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# Increase in the Erosion Rate Due to the Impact of Climate Change on Sea Level Rise: Victoria Beach, a Case Study

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**Abstract:** This article provides a general methodology for calculating the retreat of the coastline and the volume of sand necessary to renourish a beach due to sea level rise (SLR) in the medium-long term. An example is presented, Victoria Beach, and a projection is made for the years 2030, 2040, 2050, and 2100. The results obtained take into account global sea level rise (GSLR), which is worldwide, and local sea level rise (LSLR), which considers climate variability and vertical land movements. Regarding GSLR, data were provided by the projections from IPCC (Intergovernmental Panel on Climate Change) scenarios and empirical models, such as Rahmstorf and Pfeffer. The LSLR data came from the tide gauge station located in Cadiz. Finally, the results obtained showed that global warming impacts erosive effects and the subsequent volume of sand required to renourish beaches. The total sea level rise (TSLR) projections indicated for Victoria Beach are relatively higher than the GSLR projections. Even in the best IPCC scenario (RCP 2.6), Victoria Beach presents a significant erosion of 52 m, requiring a volume of sand of 1.0 $Mm^3$ to supply renourishment.

**Keywords:** sea level rise; Victoria Beach; climate change; shoreline retreat; erosive trend; artificial nourishment



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## 1. Introduction

The IPCC's (Intergovernmental Panel on Climate Change) evidence has confirmed that climate warming is a reality, and sea level rise (SLR) is one of the most likely effects [1]. Some realistic forecasts have been made regarding this phenomenon around the world, e.g., in some countries and regions of America. For instance, in Chile [2], a synthesis of glaciological studies was carried out during recent decades, including inventories and records of glacier variations, fluctuations of which are related to regional climate change and their contribution to eustatic sea-level rise. In Mexico [3], it was demonstrated that the typical 1 m sea level rise expectation by 2100 is unlikely. In the Mexican Caribbean, the likely SLR will be 67–76 mm higher by 2050, and 201–223 mm higher by 2100, with reference to values from 2018. Likewise, in Argentina, Lanfredi et al. [4] demonstrated that the accelerated rate of sea-level rise predicted will exacerbate the existing impacts of beach erosion. Moreover, some other recent works have deepened the research of the influence of SLR on the morphological evolution of beach nourishment. For instance, a study about wave dissipation and sediment transport patterns during shoreface nourishment [5], and a laboratory investigation performed by Atkinson and Baldock [6] related to the nourishment options to mitigate SLR-induced erosion provided further knowledge in this area.

SLR leads to an increase in beach erosion [7]. Consequently, the frequency and the volume of beach renourishment required will become greater. The importance of knowing how SLR, caused by climate change, may affect erosion rates has increased dramatically in recent years. The effects produced by climate change must also be considered for future artificial renourishment activities, since coastal systems are particularly sensitive to SLR.

Due to the problem of SLR becoming of critical importance over the next few years in coastal areas, it is of great significance to estimate, as accurately as possible, the coastal retreat and the volume of sand necessary to solve the consequent deficit of sediment. This work will permit a fairly precise estimation of the coastline retreat and the volume of sand required to renourish any area for any horizon year. However, as yet, a particular methodology has not been developed.

In order to estimate the future TSLR, it is necessary to properly combine both the information from tide gauges and the information from global scenarios developed from complex physically based climate models. Very few publications have evaluated future SLR from local records.

At the present time, artificial nourishment carried out at Victoria Beach in Cadiz fulfils the tourist and recreational needs of the population. However, due to SLR originating from climate change, it is anticipated that the erosion rates at Victoria Beach will be greater by 2100. Consequently, future artificial nourishment will need to increase substantially, and so a local study of the sea level variability was needed.

Moreover, coastal managers need tools to use when managing vulnerable coastal systems, to make them sustainable under the short and long-terms effects produced by SLR. This must be interpreted in terms of coastal functionality, including natural services and support for socio-economic activities. In the case of Spain, the situation is reflected in the National Plan for Adaptation to Climate Change [8,9], which identifies the main problems that need to be addressed in coastal areas.

Therefore, the aim of this article was to present an easy methodology for predicting the increase in the erosion rate at any beach (as a result of climate change) and to estimate the extra volume of sand that will need to be supplied in advance. Translating the projections of SLR into the volume of sand needed to renourish one zone is very interesting in terms of the assessment of the costs and environmental impacts. An example of the application of this methodology to Victoria Beach (Cadiz) is also presented.

## 2. Material and Methods

### *2.1. Study Area*

Victoria Beach is located in the southwest of the Iberian Peninsula. It belongs to the Gulf of Cadiz and faces the Atlantic Ocean (Figure 1).

The region's climate is Mediterranean-oceanic. The swell comes from the west (46%) and the south-east (22%), and usually has low energy, with an average wave height of 1 m. Nevertheless, during storms, the average significant wave height can exceed 4 m [10].

The study area is a mesotidal environment and the tidal range reaches 3.81 m. At low tide, the width of Victoria Beach is around 200 m and the length is around 3000 m. It is dissipative with a moderate-low slope. The beach has a sand-rich biparabolic profile [11,12].

Regarding its sedimentary characteristics, it is composed of medium-fine golden sand ($D_{50}$ = 0.25 mm) of a siliceous nature. The sand consists of 90–95% quartz and 5–10% bioclastic material [13].

Victoria Beach is the main tourist attraction of Cadiz City, and it maintains its recreational use during the whole year. Data collection was carried out using UAVs [14]. It received uninterrupted Blue Flag status from 1987 to 2011. In addition to this, it was the first beach in Spain to have been certificated with an environmental management and tourism quality 'Q'.

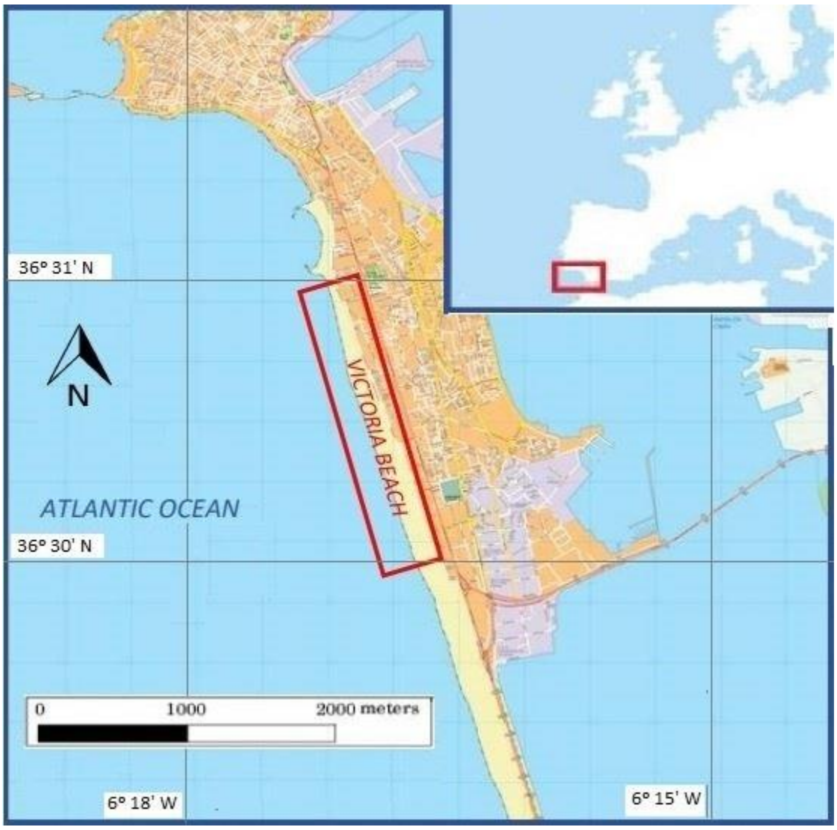


**Figure 1.** Location of Victoria Beach, the study area where the methodology was applied.

It should be noted that, before 1991, the width of Victoria Beach was practically non-existent. For this reason, renourishment activities were undertaken in this area (Table 1).

**Table 1.** Volume of sand ($m^3$) deposited on Victoria Beach in the last three decades [13].

| Year | Volume ($m^3$) | Volume per Unit of Beach Length ($m^3$/m) |
|---|---|---|
| 1991 | 2,000,000 | 666.66 |
| 2004 | 260,000 | 86.66 |
| 2010 | 57,000 | 19.00 |
| 2015 | 50,000 | 16.66 |
| 2019 | 65,000 | 21.66 |

After the 1991 renourishment, the width of Victoria Beach increased until it reached 80–250 m [13].

## 2.2. Methods

### 2.2.1. Global Sea-Level Rise (GSLR) and Local Sea-Level Rise (LSLR)

SLR is not the same for all of the world's coastlines [7]. The total sea-level rise (TSLR) takes into account the sum of two components: global (G) and local (L). This work calculated the TSLR at Victoria Beach.

Local sea-level rise (LSLR) considers climate variability and vertical land movements, such as slow movements in the Earth's mantle, tectonic displacements of the crust, and subsidence induced by natural causes or anthropogenic activities [15].

On the other hand, global sea-level rise (GSLR) is fundamentally affected by two factors: the thermal expansion of sea water and melting of glaciers [16]. In this work, the GSLR data came from projections of IPCC scenarios, as well as other empirical models, such as Rahmstorf and Pfeffer.

Human influence on the climate system is clear [17]. IPCC scenarios are defined using Representative Concentration Pathways (RCP) based on population size, energy use, and economic activity.

For the period 2081–2100, compared to 1986–2005, GSLR prediction ranges between 0.26 and 0.55 m for RCP2.6, 0.32–0.63 m for RCP4.5, and 0.45–0.82 m for RCP8.5. For RCP8.5, the rise by 2100 is predicted to be 0.52–0.98 m, with a rate during 2081–2100 of 8–16 mm $yr^{-1}$ [18].

However, recent observations have been higher than the ranges given by IPCC projections [19]. For this reason, other empirical models (e.g., Rahmstorf [20] or Pfeffer [21]) were considered, which present higher values of GSLR.

The Rahmstorf model [20] shows GSLR values between 0.75 and 2.00 m by the year 2100 and considers the melting glaciers in Greenland and West Antarctica. Although the occurrence is relatively low, it must be taken into consideration due to the fatal consequences that it might trigger.

The Pfeffer model [21] also considers the glaciological conditions and concludes that GSLR could reach 2 m by 2100, if all factors accelerated very quickly, reaching critical limits ('Pfeffer High'). In this case, the rate would be 21.5 mm $yr^{-1}$, measured from the year of the study (2007). GSLR could reach 0.8 m by 2100, with more plausible conditions ('Pfeffer Low'), e.g., with a rate of 8.6 mm $yr^{-1}$.

Table 2 shows the synthesis of values of GSLR, according to the different models and scenarios. They were used in the subsequent methodology to obtain the TSLR at Victoria Beach and the corresponding shoreline retreat.

**Table 2.** Global sea-level rise (GSLR) projecting the years 2030, 2040, 2050, and 2100, according to the different models and scenarios.

| Year | IPCC (2013) RCP 2.6 | IPCC (2013) RCP 4.5 | IPCC (2013) RCP8.5 | Rahmstorf Model (2007) | Pfeffer Model Low (2008) | Pfeffer Model High (2008) |
|---|---|---|---|---|---|---|
| 2030 | 0.12 m | 0.13 m | 0.16 m | 0.15 m | 0.20 m | 0.50 m |
| 2040 | 0.17 m | 0.18 m | 0.23 m | 0.20 m | 0.28 m | 0.71 m |
| 2050 | 0.20 m | 0.22 m | 0.28 m | 0.32 m | 0.37 m | 0.92 m |
| 2100 | 0.40 m | 0.47 m | 0.63 m | 0.90 m | 0.80 m | 2.00 m |

### 2.2.2. $TSLR_P$ (Total Sea-Level Rise Projected)

This article provides a methodology to calculate the shoreline retreat resulting from changes in SLR. The methodology is applicable to a specific area, in the medium-long term. Tide gauge data from the study area must be consulted in order to apply this methodology. Tidal records are one of the most comprehensive and reliable oceanic time series in the world. Their independent use and correlation with other parameters provides valuable information about the oceanic variability on seasonal and yearly scales, allowing the monitoring of their impact on continental margins [22].

We also aimed to estimate the volume of sand required to renourish the study area in the future. Wind set-up, run-up, wave set-up, and inverted barometers were not considered. The methodology only considered calm weather conditions.

According to Fraile-Jurado and Fernandez-Diaz (2016) [23], by comparing the tide gauge data of one specific zone with GSLR data from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) [15], it is possible to estimate the predicted TSLR by 2100 in this specific area. The trend of mean sea level change (mm $yr^{-1}$) for every tide gauge in Spain and the trend of mean sea level change in the comprehensive series published by CSIRO were calculated by linear regression [24], and then compared for the same period. The CSIRO series were reworked for each tide gauge, including the same time gaps [23]. The Pearson correlation coefficient must be positive between the local tide gauge series and CSIRO global series, so that they can be compared.

The difference found between the tide gauge series and CSIRO series was called the 'local factor' (L) and is considered to be unrelated to past or future global events which affect GSLR [25]. If the local factor L is positive, it means that the TSLR of that zone is higher than GSLR projections.

Considering this, TSLR can be calculated for one specific zone, projecting the desired year from the following Equation (1):

$$TSLR_P = (L * (P - B)) + GSLR \quad (1)$$

where:

- '$TSLR_P$' is the total sea level rise for the projected year 'P'.
- 'L' is the identified local factor. It is the difference between the total and global recorded mean sea levels. According to the study conducted by Fraile-Jurado and Fernandez-Diaz (2016) [23], the value 'L' in Cadiz is 2.01 (difference total/global) (Table 3).
- 'P' is the projected year.
- 'B' is the base year. B = 2004 for the models in IPCC2013 [17] and B = 1990 for the Rahmstorf [20] and Pfeffer [21] models (the year when the study was conducted and projections were established).
- 'GSLR' is the global sea level rise (affected by climate change) according to the models and scenarios of IPCC2013 [17], Rahmstorf [20] and Pfeffer [21] (see Table 2).

**Table 3.** Trend of mean sea level changes in the Cadiz tide gauge (a series of more than 30 years), with the adapted CSIRO series and the difference between them [19].

| Tide Gauge | Period | Years | Trend Tide Gauge (mm yr$^{-1}$) | CSIRO Global Trend (mm yr$^{-1}$) | 'L' Total/Global Difference |
|---|---|---|---|---|---|
| Cadiz | 1960–2011 | 47 | 3.95 | 1.94 | 2.01 |

The trend tide gauge observed in Cadiz over 47 years was 3.95 mm yr$^{-1}$, where the global and local components are involved. If we want to know $TSLR_P$ by projecting the desired year 'P', it is not enough to simply multiply 3.95 mm yr$^{-1}$ by the number of years to arrive at 'P', because this would not consider climate change effects. The speed of TSLR is going to increase due to climate change.

As commented previously, 'L' (the difference between total and global trends) only considers climate variability and vertical land movements, such as slow movements in the Earth's mantle and tectonic displacements of the crust. Therefore, regarding Equation (1), to obtain TSLR, it is necessary to multiply the local trend 'L' by the number of years, until we arrive at the desired year 'P' and the value of GSLR (Table 2) is added, according to the model and scenario chosen.

The importance of local factor "L" must be emphasised since this parameter permits us to stop using single values from global models that only consider eustatic movement. This concept was developed for the first time by Titus y Narayanan (1998) [25]. The subtraction of local series data from the global series data allows a homogeneous comparison between local and global data. The methodology presented assumes that the local factor "L" is stable over time, since it is frequently associated with tectonic phenomena with poor interannual variability. Thanks to this parameter, it was possible to add the local component to the expectations of a global model of SLR (GSLR).

In relation to its application to other places, this method can be extrapolated as long as enough and reliable registered data are available. Two types of time series are needed to apply this methodology to any place:

(a) Long series data registered by tide gauges on the coast (more than 30 years) (which shows TSLR).
(b) The series data elaborated by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), of global nature, from the longest series of tide gauges on the planet [15] (which shows GSLR).

Moreover, the correlation between the two series needs to be estimated for the reliability of the prediction. If low correlation levels are obtained (or a negative Pearson correlation coefficient), the results must be discarded.

Regrettably, there are still large coastal areas where there is not enough reliable information. In some developing countries there are insufficient long-term sea level records to allow comprehensive and predictive studies to be undertaken. Especially in areas of difficult access, data are only taken during the summer season, or for specific projects, and, generally, the data are taken over a year or less duration [22]. Obviously, this methodology cannot be applied in these cases.

However, spatial interpolation techniques and analysis of altimetric records should cover these deficiencies in the future. It should be taken into account that from 1992, SLR was started to be measured by satellites as well.

#### 2.2.3. Shoreline Retreat, the Bruun Rule [26]

We anticipate that the shoreline retreat rate will remain highly uncertain, since beaches are dynamic environments that respond to a variety of complex processes. Bruun's model was developed to explain how SLR affects the shoreline retreat in the long-term, not considering other possible factors that influence erosion, such as the variability of waves, the supply of sediment from rivers, or onshore sediment transport due to overwash. Thus, the existence or absence of these factors should be considered when the Bruun Rule is applied to a particular beach [27].

Nevertheless, for the last 60 years, the Bruun Rule [26] has been the most commonly used method for estimating coastline retreat in the long term, due to SLR. The Bruun Rule is increasingly used in current coastal impact models, whether at a global scale or local scale, often without full consideration of its underlying physics [27].

Bruun (1962, 1988) [26,28] provided a simplistic method, assuming a closed material balance system so that the migrating beach has no net loss of sand volume and there is a uniform sandy shoreline with no outcrops or other obstacles that could cause non-uniform retreat rates [28–30]. The Bruun model assumes that, with increased sea levels, the equilibrium beach profile and nearshore bottom migrates upward and landward. The upper beach is eroded due to the landward translation of the profile. The material eroded from the upper beach is deposited immediately offshore, and the rise in the nearshore bottom equals the rise in sea level (Figure 2).

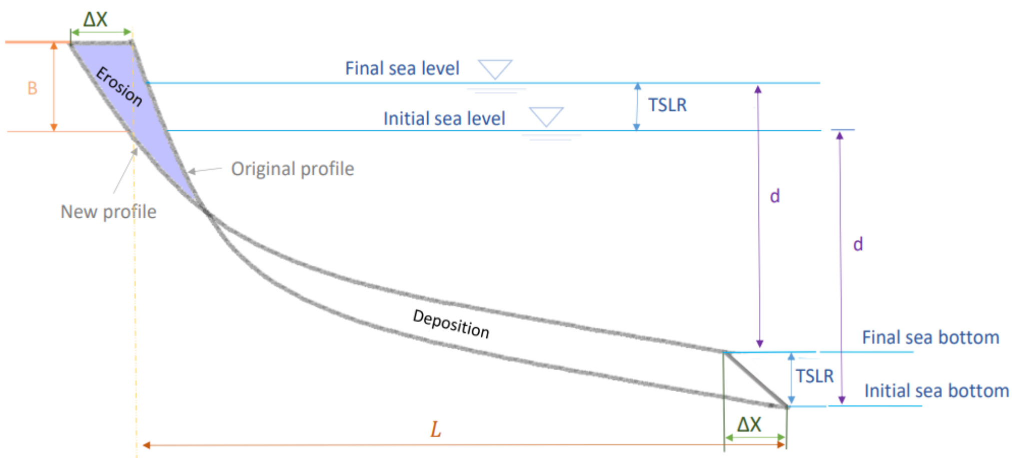


**Figure 2.** Bruun Rule variables.

By equating the volume eroded to the volume deposited, we obtain Equation (2).

$$\Delta X = \frac{\mathrm{TSLR} * \mathrm{L}}{\mathrm{B} + \mathrm{d}} \quad (2)$$

where:

- ‘TSLR’ is the total sea level rise.
- ‘$\Delta X$’ is the shoreline retreat.
- ‘B’ is the berm height.
- ‘d’ is the depth of closure.
- ‘L’ is the length of the active profile.

Simplifying Equation (2), we obtain Equation (3), which is used to calculate the shoreline retreat. It relates the slope of the active profile directly with the shoreline retreat.

$$\Delta X = \frac{TSLR_P}{\tan\theta} \tag{3}$$

where:

- ‘$TSLR_P$’ is the total sea level rise in the projected year ‘P’ (calculated in Equation (1)).
- ‘$\tan\theta$’ is the slope of the active profile.
- ‘$\Delta X$’ is the shoreline retreat.

2.2.4. Volume of Sand for Renourishment

The aim of calculating this volume is to quantify how much climate change affects beach renourishment. Apart from the volume of sand that is deposited on beaches today, for different reasons, the cause of climate change must also be added to those existing reasons.

To estimate the volume (Equation (4)), the length of the beach is multiplied by the area of the parallelogram resulting from drawing a parallel profile at a distance $\Delta X$ (the shoreline retreat having been calculated in (Equation (3))) [26]. The estimated area is shown in Figure 3.

$$\text{Volume}\left(m^3\right) = \Delta X \cdot d \cdot L_b \tag{4}$$

where:

- ‘Volume’ ($m^3$) is the volume needed to renourish the studied beach.
- ‘$\Delta X$’ is the shoreline retreat.
- ‘d’ is the depth of closure.
- ‘$L_b$’ is the length of the studied beach.

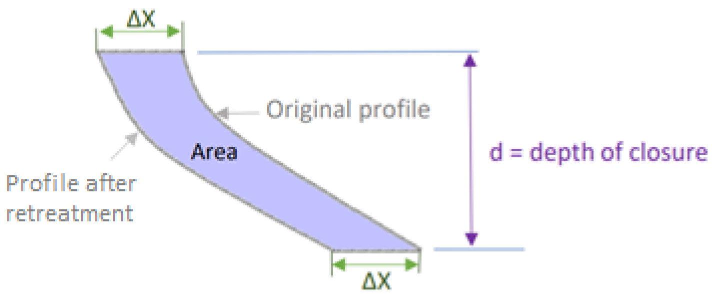


**Figure 3.** Retreat of active profile. Area to estimate the volume of sand requested.

The depth of closure of an active beach profile is the one where the sediment movement is insignificant [31]. According to Birkemeir (1985) [32], depth of closure is directly related to waves with the most energy. The used parameter was $Hs_{12}$, which is the significant wave height exceeded only 12 h per year. Id est, the probability that any wave height ($H$) would be greater than $Hs_{12}$, was just:

$$prob\ (H > Hs_{12}) = \frac{12\ hours}{365\ days \cdot 24 \frac{hour}{day}} = \frac{1}{730} = 0.137\%$$

In other words, only 1.37% of all waves are higher than $Hs_{12}$.

Beach retreat cannot be uniform on the profile because of the sandbar.

Obviously, the uniform retreat of the profiles is a simplification, given that the influence of some morphological phenomena such as a sandbar [33] or other important physical processes, such as the onshore sediment transport due to overwash [34], are not taken into account in this first approach. In future, considering these aforementioned processes should improve the accuracy of the predictions.

## 3. Results

### *3.1. Total Sea-Level Rise ($TSLR_P$) at Victoria Beach*

In this work, $TSLR_P$ was projected for Victoria Beach in the years 2030, 2040, 2050, and 2100, according to the different models and scenarios (Table 4).

**Table 4.** Total Sea-Level Rise (m) ($TSLR_P$) at Victoria Beach, projecting the years 2030, 2040, 2050, and 2100, according to the different models and scenarios.

| Year | RCP 2.6 | RCP 4.5 | RCP 8.5 | Pfeffer Low | Pfeffer High | Rahmstorf |
|---|---|---|---|---|---|---|
| 2030 | 0.17 | 0.18 | 0.21 | 0.28 | 0.58 | 0.23 |
| 2040 | 0.24 | 0.25 | 0.30 | 0.38 | 0.81 | 0.30 |
| 2050 | 0.29 | 0.31 | 0.37 | 0.49 | 1.04 | 0.44 |
| 2100 | 0.59 | 0.66 | 0.82 | 1.02 | 2.22 | 1.12 |

### *3.2. Shoreline Retreat at Victoria Beach Using the Bruun Rule*

The main issue regarding the application of the Bruun Rule to any location is the determination of the active profile slope. To determine the active profile slope at Victoria Beach, seven surveys were carried out between 1991 and 1994. The active profile slope of Victoria Beach is approximately 1.13%.

It is assumed that the active profile slope is the same today (2022) as it will be in future years (2030, 2040, 2050, and 2100), since the sand that will be deposited is going to be very similar to that currently present. Applying the Bruun Rule [26], the results are shown in Table 5.

**Table 5.** Shoreline retreat (m) projected for the years 2030, 2040, 2050, and 2100, according to the different models and scenarios.

| Year | RCP 2.6 | RCP 4.5 | RCP 8.5 | Pfeffer Low | Pfeffer High | Rahmstorf |
|---|---|---|---|---|---|---|
| 2030 | 15 | 16 | 19 | 25 | 51 | 20 |
| 2040 | 21 | 22 | 27 | 34 | 72 | 27 |
| 2050 | 26 | 27 | 33 | 43 | 92 | 39 |
| 2100 | 52 | 58 | 73 | 90 | 197 | 99 |

### *3.3. Volume of Sand Required to Renourish Victoria Beach Due to Climate Change*

In order to estimate the volume of sand, it was necessary to know the depth of closure. As previously mentioned, the depth of closure is directly related to $Hs_{12}$. $Hs_{12}$ is currently 4 m in Cadiz. Variations of $Hs_{12}$ have been analysed over the last 60 years, in order to estimate the value of $Hs_{12}$ in the future [7]. At Victoria Beach, the variation is practically zero (Figure 4). Therefore, it was considered that $Hs_{12}$ will be constant in the projected years 2030, 2040, 2050, and 2100 and, consequently, the depth of closure will not vary either.

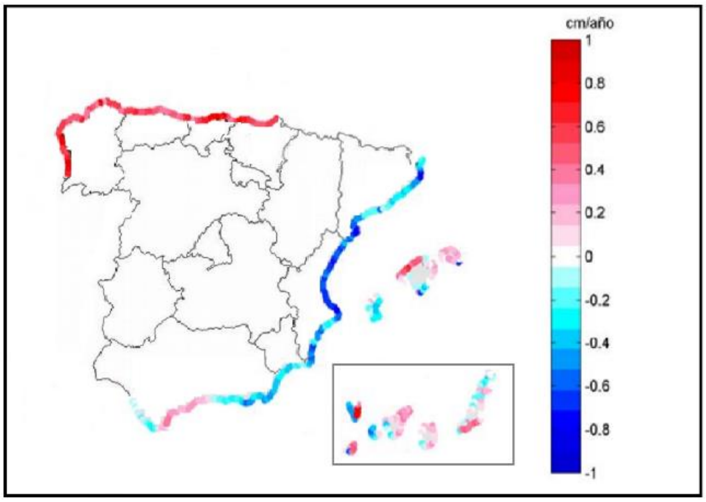


**Figure 4.** Trend of change of $Hs_{12}$ over the last 60 years, as observed in Spain. Adapted from Losada et al. [7].

Applying the formula of Birkemeir [32], with $Hs_{12}$ = 4 m, the depth of closure at Victoria Beach will remain at a constant 6.5 m over time. Using these parameters, the results of the volume needed to renourish Victoria Beach (in $m^3/m$) are shown in Table 6 (the length of Victoria beach is 3000 m).

**Table 6.** Volume required to renourish Victoria Beach ($m^3/m$) for the projected years 2030, 2040, 2050, and 2100, according to the different models and scenarios.

| Year | RCP 2.6 | RCP 4.5 | RCP 8.5 | Pfeffer Low | Pfeffer High | Rahmstorf |
|---|---|---|---|---|---|---|
| 2030 | 97.5 | 104.0 | 123.5 | 162.5 | 331.5 | 130.0 |
| 2040 | 136.5 | 143.0 | 175.5 | 221.0 | 468.0 | 175.5 |
| 2050 | 169.0 | 175.5 | 214.5 | 279.5 | 598.0 | 253.5 |
| 2100 | 338.0 | 377.0 | 474.5 | 585.0 | 1280.5 | 643.5 |

## 4. Discussion

Two contributing factors to SLR are considered herein:

(a) Global warming (which contributes to GSLR) produced by greenhouse emissions. In addition, apart from the IPCC scenarios, other models, such as the Rahmstorf or Pfeffer models, were considered. This approach provided more accurate results.

(b) Vertical land movements such as slow movements in the Earth's mantle and tectonic displacements of the crust, as well as subsidence or climate variability, occurred in each local zone (which contributed to LSLR). In this case, study, the projections were carried out for the years 2030, 2040, 2050, and 2100, as an example, to have a complete medium–long term vision. The reader can project this methodology to any horizon year by using Equation (1).

### *4.1. Total Sea-Level Rise ($TSLR_P$) at Victoria Beach*

Figure 5 and Table 4 illustrate that the $TSLR_P$ at Victoria Beach should be moderate in the years 2030, 2040, and 2050 (excluding the Pfeffer High scenario). $TSLR_{2030}$ varies from 0.17 m (RCP2.6) to 0.28 m (Pfeffer Low), and $TSLR_{2050}$ from 0.29 m (RCP2.6) to 0.49 m (Pfeffer Low), which translates as 7 mm $yr^{-1}$ and 11.7 mm $yr^{-1}$, respectively. However, $TSLR_{2100}$ is significant, ranging from 0.59 m (RCP 2.6) to 1.12 m (Rahmstorf), or 22.7 and 28.0 mm·$yr^{-1}$, respectively.

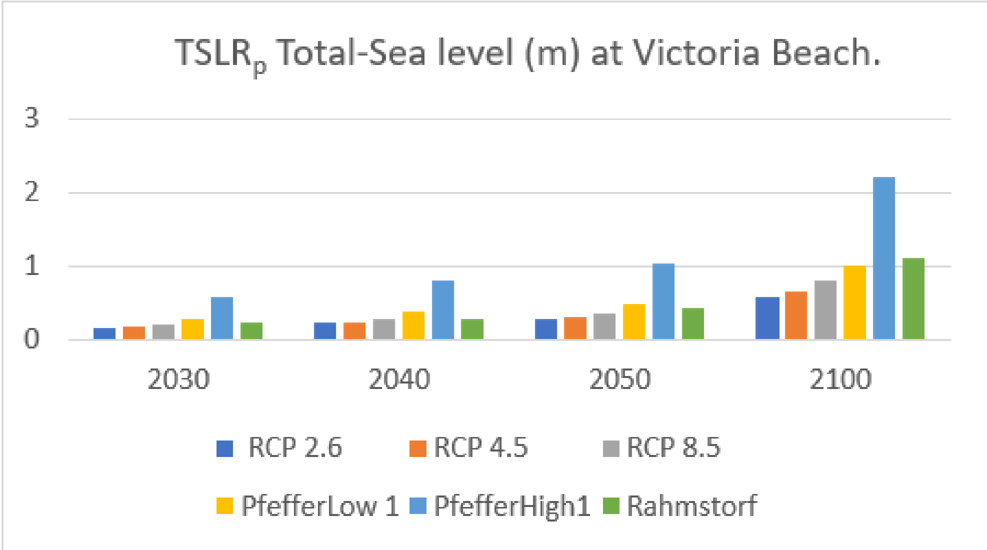


**Figure 5.** Total Sea-Level Rise (m) ($TSLR_P$) at Victoria Beach projected for the years 2030, 2040, 2050, and 2100, according to the different models and scenarios.

Comparing IPCC scenarios, the variation between them was small. However, these small variations are due to big differences in the future behaviour of society, with regard to the emissions of greenhouse gases during the rest of the twenty-first century. On the other hand, the Pfeffer model showed completely different results depending on whether the high scenario (Pfeffer High) or the low scenario (Pfeffer Low) was used.

The Pfeffer High model stands out from the rest. It considers the melting glaciers in Greenland and West Antarctica, with the acceleration of variables arriving at extreme limits. Although the likelihood is relatively low, it must be taken into consideration due to the fatal consequences that it might trigger. $TSLR_{2100}$ in the Pfeffer High model was 2.22 m, almost four times higher than the IPCC RCP 2.6 scenario of 0.59 m.

In short, at Victoria Beach, $TSLR_P$ is not very high in the medium-term, but $TSLR_{2100}$ is still relevant because of the variability between different scenarios and models.

### *4.2. Shoreline Retreat at Victoria Beach Using the Bruun Rule (1962) [26]*

Regarding Equation (3), for each metre of TSLR, a shoreline retreat of 88 m would be expected at Victoria Beach. In Spain, it is estimated that the shoreline retreat range is 50–100 m for each metre of TSLR [7]. Thus, this ratio was between the ranges estimated by Losada et al. [7] for beaches in Spain.

The results provided in Table 5 indicate that climate change is going to substantially increase the shoreline retreat at Victoria Beach, from 52 m to 197 m by 2100, depending on the model and scenario chosen. These results are very worrying from an economic and environmental point of view.

Currently, the width of Victoria Beach ranges from 120 to 180 m along its southern half. At low tide, the width of Victoria Beach reaches 200 m. At high tide (the most pessimistic), the width of Victoria Beach is about 100 m. The beach will disappear if the higher shoreline retreat scenarios prove to be the more accurate models (Figure 6).

By the year 2100, the only model that presents a shoreline retreat higher than the width of Victoria beach at high tide (100.7 m) is the Pfeffer High model. In the Rahmstorf and Pfeffer Low models, the shoreline retreat is very close to this limit, reaching 99 and 90 m, respectively, by 2100. This means that the seaside promenade will be flooded.


**Figure 6.** Shoreline retreat (m) at Victoria Beach projected for the years 2030, 2040, 2050, and 2100, according to the different models and scenarios.

Looking at Figure 7 and Table 5, the shoreline retreat will not be very high in the medium-term (excluding the Pfeffer High scenario) because, for the years 2030, 2040, and 2050, the retreat ranges between 15 and 43 m. On the other hand, by 2100 the results will be important. These losses are only the consequence of climate change. In addition, there will be more factors that cause shoreline retreat that will have to be taken into account, e.g., storm surges, intensity and direction of waves, etc.

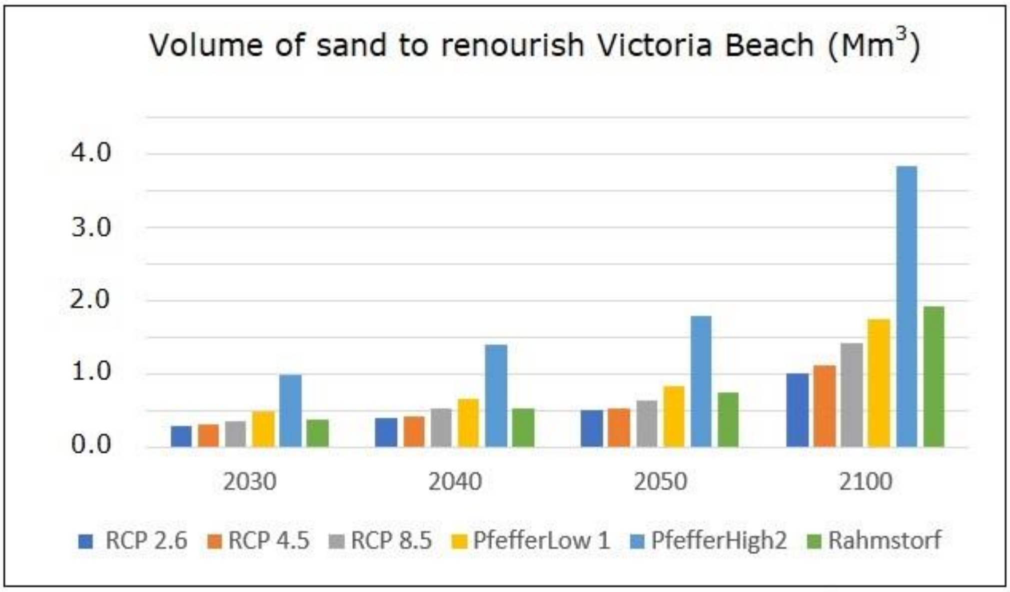


**Figure 7.** Volume of sand ($Mm^3$) required to renourish Victoria Beach in the projected years 2030, 2040, 2050, and 2100, according to the different models and scenarios.

### *4.3. Volume of Sand Required to Renourish Victoria Beach due to Climate Change*

Figure 7 compares the volume of sand needed to renourish Victoria Beach, according to the projections of different models and scenarios.

The results obtained in Table 6 and Figure 7 were compared to the volumes of sand provided to Victoria Beach over recent decades (Table 1).

Figure 7 shows that almost 4,000,000 $m^3$ of sand would be needed if the Pfeffer High model was proved to be correct. This is almost twice the volume of renourishment which was provided in 1991 (2,000,000 $m^3$ or 666.66 $m^3$/mL). It must be noted that the project carried out in 1991 was huge; it represented one of the most important supplies of artificial sand made to the South-Atlantic coast of Europe [35]. Therefore, all values that are above 2 $mm^3$ represent a very large contribution of sand.

Thus, for the Rahmstorf and Pfeffer Low models, almost 2,000,000 $m^3$ would be needed by 2100, which is also a very high volume of sand. The amount of sand required will be significant under any model or scenario by 2100.

Comparing the results of Table 6 with the maintenance contributions made in 2004, 2010, 2015, and 2019, (86.7 $m^3$/mL, 19.0 $m^3$/mL, 16.7 $m^3$/mL, and 21.6 $m^3$/mL, respectively), all values higher than 200 $m^3$/mL must also be considered to be excessive. The maintenance contribution of 2010 is extremely low when compared to the large values in Table 6.

We can conclude that climate change will influence the volume of sand required considerably, with the quantities required becoming enormous compared to the regenerations previously undertaken at Victoria Beach. From a coastal management point of view, even under the best scenario (IPCC RCP 2.6) where TSLR (0.59 m) is small in comparison with the rest of the scenarios, a considerable retreat of 52 m is predicted in the case of Victoria Beach. This minimum retreat would mean a volume of sand of 1 $Mm^3$ necessary for renourishment in 2100. This result, together with the socioeconomic characteristics of Cadiz, allows us to conclude that the study area is very vulnerable to the effects of climate change.

Therefore, in agreement with Mucova et al. [36], to prevent these consequences in any location, two paths could be followed as solutions:

(a) Reducing greenhouse gas emissions and complying with the Paris Climate Agreement.
(b) Introducing transformative responses and adaptation measures, and fully complying with sustainable development goals.

Beach erosion will require substantial expenditure of public funds to maintain existing recreational beaches. The responses to accelerated sea-level rise must be based on more than a simple cost–benefit ratio. Each area must be considered on a site-specific basis, as there is considerable geographical variation in the environmental and cultural aspects of each location [37]. Moreover, and coinciding with Walsh et al. [38], TSLR should be considered for coastal urban planning because its effects will be apparent during the typical replacement time of urban infrastructure, such as buildings (about 70 years).

Eventually, coastal managers can use this model as a new predictive tool when it comes to addressing the impact of SLR on our beaches.

## 5. Conclusions

In this paper, we proved that sea level rise (SLR) caused by global warming will clearly affect future nourishment projects all over the world and, particularly, at Victoria Beach. Therefore, alongside other causes for the erosion of beaches, climate change has to be taken into consideration as an additional cause when planning future renourishment.

This paper provided a methodology for calculating the shoreline retreat resulting from changes in SLR in one specific area, taking local variations into account. By subtracting the CSIRO global series from total series measured by tide gauges, it was possible to separate the data that are subject to changes produced by global warming from those which are not. Therefore, on the one hand, the speed of SLR produced by climate change will not be constant but will probably increase over time [18,19] but, on the other hand, phenomena such as tectonic displacements or subsidence will be added, considering that they will increase by the same rate as before. To separate phenomena influenced by climate change from those which are not, we used the 'local factor identified' (L) [25]. Given this knowledge, authorities can apply this methodology to every zone of Spain by consulting the value of 'local factor identified' (L) from the work of Fraile-Jurado and Fernandez-Diaz [23]. If the reader wants to apply this outside of Spain, they can calculate (L) by following the methodology presented.

By 2100, the seaside promenade of Victoria Beach will be flooded according to the Pfeffer High model, and almost flooded according to the Rahmstorf and Pfeffer Low models.

This shows that floods will be intensified. Therefore, we will have to consider TSLR for future territorial planning. Coastal urban planning needs to take TSLR into account because its effects will be apparent during the current infrastructure lifetime.

With respect to nourishment, this paper demonstrated that climate change will influence the volume of sand required considerably, reaching the enormous amount of 4,000,000 $m^3$ of sand in the Pfeffer High model by 2100. This amount is double that of the biggest renourishment carried out at Victoria Beach to date, in 1991. This gives an idea of the large volume of sand that will be lost as a result of climate change.

Finally, the model presented here can be used to predict medium and long-term sand needs due to SLR and help coastal managers to implement long-term adaptation measures for shoreline retreat.

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