic coastline extraction method can be observed. For example, for a given date with an area overlapping between two satellite scenes, the coastline will be interpreted differently (Figure 7).

The delimitation by the manual method is more related to 'scientific' criteria but requires knowledge and understanding of satellite images, which is also indirectly dependent on the quality of the image processing.

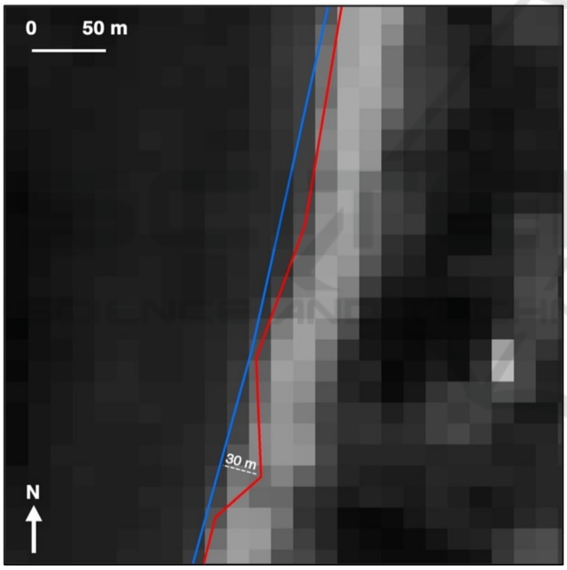

Figure 7: Two coastlines interpreted differently according to the automatic extraction method for the same date, the same area but with two superimposed satellite images.

5.2.3 Comparison of the Results

The automatic method presents robust results between the calculations of the multi-year coastal variations with and without weighting by the most reliable data.

Over the period 1988-2018, the results obtained with the manual method, weighted by the most reliable data, are similar to those obtained with the automatic method, independently of the weighting or not.

The results analysed by decades, in particular for the periods 1999-2009 and 2009-2018 show significant differences between the manual and automatic approaches. The calculations by decade do not use the margin of error given for each coastline. This could explain the differences in the results between the two methods compared to the multi-annual calculations made between 1988 and 2018 with the margins of error.

The largest variations are mostly located on wide beaches (up to 100m wide). The relationship between spatial resolution and beach width is questionable.

Finally, if we compare the results obtained with studies carried out on the Russian coast between 2007 and 2017 (Karmanov *et al.,* 2018) or on the Lithuanian coast between 1947/1955-2010 (Bagdanavičiutė *et al.*, 2012), the results of the automatic method are systematically the closest (differences less than 1 m).

6 CONCLUSIONS

In recent decades, coastal erosion has emerged as an important environmental issue for public authorities in the south-east Baltic Sea countries.

However, measuring the evolution of the coastline with Landsat 4-5 TM and Landsat 8 OLI satellite images between 1988 and 2018 have allowed us to determine a relative stability with an annual variation rate of -0.21 m/year.

Nevertheless, the annual rates of change by decade indicate other trends. During the period 1988-1999, there is an alternation between eroding and accreting areas, representative of a redistribution of sediments by the littoral drift. Calculations for the periods 1999-2009 and 2009-2018 seem to show a disruption of this cyclical evolution in favour of more intense erosion or changing spatial dynamics of coastal evolution.

New factors of natural origin (rise in sea level, reduction in ice periods, etc.) or anthropogenic origin (degradation of dunes, coastal protection structures, etc.) could cause these changes.

This research also compared two methods of coastline extraction: manual, by photointerpretation and automatic, by MNF transformation and Laplacian enhancement filter of the Landsat multispectral bands. The automatic method demonstrated its advantages in terms of processing time and robustness in terms of results.

Nevertheless, we would like to point out that the differences between the two methods over the long term (1988-2018) with calculations including a margin of error are insignificant. Further developments of this research could consist in using satellite images with a better spatial resolution such as Sentinel 2 MSI. However, the relevance of using the automatic method for the extraction of the coastline could be questioned by a less complete spectral resolution than on Landsat satellite images.

Finally, our research could be completed by multi-source data (aerial photos, field data, historical maps) to control the results of the satellite image analysis. Nevertheless, these data are not systematically available, of satisfactory quality and standardised for our study area, in the time period analysed.

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