4- RESULTS

Once the background has been outlined, both regarding the study area and the program to be used, the different steps and partial results that will lead to the sediment transport along the coast can be given. These will consist of wave climates at different locations of the study area, each of which will constitute a section of this chapter.

First of all, in section 4.1, the wave climate at the buoy will be presented. Furthermore, the basic assumptions whereupon this work is funded will be introduced and justified. These will lead to a trimming of the original wave data which will conclude with the establishment of a reference buoy wave climate.

In section 4.2, the deep water wave climate will be established. A coarse backward propagation will provide a first approximation to its values, after which a cycle of forward propagations using SWAN will begin until the values it is fed with yield results similar enough to the reference buoy climate.

Section 4.3 will present the wave climate nearshore, the result of the SWAN propagation previously described.

A new forward propagation will bring the wave data from nearshore to the breaker zone, filling section 4.4.

Finally, on section 4.5 CERC and Kamphuis sediment transport formulae will be applied, so that patterns and erosion/accretion zones can be found along the coast.

The chapter will conclude on section 4.6 with a comparison between the results obtained at 4.5 and a look into its implications.

4.1- Buoy wave climate and basic assumptions

4.1.1- Assumptions

In this fourth chapter, the different steps and methods used to determine the wave climate at the breaker zone are presented. As stated in the introduction, this goal is pursued using exclusively a wave record from one intermediate-water location in the study area and bottom/coast data, both regarding its morphology and grain size. Such an approach is clearly a simplification, done under the following assumptions:

- The waves coming from the north are negligible compared to those from the south.
- The waves coming from the south are essentially swell.
- The tides and the currents are negligible.
- The period is constant for each wave.
- The one year wave record at the buoy validly represents the wave climate at that point.
• Given adequate boundary conditions, the propagation methods can find wave conditions at any point of the study area.

These assumptions allow to simplify the problem in the following ways:
• The wind is not taken into account. Both the waves it generates from the north and the effect it may have in the waves coming from the south while running across the study area are ignored.
• Only waves comprised between 135.1 and 254.9 degrees are taken into account (of the original wave record).
• Tides and currents are not taken into account.
• The offshore wave climate is the main boundary condition to be determined.

The first two simplifications are derived from the fact that wind doesn’t play a significant role in the problem: thus, the waves from the north, which are strictly wind-generated, can be skipped (not only are they very small having had such a short fetch run, they also tend to leave the study area), and those from the south can be modelled as swell that propagates from deep sea into the study area. Thus, the last points of both lists are the basis for finding the wave climate at different locations along the breaker zone: a propagation of the offshore climate will suffice, in the absence of any other factors seriously conditioning the waves’ evolution.

Finally, a last assumption that is made but has not been explicitly stated yet, is the fact that the human equipment dotting the shores in the study area is ignored. At least, it is not taken into account directly (that is, as a modifier of the waves, or, later on, as a barrier to the sand transport), although, the protuberance in Saintes-Maries-de-la-Mer does appear in the bathymetry, and it is therefore an indirect acknowledgement of the presence and role of the breakwaters and walls in the area.

4.1.2- Reference wave climate at buoy

The original wave climate record as registered in the buoy comprises 8996 wave data triads (H, T, θ). Its average wave height is 0.79 m (ranging from 0.08 to 4.56), the average period is 5.36 s (ranging from 1.75 to 12.50 s) and the predominant directions are WSW, SSW, S and SSE, as can be seen in the figure below. In order not to have to deal with each one of these “waves”, these have been grouped into “events”, each characterised by a wave height (in a half meter gap), a period (with a one second spacing) and a direction (10˚ sectors). Thus, waves with periods ranging from 7.50 to 8.49 s were tagged as “8 s”, and analogously, multiples of ten were taken for the directions. As for the wave height, an average of the maximum and minimum values entering the event was deemed not good enough because it would diminish the energy of the wave climate, and ultimately reduce the sediment transport calculated. Since many of the transport formulas are dependent on the square of the wave height (or higher), the reference value \( H_{ref} \) chosen for an event was that that would have the same energy as the whole set wave heights ranging from the minimum \( H_{min} \) to the maximum \( H_{max} \) values allowed to enter that group:

\[
H_{ref} = \sqrt{\frac{H_{max}^2 - H_{min}^2}{2}} \tag{eq. 4.1}
\]
Appendix B bears the classification of waves into events. In total, the waves were sorted into 443 events.

The original wave climate record as registered in the buoy included some data which were physically impossible (e.g. $H=0.5$ and $T=2s$; $H/L>>1/7$), probably the result of fumbling with the buoy or the passage of boats nearby. Furthermore, these awkward values stood “alone” in a sea of perfectly plausible values both preceding and following them. They were removed straight away.

More important has been the trimming due to the previous suppositions, which has meant reducing the number of waves to 7826 and that of events to 335. As it can be seen in the figure below, though, the associated wave rose hasn’t changed much from the original. This confirms the adequacy of the assumptions made.

Figure 4.1: Original wave rose at buoy.
4. Results

4.2- Deep water wave climate

Determining the offshore wave climate is of paramount importance since its events will constitute the main boundary conditions to be fed into the propagation methods when calculating the wave climate at other locations. A backward propagation from the buoy, if perfect, would suffice, but this is plainly impossible because it is precisely the boundary conditions for SWAN (the most precise propagation method for deep and intermediate waters available) what is sought here, and thus SWAN itself cannot be used.

The adopted procedure consists on performing a coarse backward propagation to have departure values from where an iterative method will be launched in the quest for appropriate offshore boundary conditions: an event (that has been propagated backwards) is fed into SWAN and its output at the buoy location is compared with the reference data record. If their difference is within a given range, the deep water boundary condition is accepted as “correct”, and the output values nearshore at intermediate depth can be adopted and the propagation can proceed. If not, the offshore values for the event are modified according to the deviation between their output at the buoy and the record and newly fed into SWAN. This cycle continues until the forward propagation performed by SWAN yields values within tolerance at the buoy output location, as seen in the figure below:

Figure 4.2: Reference (trimmed) wave rose at buoy.
In 4.2.1 the backward propagation is explained. Sections 4.2.2 and 4.2.3 deal with the preparation and parameters’ choice of SWAN before the forward propagation, which occupies section 4.3.3 along with the tolerance range chosen.

**4.2.1- Backward propagation**

A first estimate of the (tentative) offshore boundary conditions can be calculated performing a backward propagation of the (trimmed) wave climate available at the buoy. Only reflection and shoaling are taken into account, in a straight coast of parallel bottom isolines. Thus, for each event, the following formula will give an approximation for the deep water wave height:

\[
H_o = \frac{H_{\text{ref}}}{K_r \cdot K_s} \quad \text{(eq. 4.2)}
\]

Where:

- \(H_o\) : Offshore wave height
- \(H_{\text{ref}}\) : Reference wave height at the buoy
- \(K_r = \sqrt[\cos \alpha_{\text{ref}}]{\frac{C_{g,\text{ref}}}{C_{g,o}}}\) : Refraction coefficient
- \(K_s = \sqrt[\cos \alpha_{\text{ref}}]{\cos \alpha_o}\) : Shoaling coefficient
The direction is found with the following formula:

\[ \alpha_o = \arcsin\left(\frac{L_o}{L_{ref}} \sin \alpha_{ref}\right) \]  

(eq. 4.3)

With:

- \( \alpha_o \): Angle between coast and wave front offshore
- \( \alpha_{ref} \): Angle between coast and wave front at buoy
- \( L_o = \frac{gT^2}{2\pi} \): Offshore wave length
- \( L_{ref} = T\sqrt{gh} \): Wave length at buoy

Since this is parallel coast is not the real situation (both at the buoy and offshore) a choice has to be made between idealising the coast as following an E-W direction (general trend for the study area except for the spit) or a NW-SE direction, which corresponds to the local orientation of the isolines at the buoy (deviated 37° from the horizontal). After some test runs with representative values, the first option was retained, although the differences amongst the two weren’t usually great, and in some occasions where the E-W didn’t yield results the NW-SE were used instead. It has to be considered that those values would merely be used as an “educated initial guess” anyway. Analogously, the depth offshore is taken as 90 m, which is not strictly true but is deep enough so as to have no effect on the waves anyway.

Details regarding this backward propagation and each of the events (tentative) values can be found in appendix D.

**4.2.2- SWAN grids**

Having the same rectangular boundaries for bottom and computational grids was a general guideline adopted for the sake of simplicity. Therefore, many of the considerations presented below regarding the bottom grid also apply to the computational grid, with which it has been deliberately intertwined.

**Bottom grid**

Several options exist in order to convert the given bathymetrical points into a bottom grid that can be inputted into SWAN. These stem from the fact that the bathymetrical points available do not conform to a rectangular grid (and therefore, either some borders need to be trimmed or some points have to be “sensibly” added) and the shadowing effect that the lack of input in lateral boundaries may have on the study area. This last factor allows for an initial classification of the available options depending on whether this shadow is solved via extra computations or extra distance:

- **Option I:** Small bottom grid covering only the study zone of interest. Extra points are limited to those strictly necessary to achieve a rectangular grid from the points available. Lateral boundary conditions will have to be found and input in order not to have energy shadows. Energy enters the study area from three different borders.
• Option II: Massive lateral extension of the grid both east and west. A bathymetry large enough so as to overcome the shielding effect due to the lack of input on the lateral boundaries on the study zone. Since wave directions might be nearly parallel to the coast, the bottom grid has to be more than six times (305 km) wider than the study zone.

• Option III: Moderate lateral extension of the grid both east and west, shorter than that of II but feeding the lateral borders with the same boundary conditions as those applied at the south. This is obviously physically impossible (e.g. having a 2 m wave height constantly all along a cross-shore profile), but precisely because of this impossibility SWAN disperses the excess energy quickly when moving away from the borders until only physically sensible values exist in the study zone. Overall this last option is actually a small variation of option II, above which it bears the recommendation of the technicians who designed the programme as a way of taking into account waves’ energy that might escape II.

The advantage of the last two options is that they demand no extra calculations per run, and each of Swan’s runs can be done at once. Option I, on the contrary, bears the need, before the main SWAN calculation is performed, of lateral 1-D runs in both the eastern and western boundaries so that their state can be determined and used as input. Its advantages, though, are more fidelity to the known data and (when referring to the computational grid) a denser and therefore more precise distribution of the points of computation. In options II and III the disadvantage is obviously that the prolongation of the bathymetry to its sides (being unknown) has to be guessed. The most simple and at the same time most logical way of doing this is to translate the last bathymetrical profiles available (that is, those of the lateral boundaries of the study zone) all over the new zones. In theory, this should yield exactly the same result as option A, since this is what SWAN assumes when running 1-D lateral runs. Propagations performed on the same study area using option III have been proven to yield satisfying results (Boada, 2004).

In this study the chosen option was the first one. This is for the sake of fidelity to the physical reality of the involved area and precision when computing. However, despite not needing a major extension, some minor adjustments are still needed in order to have the points ready for inputting. Not all the contour lines end at the same longitude. In order to have a perfectly rectangular grid, these have to be either prolonged manually or trimmed up to a longitude were data is available for all. Since the area is sandy and with no brusque variations, the latter option has been chosen under the assumption that no gross error would be made if all the contour lines were prolonged up to the latitudes of the furthest reaching point amongst them. Extra emerged points have also been added (again, to achieve a rectangular shape).
From these data, SWAN generates a terrain model triangulating:
Computational grid

SWAN will perform the computations over a general grid covering exactly the same area as the bathymetrical one and three smaller nested grids nearshore, where more precision is sought.

The maximal number of nodes SWAN can operate with (under the standard configuration used) is 20,500. These have to be distributed in such a way that both the longitudinal (E-W) and transversal direction (N-S) have enough resolution. Along regular straight sandy coasts, variation on the waves’ parameters is sharper in a cross-shore direction than along-shore, thus a nodes need to be closer longitudinally than transversally. This is the case of our study area except for the zone around the spit, where the coast doesn’t follow an E-W direction. It is because of this, and again for the sake of simplicity, that squared computational cells have been chosen for the general computational grid. In total, 164 stretches in the x direction and 123 in the y direction, each with a length of \( \Delta x = \Delta y = 291 \text{ m} \), totalising 20,460 nodes.

<table>
<thead>
<tr>
<th>Grid</th>
<th>( x_{\text{min}} )</th>
<th>( x_{\text{max}} )</th>
<th>( y_{\text{min}} )</th>
<th>( y_{\text{max}} )</th>
<th>( \text{x nodes} )</th>
<th>( \text{y nodes} )</th>
<th>( \text{Step x} )</th>
<th>( \text{Step y} )</th>
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<tbody>
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<td>797,824</td>
<td>96,000</td>
<td>131,793</td>
<td>165</td>
<td>124</td>
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<td>Nested 1</td>
<td>750,100</td>
<td>781,841</td>
<td>127,000</td>
<td>131,900</td>
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<td>99</td>
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<td>50</td>
</tr>
<tr>
<td>Nested 2</td>
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<td>117,750</td>
<td>127,000</td>
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<tr>
<td>Nested 3</td>
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<td>119,500</td>
<td>205</td>
<td>101</td>
<td>72,7</td>
<td>50</td>
</tr>
</tbody>
</table>

*Table 4.1: Computational grids used in SWAN.*

In the nested grids, higher resolution is sought, reducing the area between nodes in a transversal direction to 50 m. Since two of the grids (those at the E and W) encompass essentially E-W stretches of coast, their resolution alongshore has been reduced. Only around the spit were the cells \( 50 \times 50 \text{ m} \).
Output

The output is given at 78 points. Of these, one corresponds to the buoy’s location, so that the offshore climate can be calibrated with the feed-up mechanism by comparing the output with the reference climate.

The other 77 points follow the -5 m depth isoline near the shore. This depth has been chosen as that which is as close as possible to the coast before bottom induced breaking has begun. The reason for doing this is that Swan’s not precise enough in the breaker zone, so that its use at determining each wave’s breaking position as well as its height and direction is not recommended, and will be done otherwise in section 4.4.

In the case of many waves, this -5 m value is extremely conservative (the breaker depth being effectively located around 1 m depth), but higher waves do exist and, although not abundant, they account for most of the sediment transport, which makes the precise determination of their breaker depth crucial.

All the requested output points lay on the area covered by the nested grids. Thus, the output given by SWAN will be the result of two computations: a general one covering the whole study area and a local one at the specific part of the coast where the given output point belongs. No regular output grid has been used, since the wave characteristics at other points of the study area are not needed.
4.2.3- Other parameters

Besides the wave conditions at the boundaries of the study area, other parameters need to be specified in the model:

- **Directional spreading**: An average amongst the directional spreading of all the waves composing an event has been made, and fed into SWAN as part of the boundary conditions. However, its output has not been controlled (and consequently tuned and refed).

- **Physical parameters**: Most of these parameters have been kept at the default values. This means that the gravity was taken as 9.81 m\(^2\)/s, the water density 1025 kg/m\(^3\), and the direction of north referring to the x-axis as 90\(^\circ\) (as stated, all grids are rectangular, with the horizontal ridges in a E-W direction and the verticals N-S). No wind is taken into account: its input was a speed of 0 m/s. All of the processes were activated (3\(^{rd}\) generation model, bottom friction, depth induced breaking and non-linear triad interactions) but the quadruplets are deactivated (due to lack of wind).

- **Numerical parameters**: Again, for most of them, the default values have been adopted, (regarded as balanced when trying to limit time consumption while at the same time remaining accurate). The diffusion of the spectral space is 0.5 and the frequency space too. The percentage of wet grid points is 98% and the maximum number of iterations is 15.

4.2.4- Forward propagation

After the first estimates of the offshore boundary conditions have been calculated, these can be input into SWAN and the forward propagation cycles can begin. However, since a small grid has been chosen, lateral boundary conditions E and W are needed as well (the N boundary needs no input because it is fully occupied by land). Since the values
along these borders are not constant and equal to the offshore ones, they need to be calculated before the global, to which they’ll be fed as boundary conditions.

SWAN allows to run 1-D runs (that is, not across a surface but merely along a line). Only a bottom profile must be introduced and, in the absence of wind or currents, a boundary condition at one of its ends. The calculation will be done as if an infinitely wide coast with such a profile were present. Although the output can be given anywhere along the line, the 2-D run to be done afterwards limits it: only 11 points can be used as input along a border. Between them, SWAN interpolates linearly the values along the line. Therefore, in the 1-D run, eleven points of output were chosen. A quadratic distribution of points was chosen instead of a regular one because it is nearshore that more detail is needed.

![Figure 4.8: 1-D calculation output points at the E boundary. Note that the quadratic distribution of output points is only applied on the wet part of the profile, not in the emerged section.](image)

![Figure 4.9: 1-D calculation output points at the W boundary.](image)

Each event needs, in order to undergo the SWAN propagation, three SWAN runs: two lateral ones and a global one (examples of their input can be found in appendix F).

All three boundary conditions available, the global 2-D SWAN run is performed, and its output at the buoy is compared with the reference data. In order to decide if they are similar enough, maximum deviations between output and record data have to be established:

- 5 cm for the wave height
- 3 degrees for the direction
A cycle involving lateral runs, general run, comparison with data record and correction is triggered for each event, and stops when the differences between calculated and reference values are small enough. If a given event has just one of these parameters within tolerance, yet another iteration is performed, and the results accepted if both fall within maximum deviation.

In order to correct the offshore values for the next iteration, they are modified with the proportion that the output at the buoy deviated from the reference. For example, in the case of wave height, the input for a given iteration $i$ would be:

$$H_{o,i} = H_{o,i-1} \cdot \frac{H_{ref}}{H_{cb,i-1}}$$

(eq. 4.4)

Where:
- $H_{o,i}$: Input offshore wave height for iteration $i$
- $H_{o,i-1}$: Input offshore wave height for iteration $i-1$
- $H_{ref}$: Reference wave height at the buoy
- $H_{cb,i-1}$: Calculated wave height at buoy for iteration $i-1$

This goes on until both wave height and direction of an event are within tolerance, or it is decided that it is not possible to establish a satisfactory offshore conditions for an event (in no case more than 5 iterations were done). If an event cannot be correctly calibrated, it is not ignored. The number of waves it includes is transferred to the “most similar event possible”. That is, amongst the events classed in its same direction and wave height, the one with the nearest period (usually this means *increasing* the period). If this is not possible due to the absence of events with the same height, then the event is “downgraded” to the next wave height keeping the previous direction and period. The latter will be changed until a coincidence is found. This politic of trying to maintain the wave height rather than the period was chosen with the aim of not loosing much energy in the transfer, so that the effects of waves to the coast are as similar as possible.

Finally, after all events have been propagated or moved to similar ones, both the wave climate offshore and at the buoy have been found. The waves offshore were found to be globally much higher than those at the buoy: their average was 1.40 m, ranging from 0.29 to 5.87 m. Their directions were, too, more scattered, and they comprised values from 100° to 313°. (please see appendix E for the wave the definitive values of the offshore boundary conditions).
Figure 4.10: Wave rose of the offshore wave climate (boundary conditions).

Figure 4.11: Wave rose of the calculated climate at buoy.

The moving of events that could not be calculated has meant reducing its number from 335 to 236 representing 6342 waves instead of the 7826 taken as reference. However, the total number of waves has not been lost, because when an event was moved its waves were added to the receiver.
4. Results

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<th># events</th>
</tr>
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<tr>
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</table>

Total: 8996 443

Table 4.2: Number of waves and events: initially, after the trimming (and therefore, those taken into account), correctly calibrated and moved from other events into those correctly calibrated.

4.3 Nearshore wave climate

The calculated wave climate at the buoy meeting the tolerance requirements, SWAN output (for the same calculation; that is, with the same boundary conditions) can be accepted at nearshore locations. These were chosen around the -5m contour line, a depth deemed big enough so as to safely assume that no depth-induced breaking has occurred yet, but, at the same time, as close as possible to the breaker zone (so that SWAN capabilities optimized). In total, 236 events were propagated for each of the 77 nearshore points, yielding an output of 18,172 wave conditions. Each location has its own wave climate, summarised in appendix G with wave roses at some representative locations (denser near the spit). The sheltering effect of the spit at the eastern end of Beauce’s gulf (points 45 through 55) is clearly seen in the shape of the wave roses, where no waves from east are present. This is the case of point 54, as opposed to transitional point 47 and points 2 and 66, already quite free from such an influence.
The sheltering effect also affects the wave height, as seen in the graphs below corresponding to waves from the south-east and the south-west respectively:
4. Results

Figure 4.16: Wave height in the study area according to SWAN for offshore conditions $H = 1.40 \text{ m}; \ T = 5 \text{ s}; \ \theta = 115.2^\circ$. Buoy reference conditions: $H = 0.76 \text{ m}; \ T = 5 \text{ s}; \ \theta = 140^\circ$.

Figure 4.17: Wave height in the study area according to SWAN for offshore conditions $H = 0.86 \text{ m}; \ T = 5 \text{ s}; \ \theta = 232.9^\circ$. Buoy reference conditions: $H = 0.76 \text{ m}; \ T = 5 \text{ s}; \ \theta = 230^\circ$.

At the same time, these results also illustrate the limitation of not taking the wind into account: in both situations, the reference wave height at the buoy was 0.76 m, but when
the waves had a south-eastern origin, the offshore height value was much bigger. Since no energy is entering the system, the waves keep losing energy when moving through the study area, and the only way to compensate for this loss, especially when having an adverse origin (that is, closer to the east), is to increase the offshore height boundary condition. The same can be said about the direction: the first waves (e.g., from the south-east) undergo much more refraction than those originally from the west. The position of the buoy, already under the underwater bulb of the spit, makes it more prone to this effect in oriental waves: the bathymetrical isolines there have an orientation of 137° instead of the 90° common along the coast outside the spit.

### 4.4- Breaking zone wave climate

Sediment transport formulas require the wave condition at the breaker zone. In order to get there from SWAN’s nearshore output locations, yet another forward propagation is needed. Just like in the backward propagation, a simple method taking refraction and shoaling into account will be used. In this case, however, the assumption of a straight coast with parallel isolines is fully acceptable in a local scale, from a nearshore location to its corresponding breaker point. The problem is though that no particular breaker point exists for each nearshore location, because each event, with a different height, direction and period, will brake at a different place. Since 236 events describe the wave climate at each location, a cloud of 236 breaker points are associated with one SWAN’s nearshore output location.

In order to find them and the wave height and direction when breaking, the formulae seen in 4.2.4 are applied with the particularity that the breaker depth is unknown. This will be determined with the parameter:

\[ \gamma = \frac{H_b}{h_b} \]  

(eq. 4.5)

Where:
- \( H_b \): Wave height at breaking point
- \( h_b \): Water depth at breaking point

Both numerator and denominator are initially unknown. An iterative process beginning at \( h_b = 0 \) and with an increase of 0.01 m will be launched, in order to determine the first wave height that fulfills the condition that \( \gamma < 0.68 \). The formulae used will be again:

\[ H_b = H_{\text{near}} \cdot K_s \cdot K_r \]  

(eq. 4.6)

Where:
- \( H_b \): Wave height nearshore
- \( K_s \): Shoaling coefficient
- \( K_r \): Refraction coefficient

Twenty of the waves could not be propagated till its breaking point due to the fact that their front angle nearshore was bigger than 90°, and therefore unable to fit the formulation. They corresponded to events with a low energy (\( H < 0.35 \) m) and a low
period \((T \leq 5 \text{ s})\) around and on the lee of the spit. Given their small number and their small height they were ignored assuming that the effect on the sediment transport would be negligible.

Thanks to the assumption of a seabed with parallel isolines parallel in turn to the shore, once the water depth at breaking point for a given event has been determined, the distance to the nearshore point from where the wave came from can be determined, and the breaker point coordinates as well. However, to calculate the sediment transport, a common point needs to be determined for all events stemming from one nearshore location. Again, instead of adopting an average between all the available \(x_b\) and \(y_b\) points of an event, these will be weighed according to the energy of their associated event. Thus, the following formulae are applied for each location \(j\):

\[
x_{b,j} = \frac{\Sigma x_{b,j,i} \cdot H_{b,j,i}^2}{\Sigma H_{b,j,i}^2} \quad \text{(eq. 4.7)}
\]

\[
y_{b,j} = \frac{\Sigma y_{b,j,i} \cdot H_{b,j,i}^2}{\Sigma H_{b,j,i}^2} \quad \text{(eq. 4.8)}
\]

Where:
\(x_{b,j}\): \(x\)- coordinate of weighed breaking point \(j\)
\(x_{b,i,j}\): \(x\)- coordinate of breaking point \(j\) for event \(i\)
\(H_{b,i,j}\): Wave height at breaking point \(j\) for event \(i\)
\(y_{b,j}\): \(y\)- coordinate of weighed breaking point \(j\)
\(y_{b,i,j}\): \(y\)- coordinate of breaking point \(j\) for event \(i\)

The total number of breaking points is 75 instead of the 77 nearshore (see figure 4.7 and appendix H). The fact that the angle between the wave front (nearshore, initially, and
breaking afterwards) and the shore is needed to perform this last propagation is the reason for this reduction: in order to find this angle, each nearshore point was assigned the coast angle orientation corresponding to that taken by the segment linking the previous and following point. Therefore, those at the beginning and at the end couldn’t be calculated. However, the numeration for the graphs (and in appendix I) beneath showing the assembled wave climate in those “fictitious” breaker points has been kept like the one used nearshore because a direct correspondence exists between them.

Figure 4.19: Wave rose a breaker point 2.

Figure 4.20: Wave rose a breaker point 47.

Figure 4.21: Wave rose a breaker point 54.

Figure 4.22: Wave rose a breaker point 66.

A great concentration of waves is observed in most locations when comparing the directions present at the breaking points with those nearshore. This tendency is especially acute in the lee side of the spit, where waves even adopt a southern component. That means that the waves undergo a lot of refraction and do actually get close to having their front parallel to the shore. Furthermore, most of this refraction takes place when covering the distance between the nearshore points and breaking, therefore when computed with the coarse “shoaling + refraction method”, in the last
forward propagation. This confirms that the 5 m isoline chosen was indeed before the breaker zone, albeit too far away: for most of the waves, SWAN could have been used until other shallower locations, having more precise calculations. A few high waves though, which render the average wave height some 15 cm higher than the median wave height, make it necessary to use the 5 m isoline to finish SWAN’s forward propagation: while the average breaking happens at a depth of 1.43 cm, the earliest wave breaks at 4.72 m.

The average wave height remains quite similar (around 1.10 m) all along the study area except for the points sheltered by Beaduc’s spit. Its effect is clearly seen in the graph below. It is strongest in point 51, corresponding to the eastern end of Beaduc Gulf. Going west from there, a gradual increase in wave height is observed, whereas eastwards towards Faraman (that is, around the spit), the change is quicker.

![Average wave height in breaker points (m)](image)

*Figure 4.23: Average wave height at each breaker point in m.*

### 4.5- Sediment transport

Alongshore sediment transport is the movement of sediment particles in a direction parallel to the shoreline and the corresponding bottom isolines. It depends on the hydrodynamics in the breaker zone and on the sediment properties, local seabed and shoreline characteristics. Furthermore, it is not constant through a vertical plane perpendicular to the shore. Therefore many formulae exist that try to quantify it, be it from a theoretical approach often based on the equation 4.9 or be it from empirical observations. Differences also exist depending on whether they provide the transport distribution along a profile perpendicular to the coast or they are “integral” (i.e. summarising all transport across a given profile as a single number).
4. Results

\[ S = \int_0^{h+\eta} V(z) \cdot \bar{c}(z) dz \]  
(eq. 4.9)

Where:
- \( S \): Alongshore sediment transport \( (m^3/m/s) \)
- \( V(z) \): Alongshore current velocity at height \( z \) above the bottom \( (m/s) \)
- \( \bar{c}(z) \): Time averaged sediment concentration at height \( z \)
- \( h \): Local (still) water depth \( (m) \)
- \( \eta \): Instantaneous water surface elevation \( (m) \)

Given the limited data available, the huge scope of the area involved and the manifested will of trying to stick to the essential factors driving alongshore transport, two simple integral formulae have been chosen for use here: those by CERC and Kamphuis.

It must be stressed, though that these are merely potential sediment transport formulae, and therefore, if correct, they would still only provide an upper limit for transport, attainable only if enough sediment was indeed present and in the absence of entropic barriers or perturbations (which, as seen in section 3.3, do exist).

4.5.1- CERC

The Coastal Engineering Research Center (CERC) introduced its empirical alongshore sediment transport formula in 1984, and it is still the most used formula around the world. It is rather simple, with the energetic component of the breaking waves as the main factor driving the transport. The characteristics of the sediment are barely taken into account (only its porosity).

\[ Sl = \frac{K}{(\rho_s - \rho_w)g(1-p)} Pl_b \]  
(eq. 4.10)

Where:
- \( Sl \): Longshore sediment transport \( (m^3/s) \)
- \( \rho_s \): Sediment’s density \( (2650 \text{ kg/m}^3) \)
- \( \rho_w \): Water’s density \( (1025 \text{ kg/m}^3) \)
- \( g \): Gravity’s acceleration \( (9.81 \text{ kg/m}^2) \)
- \( p \): Sediment’s porosity \( (0.4) \)
- \( K \): Tuneable coefficient \( (0.12) \)
- \( Pl_b \): Longitudinal component of the energy flux

This last variable, in its turn, being determined with the formula below:

\[ Pl_b = \frac{1}{16\sqrt{\gamma}} \rho_w g^{1.5} H_b^{2.5} \sin(2\alpha_b) \]  
(eq. 4.11)

Where (besides the variables explained above):
- \( H_b \): Wave height at breaking point
- \( \alpha_b \): Angle between coast and wave front at breaking point
4. Results

\( K \) should be calibrated for every particular site where the formula is applied. If this is not possible, a value commonly accepted for grain sizes of \( d_{50} \in [0.15, 1.0] \text{mm} \) is \( K = 0.29 \). However, such an approximation, already lower than the initial 0.39 proposed by CERC, was devised for oceanic coasts, with higher waves and longer periods than those encountered in the Rhone delta. In his study thesis about the Rhone delta, Sabatier (2001) recommends the value \( K = 0.12 \), as that fitting more appropriately the observed sediment transport along the delta’s shores. That is the value chosen for the present study.

Applying the aforementioned formulae only gives the instantaneous transport due to one event, that corresponding to the wave conditions entered into the computation. In order to obtain total yearly values the different events have to be weighted according to the number of waves they represent, and the time scope needs to be modified (to a year). Mathematically:

\[
SI = \frac{\sum_{i} S_{li} \cdot n_{i}}{\sum_{i} n_{i}} \cdot 365 \cdot 24 \cdot 60 \cdot 60
\]

(eq. 4.12)

Where:

- \( n_{i} \): Number of waves associated with event \( i \)
- \( S_{li} \): Sediment transport caused by event \( i \)

In this way, the longshore net transport has been calculated along the coast, following the output points. Depending on whether values provided by each \( Pl_{b} \) have been taken into account with its sign or not, the net or the gross longshore transports have been found. The graphs below summarize the results that can be found in appendix J:

![Figure 4.24: Net longshore sediment transport with CERC’s formulation in m³/year (SI net, yearly). A positive value implies transport towards west (Espiguette spit) and a negative value towards east (Grand Rhone mouth).](image)

For most of the coast the transport adopts an eastward direction, except for the area at the eastern end of Beaduc’s gulf and the spit, where a very marked 500,000m³/year peak is found.
Thus, a first glance seems to confirm the existence of the sediment cells outlined by Sabatier and Suanez: convergent transport towards the spit (tip: point 58) from both east and west coupled with ultimately outbound transports at the extremes of the study area fit the Beaduc spit convergent cell surrounded by those pointing to the Grand-Rhone river mouth’s and the Espiguette spit seen in figure 3.2. However, it must be borne in mind that it is not the transport values that determine the sediment accumulation but the gradient of this transport.

If the sediment transport is then split into strictly westward or eastward motions, the partial transport graphs below appear.

The spit’s effect on the otherwise mostly straight east-west coast is manifested on the absence of eastward transport between points 48 and 58. Outside this area and its neighbouring regions, westbound transport remains fairly regular along the coast.
Westward transport, although more irregular and with a marked peak around point 58, never disappears completely.

When the values of partial transports above are aggregated, gross transport appears.

![Fig 4.27: Gross longshore sediment transport with CERC's formulation in m$^3$/year (Sl gross, yearly).](image)

Again, gross longshore sediment transport displays a maximum at point 58, preceded when approaching it from the west by a rather static (in absolute terms) zone at the easternmost point of the gulf.

In order to smooth the results, and make them less prone to brusque differences due to inexact determinations of the bottom isolines' direction at each output point, the results at each point have been averaged with those of the preceding and subsequent points. This implies that the first and last points (i.e., 2 and 76, since two extreme points had already been lost in the last forward propagation) will be skewed due to the inability of having a 3-average. Instead of accommodating a 2-average with strictly their unique neighbouring points, they have been skipped altogether from the graphs below, where, again, the 4 different yearly transport graphs have been displayed.

Furthermore, figures 4.28 through 4.31 show the contribution to the transport of different wave heights, grouped in a decreasing manner, from waves strictly bigger than 2.5 m to lower than 1.0 m. The point where this sorting of heights applies is not offshore but the buoy. The reason for choosing it so is that that is the place where data stems from, and, most likely, where any further data would be collected.
Fig 4.28: Net average-3 longshore sediment transport with CERC’s formulation in m$^3$/year (Sl net av-3, yearly).

The fact that in some points the lines delimiting the contribution of each wave-height group cross or overlap each other is not only due to transitions from westward to eastward transport directions, but also to the different partial wave climate that each group stands for (with, even, different wave roses) in a manner that their contribution is not uniform. Thus, the contribution is sometimes in the opposed sense of the net global transport for a given point; or the contribution of one single group is bigger than the total. This is the case of points, 66 and 67, where waves between 1.0 and 1.5 m push for a net westward transport against the eastward direction of all other groups.

Performing a separation into partial directional transports:

Fig 4.29: Westward average-3 longshore sediment transport with CERC’s formulation in m$^3$/year (Sl west av-3, yearly).
4. Results

Fig 4.30: Eastward average-3 longshore sediment transport with CERC’s formulation in m³/year (Sl east av-3, yearly).

It is noted here that the number points where no eastward transport occurs have diminished in relation to graph 4.20, because both points 48 and 58 do get “some transport” thanks to the averaging of its values with those from their surrounding points.

Fig 4.31: Gross average-3 longshore sediment transport with CERC’s formulation in m³/year (Sl gross av-3, yearly).

The differences between the contributions of the wave-height groups become blurred in the gross transport graph, where each seems to contribute to a fixed proportion of the final result. This might be due to the fact that the differences amongst the groups consist essentially (besides height) in direction, and thus, the final direction of the transport caused might change from group to group depending on the predominant direction inside each one of them. However, its absolute proportion remains fairly constant, as the transport, be it in the direction it might, is indeed caused by the waves in that group.
Finally the gradient of the net sediment transport has been calculated at each stretch bound for the same direction. Convergent transition points (joints) were left intact, whereas divergent ones (to be found somewhere between a left hand-side westward transport point and a right hand-side eastbound transport one) were treated as if the contiguous points received no sediment at all.

Figure 4.32 below displays the gradient of transport when applied to both regular (blue columns) and average-3 (green line) values.

The area before the spit concentrates much of the sedimentation, whereas erosion should be experienced both around the Petit Rhone’s river mouth (point 22) and on the southern side of the spit. This can be seen in the next figure, where the yearly sedimentary budget is shown, with the change in volume in each erosion or accretion zone.

Fig 4.32: Increase/decrease in sediment volume using CERC’s formulation in m³/year ($\Delta V$, yearly).
4.5.2- Kamphuis unigrain

Kamphuis formula, developed from dimensional analysis, departs from a consideration of all the parameters that might have influence in the transport, to progressively trim and exclude all those redundant or unimportant according to established hypothesis. The formula eventually becomes:

\[ Q = K \cdot H_b^2 \cdot T_p^{1.5} \cdot m_b^{0.75} \cdot d_{50}^{-0.25} \cdot \sin^{0.6}(2\alpha_b) \]  

(eq. 4.13)

Where:
- \( H_b \): Wave height at breaking point
- \( T_p \): Peak period
- \( m_b \): Beach steepness
- \( d_{50} \): Median grain size
- \( \alpha_b \): Angle between coast and wave front at breaking point
- \( K \): Constant dependent on the time span; 63,950 if a year.

As it can be seen, parameters ignored in CERC’s formula are taken into account by Kamphuis, so that the sediment’s characteristics \( (d_{50}) \) become more important and the beach morphology \( (m_b) \) and even other wave data \( (T_p) \) now play a role as well.

Unfortunately, sediment size data were not available throughout all the study area’s coast, only its eastern end. This section presents the results when the formula is applied with a uniform grain size of 0.2 mm. On the next section, the same study is pursued with the varying grain sizes available, so that a comparison between them but also CERC can be drawn at section 4.6.

The procedure followed to properly acknowledge the different weight of the events when applying CERC (see equation 4.12) has been repeated for the Kamphuis formula,
except for the fact that the latter already gives a yearly result, and therefore only the weighing of the different events at one point is needed. Its results are found in appendix K, or, graphically summarised below.

![Graph](image1)

**Fig 4.34: Net longshore sediment transport with Kamphuis formulation in m³/year (Q net, yearly).**

Again, most of the study area undergoes a globally eastward transport with the exception of the area north of the spit, where high westward values are attained. A sharp negative abyss at points 27 and 28 are the other extreme values present.

Taking westward and eastward partial transports separately, the values can be charted as follows:

![Graph](image2)

**Fig 4.35: Westward longshore sediment transport with Kamphuis formulation in m³/year (Q west, yearly).**
Westward transport presents a similar irregular pattern to the one featured in the CERC section, accompanied by a lack of eastward transport between points 48 and 58. The maximum in this case is located in point 28.

Point 22 is located just in front of the Petit Rhone river mouth, while points 23 through 29 correspond to the urban littoral of Saintes-Maries-de-la-Mer, which, with its huge coastal defence infrastructure, has been left slightly intruding into the sea when the surrounding coast retreated. The coast’s direction, despite veering in a counter-clockwise direction, doesn’t change much, but the distance between the 0 m and the -5 m isoline does, and, accordingly, the steepness. This is especially true in points 27 and 28, where extreme values are attained due to steepnesses twice as sharp as in the rest of the coast, where it remains slightly under the 1% (see appendix H for more details on the steepness). Since CERC’s formula does not take steepness into account, figure 4.27 did not portray the peak visible in figure 4.37 above.
Applying the average-3 to the previous results yields the graphs below:

Fig 4.38: Net average-3 longshore sediment transport with Kamphuis’s formulation in m³/year (Q net av-3, yearly).

Some crossing between the lines delimiting the contributions of the different wave groups is present in the net longshore transport graph above, but it obviously disappears in the partial directional ones below.

Fig 4.39: Westward longshore sediment transport with Kamphuis formulation in m³/year (Q west av-3, yearly).
Fig 4.40: Eastward longshore sediment transport with Kamphuis’ formulation in m³/year (Q east av-3, yearly).

Coupling the values of the last two graphs the gross average-3 longshore transport is plotted.

Fig 4.41: Gross average-3 longshore sediment transport with Kamphuis’s formulation in m³/year (Q gross av-3, yearly).

As seen in figure 4.42 below, with the sediment transport data yield by the calculations performed with Kamphuis formula, the erosive/accretive patterns along the coast remain equally variable, even if a clear accretive zone appears to the lee side of the spit (points 51 through 57) fed by the erosion on its opener edge, and contiguous Faraman beach.
4. Results

Fig 4.42: Increase in sediment volume using Kamphuis formulation (unigrain) in m³/year (ΔV, yearly).

Graphically:

Fig 4.43: Yearly sedimentary budget of the accretion and erosion stretches using Kamphuis formulation (unigrain) in 10³ m³/year.

4.5.3- Kamphuis multigrain

The same formulae as in 4.5.2 have been used, producing the results summarised in the graphs below (or in appendix L), albeit with less points: only those where the varying grain size was available (luckily encompassing the most morphodynamically complex spot in the study area: the spit).
4. Results

Fig 4.44: Net longshore sediment transport with Kamphuis formulation (varying grain size) in m³/year (Q<sub>net</sub>, yearly).

The spit’s presence manifests itself with a net westward transport on its lee, coupled with predominantly eastward net transport from its tip and most of Faraman. This can be nuanced, however, with the partial transport graphs below:

Fig 4.45: Westward longshore sediment transport with Kamphuis formulation (varying grain size) in m³/year (Q<sub>west</sub>, yearly).

The maximum westward transport occurs at point 58, surrounded by low transports at the east of the gulf and average values (round 60,000 m³/year) along Faraman.
4. Results

The absence of eastward transport is once again confirmed at the eastern end of Beaduc’s gulf and the northern edge (lee side) of the spit.

The gross transport sees its spit values equalled, and even surpassed by those attained at Faraman, where a transport of around 130,000 m³/year is registered.

Averaging each value with those belonging to the previous and next point, and taking the contribution of each wave-height group into account, the smoother graphs below have been found.
Fig 4.48: Net average-3 longshore sediment transport with Kamphuis’s formulation (varying grain size) in m³/year ($Q_{net \ av-3}$, yearly).

Again, much crossing is noticeable, especially in Faraman beach, where the lower waves tend to push the net transport westward against high waves driving it eastward.

Fig 4.49: Westward longshore sediment transport with Kamphuis formulation (varying grain size) in m³/year ($Q_{west \ av-3}$, yearly).
Fig 4.50: Eastward longshore sediment transport with Kamphuis (varying grain size) formulation in m$^3$/year (Q east av-3, yearly).

Fig 4.51: Gross average-3 longshore sediment transport with Kamphuis (varying grain size) formulation in m$^3$/year (Q gross av-3, yearly).

Finally, the erosive tendencies and accretive tendencies have been plotted both with regular and average-3 values.
4. Results

![Graph showing sediment volume using Kamphuis formulation in m³/year (ΔV, yearly).](image)

Fig 4.52: Increase in sediment volume using Kamphuis formulation (multigrain) in m³/year (ΔV, yearly).

![Graph showing yearly sedimentary budget of the accretion and erosion stretches using Kamphuis formulation (multigrain) in 10^3 m³/year.](image)

Fig 4.53: Yearly sedimentary budget of the accretion and erosion stretches using Kamphuis formulation (multigrain) in 10^3 m³/year.

### 4.6- Comparison and implications

Once the sediment transport and the sedimentary budget have been calculated with both CERC and Kamphuis formulations, comparisons can be drawn between them. First, though, the graph below focuses on the net longshore transport calculated with Kamphuis formula both with and without varying grain size, in the area where that is possible.
4. Results

Fig 4.54: Net longshore sediment transport with Kamphuis formulation (with and without varying grain size) in m$^3$/year (Q net av-3, yearly).

The results with a varying grain size are not much different from those with a uniform $d_{50}$. They tend to be a little bit lower, as expected since the grain size is slightly bigger along most of the coast considered (except its north-western end) to the unigrain assumption of $d_{50} = 0.2$ mm. (see appendix C for more details on $d_{50}$). Thus, only points 49 and 50 have bigger net transport values in the multigrain approach (49, 50 and 51 for the gross longshore value; not shown). On average, the multigrain results are nearly 4% smaller than unigrain’s, with a maximum divergence of 7% at point 68.

The erosion patterns show consistent similarities too, as seen in the graph below, displaying the erosion/accretion per point calculated from the 3-average values. Again, since the transport values are lower for the multigrain approach, its volume changes are smaller.

Fig 4.55: Comparison between increase in sediment volume using Kamphuis unigrain (blue) and multigrain (green) formulations, in m$^3$/year ($\Delta V$, yearly).

This is also evident in figures 4.43 and 4.53, where a total coincidence between the erosive and accretive stretches is matched by very similar erosion/accretion values.
Considering this manifest similarity, further comparisons in this chapter will not take the Kamphuis multigrain approach into account, since the simpler and more comprehensive unigrain represents it well enough. However, that doesn’t imply that the multigrain approach is wrong or even not necessary. It can merely be said that in that particular area of the delta, differences in grain size are not large enough so as to seriously affect the sediment transport (if a good representative value is taken).

Comparing CERC’s and Kamphuis formulation on the contrary, does lead to some divergences:

First and foremost CERC’s values are consistently bigger than those of Kamphuis, as seen in the graphs above or the table below. Their patterns, though, remain essentially
similar, and only in the aforementioned eastern end of Saintes-Maries-de-la-Mer are they blatantly divergent.

<table>
<thead>
<tr>
<th>Net</th>
<th>Westward</th>
<th>Eastward</th>
<th>Gross</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Average</td>
<td>33.8</td>
<td>- 48.6</td>
<td>- 37.9</td>
</tr>
<tr>
<td>Maximum</td>
<td>75.0</td>
<td>47</td>
<td>134.2</td>
</tr>
<tr>
<td>Minimum</td>
<td>-57.4</td>
<td>67</td>
<td>27.1</td>
</tr>
</tbody>
</table>

Table 4.3: Percentual relation for the different longshore transports between CERC (100%) and Kamphuis (expressed in % of CERC’s results).

Furthermore, a glance at figures 4.33 and 4.43 shows similar erosion and accretion stretches, with CERC lodging 40 accretive points along 52.3 % of the coast’s length instead of 35 covering 46.7% by Kamphuis. These differences affect, besides Saintes-Maries-de-la-Mer, one point at Faraman and a couple more in the inner Beaduc gulf.

As referring to the magnitudes, it might seem that CERC’s greater results confirm the widely spread assumption that this formulation is prone to overestimations of the sediment transport (Wang et al., 2002). However, comparing the volume variations at the erosion and accretion stretches to those compiled by Sabatier (2003) in his sedimentary cells leads to think otherwise: CERC’s values are mostly lower than those that have been registered historically (despite some of them being already affected by the hindrance to transport that the human-built infrastructure represents). A plausible explanation is that Kamphuis accurately tracks the erosive/accretive phenomena along the delta, but underrates their value in the grounds of the rigidity caused by its lacking of any calibration constant. In the case of CERC, a higher value for the coefficient K might apply.

In short, the differences between CERC and Kamphuis, though quantitatively big, are qualitatively small with both displaying the same tendencies along the coast, even in the share of erosion caused by the higher waves, as it can be seen below:

<table>
<thead>
<tr>
<th>Wave height</th>
<th>waves</th>
<th>Net</th>
<th>Westward (E to W)</th>
<th>Eastward (W to E)</th>
<th>Gross</th>
</tr>
</thead>
<tbody>
<tr>
<td>H&gt;2,5</td>
<td>84</td>
<td>1.1</td>
<td>11.9</td>
<td>12.6</td>
<td>9.2</td>
</tr>
<tr>
<td>H&gt;2</td>
<td>249</td>
<td>3.2</td>
<td>26.7</td>
<td>29.9</td>
<td>21.5</td>
</tr>
<tr>
<td>H&gt;1,5</td>
<td>604</td>
<td>7.7</td>
<td>70.3</td>
<td>44.5</td>
<td>33.5</td>
</tr>
<tr>
<td>H&gt;1</td>
<td>1799</td>
<td>23.0</td>
<td>81</td>
<td>75.0</td>
<td>70.6</td>
</tr>
<tr>
<td>total</td>
<td>7826</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table 4.4: Percentual contribution to the different sorts of longshore sediment transport of the higher waves according to CERC and Kamphuis (unigrain) formulations averaged over the whole shore.

Barely 1% of the waves causes around 10% of the transport, and the top fourth accounts for three quarters of the transport.

It must be stressed that the study area is globally eroding, since it is sending sediment outwards (both in its eastern and western ends) and concentrating it in the few accretion stretches it has (odd sediment input rushes from the Petit Rhone notwithstanding). A significant transfer of sediment between the western and the eastern end of Beaduc’s gulf occurs.
Finally, focusing on the spit, all of its lee side, point 48 (western end of Beaduc’s gulf) through point 58 (tip of the spit), see no transport moving eastwards (in the local context, southwards: towards the spit’s tip/offshore). This means that any grain entering the lee side of the spit, will either remain there or be pushed further north. As sand from Faraman surpasses the spit’s tip, the low energetic conditions provoked by the spit’s energetic shadow prevent it from moving, and, in case it does, the only possible motion is northwards thanks to the coast’s relative orientation to any incoming waves even after refraction, with $\alpha_b$ consistently bigger than $0^\circ$. This last statement is, in fact, not completely true. If wind were taken into account the small fetch between the centre of Beaduc’s Gulf and the spit when northerly winds were blowing would create some waves with negative $\alpha_b$. Nevertheless, the accreting tendency of that spot is confirmed by the three calculations performed, and matches the tendencies marked by the literature.