LABORATÓRIO NACIONAL
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SOFT COASTAL PROTECTION MEASURES FOR LANGUE DE BARBARIE AND SAINT LOUIS, SENEGAL

Dynamics and potential long-term evolution of the proposed solutions

REPORT 37/**2024 – DHA/NEC**

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Fundación Canaria Parque Científico Tecnológico de la Universidad
de Las Palmas de Gran Canaria

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R&D HYDRAULICS AND ENVIRONMENT

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Title

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SOFT COASTAL PROTECTION MEASURES FOR LANGUE DE BARBARIE AND SAINT LOUIS, SENEGAL

Dynamics and potential long-term evolution of the proposed solutions

Abstract

This report presents the methodology and results of a study of the sediment dynamics and potential medium-term coastline evolution induced by hybrid-type coastal protection solutions for the *Langue de Barbarie* and the city of Saint-Louis, Senegal. The analysed solutions considered four designs of an artificial island, or a peninsula/spit connected to the mainland. The study includes gathering of study site data, preparation of model inputs, set-up and calibration of the shoreline evolution model *ShorelineS*, simulations of the potential coastal evolution for the proposed interventions, and critical and comparative analysis. The model succeeded in reproducing the main coastline modifications observed during the calibration period (2015 to 2019). It was found that any of the proposed hybrid solutions are likely to trigger substantial instabilities in the delicate sediment dynamics of *Langue de Barbarie*, eventually breaching this spit not far from the city of Saint-Louis. The analysis of alternative soft solutions led to similar conclusions.

Keywords: Shoreline evolution / *ShorelineS* model / Sand barrier / Spit / breaching / Erosion

MEDIDAS SUAVES DE PROTEÇÃO COSTEIRA PARA A LANGUE DE BARBARIE E SAINT LOUIS, SENEGAL

Dinâmica sedimentar e potencial evolução a longo-termo das soluções propostas

Resumo

O presente relatório contém a metodologia e resultados de um estudo da dinâmica sedimentar e potencial evolução a médio prazo da linha de costa, originada pela implementação de soluções de proteção costeira híbridas, para a restinga Langue de Barbarie e cidade de Saint-Louis (Senegal). Consideraram-se quatro soluções de proteção em forma de ilha(s) ou penínsulas/restingas artificiais. O estudo incluiu a recolha de dados do local de estudo e sua preparação para a modelação, a configuração e calibração do modelo de evolução de linha de costa *ShorelineS*, a execução de simulações das respostas da linha de costa às soluções propostas e a análise crítica dos resultados. O modelo teve bom desempenho na reprodução da evolução passada verificada para o período de calibração (2015 a 2019). Para as configurações das soluções híbridas propostas, o modelo prevê a geração de instabilidades na linha de costa, com padrões de erosão e acreção localizados, que acabam por forçar a criação de brechas ou abertas na restinga, próximo de Saint-Louis. A execução de soluções alternativas suaves conduziria a conclusões similares.

Palavras-chave: Evolução da linha de costa / Modelo *ShorelineS* / Ilha-barreira / Restinga / Aberta / Erosão

Executive summary

The city of Saint-Louis, Senegal, is located near the mouth of the Senegal river and is separated from the sea by the *Langue de Barbarie*, a sandy spit at risk of erosion. This spit is an extremely mobile coastal barrier, spanning a width of 100 to 400 meters. Throughout the past century, its length has exhibited fluctuations ranging from 10 to 30 kilometres, and it has been subject to recurrent breaches. The breaches affect the whole lower Senegal river dynamics and shore-installed communities, calling for a sensible and effective management. Given this coastal erosion risk and the challenges associated with climate change, the project "*RESCOAST: Infrastructure Planning and Risk Management Tools for the Development of Climate-Change-Resilient Coastal Economies in western Africa*" was born to anticipate and respond to climate change effects at the coastal and fishing communities of some countries, including Senegal.

Hence, the "*Fundación Canaria Parque Científico Tecnológco de la Universidad de Las Palmas de Gran Canaria*" (ULPGC) commissioned the "*Laboratório Nacional de Engenharia Civil*" (LNEC) to perform a study of the dynamics and potential long-term evolution of coastal protection solutions for the *Langue de Barbarie* and the city of Saint-Louis. The solutions proposed by ULPGC considered four designs of an artificial island or a peninsula/spit connected to the mainland. The objective of the present study was to evaluate the sediment dynamics, long-term evolution, and sand trap behaviour of the proposed designs.

The study contemplated the following activities: i) collection of local hydrodynamic, sedimentary and morphologic information, ii) preparation of the wave time series and other model inputs; iii) set-up and calibration of the shoreline evolution model *ShorelineS* (Roelvink et al., 2020); iv) simulations of the potential medium-term coastal evolution for the proposed interventions; v) critical and comparative analysis of the results for the four solutions in terms of erosion/accretion, breaching patterns, and sand trap behaviour.

The shoreline model was initiated and validated against Satellite Derived Shorelines (SDS). These were extracted using LNEC's Coastline Detection online service WORSICA (https://worsica.incd.pt/index/). The interface between the land and the sea, computed by the Normalized Difference Water Index (NDWI) from satellite Sentinel 2 images, was obtained for three images dating from 25th November 2015, 20th October 2019, and 26th June 2023. The shorelines from 2015 and 2019 were used for validation purposes, whilst the 2023 shoreline was taken as the initial condition for predictive simulations. Hindcasted wave time series from 1980 onwards were used as representative of the coming wave climate.

ShorelineS (Roelvink *et al.*, 2020) is a recent, open-source, free-form coastline model that can describe drastic coastal transformations, allowing for coastline curvatures and spit formation at high-angle wave incidence. This model was selected and applied in this project, using a beta-version provided by the developer (updated relative to the public version). Despite the recent improvements, the model can be considered as in development, meaning that some modules lack further assessment. In general, the

default model parameters were specified, and the model study area comprised a coastal stretch long enough to minimise any boundary effects in the results at the intervention area.

The four “candidate solutions” proposed by ULPGC were designed as “mixed” or “hybrid” solutions in terms of coastal intervention, combining a *hard* coastal structure (a conventional detached breakwater or a groyne) with a *soft* coastal nourishment. These four solutions differed basically in terms of plan-shape, with two being considered an oblique groyne-type structure (with the two-thirds of its development parallel to the shore), and the other two a single or multiple detached breakwaters. The breakwater segment of all solutions measures circa 4000 m alongshore and is placed at depths ranging from 6 to 12 m. Additional model simulations were also performed, excluding the hard structures from the solutions, that is, considering only the soft-solutions’ configurations.

Model parameters were set to reproduce the estimated net average littoral drift in this area, i.e., of the order of ~680x10^3 m^3/year, after calibration. The simulations for the calibration period (2015-2019) yielded an estimated southward migration of the spit-end of approximately 1400 m (~357 m/year), lesser than the measured one (1800 m). In front of Saint-Louis, the model predicted small shoreline retreat (of the order of 10 m) yet failing to reproduce observed erosion hotspots (locally reaching 40 m).

Nine model simulations were carried out for the exploitation phase, comparing the 4 hard (or hybrid) proposed solutions with their counterparts’ soft solutions and with the reference case (evolution without any intervention). For the latter case, no significant changes were predicted for the shoreline position, except for the natural elongation of the spit and respective southward migration of the river inlet. Completely different shoreline positions resulted from the implementation of any candidate solution. All the soft-solution implementations caused the breaching of *Langue de Barbarie* within less than 3 years of simulation, except for solution 4. These breaches occurred mostly south of Saint-Louis (within 1-3 km away). They were likely caused by shoreline instabilities triggered by the partial and transitional sheltering effect of the interventions. These instabilities and the erosion/accretion patterns at *Langue de Barbarie*, however, are not restricted southwards of Saint-Louis. In the case of the hybrid solutions, there is sediment retention updrift of the groynes (when existent) or as salient formations (in the case of the detached breakwater-type solutions), which induce sediment starvation further south, eventually leading also to the breaching of *Barbarie* spit, circa 3 km south of the city. Hybrid solutions 1 and 2 act positively in protecting the city of Saint-Louis and its coastal front, in terms of coastal erosion risk. However, the gap between the detached breakwaters of solutions 3 and 4 may induce significant erosion or breaching immediately south of Saint-Louis.

To conclude, any of the proposed hybrid solutions are likely to trigger substantial instabilities in the delicate sediment dynamics of *Langue de Barbarie*. In this naturally unstable environment, with a high rate of longshore sediment transport, the proposed solutions are likely to create breaches near the city of Saint-Louis. The implementation of soft solutions, in the form of sandy groynes or islands, have short lifetimes, and would cause undesirable shoreline instabilities. Finally, it would be desirable to confirm these results by confronting them with those from alternative shoreline evolution models. All models have limitations, and ShorelineS is still in a development stage, and it would be desirable to exist more experience with its application to real cases in the scientific and technical community.

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1 | Introduction

1.1 Presentation and objectives

The historical and UNESCO world heritage city of Saint-Louis (Senegal) has a population estimated at approximately 260,000 (in 2021)[1]. The cultural attractiveness of Saint-Louis, a former French colonial city, and the biodiversity of the surrounding deltaic wetlands and lagoon have also generated a substantial rise in tourism (Sadio *et al*., 2017). The city is located near the mouth of the Senegal river (Figure 1.1) and is separated from the sea by the *Barbarie spit*, at risk of erosion (e.g., Tavenau *et al*., 2021). Much of Saint-Louis lies at an elevation of less than 2.5 m above mean sea level, and the city has, therefore, been prone to the flooding that affects the lower Senegal valley in the rainy season (Sadio *et al*., 2017).

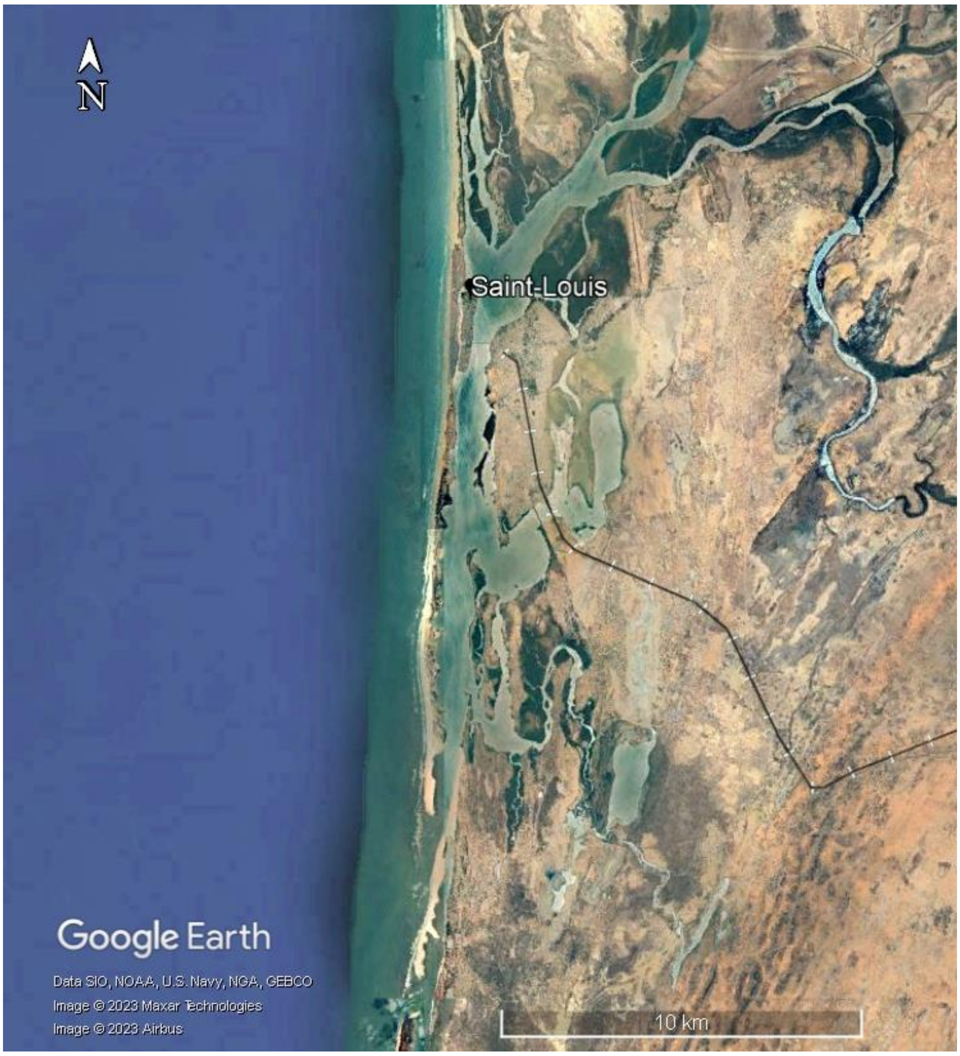

Figure 1.1 – Satellite view of the coast in front of Saint-Louis, Senegal

[1] https://en.wikipedia.org/wiki/Saint-Louis,_Senegal

Given the coastal flooding and erosion risks at *Langue de Barbarie*, and climate change challenges, the project "*RESCOAST: Infrastructure Planning and Risk Management Tools for the Development of Climate-Change-Resilient Coastal Economies in western Africa*" was conceived to anticipate and respond to the effects of climate change suffered by the coastal and fishing communities of the Canary Islands, Mauritania and Senegal[2]. This initiative seeks a common management model that minimizes the vulnerability of these population centres affected by Climate Change through the development of a prediction and territorial planning tool[2].

For such, the "Fundación Canaria Parque Científico Tecnológico de la Universidad de Las Palmas de Gran Canaria" (ULPGC) invited the "Laboratório Nacional de Engenharia Civil" (LNEC) to submit a proposal to perform a study of the dynamics and potential long-term evolution of soft coastal protection solutions for the *Langue de Barbarie* and the city of Saint-Louis. Following LNEC's proposal sent out on 26th July 2023, ULPGC accepted it and commissioned LNEC to initiate the study on the 26th of September 2023.

The solutions initially proposed by ULPGC considered three designs of an artificial island or a peninsula/spit connected to the mainland, in front of the Langue de Barbarie coast and Saint-Louis. These three designs were later extended to four, which are detailed in Chapter 4. The objective of this study is thus to evaluate the dynamics, long-term evolution and sand trap behaviour of the different proposed solutions to improve coastal protection.

This study included the following activities:

1) collection of study site hydrodynamic, sedimentary, morphologic and sediment transport magnitude (littoral drift) information, relevant for the modelling stage. This includes, amongst others, tidal levels, wave climate conditions, characteristic beach sediment size, bathymetry, topography, alongshore sediment transport fluxes, and shoreline evolution rates;
2) definition of the long-term time horizon and preparation of the wave time series conditions, to force the shoreline evolution model;
3) set-up of the shoreline evolution model ShorelineS (Roelvink *et al*., 2020) to simulate the coastline evolution of the study site, for the island/peninsula proposed solutions. The model is calibrated for the present coastline configuration;
4) simulations of the potential long-term coastal evolution for the proposed interventions. Analysis of the shoreline accretion/erosion results;
5) critical and comparative analysis of the results for the four solutions in terms of sand trap behaviour and conclusions;
6) report writing.

[2] https://proyectorescoast.itccanarias.org/es/

1.2 Report organisation

This report is organised in six main chapters and two appendices. Chapter 1 contains the presentation of the work and main objectives. The study site characteristics relevant for the model set-up are described in Chapter 2. The used shoreline evolution model and its parameterisation are presented in Chapter 3. Chapter 4 portrays the client-proposed four coastal protection interventions. In Chapter 5, the main modelling results are organised and presented; first, one shows the calibration-phase results and then the exploitation-phase ones. Finally, the main conclusions and recommendations of this work are described in Chapter 6. Appendix I contains supplementary study-site data, and Appendix II a list of the most relevant model parameters.

2 | Study site

2.1 Identification

The coast of Senegal is located on the relatively narrow West African continental shelf and is characterized essentially by sand barriers. According to Anthony (2015), this coast is under the influence of dominantly long and regular swell and shorter-fetch trade-wind waves. Combined with abundant fluvial sand supplies during the Late Pleistocene, the dominant swell-wave regime generated in the Atlantic Ocean generates sustained longshore sand drift responsible for the construction of numerous sandy barrier systems and spits. These form a rather irregular coastline, with various lagoons and tidal embayments, particularly at conjunctions with outgoing rivers and delta developments, such as the Senegal river delta.

The Senegal delta (Figure 1.1) is a classical wave-dominated delta, characterised by the presence of a persistent sand spit – the *Langue de Barbarie*. This spit is an extremely mobile feature, subject to repeated past breaches, associated with phases of delta-mouth migration over a total distance of about 30 km at least since the mid-seventeenth century (Anthony, 2015).

The relatively moderate Senegal river discharge, including during the flood season, the permanence of moderate waves propagating across a relatively narrow shelf, and the microtidal regime are three conditions that explain the wave-dominated character of the Senegal River delta and the quasi-permanent river-mouth diversion by the *Langue de Barbarie* (Anthony, 2015). Morphologically, this feature is a 100 to 400 m-wide coastal barrier that has fluctuated in length between 10 and 30 km over the last century. The changes in length reflect the variable position of the Senegal river mouth, where rates of spit growth vary widely (growth-rates from 100 to 700 m per year have been reported), depending on variations in wave characteristics, river discharge and river mouth dynamics, combined with barrier-breaching events (Bergsma *et al*., 2020).

The *Langue de Barbarie* sandy barrier protects the island of Saint-Louis, within the Senegal lower river stretch (Figure 1.1). Of particular significance in terms of coastal management is the historic and picturesque city of Saint-Louis, a UNESCO world heritage city (Anthony, 2015). Moreover, the coast in front of the city is home to small-craft fishing activity, with high economic and social implications. Given the Saint-Louis settings and the *Barbarie* spit dynamics, the city is at high coastal erosion and flooding risk. Along the 2-km stretch in front of Saint-Louis, coastal erosion can be severe, with the barrier's oceanic coastline retreating in places at rates of up to 20 m/year (Tavenau *et al*., 2021).

Sadio *et al*. (2017) estimated at this coast a longshore sediment transport rate (net drift) over a 32-year period, induced by swell waves of the order of 611x10^3 m^3/year, directed southwards. The total transport is slightly larger, of the order of 670x10^3 m^3/year, due to a much smaller northward oriented flux. This estimate of the net drift is in accordance with the value between 600 and 700x10^3 m^3/year estimated by SOGREAH (1994), but slightly overestimates the value of 530x10^3 m^3/year, estimated for a period of 5 years by Tavenau *et al*. (2021).

With the aim of protecting the city of Saint-Louis and the coastal barrier in front of it, the present work focuses on the shoreline evolution of the *Langue de Barbarie* and, in particular, of the coastal stretch fronting Saint-Louis.

In the following, geographical (Easting and Northing) coordinates are referred to WGS 84 / UTM zone 28N (EPSG: 32628). The vertical coordinate is referred to EGM2008 geoid.

2.2 Morphological characteristics

The three parameters representative of the study site morphology, considered static by the ShorelineS model during the calculation of the coastline evolution, are the depth of closure, the beach berm and the foreshore orientation.

The **depth of closure** is the depth of the seaward limit of the cross-shore profile beyond which there are no significant changes in the seabed level. Based on a larger amount of beach profile data than the initial study of Hallermeier (1978), Birkemeier (1985) proposed the following formula for the depth of closure, D_c, which was applied for the study site:

$$D_c = 1.75\, H_e - 57.9 \left(\frac{H_e^2}{g\, T_e^2} \right)$$

where H_e is the local significant wave height which is exceeded 12 hours per year (with a cumulative exceedance probability of 0.137%), T_e is the associated period and g is the gravitational acceleration.

The 10-year wave data series, from the period 2011-2020, was analysed yearly to obtain the annual values of H_e, T_e and D_c (Table 2.1). The maximum value of the depth of closure was 4.4 m in 2018.

Table 2.1 – Yearly H_e, T_e and D_c between 2011 and 2020

Year	H_e(m)	T_e (s)	D_c (m)
2011	2.068	14.254	3.495
2012	1.777	6.467	2.664
2013	2.089	13	3.503
2014	2.179	8.969	3.465
2015	1.866	15.554	3.181
2016	1.907	14.027	3.228
2017	1.9	14.992	3.230
2018	2.593	15.258	4.367
2019	1.961	15.096	3.332
2020	1.714	15.392	2.926

The **beach berm** is, by definition, a shore parallel ridge formed due to the landward transport of the coarsest fraction of the beach material by the wave uprush. Under normal conditions a beach berm is formed on the upper part of the beach face, and over the backshore during severe events.

For the study site, the berm was obtained from the analysis of the topo-bathymetric survey of the coastal area of Saint-Louis, Senegal, performed by Shore Monitoring & Research BV, in January 2019, within the project "Measurement Campaigns and Capacity Building, Saint-Louis, Senegal" commissioned by Deltares (Netherlands). A digital terrain model (DTM) was created based on these data and 10 two-kilometres-equidistant profiles, designated by P1-P10, from north to south respectively, were extracted from the DTM (Figure 2.1). The profiles were analysed individually, and the berm was detected visually. Once this feature was identified, its elevation was extracted (Table 2.2). The average value of the berm elevation for the 10 cross-shore profiles is 2.1 m EGM2008.

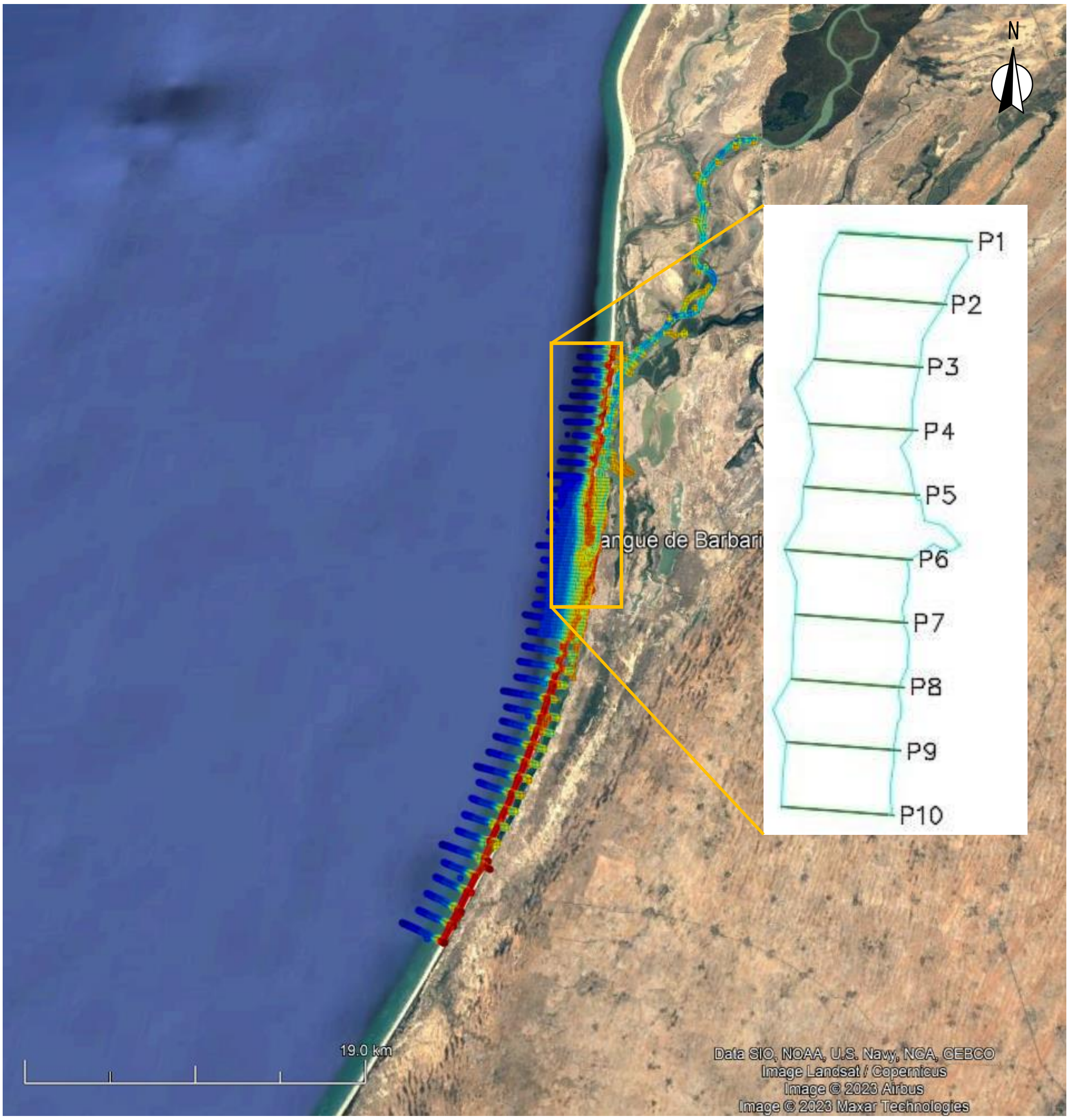

Figure 2.1 – Comprehensiveness of the topo-bathymetric survey of the coastal area of Saint-Louis, Senegal, performed by Shore Monitoring & Research BV, in January 2019; schematic layout of the location of the cross-shore profiles P1-P10 extracted from the DTM developed in this study

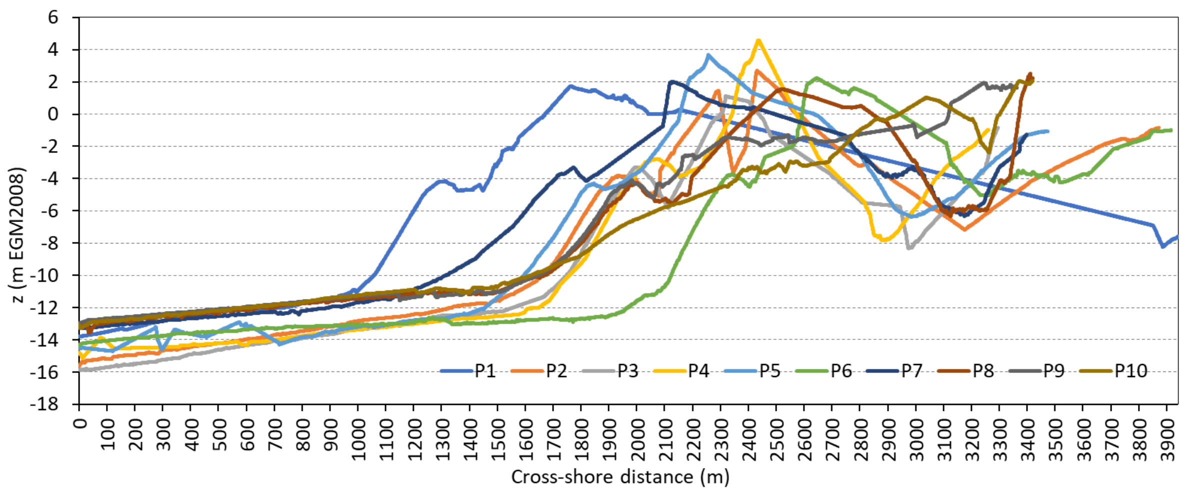

Figure 2.2 – Two-kilometres-equidistant cross-shore profiles, P1 - P10, from north to south, used to identify the berm position in the coastal area of Saint-Louis, Senegal

Table 2.2 – Berm elevation of profiles P1-P10 in the coastal area of Saint-Louis, Senegal

Profile	z (m EGM2008) of the berm
P1	1.749
P2	1.468
P3	1.102
P4	4.589
P5	3.673
P6	2.238
P7	2.022
P8	1.543
P9	1.954
P10	1.037

For the ShorelineS model application, the foreshore is understood as the region outside the depth of closure that does not react to changes in the waterline. The foreshore orientation is thus specified when the coastline orientation is not representative of the deeper foreshore orientation, as is the present case (Figure 2.3). Attending to this figure, the **foreshore orientation** is 281° (relative to the North, clockwise) at 20 m depth, whereas the coastline is approximately oriented 357°.

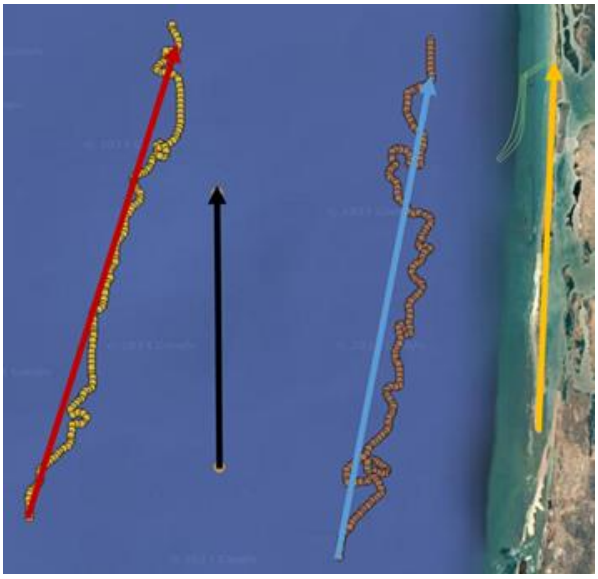

Figure 2.3 – Vectors indicating the coastline and foreshore orientations at 0 m (yellow arrow), 20 m (blue arrow) and 50 m (red arrow) isobaths; the black arrow stands for the geographical "true" north orientation (-0.45º in the study reference system)

2.3 Sediments

In order to acknowledge the study site representative sediment median diameter, D_{50}, another parameter required for the application of the ShorelineS model, the sedimentological data obtained from the sediment grain size surveillance campaign performed in January 2019, the same date as the topo-bathymetric campaign, was analysed. The cross-shore profiles which pass by the position of the 37 sediment samples were extracted from the DTM developed in this study in order to identify the samples position relatively to the profile zone (Figure 2.4; and Figure I.1 to Figure I.4 of Appendix I).

The sedimentological analysis indicates that the average D_{50} of the beach sediment samples is 0.25 mm. Nevertheless, the grain size of the sediments is smaller in the deeper part of the profile, with average D50 = 0.17 mm; and the grain size of the sediments is larger at the beach face, with average D50 = 0.29 mm (Table I.1 of Appendix I).

Figure 2.4 – Location of the sediment samples collected in the sedimentological campaign of January 2019 in the coastal area of Saint-Louis, Senegal; schematic layout of the cross-shore profiles extracted from the DTM developed in this study that contain the position of the sediment samples

2.4 Coastlines

The shoreline model was initiated and validated against Satellite Derived Shorelines (SDS). The SDS were built with the Coastline Detection tool of the online service WORSICA (https://worsica.incd.pt/index/), developed by LNEC. The Coastline Detection tools was used to compute the Normalized Difference Water Index (NDWI) from satellite Sentinel 2 images, with an automatic threshold to locate the interface between the land and the sea. This position was computed for three images dating from 25 November 2015, 20 October 2019 and 26 June 2023 (Figure 2.5). The shorelines from 2015 and 2019 were used for validation purposes (Figure 2.6), whilst the 2023 shoreline was taken as the present situation to test the behaviour of the different solutions. In the period of validation, the shoreline retreated up to 40 m in front of the study area, while the *Barbarie spit* extended 1.8 km southward. These observations were used as a basis for the calibration process.

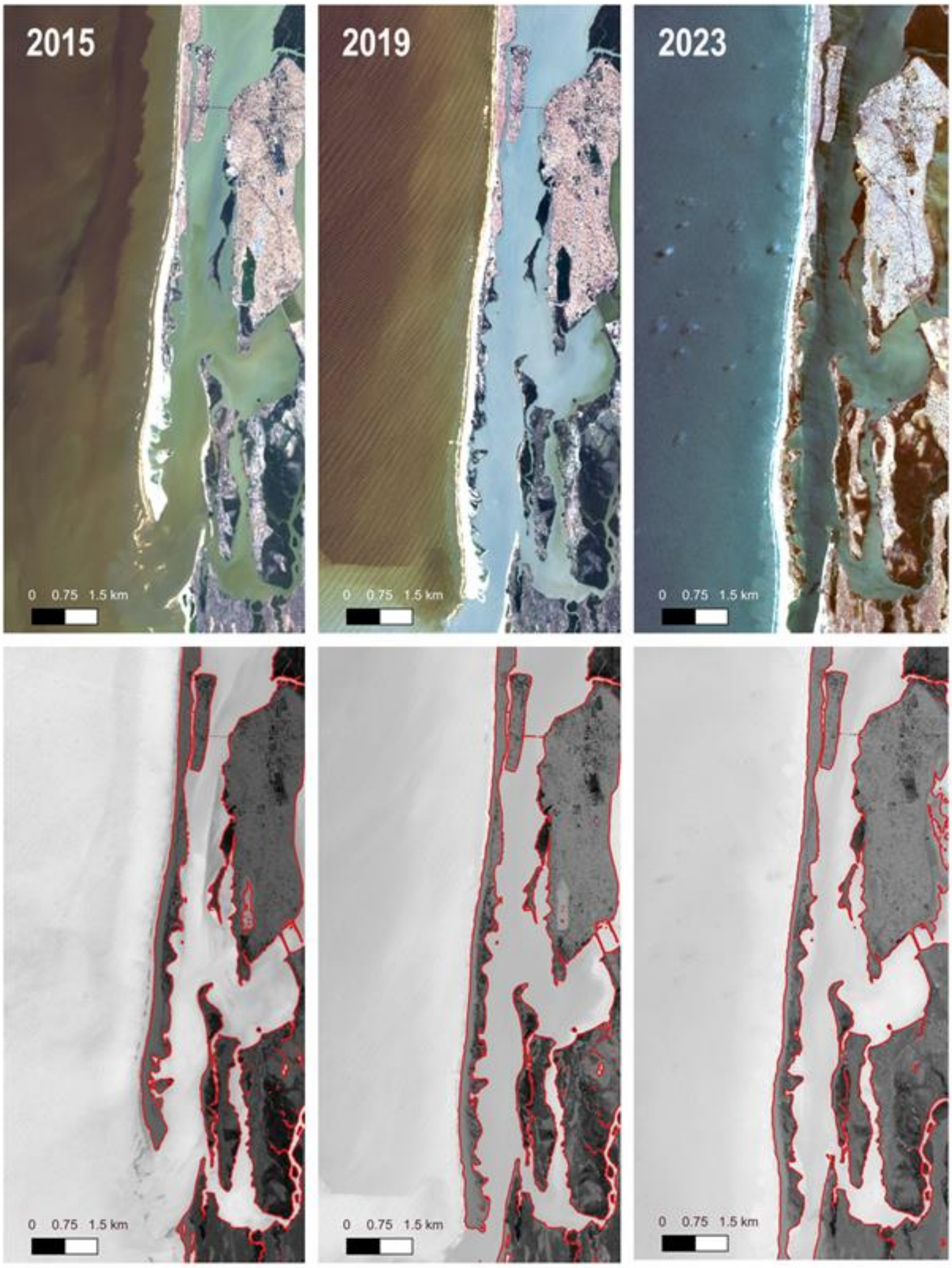

Figure 2.5 – RGB Sentinel 2 Satellite images (upper panels) and the associated NDWI images (Lower panels) with the extracted "Satellite Derived Shorelines" (SDS) in red, from 25th October 2015, 25th November 2019, and 26th June 2023

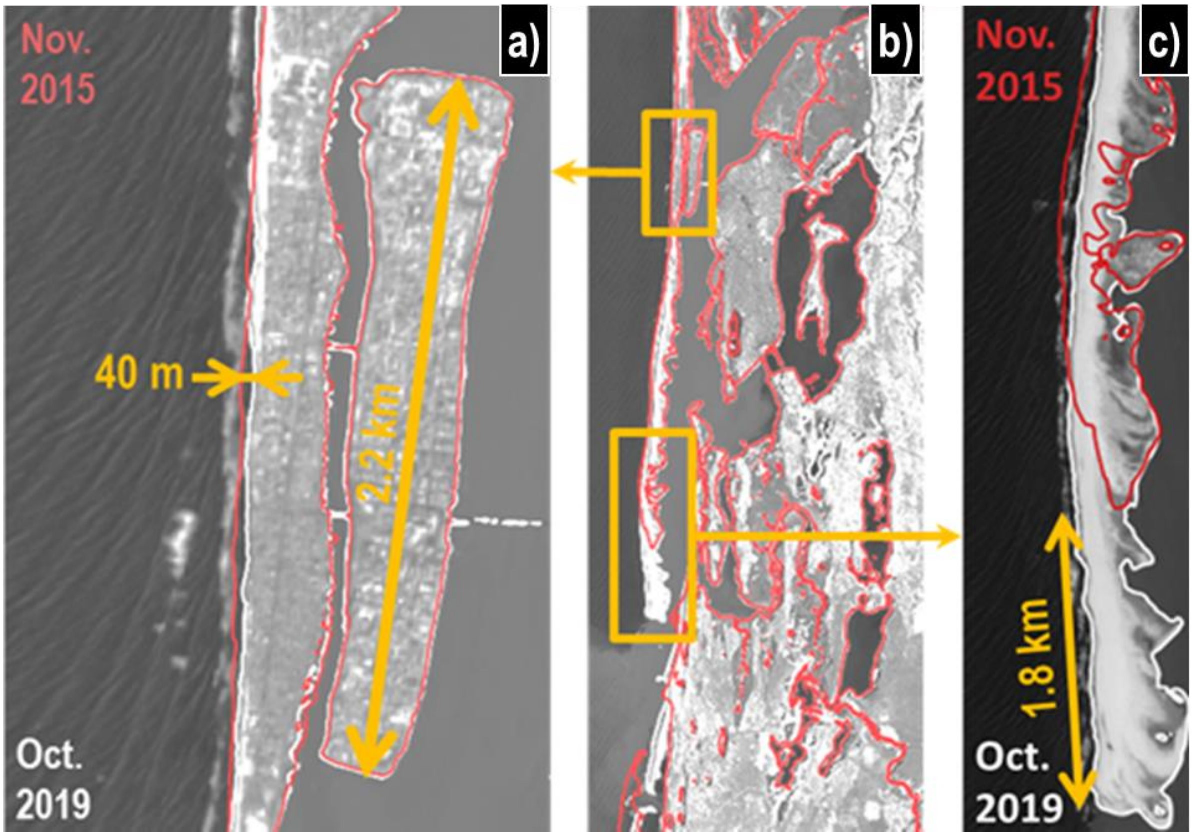

Figure 2.6 – Geomorphological evolution during the model validation period, between November 2015 (red contours) and October 2019 (white contours), observed from SDS: a) detail in front of the study area; b) over the *Langue de Barbarie*; c) detail of the spit head

2.5 Wave climate

The wave climate for model input consists of a time series of the basic wave properties (namely, significant wave height, wave period and wave direction) offshore of the study site location. Most often and in the present case, the wave time series is obtained from an hindcast simulation of a coupled wind-wave ocean model.

Here, ULPGC[3] provided LNEC with a wave hindcast time series, from 1st January 1952 until 30th December 2012, obtained from the wave database SONEL (https://www.sonel.org/-Waves-.html) at a deep water point, located 22.0W, 21.0N (longitude, latitude). The wave timeseries in this database were obtained using a WaveWatch III model (WW3) configuration in combination with winds from NCEP, over a 1-degree latitude and longitude grid. Analysis of this wave climate showed that it contained a significant percentage of waves (26%) from the northeastern quadrant, as that location is exposed to waves propagating along the Northwestern African Moroccan coast. As seen in Figure 2.7, that point is quite distant from Saint-Louis coast, which is protected from waves from the northeast, and thus may not correctly represent the wave climate in front of Saint-Louis.

[3] Iin association with their partner RALEY Estudios Costeros S.C.P., www.raleyestudioscosteros.com

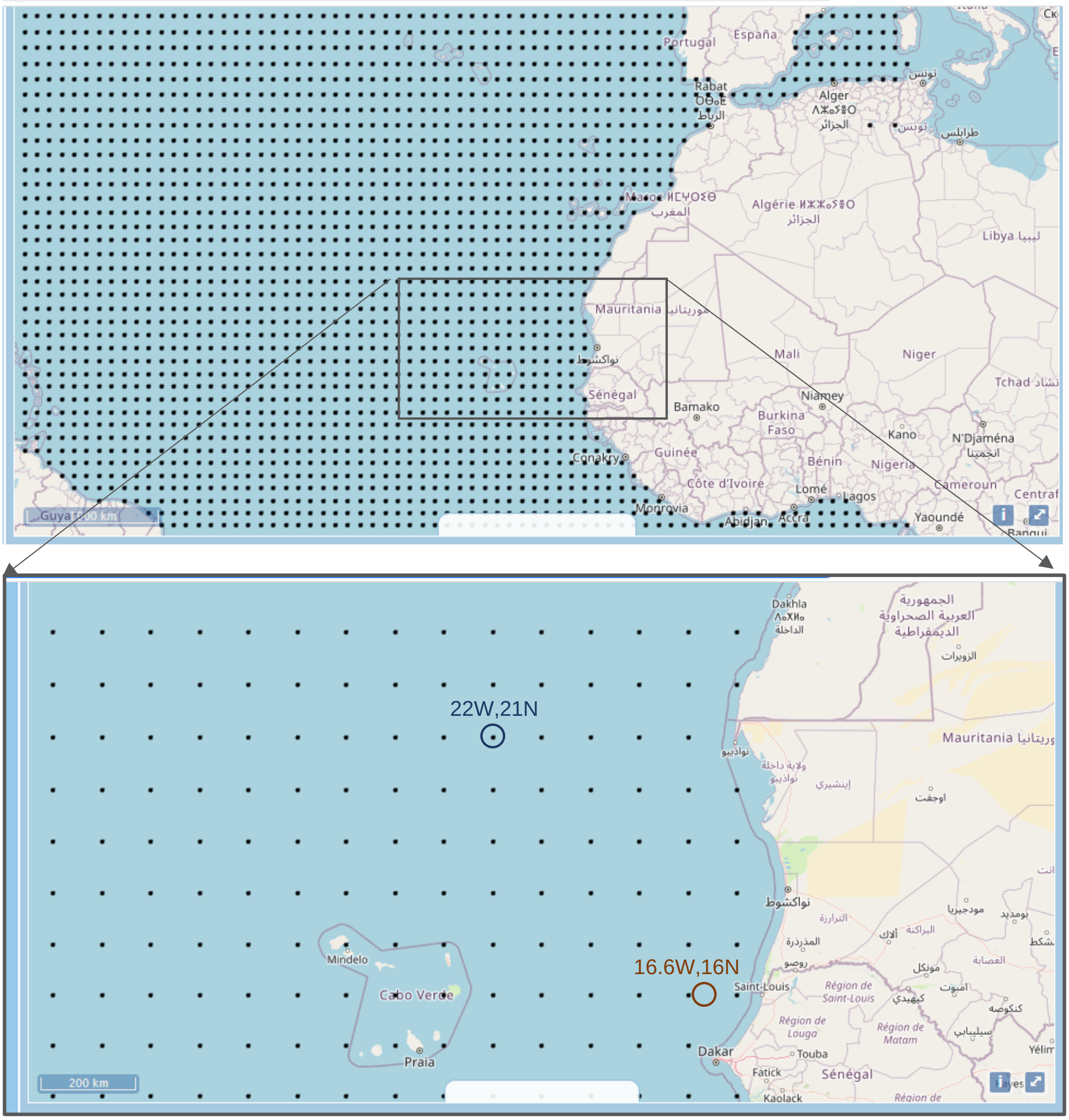

Figure 2.7 – Wave climate hindcast locations (original SONEL hindcast point in blue; WW3 hindcast point in brown)

In order to avoid the contamination of waves from the northeastern sector, LNEC obtained a new hindcast data time series, from the work of Samou *et al*. (2023). This hindcast was obtained using the WW3 model with ERA5 wind forcing, for the period between 1st January 1980 and 30th December 2021. A 0.05-degree high-resolution grid was used for the Senegalese shelf. Figure 2.7 shows the location of the point located 16.6W, 16.0N, at 27 m water depth, where the wave time series was extracted.

Figure 2.8 shows the significant wave height, mean wave direction and wave peak period histograms obtained from the data analysis of the Samou *et al*. WW3+ERA5 hindcast, for the 16.6W, 16.0N location, right in front of Saint-Louis, at 27 m water depth. As expected, this does not contain waves from the northeast (Figure 2.8c). As observed, most waves have heights between 0.5 and 1.5 m, and northwestern wave directions. Wave peak periods range, typically, from 6 to 15 seconds.

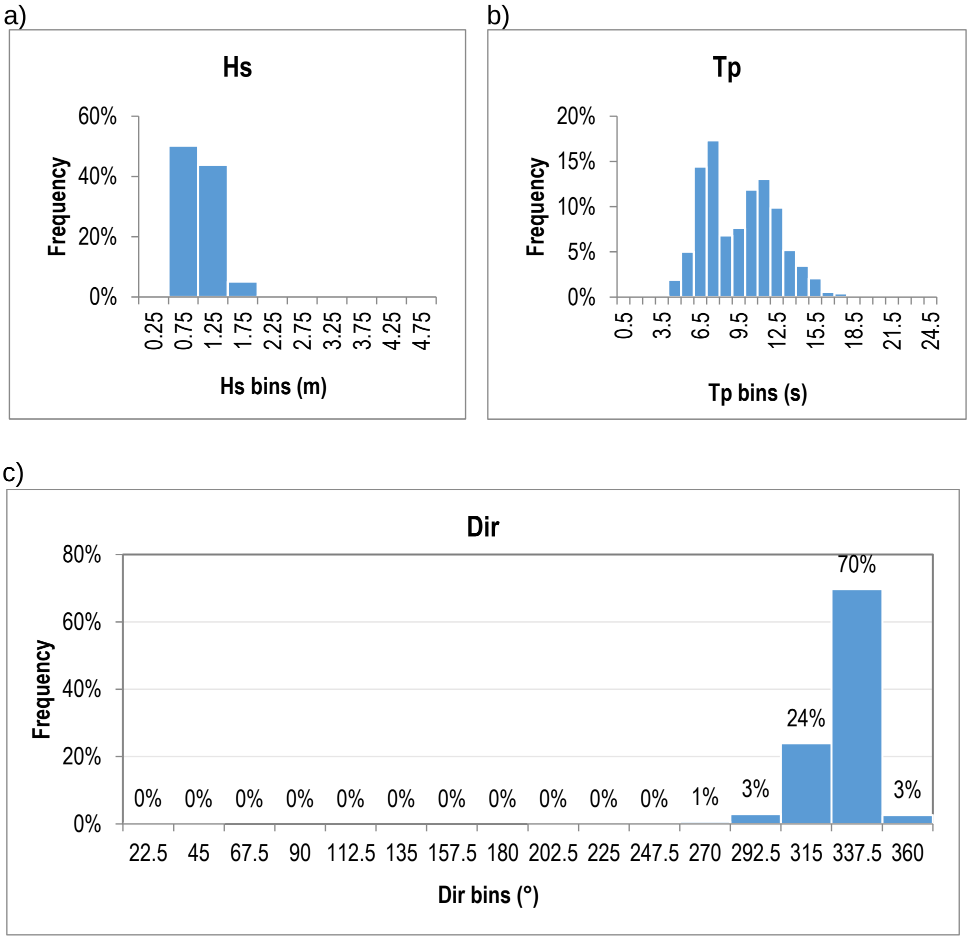

Figure 2.8 – Wave climate histograms from hindcast at point 16.6W, 16.0N (27 m depth): a) Significant wave height, Hs; b) Wave peak period, Tp; c) Mean wave direction, Dir. (Numbers at the abscissas axes are the median of each bin interval)

Table 2.3 – Simple statistics from time series of Hs, Tp and Dir, at point 16.6W, 16.0N (27 m depth)

Statistical Parameter	Hs (m)	Tp (s)	Dir (°)
Mean	1.023	9.65	319.1
Std. Deviation	0.276	2.85	12.1

Table 2.3 shows the means and standard deviations of the significant wave height, Hs, wave peak period, Tp, and (spectral) mean wave direction, Dir, obtained from the used 40-year wave time series hindcast. Mean wave direction (319°) is close Northwest (315°), and mean wave height equals 1.0 m. Despite the mean wave height being quite moderate, the extremely oblique mean wave direction (nearly 40° relative to the coast) and narrow wave direction spreading (small standard deviation), are thus responsible for the high annual mean littoral drift observed (or estimated) at the *Langue de Barbarie* coastline (between 600 and 700x10^3 m^3/year, as provided in Section 2.1).

It is noted that, using the above hindcast wave dataset for the Senegalese coast, Sadio *et al*. (2023) analysed the wave climate variability over the past 40 years. They concluded that there were no tendencies of change for Hs and Tp, and a tendency for a slight counterclockwise rotation of the wave direction, of the order of 0.04°/year in front of Saint-Louis. Given these negligible or small trends, wave climate variability is ignored in the present modelling simulations.

2.6 Sea-level change and tidal regime

Sea level rise is recognised to occur because of planetary climate change effects. Global sea level change time series from 1950 to 2050, derived from reanalysis and high-resolution CMIP6 climate projections, were extracted from the EU Earth Observation Copernicus service. The extracted dataset is available at: https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-water-level-change-timeseries-cmip6?tab=overview. Figure 2.9 depicts the projected sea level rise for the period 2015 to 2050, with a linear fit superposition ($R^2 = 0.996$), yielding a trend equal to 0.0061 m/year.

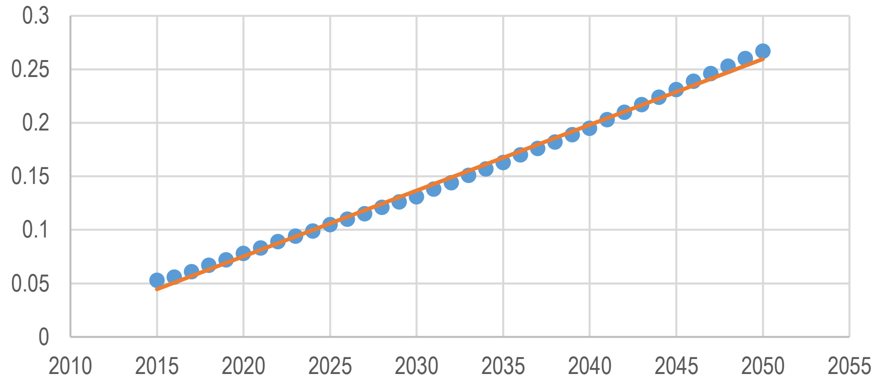

Figure 2.9 – Sea level rise (m) projection from 2015 to 2050

According to Sadio *et al*. (2017), the tidal regime along the *Langue de Barbarie* is semi-diurnal and the range is microtidal, comprised between 0.5 m at neap tides and 1.6 m at spring tides. This microtidal regime shall, therefore, have a negligible influence on the long-term shoreline evolution, and the contact line between the “mean sea level” and the beach(/land) is a good representative of the coastline, and will be the “modelled” coastline.

3 | Shoreline evolution model

3.1 Model description and limitations

Given the strong dynamic behaviour of the *Langue de Barbarie*, it was envisaged that it would be desirable to model the spit migration and possible breaching, due to longitudinal sediment transport gradients. Moreover, during the model selection phase, the contractor favoured the use of an open-source model, able to cope mainly with (and tested for) soft solution interventions. Therefore, the coastline evolution model **ShorelineS** (Roelvink *et al*., 2020) was selected and applied in this project.

ShorelineS is a recent, open-source, free-form coastline model that can describe drastic coastal transformations based on the relatively simple principles of longshore transport gradient driven changes as a result of coastline curvature, and spit formation at high-angle wave incidence (Elghandour and Roelvink, 2020). A vector-based coastline concept was proposed, describing the coastline like a freely moving string of points. An arbitrary number of coastal sections is supported, which can be open or closed, and can interact with each other through relatively straightforward merging and splitting mechanisms. Rocky parts or structures may block wave energy and/or interrupt longshore sediment transport. These features allow for developing shoreline undulations and formation of spits, migrating islands, merging of coastal shapes, salients and tombolos.

Other model developments were later incorporated and validated, such as wave diffraction behind shore-parallel or shore-normal structures (Overgaauw, 2021) and inlet migration (Elghandour *et al*., 2021, 2023). Despite these recent improvements, the model can be considered as in development, and some features may fail or are not robust enough. In particular, activating in the model the wave diffraction effect on the sediment transport rates, in the lee of multiple structures, posed a difficulty. Also, if the present version of ShorelineS does allow the representation of hard structures such as breakwaters or groynes, these cannot be associated with a transmission coefficient. Therefore, they are represented as fully emerged. Because of this, the design islands in the model are expected to behave mostly as a hard structure. Regarding inlet dynamics, the model has only been validated in terms of inlet migration rates, without a robust assessment of the shape of the inlet channels and spits.

A beta-version of the model (provided by the developer) has been used here, which is an updated version of the public one (https://github.com/danoroelvink/shorelines), presently outdated. This version has, according to the developer, much more features and is more robust.

3.2 Model set-up and parameterisation

In general, the default model parameters were used in the present applications. The most relevant parameters and their used values are listed in Appendix II.

The model allows for choosing several (alongshore) sediment transport formulations. Here, after a few sensitive tests, the formula parametrised by Mil-Homens *et al*. (2013) was chosen. The sediment transport along the *Langue de Barbarie* was calibrated based on the available site information, by means of adjusting the model parameter "*S.qscal*" (default equals 1) and the foreshore orientation. From the calibration it resulted the best values to be *S.qscal*=1.4 and *S.phif*=300°. It is noted that this foreshore orientation is slightly larger than that estimated from the 20 m isobath orientation (281°), but within this value and the one calculated at the shoreline (357°).

From the results of section 2.3, the median grain size for the sediment transport formula is 0.25 mm. Other parameters affecting the sediment flux are the default ones (see Table II.1).

The total active profile height is 5.5 m. This value is smaller than the value 6.5 m, resulting from the sum of the berm height (2.1 m) and the depth of closure (4.4 m). The use of a smaller value follows from calibrating the shoreline positions (and respective erosion/accretion rates), as for the same sediment flux gradient, a smaller active profile height induces a larger shoreline movement.

The model study area comprised a coastal stretch long enough to minimise any boundary effects in the results at the intervention area. The longest model domain comprises the region shown in Figure 3.1, ranging from Easting∈[335000, 340000] and Northing∈[1754100, 1778800]. This domain was used in the calibration phase (2015 to 2019) as well as in the exploitation phase (2023 onwards), in the case of no interventions. The Northing model domain extension for the proposed solutions (see Chapter 4) simulations was smaller than the range given above, namely, Northing∈[1763000, 1778800], to reduce the computational time and because the intervention would have no effect outside that model domain, within the simulation period. It is noted that, in the study area, the Senegal river estuary was simplified into its main channel, and thus all meanders and estuarine bays were removed. This does not affect the coastline evolution, since this is wave dominated and no waves penetrate through the river, except at its mouth, where the shorelines are exactly reproduced. The inlet migration processes are included in the model simulations.

The coastline initial grid size varied between 80 and 100 m. At the northern and southern domain boundaries, a fixed ("Neumann") shoreline position was defined, compatible with the historical shoreline evolution and providing reliable numerical solutions over the entire domain. Other boundary conditions did not provide reliable results.

In order to reduce the computational time, the simulation time step equals 1 day. This value is eight times larger than the one provided by the wave time series (every 3 hours), but the model preserves wave energy when the model time-step is larger than the wave time series step, i.e., the model time-step integrates the data available within that time-step. The chosen time-step value was within the limits allowed by the Courant number and grid size.

The wave time series provided in Section 2.5 is used for shoreline projections. Arbitrarily, one can use any part of the observed/projected wave time series as a representation of the future one, for the model simulations. In fact, one could use different sequences of observed waves, or even synthetic wave series from multivariate statistical analysis (e.g., Teixeira-Canelas *et al*., 2022) for the model input. Here, we chose (arbitrarily) the observed(/hindcasted) sequence starting in 01-01-1980 for the wave time series input.

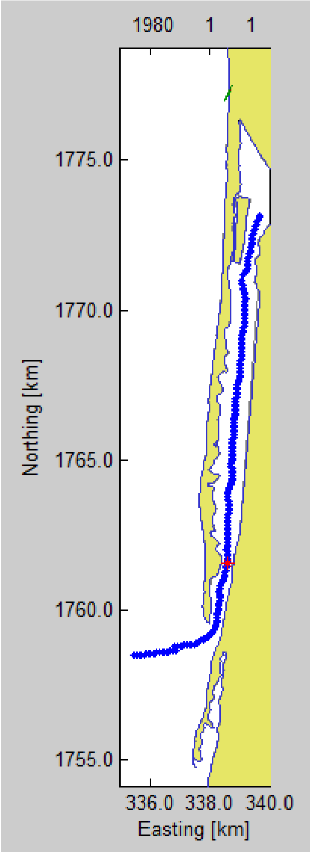

Figure 3.1 – Model domain

The parameters affecting the spit-overwashing process, spit migration and inlet-channel dynamics are the default ones or close to them (Table II.1) and were chosen upon calibration and several parameter-sensitivity tests.

Regarding sea level rise, it was seen in Section 2.6 that the annual trend is 0.0061 m/year. All simulations were performed for a period no longer than 10 years, as physical or numerical instabilities arose on computations for longer times, that caused model crashing. Given the fact that in a 10-year period the estimated sea level rise would be 6 cm, the effect of this rise on the shoreline evolution is negligible compared to the effect of the proposed solutions or even in the case of no interventions, because of the magnitude of the sediment dynamics along this coast. Therefore, sea level rise was not introduced in the modelling parameterisation for the present simulations.

4 | Proposed solutions

The solutions analysed herein were proposed and provided by the RESCOAST project (https://proyectorescoast.itccanarias.org/es/). They resulted from the analysis of several socio-economic-physical-geographical dimensions, taking into account the knowledge of the barrier islands and the *Langue de Barbarie* sedimentary dynamics.

Four final "candidate solutions" were proposed by the client, all designed as a mixed or hybrid solution in terms of coastal intervention. That is, all these solutions were conjectured as a combination of a *hard* coastal structure (a conventional breakwater or groyne) and a *soft* coastal nourishment intervention. The former is designed and placed to protect and enhance the lifetime of the latter, that without any conventional protection would likely erode rapidly. The armoured-structures are planned to be a conventional rubble-mound structure with a protective layer and filters at the seaward-facing coastline of the island or spit configured nourishments.

A plan view of the four proposed solutions is shown in Figure 4.1 (scale 1:100000) and are briefly described below:

- Solution 1 is formed by an oblique groyne, south-westward oriented from land to sea, which at a distance of circa 1000 m perpendicular to the coast turns southward and develops as a detached breakwater. The groyne segment measures approximately 1350 m, whereas the breakwater segment develops for 4000 m. The breakwater extends roughly parallel to the coast, but the southern end develops seawards. This solution comprehends a spit-configuration sand fill and a coastal structure at the seaward (or outward) face of the spit sand fill. It is anticipated that this solution will block the predominant sediment transport until a complete beach fill occurs north of the groyne, and subsequent partial sediment by-pass occurs.
- Solution 2 is a simplification of the former, removing the coastal-attached groyne. Potentially, this solution would not block the littoral drift but reduce the wave energy at the lee of the breakwater, potentially enabling the formation of a coastal tombolo or salient. In terms of components, it is formed by 4 km long island-configured sand fill and a protective structure at its seaside. This island is 1000 m seaward of the present coastline.
- Solution 3 basically splits into three parts the one-island solution 2. It is thus constituted by three small islands (approximately, 1200, 1100 and 1350 m, respectively, from north to south), connected by submerged breakwaters. The sand-filled islands are also protected by an armoured structures at the seaward side. Therefore, in terms of coastal dynamics, this solution has the potential to let the waves partially propagate through the breakwater gaps, activating more the sediment transport within the 4 km long protected region.

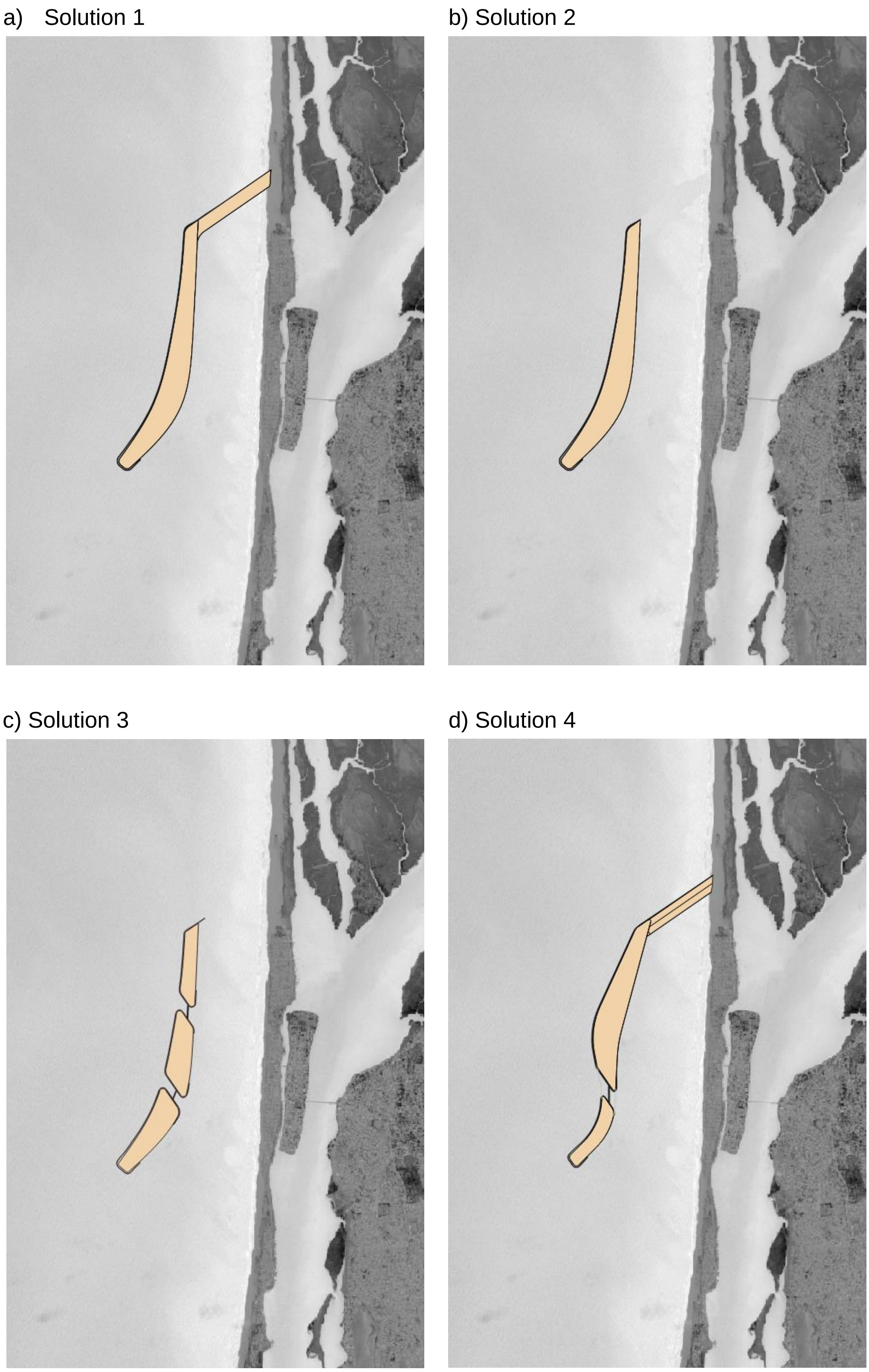

Figure 4.1 – RESCOAST proposed solutions for coastal intervention in front of St.-Louis (scale 1:100000)

– Finally, solution 4 can be interpreted as a modification of solution 1, with one breakwater/island gap (solution 3 included two gaps), and an overall shoreline design different from the other three solutions. The first groyne-type section is identical to that of solution1, but slightly shorter (length equals 1270 m). The middle or second segment has a 2700 m long land-facing concave shape and is connected to the third (southern) segment by a submerged breakwater. The third segment is a convex-shaped 1100 m long island. Like all the other solutions, a hard structure protects the seaward side of all segments.

Overall, solutions 1 and 4 act essentially as a combination of oblique groynes plus breakwaters, whereas solutions 2 and 3 are simply detached breakwaters. The breakwater segment of all solutions measures circa 4000 m along the shore and is placed at depths approximately ranging from 6 to 12 m.

All these solutions were specified into the ShorelineS model. However, a few constraints were overcome, such as the model initially not allowing for multiple breakwaters. Also, (island-connecting) submerged structures are not allowed into the model, as this allows only for emerged structures. Therefore, since the designed submerged structures are quite deep, with crests at 6 m depth, these were totally excluded from the simulations.

Other design simplifications were carried out to accomplish the ShorelineS simulations. It was verified that the sediment dynamics of the proposed sandy islands or spits was negligible. That is, none of the spit/island configurations had shoreline movement at the non-protected (leeward) coast, and there was no sediment interaction between the fill of these new islands and the existing *Langue de Barbarie*. Therefore, in some simulations, it was decided to remove the inputs into the model of the sandy islands configurations and keep only the structures.

Finally, it is worth noting that the ShorelineS model was initially chosen amongst other alternative models because its foundation was to allow for developing shoreline undulations, formation of spits, migrating islands and merging of coastal shapes (Roelvink *et al*., 2020). Hence, the focus of the model development was in allowing for natural sedimentary forms, and not so much in coastline evolution at hard-protected coastlines. Hence, in the present work, additional simulations were carried out for entirely non-structural interventions, that is, purely “soft-solutions”, corresponding to the client-proposed hybrid solutions without the seaward-facing rubble mound breakwaters (and groynes). These are thus presented in the following chapter, prior to the hybrid solutions, to show the effect of soft-coastal interventions individually.

5 | Results

5.1 Calibration phase

The ShorelineS model was calibrated against data for the period from 2015-11-25 until 2019-10-19. For such, as mentioned in section 2.4, one satellite image was retrieved for each of those dates. The coastline of the earlier image is defined as the model initial condition, and the model is run for this whole period, using the wave climate time series described in Section 2.5.

During this period, the *Langue de Barbarie* tip migrated southward circa 1800 m (Figure 2.6c and Figure 5.1c), with an average rate of 460 m/year. At stretches in front of Saint-Louis, the shoreline eroded approximately 40 m during that period (Figure 2.6a). This number agrees with other referred erosion rates, such as -4.2 m/year after the 2003 breach (Tavenau *et al*., 2021).

Moreover, based on the published sediment transport estimates (given in section 2.1), it is assumed for calibration purposes that the littoral net drift ranges between 600 and 700x10^3 m^3/year, along the coastal stretch in front of Saint-Louis. The above migration and erosion rates, as well as the net littoral drift, are the target numbers to calibrate the modelled shoreline evolution.

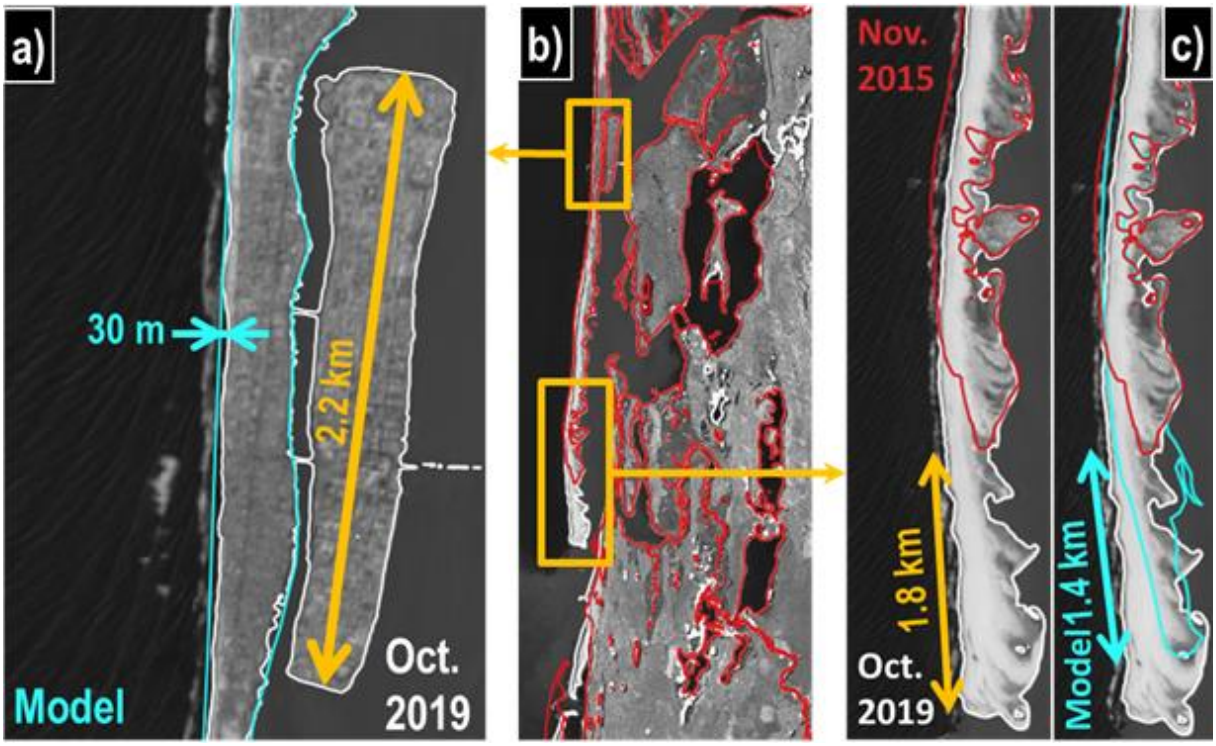

Figure 5.1 – Measured and simulated coastline positions, for the calibration period; a) detailed view near Saint-Louis; b) overall domain; c) detailed view of the spit head migration. (2015 configuration in red; 2019 model-estimation in cyan; 2019 measured configuration in contour). Background October 2019 Sentinel 2 image in grayscale

Using the model parameters and settings provided in Chapter 3, the model results for the calibration period yielded an estimated southward migration of the spit-end of approximately 1400 m (~357 m/year), lesser than the measured one (Figure 5.1c). However, the shoreline position from modelling is relatively stable, only predicting moderate shoreline retreat, of the order of 10 m, in front of Saint-Louis (Figure 5.1a). A difference of 30 m remains between the predicted shoreline and the SDS in places of the observed erosional hotspots.

In the northern half of the model domain, the model-estimated average net drift is approximately 680x10^3 m^3/year (Figure 5.2). It would have been possible to obtain larger spit-migration rates (eventually, matching the measured one) by increasing the sediment transport rate parameter (*S.qscal*, that affects linearly the magnitude of the calculated sediment fluxes), that would, however, yield unrealistically large net littoral drifts, according to the available data. Hence, the present calibration results were interpreted as the best compromise between the spit-migration rate and computed sediment transport rate.

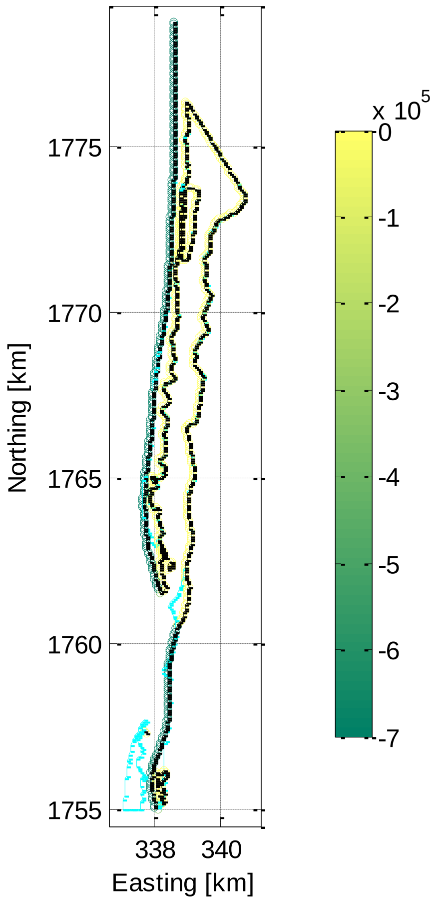

Figure 5.2 – Averaged sediment transport rate (m^3/year) for the calibration simulation (coloured palette); initial coastline (cyan line); final coastline (black line)

5.2 Exploitation phase

5.2.1 Reference case

In a first stage, and for reference, it was evaluated the coastline evolution in the absence of any intervention. Figure 5.3 shows the initial and the shoreline position obtained after 6 years and 7 months of simulation[4]. It can be clearly seen the *Lange de Barbarie* spit growing towards the south without any noticeable change of the lower Senegal river border lines, except near the mouth. As mentioned in Section 3.2, the lower river left bank shoreline was smoothed and simplified into the model inputs, as it had no effect on the ocean-facing coastline evolution. Figure 5.3 also shows that the south spit (initially attached to land at position ~1758 km Northing) migrated south and partially merged into land near point at Northing 1755 km.

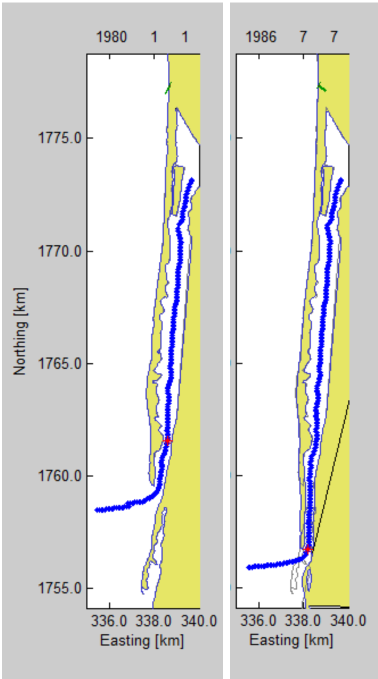

Figure 5.3 – Model-estimated shoreline positions in case of no intervention: initial (left) and after 6 years and 7 months (right)

A detailed view of the model results, after approximately 6.5 years, in front of Saint-Louis and at the spit head is given in Figure 5.4. Firstly, there is no noticeable retreat or advance of the shoreline in front of Saint-Louis, where the maximum shoreline changes are of the order of 10 m. Secondly, the spit migration is of the order of 2.8 km, corresponding to migration rates of the order of 430 m/year (larger than those estimated for the calibration period, 357 m/year). This value is compatible with the wide range of migration rates reported in the literature (between 94 and 700 m/year, according to Anthony, 2015), and measured during the calibration period (460 m/year). It is worth mentioning that Tavenau *et al*. (2021) showed that calculated migration rates based on sand conservation (and longshore sediment

[4] A longer simulation was not possible to obtain, as the model got unstable and crashed.

transport) have a large difference with the satellite-derived observations, hinting that the southward sand spit growth is not only ruled by the littoral drift but may have its own intrinsic dynamics.

The modelled mean annual sediment transport rate for this 6.5-year period, in front of Saint-Louis, is circa 650x10^3 m^3/year.

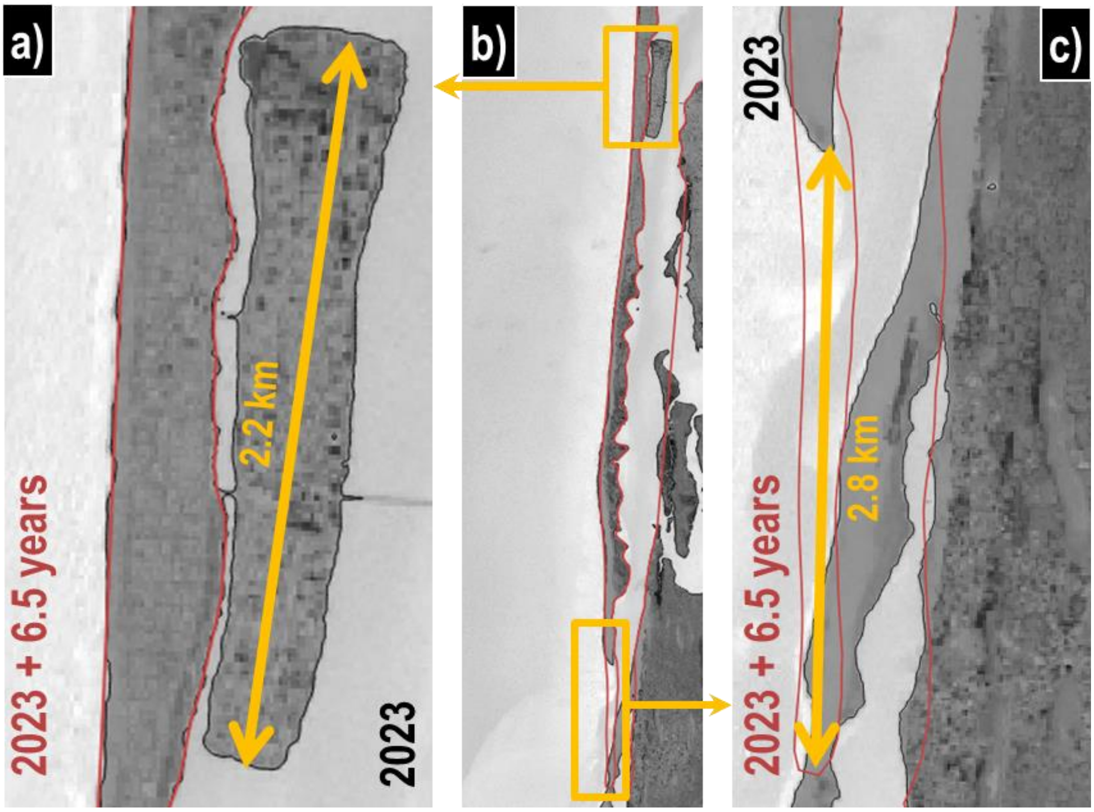

Figure 5.4 – Initial shoreline (black contour, as of June 2023) and simulated coastline positions (red contour, as after 6.5 year of simulation) for the reference state (i.e., without intervention): a) detailed view near Saint-Louis; b) overall domain; c) detailed view of the spit head migration. (June 2023 Sentinel 2 image in grayscale)

5.2.2 Soft solutions

In the following, the results of the model simulations for the cases of the proposed configurations are presented, without the hard structures. That is, inputs to the model consist of the 2023 shoreline configuration and the island/peninsula planform for each case (see Figure 4.1) that would result from an (instantaneous) sand nourishment. The model configuration used for the reference case was used for all simulations of the proposed solutions.

5.2.2.1 Soft solution 1

Figure 5.5 shows the modelled shorelines at every 6 months, for a period of 6.5 years past the initial condition (of 2023), for the soft-solution 1. One immediately observes that the sandy spit/peninsula rapidly (in 6 months) breaks its form into two, leaving a much smaller spit and a freely migrating island. That island continues to migrate southwards and decreasing its volume, eventually vanishing. The small remaining spit, in turn, triggers a coastline instability just north of Saint-Louis that nearly breaches the

Langue de Barbarie. Additionally, a breach arises approximately 4 km south of Saint-Louis, caused by reduced sediment inputs to this region partially sheltered by the island and, possibly, due to triggering instabilities from strong gradients of the longshore sediment fluxes. That breach grows rapidly in space with time, widening for over 1 km. We note that a rapid widening of a new inlet is compatible with past observations on inlet opening (e.g., Tavenau *et al*., 2021).

5.2.2.2 Soft solution 2

The results of the modelling estimates resulting from the implementation of the soft-solution 2 are shown in Figure 5.6. This depicts the coastline evolution every 6 months, for a period of 4 years and 7 months. Similarly to the previous results, the offshore island migrates southeast and coalesces with land. A breach occurs roughly past 3 years, about 3 km south of Saint-Louis. This breach widens then after, but a second breach follows immediately south of Saint-Louis.

This result and the previous one shows the extreme vulnerability of the *Langue de Barbarie* to soft-protection solutions, based on offshore island or peninsulas nourishments.

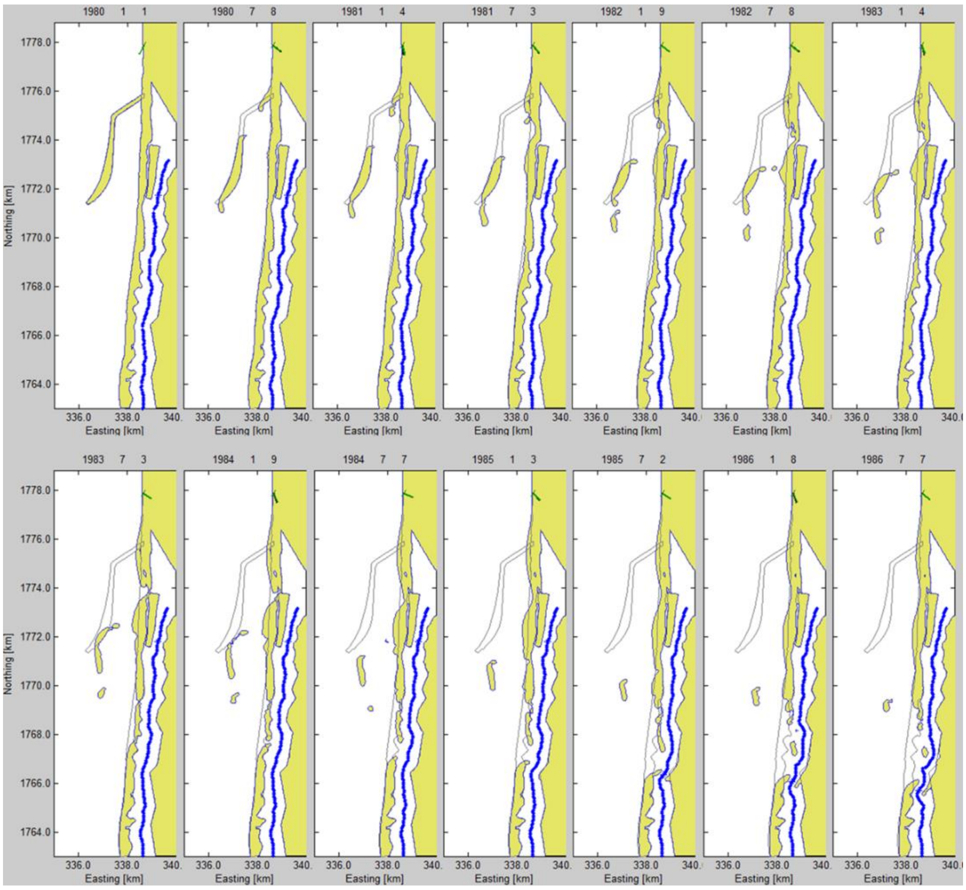

Figure 5.5 – Shoreline configurations at 6-month intervals, for soft solution 1

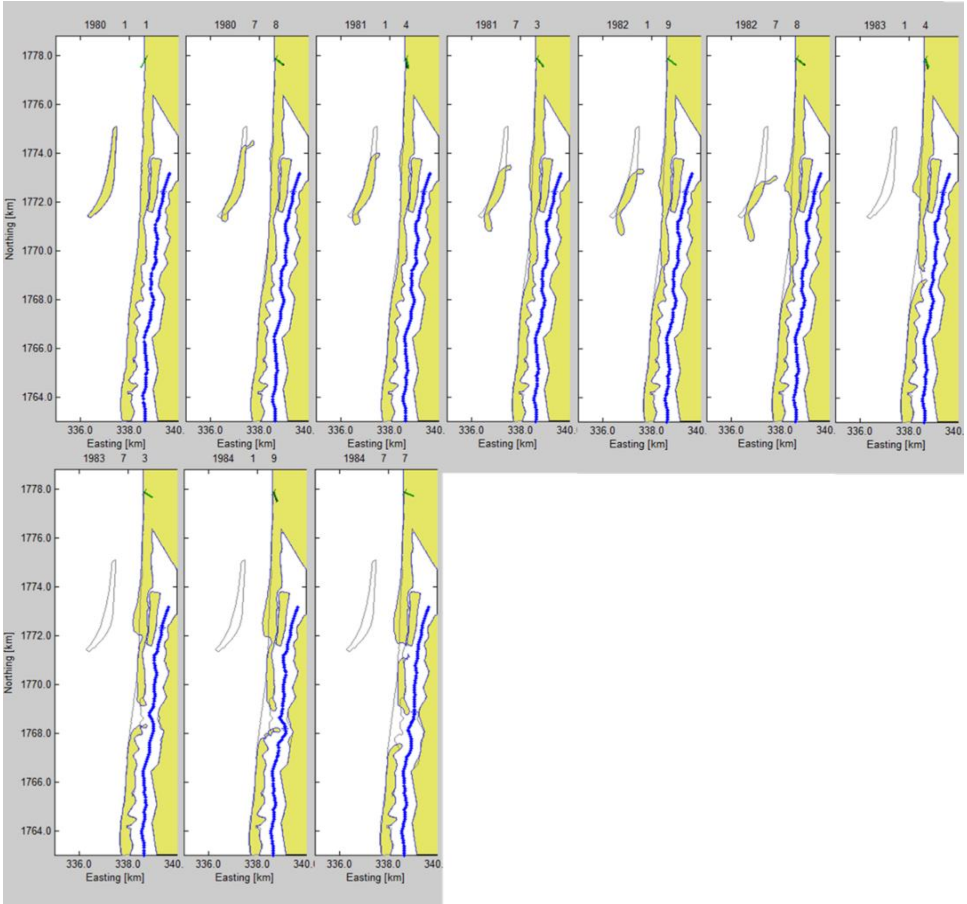

Figure 5.6 – Shoreline configurations at 6-month intervals, for soft solution 2

5.2.2.3 *Soft solution 3*

As one could anticipate, the implementation of soft-solution 3 leads to results (Figure 5.7) similar to those of soft-solution 2. Indeed, Figure 5.7 shows the south-eastward migration of the islands, and the breaching of *Langue de Barbarie* 3 km south of Saint-Louis, within less than 3 years of model simulation. This breaching, as in the case of soft-solution 2, occurs in the shadowed region of the proposed islands (considering the main wave direction, NNW).

5.2.2.4 *Soft solution 4*

Figure 5.8 shows the estimated shoreline positions at 6 months intervals for the implementation of soft-solution 4. This solution is generally similar to solution 1, and thus one can expect an analogous behaviour. Indeed, a rupture of the peninsula is predicted in solution 4 nearly after 3 years, and an instability immediately north of Saint-Louis coast is also observed, past that peninsula split. A larger, major breach of *Langue de Barbarie* occurs 4.5 years after start, circa 2-3 km south of Saint-Louis. That breach increases its width as in the previous soft-solution cases.

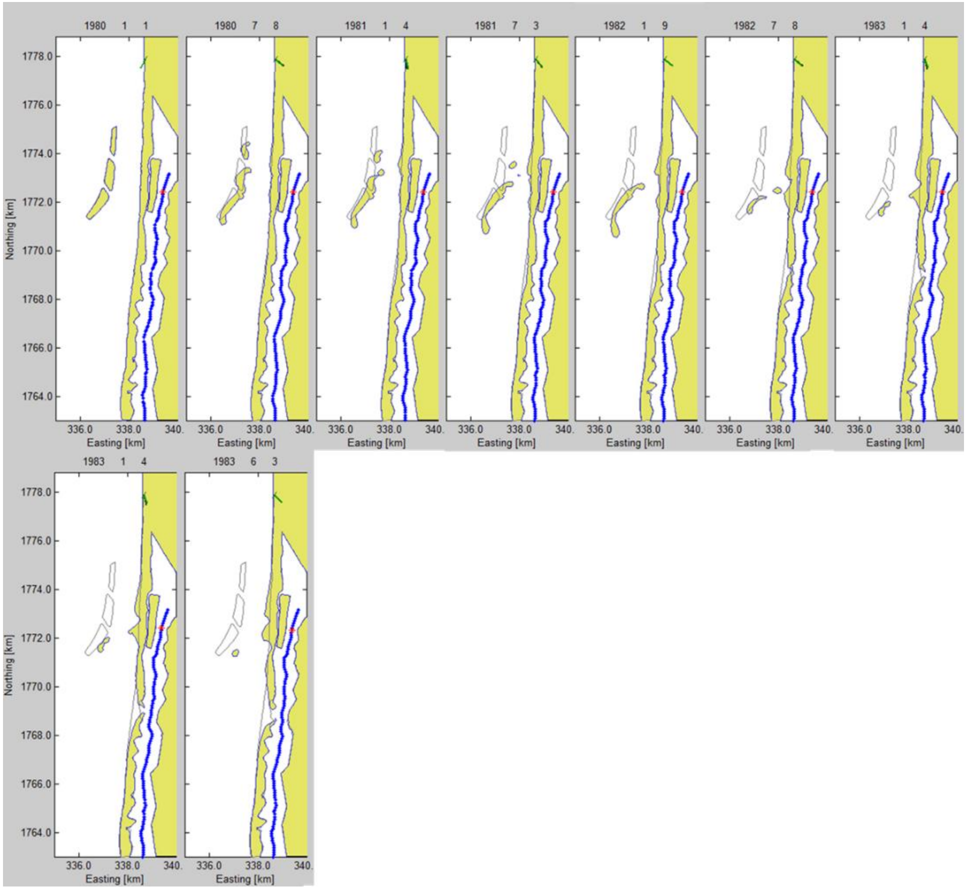

Figure 5.7 – Shoreline configurations at 6-month intervals, for soft solution 3

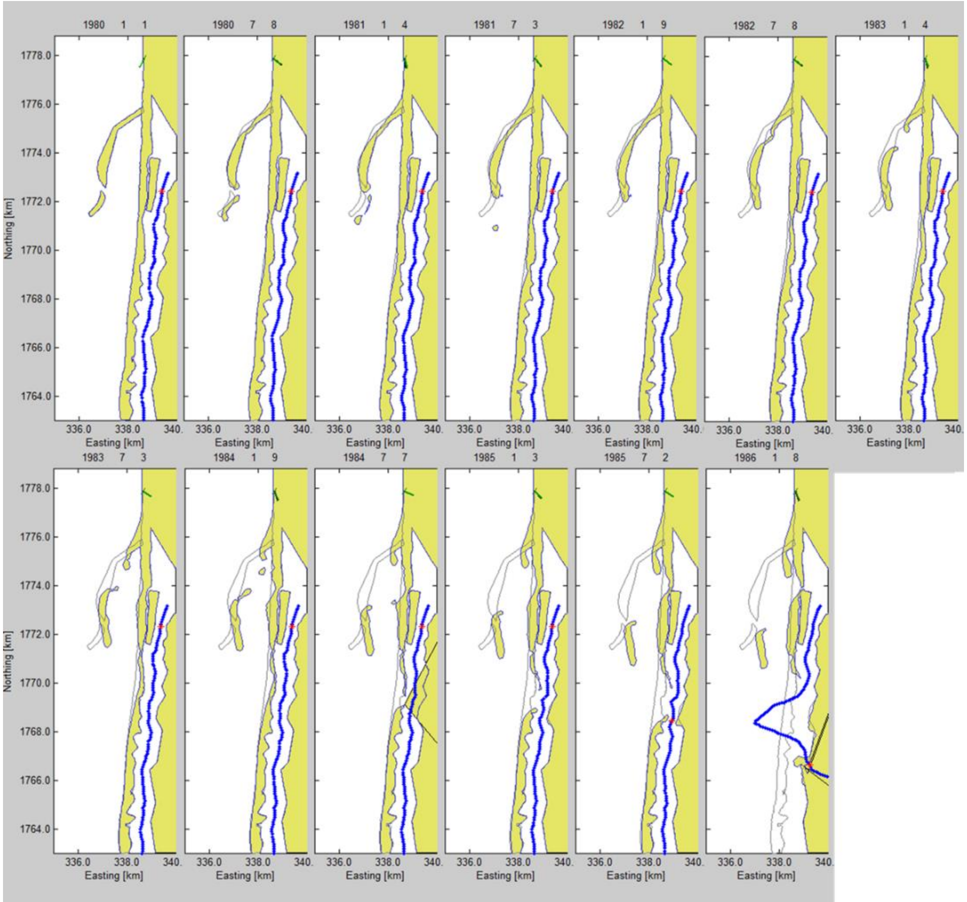

Figure 5.8 – Shoreline configurations at 6-month intervals, for soft solution 4

5.2.3 Hard and hybrid solutions

In this section we focus on presenting the results for hard solutions only. Initially the hard structures were set into the model together with the accompanying nourished volumes, as given in the proposed solutions description (Chapter 4, and Figure 4.1). A few comparisons were performed relative to the modelled coastlines, by including (hybrid solution) or removing (hard solution) those sand volumes that shaped the initial islands/peninsulas for each configuration. It was found that there were no appreciable differences in terms of coastline evolution, but including the sandy features added some model complexity and instability, that sometimes resulted in more frequent model crashes. For example, Figure 5.9 shows the coastline configurations past 4 years of simulation for the hard and hybrid solutions 1, confirming the similarity of the coastline positions. Hence, the following results are for the hard solutions only.

Moreover, due to some constraints related to activating adequately in the model the wave diffraction module, caused by coastal structures, most of the following results in this section were obtained by turning-off the wave diffraction effects on the computed longshore sediment transport. It was found, however, that activating the wave diffraction induced sediment flux did not have much effect on the coastline evolution trend, but it delayed the coastline response. Figure 5.10 shows model results for the implementation of the hard solution 1 (detailed in the following sub-section), without (left) and with (centre and right) the wave diffraction effect. For the same simulation period (2.5 years), the case of no diffraction has not yet developed an open breach south of Saint-Louis, as occurred in the case without diffraction. Nevertheless, the coast eventually breaches in the case with diffraction a certain time afterwards (in this case, after nearly 5 years of total time, that is, it lasted twice the time it took in the case without diffraction). Also, the accretion north of the groyne is not so significant in the case with diffraction, as in the case without. This behaviour is generic for all modelled solutions.

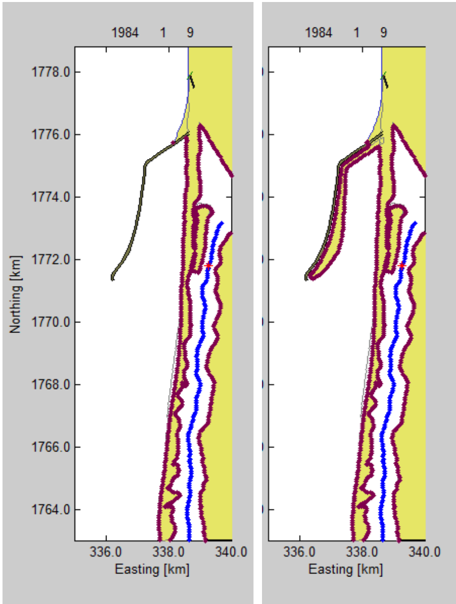

Figure 5.9 – Shoreline configurations after 4 years for solution 1, with diffraction on: simulation excluding the sandy peninsula (left); simulation including the sandy peninsula (right)

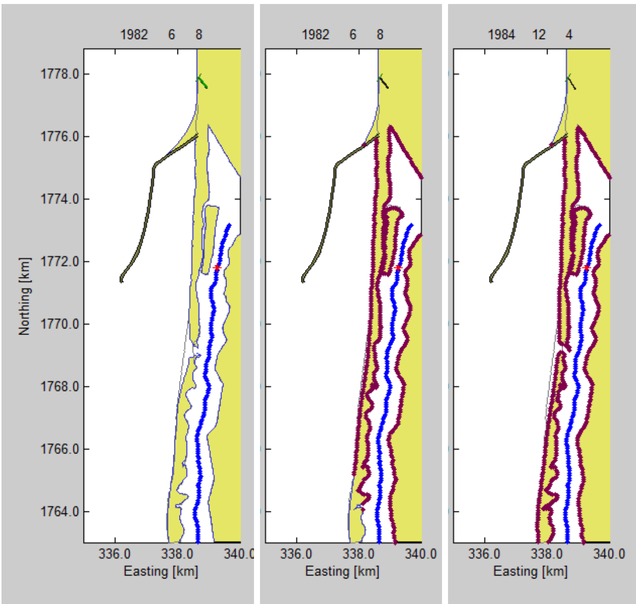

Figure 5.10 – Shoreline configurations for hard solution 1: after 2.5 years without diffraction (left); after 2.5 years with diffraction (centre); after 5 years with diffraction (right)

5.2.3.1 Hard solution 1

Figure 5.11 presents the coastline evolution at 6 months intervals for 5 years since 2023, for the implementation of hard-solution 1. As expected, the groyne-type coastal structure retains sediments at the updrift side and causes erosion downdrift. That erosion is particularly strong just downdrift of the groyne, leading to a breach of *Langue de Barbarie* approximately 3 km south of Saint-Louis. The southern spit head resulting from this breach then continues migrating southward, widening the new inlet. Sediment by-pass along the groyne eventually happens, re-establishing the sediment dynamics of the southern stretch of *Barbarie spit*. The northern half, however, may not re-establish to its natural dynamics as it will always remain protected by the constructed groyne. Thus, it appears that the structure acts positively in protecting the city of Saint-Louis, in terms of coastal erosion risk.

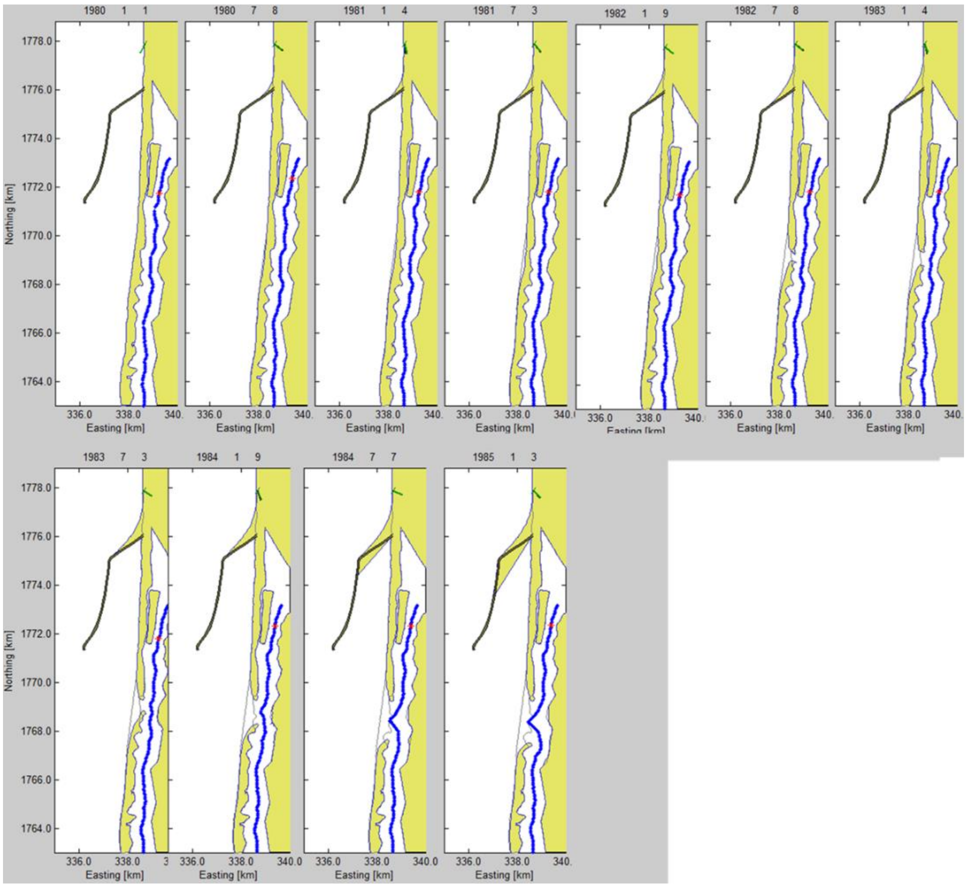

Figure 5.11 – Shoreline configurations at 6-month intervals, for hard solution 1

5.2.3.2 Hard solution 2

A similar coastal evolution is predicted from the model simulations of hard-solution 2 (Figure 5.12). Indeed, the detached breakwater in front of Saint-Louis coast causes the formation of a large salient just north of the city, due to sediment retention, and, consequently, initiates erosion downdrift, at the position located around 3 km south of Saint-Louis. That permanent starving of sediments will erode the spit of *Langue de Barbarie*, eventually generating a breach that evolves then as in the earlier described cases. Thus, apart from the difference between sand accumulation north of the groyne or at a salient, the sediment dynamics associated with the construction of the hard-solutions 1 or 2 is identical.

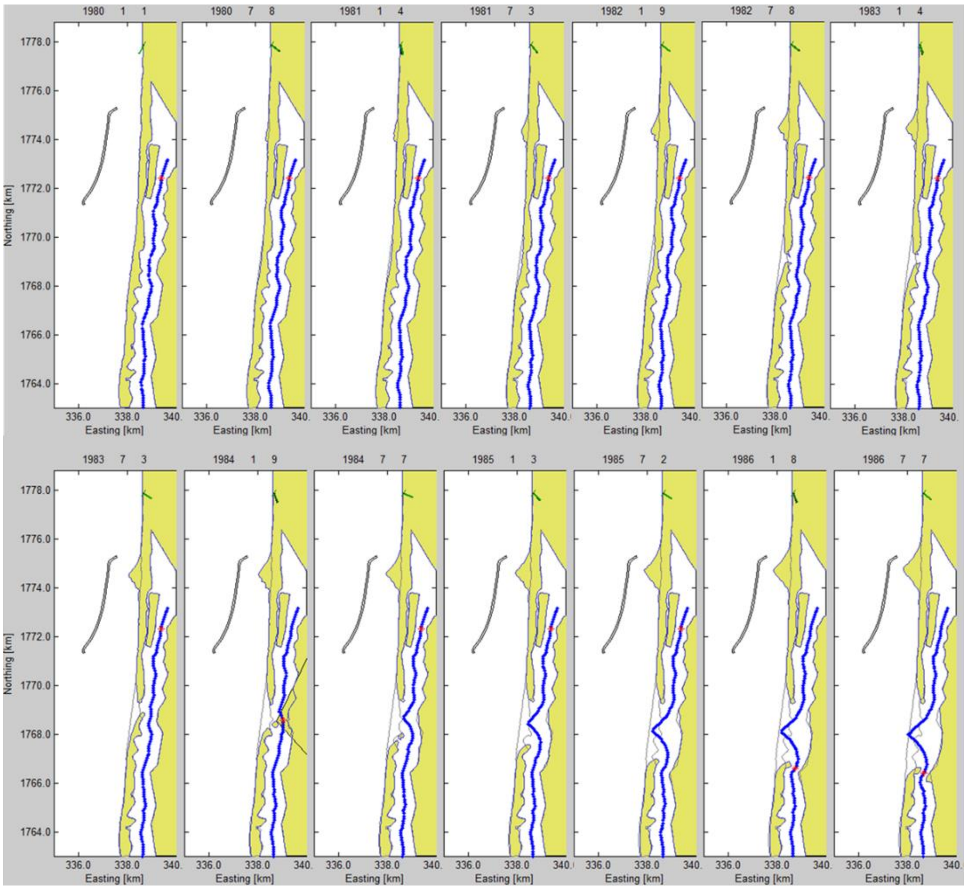

Figure 5.12 – Shoreline configurations at 6-month intervals, for hard solution 2

5.2.3.3 Hard solution 3

Figure 5.13 shows the shoreline evolution for a period of nearly 4 years, following the implementation of the hard solution 3. The simulation could not be extended for longer time, as the model failed. These results show the opening of a first breach (within 1.5 years), immediately south of Saint-Louis coast, aligned along the main wave direction with the gap between the centre and the southern detached breakwaters. That is, according to the model, the gap between breakwaters allows for waves to propagate and cause large gradients in the sediment transport rate, that induce a breach. Further south (~3 km from Saint-Louis), a second breach appears within 2.5 years, that widens gently towards the end of the simulation. During the whole simulation period, a salient develops at the coast sheltered from the northern breakwater, with similar growth rates to those verified for the hard solution 2. Indeed, the coastline evolution for the hard solution 3 is very similar to that simulated for the hard solution 2, except for the breach due to the breakwater gap.

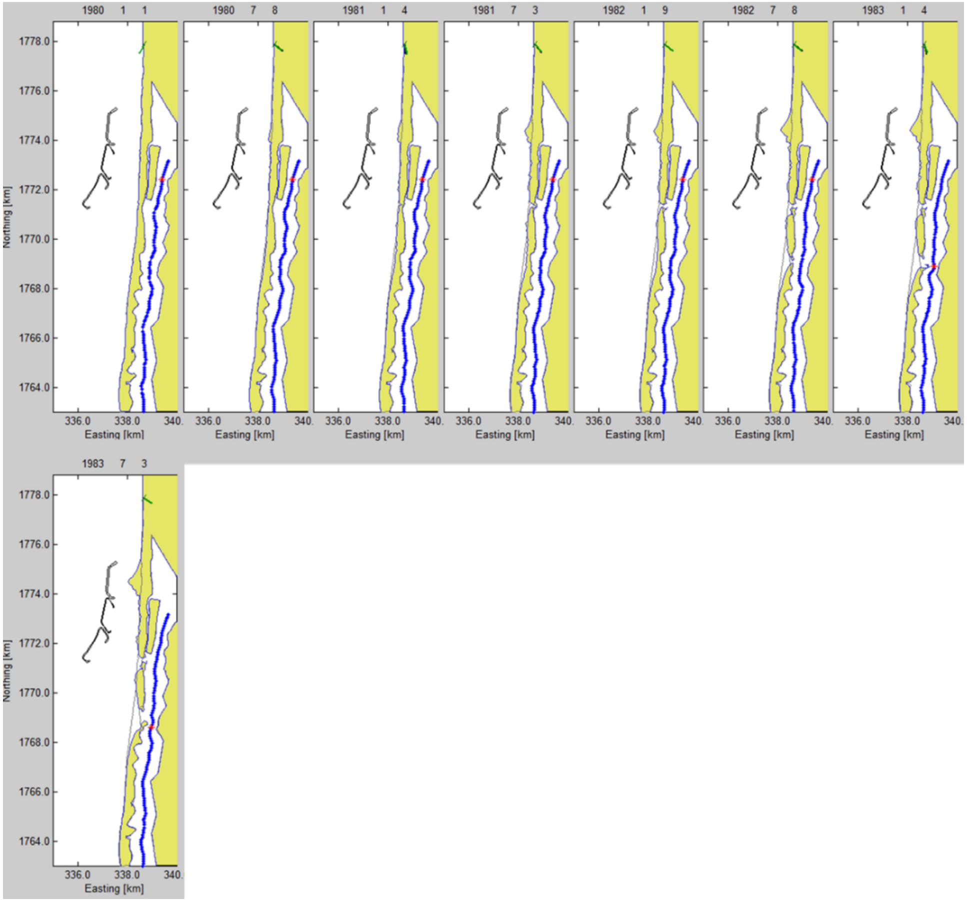

Figure 5.13 – Shoreline configurations at 6-month intervals, for hard solution 3

5.2.3.4 Hard solution 4

The shoreline evolution from the implementation of the hard-solution 4 is seen in Figure 5.14. This reveals that, upon 3 years from initial time (2023), the *Barbarie spit* breaches 3 km south of Saint-Louis. A second breach appears after 6 years, immediately south of Saint-Louis. This breach is induced by sediment transport gradients due to the breakwater gap. Sand accumulation occurs updrift of the groyne. The general coastline evolution is similar to that obtained for the hard solution 1.

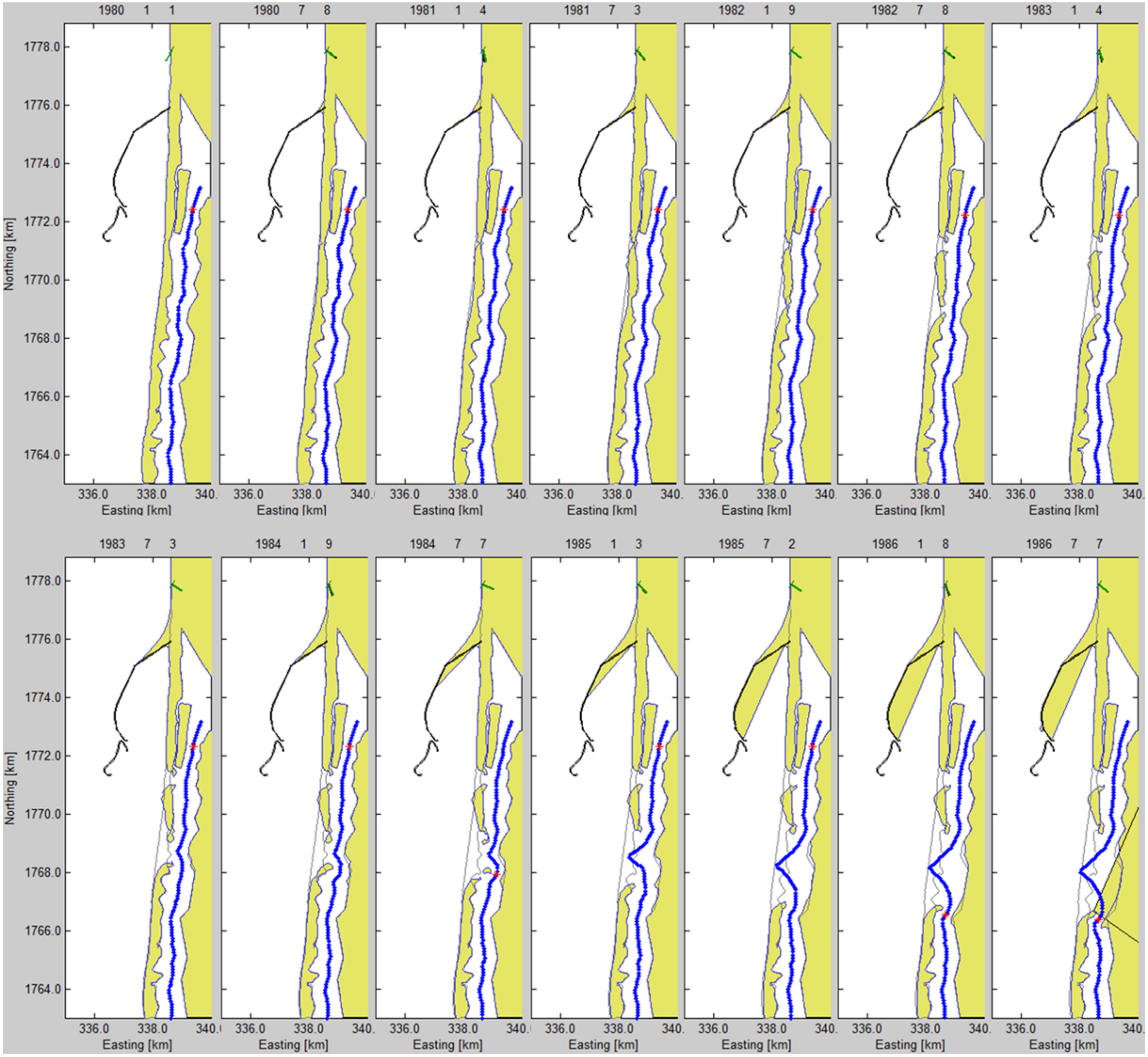

Figure 5.14 – Shoreline configurations at 6-month intervals, for hard solution 4

5.3 Comparative analysis and discussion

It was seen in Section 5.2.2 that all soft-solution implementations caused the breaching of *Langue de Barbarie* within ~3 years of simulation, except for soft solution 4. These breaches occur mostly south of Saint-Louis, but other instabilities and narrowing of the spit occurred at other places, including at the coast north of the city. Also, it appears that all the peninsula or island sand volumes are swiftly carried south-eastwards, and their longevity is quite small (circa 3 years), given their initial magnitudes. These short durations and rapid breaches are due to the strong dynamics of this coastal stretch, and high alongshore sediment transport rates (i.e., four to ten times the rates estimated at the Sand Engine site in the Netherlands, according to Luijendijk *et al*., 2017). Despite being somewhat surprising these short time-scale developments as the result of any (simulated) soft-solution, they are compatible with the modelled and observed past coastline evolutions.

For the hard or hybrid solutions (Section 5.2.3), one can fist conclude that configurations 1 and 4 yield approximate shoreline developments, which is not surprising considering that these two solutions are similar conceptually but differ in details. It is, however, the “detail” of separating a one-groyne configuration (solution1) into a groyne-plus-breakwater configuration (solution 4) that gives rise to a critical breach for solution 4 (Figure 5.14), adjacent to Saint-Louis, exposing the communities in the city and neighbouring coastal spit to erosion. That breach is caused by the breakwater gap. Likewise, hard-solutions 2 and 3 generate similar coastline evolutions, except for a major breach immediately southwards of Saint-Louis in the case of hard solution 3, also due to the gap between the offshore breakwaters. Hence, that hard solutions 1 and 2 seem to halt erosion at the coast in front of Saint-Louis, or even to enhance sand accretion, but they both induce further south significant erosion and eventually breaching of the *Langue de Barbarie*.

A detailed comparison of all solutions in the vicinity of Saint-Louis, after 3 years of simulation, is presented in Figure 5.15. All soft solutions, except solution 4, induce several erosion/accretion patterns along this coastal stretch, the same happening for the hard-solution 3. Hard solutions 3 and 4 cause a breach nearby Saint-Louis, whereas hard solutions 1 and 2 induce a breach further south. For the hard solutions 2 and 3 it forms a salient of substantial dimensions (maximum width circa 300-400 m).

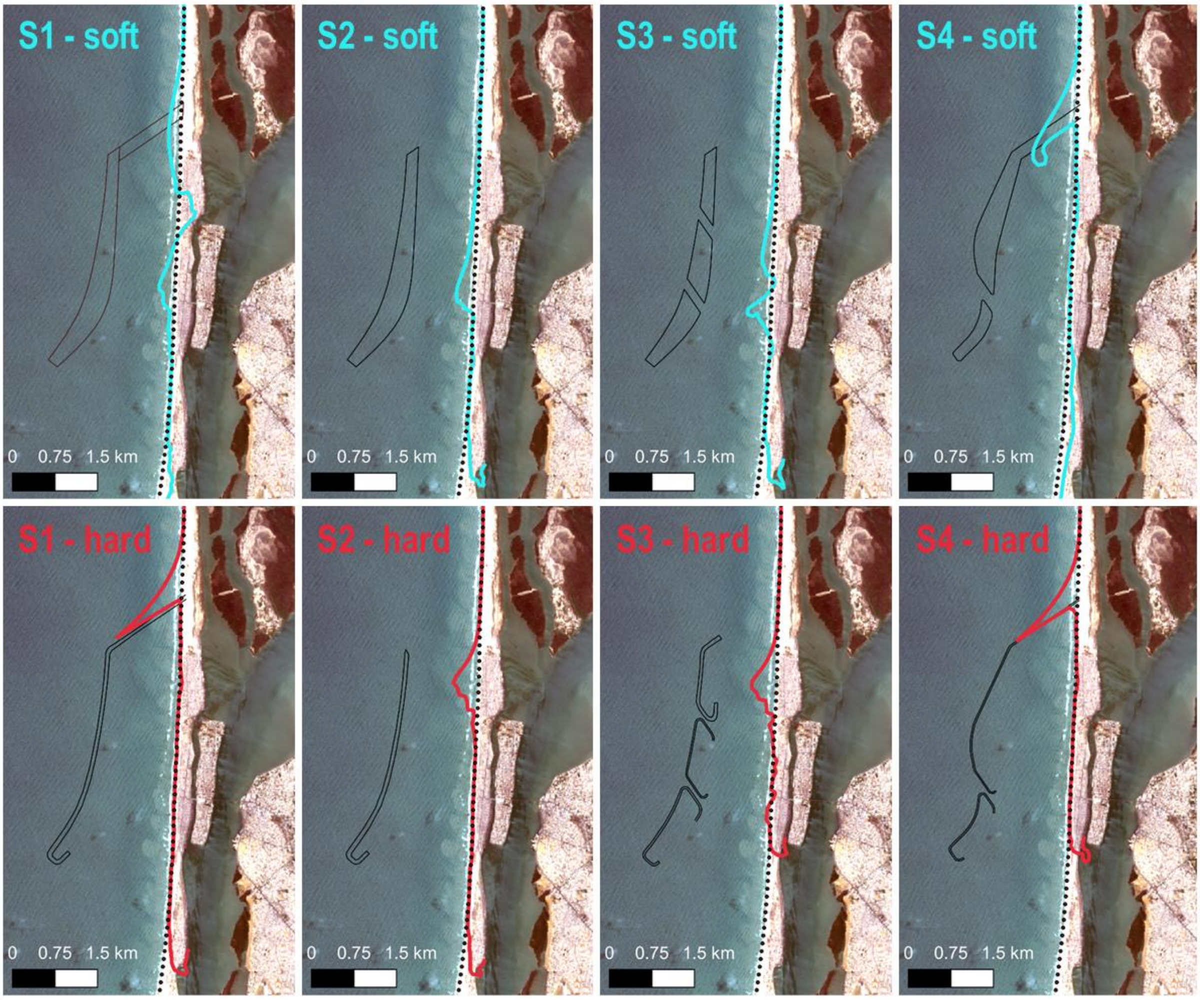

Figure 5.15 – Shoreline configurations after 3 years of simulation for soft (upper panels) and hard (lower panels) solutions (solid red lines), compared with simulation without any intervention (dotted black line). In the background is the RGB image of the Sentinel 2 image from 26th June 2023

6 | Conclusions and recommendations

The methods and results presented in the previous chapters allow to conclude the following:

- The coastline of the spit *Langue de Barbarie* is extremely dynamic due to high sediment transport rates and the predominant oblique wave direction. These phenomena can cause shoreline instabilities, which, together with the narrow spit width (100-400 m), can lead to breaching. Several breaches have occurred, and a common feature is that the Senegal river inlet migrates southward, while the spit elongates until a new breach occurs northward of the existing inlet and rapidly widens and takes over the previous inlet. This cycle has repeated several times in the past.
- The objective of the present study was to evaluate the sediment dynamics, long-term evolution and sand trap behaviour of hybrid-type coastal protection solutions (provided by ULPGC) for the *Langue de Barbarie* and the city of Saint-Louis communities.
- Satellite Derived Shorelines (SDS), extracted from Sentinel 2 images by means of the coastline detection online service WORSICA (https://worsica.incd.pt/index/), were used as modelling initial conditions and for comparison and model calibration. These proved to be an effective tool for the present case study, applicable also to most other cases.
- The recently developed, open-source *ShorelineS* model (Roelvink *et al*., 2020) was used to simulate the coastline evolution following the implementation of the proposed designs, and respective variations considering soft interventions (island/spit sand fills) only. The model calibration for the period between 2015 and 2019 was acceptable, reproducing erosion in front of Saint-Louis (albeit of smaller magnitude), the estimated net-averaged sediment transport flux for the region, and the spit-head migration. Nevertheless, a few model shortcomings were detected, that were circumvented using simpler parametrisations (e.g., the wave diffraction was disabled in the final simulations as its effect was assessed and verified to simply delaying the shoreline reactions to the proposed interventions).
- Nine model simulations were successfully executed in the exploitation phase, comparing the 4 hard (or hybrid) proposed solutions with the corresponding soft solutions and with the reference case (evolution without any intervention). For the latter case, no significant changes were predicted for the shoreline position, except for the natural elongation of the spit and respective southward migration of the river inlet.
- It was found that any of the proposed hybrid solutions trigger substantial instabilities in the delicate sediment dynamics of *Langue de Barbarie*, eventually breaching this spit at circa 3 km south of Saint-Louis within 3-10 years (accounting for a slower shoreline evolution due to wave diffraction effects). These breaches occur due to sediment starvation downdrift of the interventions, as they either cause sediment retention updrift of the groynes (when existent) or at salient formations (in the case of the detached breakwater-type solutions) in their sheltering zone.

- Nevertheless, hybrid solutions 1 and 2 have a local positive contribution in reducing coastal erosion risk at the city of Saint-Louis and its coastal front, despite the negative erosive effects they cause further downdrift. However, the gap between the detached breakwaters of solutions 3 and 4 may induce significant erosion or a second breach immediately south of Saint-Louis.
- Similarly to hybrid solutions induced coastal responses, the shoreline evolutions for the soft-solution implementations reveal also the breaching of Barbarie spit within less than 3 years of simulation, except for solution 4. These breaches occurred mostly south of Saint-Louis (within 1-3 km away) and were likely caused by shoreline instabilities triggered by the partial and transitional sheltering effect of the artificial spit/island interventions. However, unlike the cases of the hybrid solutions, these instabilities and the erosion/accretion patterns along the coast also extend to the north of Saint-Louis coastline. Results further indicate that the lifetime of the soft solutions sandy mounds (i.e., without any protective coastal structure) appears to be quite brief (of the order of 3 years), although further studies are needed to analyse these in more detail.
- Finally, it would be desirable to confirm these results by confronting them with those from alternative shoreline evolution models. All models have limitations, and ShorelineS is still in a development stage, and it would be desirable to develop more experience with its application to real cases in the scientific and technical communities.

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ANNEXES

ANNEX I
Study site data

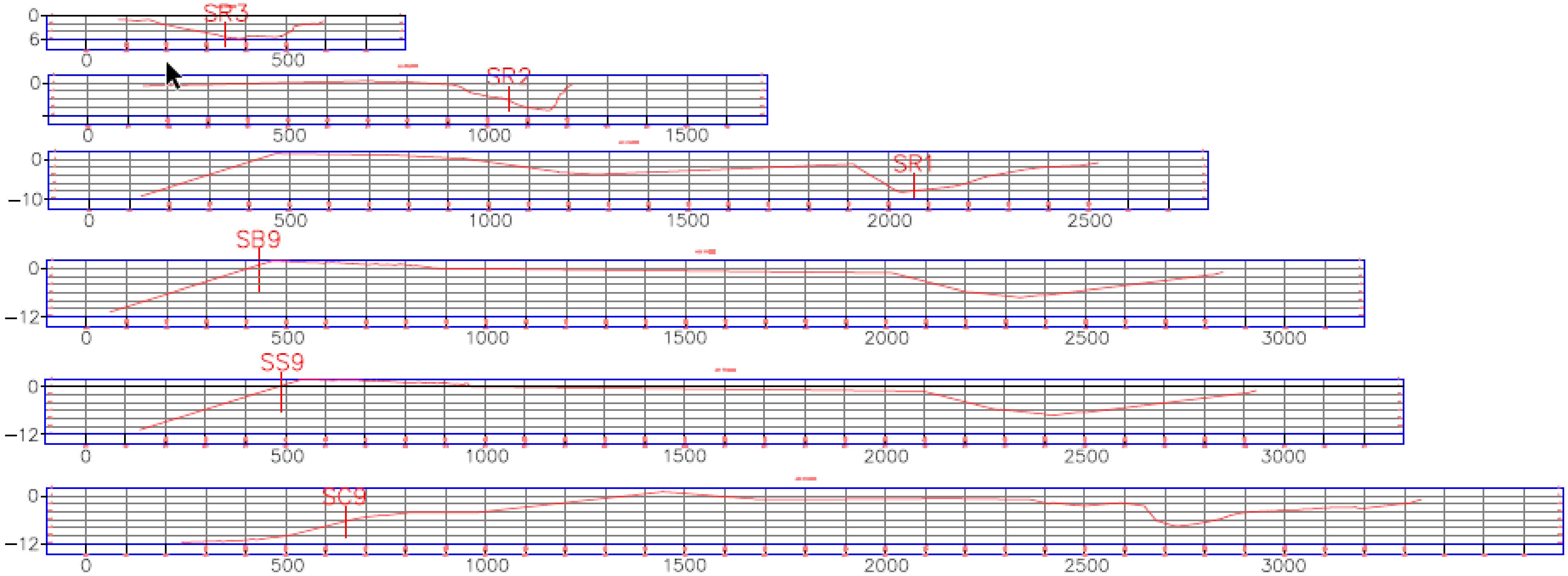

Figure I.1 – Cross-shore profiles that contain the position of the sediment samples SR3, SR2, SR1, SB9, SS9 and SC9 (from north to south)

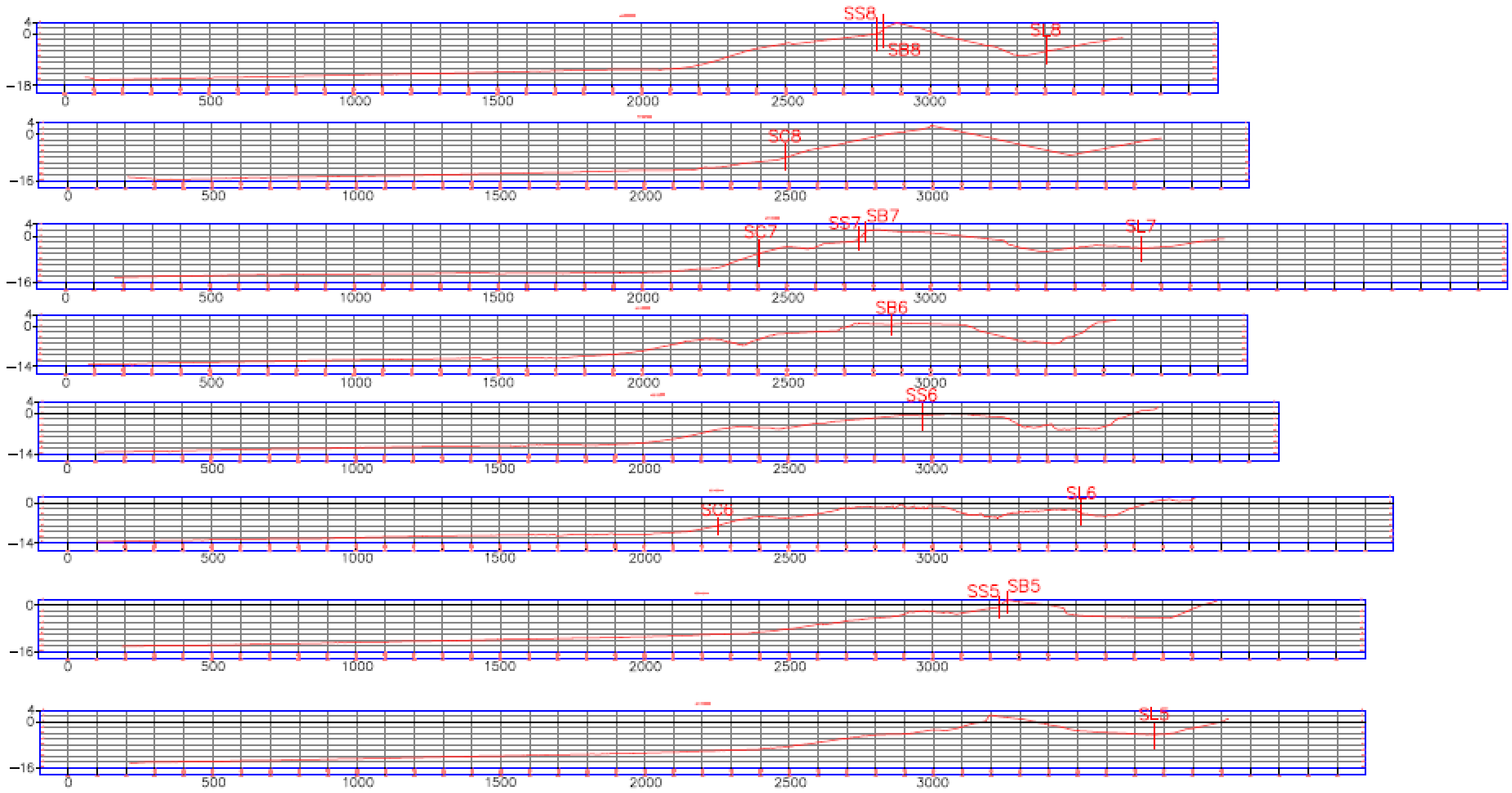

Figure I.2 – Cross-shore profiles that contain the position of the sediment samples SL8, SB8, SC8, SS8, SC7, SS7, SB7, SL7, SC6, SS6, SB6, SL6, SS5, SB5 and SL5 (from north to south)

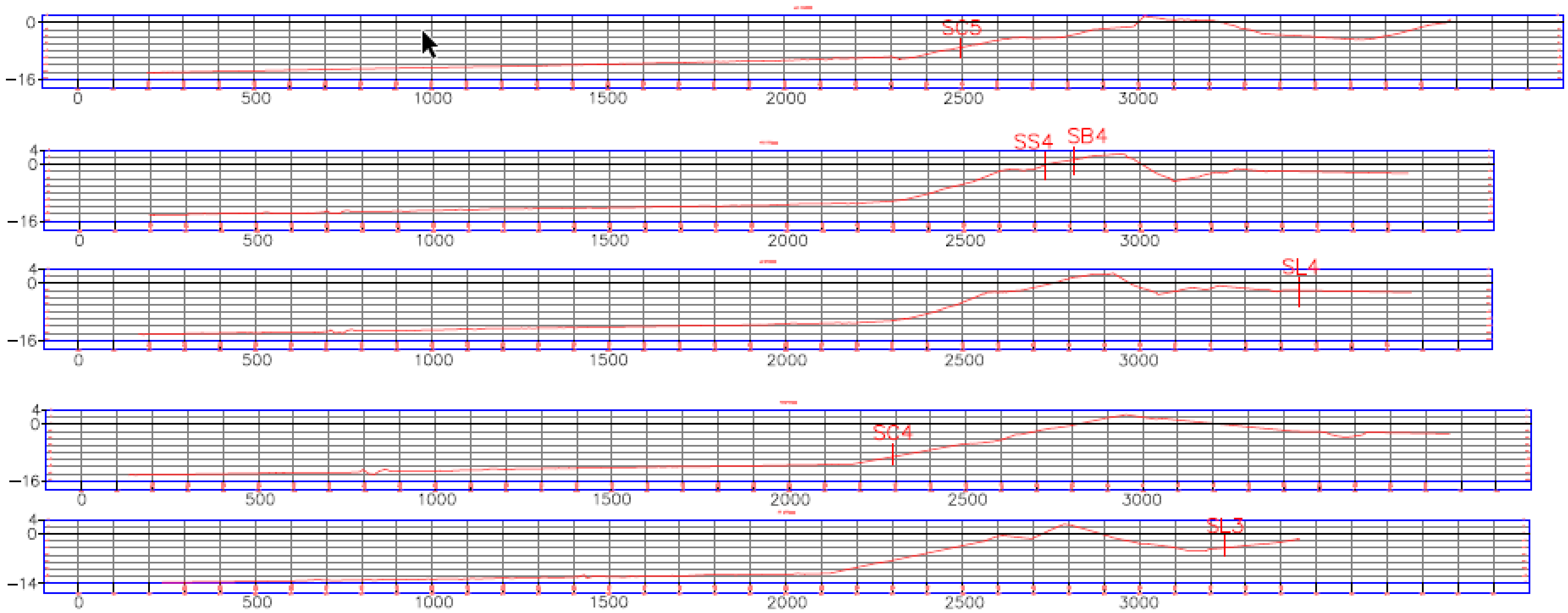

Figure I.3 – Cross-shore profiles that contain the position of the sediment samples SC5, SS4 SB4, SL4, SC4, and SL3 (from north to south)

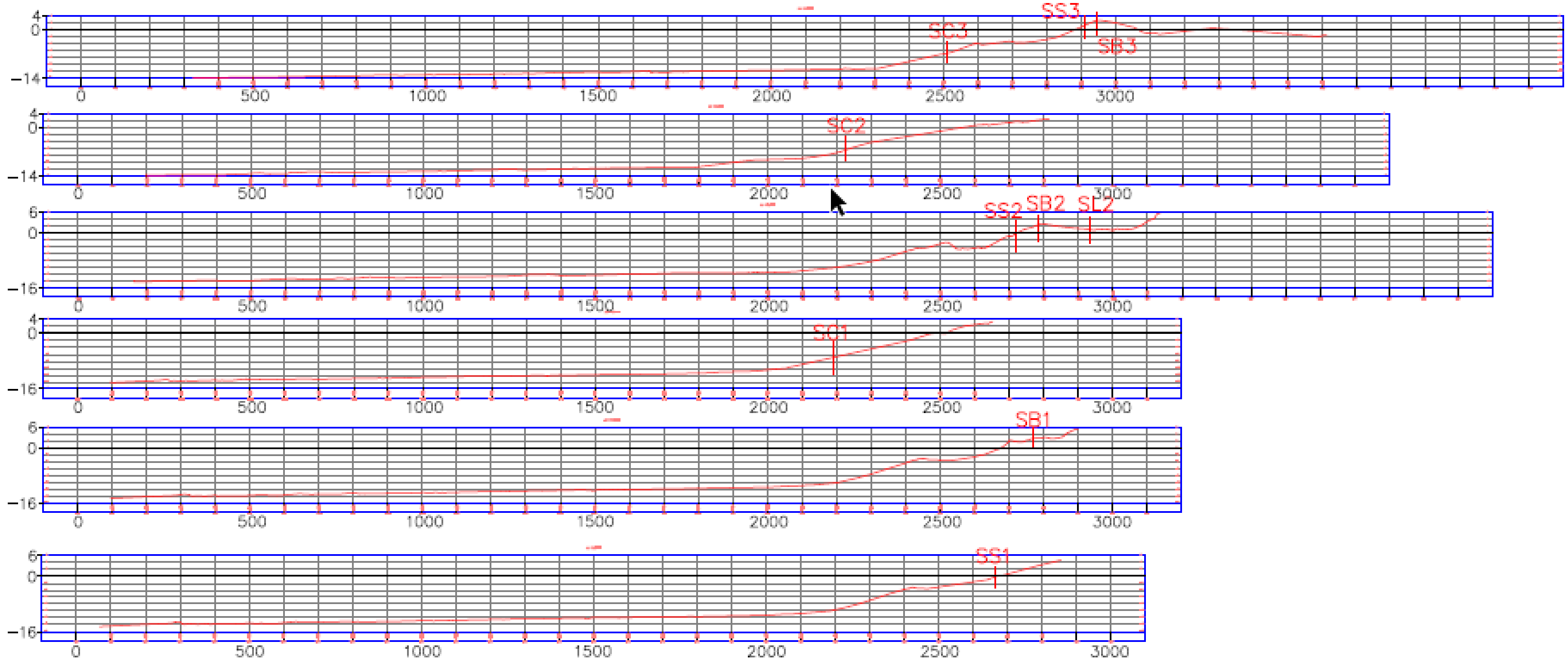

Figure I.4 – Cross-shore profiles that contain the position of the sediment samples SB3, SC3, SS3, SC2, SS2, SB2, SL2, SC1, SB1 and SS1 (from north to south)

Table I.1 – Sediment median diameter, D_{50}, of the 37 sediment samples surveyed in the campaign of January 2019

Sample ID	X m UTM 28 N	Y m UTM 28 N	Z m EGM2008	D50 (mm)
SB1	331563.498	1736835.332	2.705	0.248
SB2	333410.120	1741414.467	2.594	0.284
SB3	335044.263	1746094.297	2.716	0.293
SB4	336395.788	1751057.157	1.389	0.223
SB5	337566.430	1756031.248	1.247	0.289
SB6	338073.363	1761479.840	0.675	0.203
SB7	337881.970	1765932.935	1.193	0.307
SB8	338452.150	1770842.769	1.713	0.274
SB9	338607.751	1776012.034	0.848	0.254
SC1	331272.470	1737264.200	-6.877	0.169
SC2	333109.420	1741886.950	-6.336	0.158
SC3	334668.870	1746308.230	-6.610	0.169
SC4	335763.400	1750945.420	-9.206	0.159
SC5	336881.380	1755616.770	-6.942	0.162
SC6	337190.850	1761059.730	-7.989	0.152
SC7	337515.630	1765960.400	-6.011	0.177
SC8	337958.870	1770673.210	-8.133	0.174
SC9	338131.100	1775796.320	-6.405	0.170
SL2	333547.526	1741367.825	1.036	0.219
SL3	335531.580	1746109.640	-3.898	0.258
SL4	336972.940	1750755.760	-1.944	0.252
SL5	338022.510	1755595.340	-4.506	0.227
SL6	338430.130	1760829.430	-3.528	0.383
SL7	338832.290	1765811.420	-4.154	0.154
SL8	339002.770	1770732.010	-6.107	0.154
SR1	340595.060	1775470.840	-7.894	0.289
SR2	344488.450	1778781.510	-6.395	0.103
SR3	344604.830	1785887.840	-5.319	0.150
SS1	331472.295	1736867.978	-0.017	0.275
SS2	333348.455	1741448.170	-0.087	0.531
SS3	335011.055	1746113.227	1.277	0.366
SS4	336322.208	1751088.832	-0.169	0.369
SS5	337535.151	1756038.614	-0.292	0.233
SS6	338038.116	1761288.029	-0.634	-
SS7	337856.384	1765933.450	-0.882	0.275
SS8	338425.959	1770848.416	0.059	0.212
SS9	338576.694	1776008.885	0.433	0.334

- in blue: samples from the deeper profile
- in black: samples from the upper profile
- in grey: samples not considered (land side of the spit or inexistent data)

ANNEX II
ShorelineS most relevant parameters

Table II.1 – ShorelineS model parameters used in present application

Parameter	Value	Comment
S.smoothfac	0.01 to 0.05	Numerical smoothing factor
S.boundary_condition_start	neumann	Initial grid-point boundary condition
S.boundary_condition_endt	neumann	Final grid-point boundary condition
S.tc	0	Switch for automatic time step (S.tc=1); S.tc=0 when fixing S.dt
S.dt	0.0027397	Time step (year) [the prescribed value corresponds to 1 day]
S.Courant	1	Maximum Courant number, to compute automatic time-step
S.ds0	80 or 100	Initial grid space (m)
S.griddingmethod	2	Method for regenerating the grid (1: only splitting and merging cells if they are too small, 2: uniform grid regeneration if criteria for grid size or exceeded)
S.LDBcoastline	######.xy	File with initial coastline coordinates (land segments defined clockwise); one open coastal segment
S.d	5.5	Active profile height (m)
S.ddeep	27	Water depth at the location of wave climate (m)
S.dnearshore	20	Water depth at the nearshore, corresponding with S.phif (m)
S.phif	300	Foreshore orientation (degrees relative to North)
S.trform	MILH	Littoral drift formulation
S.qscal	1.4	Calibration factor of the sediment transport formula
S.rhos	2650	Density of sand (kg/m^3)
S.rhow	1025	Density of water (kg/m^3)
S.d50	0.00025	Median grain size
S.porosity	0.4	Sediment porosity
S.alpha	1.8	Calibration factor for point of breaking
S.gamma	0.72	Breaking coefficient (Hs/h)
S.tanbeta	0.026	Mean bed slope (in breaking wave region)
S.struct	0 or 1	Switch for using hard structures (0=no struct.; 1=struct.)
S.LDBstructure	######.xy	File with structure outline coordinates
S.diffraction	0 or 1	Switch for activating wave diffraction (0=no diff.; 1=diff.)
S.twopoints	1	Upwind treatment involving two points (1) or 1 point (0)
S.spit_width	150	Width of spit (used for overwash) (m)
S.spit_headwidth	150	Width of tip of spit (used for upwind correction) (m)
S.OWscale	0.1	Scales the rate of the overwash per timestep
S.OWtimescale	0	Timescale for overwash
S.Dsf	S.d*0.8	Underwater part of active height for shoreface
S.Dbb	1*S.Dsf	Underwater part of active height for back-barrier
S.Bheight	2	Berm height used for overwash function (m)
S.channel	1	Switch for migrating inlet (0=no migration; 1=migrating channel)
S.LDBchannel	######.xy	File with initial channel axis coordinates
S.channel_width	400	Target channel width (m)
S.channel_disch_R	500	Inlet channel affected area/radius (m)
S.channel_fac	0.08	Adaptation factor
S.channel_disch_rate	676	River discharge rate (m^3/day)
S.flood_delta	0	Switch (0/1) for flood delta losses

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