METHODOLOGY

This document presents the details of the methodology applied within the Long-Term Shoreline Retreat Tool. Specifically, it presents the formulas modified from Bruun's Rule (Bruun, 1962), describes their parameters, and explains how these parameters can be estimated.

A paper is currently under development in which we intend to provide all the details on the formulations presented here. We will update this page with information about it as long as it is available to readers.

MODIFIED FORMULAS FOR ESTIMATING THE SHORELINE RETREAT DUE TO SLR

The following tables, Table 1 and Table 2, show the formulas applied to estimate the shoreline retreat.

Table 1. General formulations.

Shoreline retreat component	General formulae	
$\boldsymbol{R_{tt}}$	$R_{tt} = R_{Bruun} + R_{Berm} + R_{Estuary} + R_{non\_SLR}$	(1)
$\boldsymbol{R_{Bruun}}$ (Bruun, 1962)	$R_{Bruun} = SLR \frac{W^*}{(B+h^*)}$	(2)
$\boldsymbol{R_{Berm}}$ (adapted from Rosati et al., 2013)	$R_{Berm} = \frac{V_{Berm}}{B+h^*}$ $V_{Berm} = SLR(L - R_{Bruun})$	(3) (4)
$\boldsymbol{R_{Estuary}}$ (adapted from Toimil et al., 2017)	$R_{Estuary} = \frac{\Delta V_e}{Le(B+h^*)}$ $\Delta V_e = A_e * (SLR - \alpha)$	(5) (6)
$\boldsymbol{R_{non\_SLR}}$	$R_{non\ SLR} = Scr * \Delta t_{target\ year}$	(7)

Table 2. Specific formulas and conditions applied according to the profile characteristics.

Specific conditions of each profile	Adapted formulae	
Profiles with wall/cliff on the backshore	$R_{tt\ corrected} = L \quad if \quad R_{tt} > L$	(8)
Profiles with dune on the backshore	$R_{tt\ corrected} = \frac{SLR * W^* - (R_{tt} - L) * H_d}{h^* + B}$ $R_{tt\ corrected} = L + L_d$ $if \quad R_{tt\ corrected} \geq L + L_d$	(9) (10)
Profiles with rocky outcrop or reef	h_L y W_L instead of h^*y W^* On the equations: (2), (3), (5) y (9)	

List of parameters:

R_{tt}: Total shoreline retreat [m].

R_{Bruun}: Profile retreat due to SLR calculated with Bruun's Rule [m].

R_{Berm}: Additional retreat due to the demand of sand to fill the berm height along the dry beach area after SLR [m].

$R_{Estuary}$: Additional retreat due to the demand of sand to fill the tidal flats within the estuary after SLR [m].

R_{non_SLR}: Shoreline retreat due to factors unrelated to the SLR (e.g. beach nourishment, chronic erosion due to the disruption in the littoral drift, etc.) [m].

$R_{tt\ corrected}$: Total shoreline retreat after corrections according to profile characteristics (e.g. limitation of the retreat due to the presence of a sea wall, reduction of the retreat due to the input of sediment from the dune, etc.) [m].

SLR: Sea level rise [m].

B: Berm height [m].

h^*: Depth of closure [m].

W^*: Active beach profile width [m].

L: Dry beach width [m].

V_{Berm}: Volume of sand per unit length, required to fill the dry beach width after the SLR (represented by the area in the case of a cross-shore beach profile) [m^2].

Le: Length of the beaches that are adjacent to the estuary [m].

$\overline{h^*}$: Average depth of closure of the beaches adjacent to the estuary [m].

ΔV_e Volume of sand required to fill the tidal flat growth inside the estuary after SLR. [m^3].

A_e: Estuary area [m^2].

α: Tidal flat growth (inside the estuary) [m/year].

Scr: Shoreline change rate of the profile obtained from historical shoreline data (Erosion or accretion, depending on the sign: positive means erosion) [m/year].

$\Delta t_{target\ year}$: Complete time of the analysis (e.g. from now until the target year [years]).

H_d: Height of the first dune ridge at the backshore of the beach [m].

L_d: Width of the first dune ridge at the backshore of the beach [m].

h_L: Depth of the rocky outcrop or reef platform [m].

W_L: Distance between the berm and the rocky outcrop or reef platform [m].

2. TIPS ON HOW TO ESTIMATE PARAMETERS

This section provides a brief description of the parameters required to estimate the shoreline retreat and some suggestions on how they can be obtained.

2.1. MORPHOLOGICAL PARAMETERS

2.1.1. Berm height (*B*)

Identifying the berm on the topographic profile of a beach is not straightforward and requires knowledge of the area and the measurements taken. Additionally, in some profiles where the structure of the berm is not well-defined, such identification may simply not be possible. This task becomes even more challenging in regional analyses, where detailed profile-by-profile verification is not feasible. Consequently, approximations, also known as 'proxies,' are often used in such studies to estimate the berm height (B).

Some studies suggest formulas to estimate the berm height based on local wave parameters (e.g., Takeda and Sunamura, 1983), and others have identified the berm height in measured beach topography according to the knowledge of an expert in that specific area. Here, the maximum elevation of the berm was estimated as the topographic level at the intersection between the beach profile and the wet and dry sand interface. It is up to the user to decide which value is the most suitable for their specific study area.

2.1.2. Depth of closure (*h**) and active beach profile width (*W**) measured from the berm.

The depth of closure can be estimated using empirical formulas. Here, the formula proposed by Birkermeier (1985) was employed and h* was identified in the topo-bathymetric profile considering zero as the Low Astronomical Tide (LAT). Subsequently, the distance between the shoreline and the point on the profile corresponding to the depth of closure (h*) was calculated to obtain the active beach profile width (W*).

The formula proposed by Birkemeier is presented as follows:

$$h^{*} = 2.28H_{s12} - 68.5\left(\frac{H_{s12}^{2}}{gT_{p}^{2}}\right) \tag{11}$$

where H_{s12} is the significant wave height of the storm of the year (wave height exceeded only 12 hours per year), T_p is the peak period associated with this wave height, and g is the acceleration due to gravity. As an example, Figure 1 shows the position and the values of *B, h*, and W** in a measured beach profile.

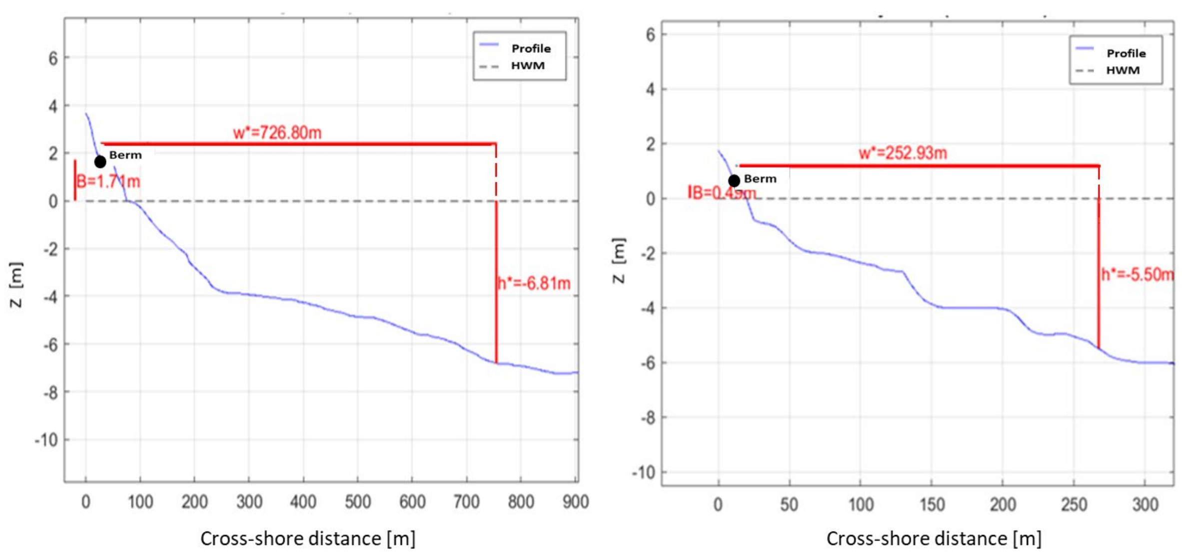

Figure 1. Cross-shore profile shape and its measurements of the parameters B, h, and W*.*

2.1.3. Dry beach width (*L*)

The dry beach width can be estimated as the distance between the backshore (dune, seawall, cliffs or other structures) and the interface between dry and wet sand (see Figure 2).

Figure 2. Images of real beaches, showing the methodology for obtaining the proxy of the dry beach width.

2.1.4. Shoreline change rate (*Scr*)

An estimate of the shoreline change rate (erosion or accretion) is necessary to calculate the shoreline retreat component not related to SLR, which accounts for additional shoreline retreat caused by factors such as chronic erosion from disrupted natural beach sediment inputs.

This value must correspond to a recent erosion rate. We suggest using the erosion rate estimated from satellite/orthophoto-derived shorelines from the last 10 years. By using a 10-year time series, we aim to ensure that the erosion rates are obtained from a record long enough to represent the chronic and actual shoreline change and short enough so that it does not include the effect of sea level rise. Note that negative values represent accretion and positive values represent erosion.

2.2. SEA LEVEL RISE PROJECTIONS

To account for the uncertainty in SLR projections, apart from using the percentile 50% (Q50), the shoreline retreat corresponding to percentile 5 (Q5) and percentile 95 (Q95) of SLR curves are also estimated (see Figure 3).

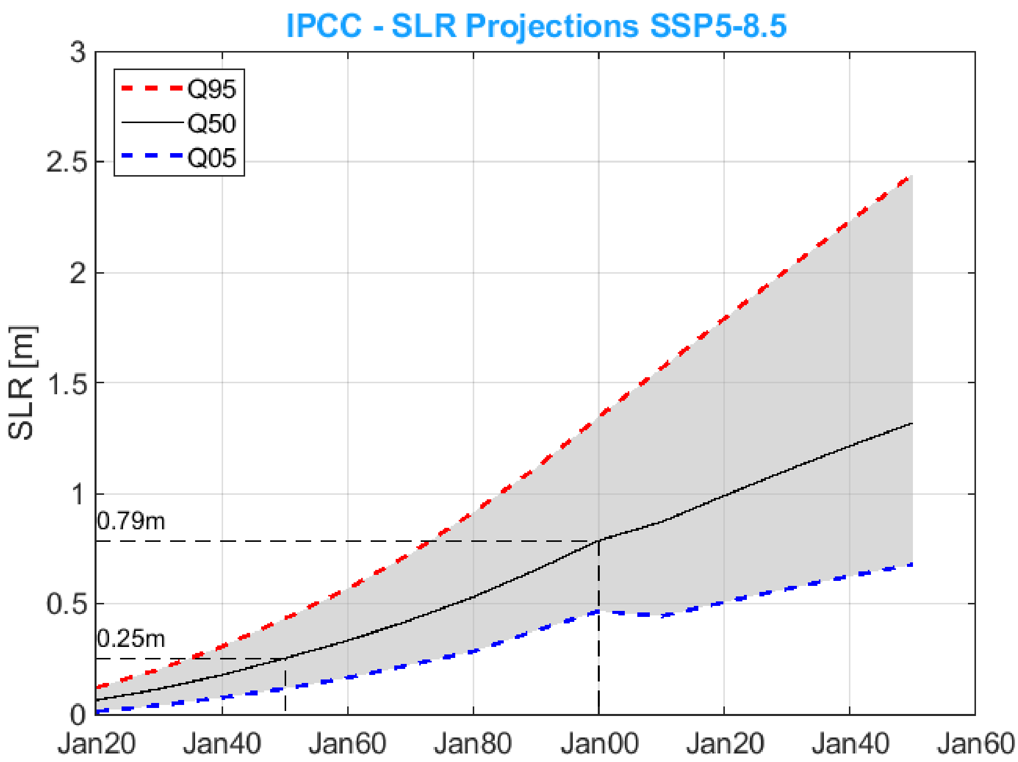

Figure 3. Example of IPCC -SLR projections, scenario SSP5-8.5, and the percentiles considered as confidence intervals.

2.3. SPECIFIC PARAMETERS ACCORDING TO PROFILE'S CHARACTERISTICS

In this methodology, there are parameters specific to profiles with certain characteristics, such as rocky outcrops or reefs, sand dunes, and nearby estuaries. Here, we describe them.

2.3.1. Beach profiles with rocky outcrops or reefs planforms

In profiles with rocky outcrops and reefs planforms located in depths shallower than h*, both the depth just before the rocky feature (h_L) and the cross-shore distance from it to the berm (W_L) are used instead of h* and W*.

2.3.1.1. Depth just before the rocky outcrop or reef (h_L) and cross-shore distance between B and hL (W_L).

The rocky features such as rocky outcrops and reef planforms can be visually identified in satellite images. Once the position of such features is identified in the beach profile, the corresponding h_L and W_L values can be obtained as the corresponding depth and the cross-shore distance from it to the berm.

In profiles affected by this type of rocky morphologies, the calculation of the shoreline retreat must be done using h_L and W_L instead of h* and W*.

For clarity, Figure 4 shows an example of how to estimate h_L and W_L using this approach.

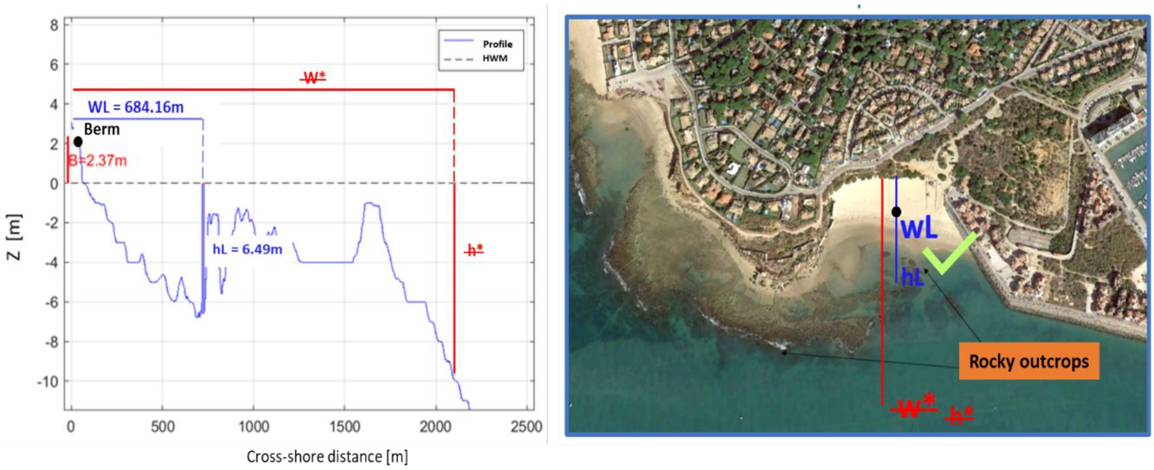

Figure 4. Schematic profile that illustrates the correction of the depth of closure (h) and the active beach profile width (W*), when the profile is affected by rocky outcrops or reef planforms.*

2.3.2. Beach profiles with dunes on the backshore

In profiles with dunes, the tool assumes that if shoreline retreat reaches the backshore, sediment from the dunes will be inputted into the beach profile, which will reduce the ongoing retreat. Such reduction will depend on the amount of sediment available in the first dune ridge, which is a function of the height and length of the ridge.

2.3.2.1. Height and width of the first dune ridge (H_d y L_d)

The dune parameters H_d and L_d can be obtained through a visual inspection of topographic measurements (e.g. digital terrain models, DTM). After identifying the first dune ridge, H_d and Ld can be obtained (see example in Figure 5).

In profiles affected by dunes on the backshore, the calculation of the shoreline retreat must include H_d and L_d.

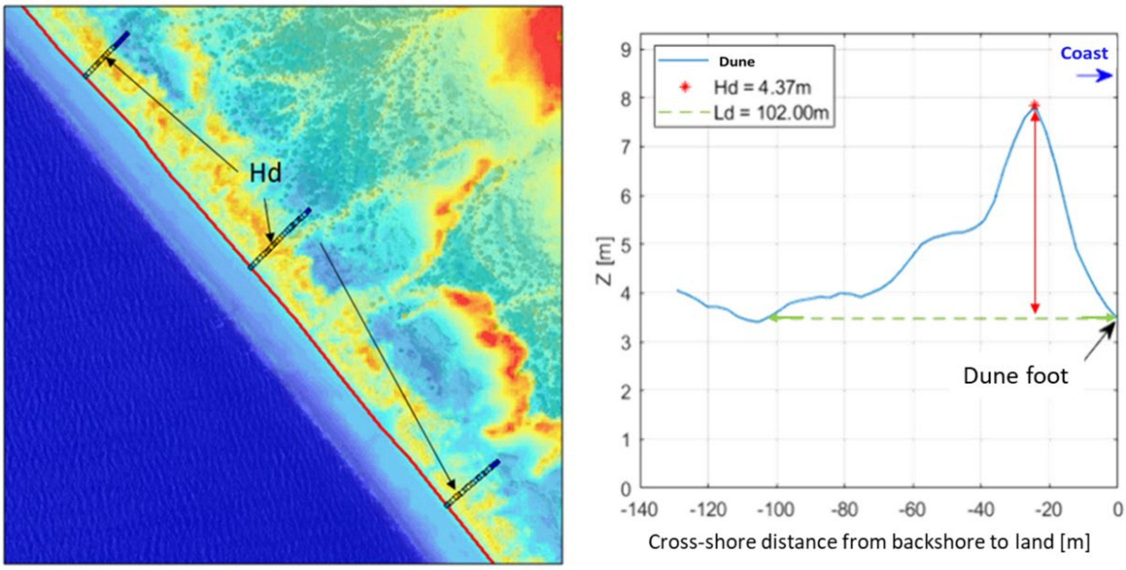

Figure 5. Schematic dune profile that illustrates how the height of the first dune ridge (H_d) and the width of the first dune ridge (L_d) were obtained from a DTM file.

2.3.3. Beach profiles near Estuaries

When the sea level rises, estuaries tend to restore their equilibrium shape, requiring sand to fill the tidal flats and restore the original bathymetry (estuary infilling) (Toimil et al., 2017). This sand can come from i) river discharges on the estuary and ii) from the beaches near the estuary mouth. This leads to an additional shoreline retreat component in profiles located nearby or adjacent to estuary basins.

If no study on sediment balance is available for the area of interest, it is not possible to ascertain whether the beach profile will be affected by estuary infilling after SLR. In such cases, we recommend considering that all beaches connected to the estuary will experience a $R_{Estuary}$ component, which will depend on the estuary area, the tidal flat growth, and the length of the adjacent beaches affected by this process.

If the beach profile of interest is not near and estuary, all estuary parameters should be set as null (value = 0).

2.3.3.1. Estuary area (A_{e1}, A_{e2}) and adjacent beach length (Le_1, Le_2)

The area of the estuary can be estimated using shorelines obtained from satellite images. The estuary area is estimated as the area inside the polygon obtained from the shorelines surrounding the estuary.

2.3.3.2. Tidal flat growth (α_{2050}, α_{2100})

The tidal flat growth inside the estuary can be estimated from detailed bathymetry data of the estuarine zone (two bathymetries allow for the estimation of tidal flat growth over the years).

3. REFERENCES

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