

## Article

# Influence of Local Factors on Coastal Erosion: The Case of Vagueira Beach in Portugal

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**Abstract:** Vagueira Beach on the Central Portuguese coast, is known as one of the places in Europe most affected by coastal erosion. The area has suffered more than 156 meters of coastline retreat over the period 1958 to 2001. With the aim to evaluate the influence of local factors on coastal erosion, this paper assesses the anthropogenic and natural factors that are related with the retreat of the coastline, by adopting statistical correlation and regression analyses. Through the Pearson's correlation coefficient ( $r$ ) it was observed that local factors such as annual dredging at the Aveiro Port entrance ( $r = 0.93$ ), the total length of groins in the Espinho-Vagueira section ( $r = 0.89$ ), and storm events ( $r = 0.52$ ) are directly related to coastline retreat in the area. A multiple linear regression model was developed in which coastline retreat is explained by these same factors over the period 1980 to 2006. With a coefficient of determination of  $R^2 = 0.91$ , it was observed that length of groins (significant at the 1% level), dredging of the port entrance (significant at the 5% level) and precipitation (as a proxy for storm events; significant at the 10% level) are significantly correlated with coastline retreat. Hence, it is shown that anthropogenic factors are the main drivers of coastline retreat in Vagueira Beach. This study provides an innovative approach for the assessment of coastal erosion, resulting in important information that can be used for decision-making related to coastal zone management as it allows to understand in greater detail the main drivers of coastal erosion.

**Keywords:** Groins; Dredging; Storm events; Natural factors; Anthropogenic factors; Regression model

## 1. Introduction

Coastal areas are among the most critical regions for humanity. Indeed, more than 30% of the world's population lives in the coastal zone – which are twice as densely populated as inland areas [1,2,3] – with the majority of the total population of more than half of coastal countries living within 100km from the coastline [4]. Coastal zones host the majority of centers of political decision, economic and technical cooperation, as well as a large part of the industries and economic activities in many countries [5]. Hence, the increase in coastal erosion directly influences the majority of the world population and economy [6,7].

The coastal zone is one of the most dynamic on the planet and coastline position constantly changes at various time scales [6]. The position of the coastline is affected by many factors, some due to natural causes (related to coastal dynamics, climate and climate change) and others due to human interventions (such as urbanization, dredging and infrastructure) [7,8,9,10]. As a result of the interaction between these factors, the coastline can move out to sea, stay in place, or move back toward the continent [8,11,12]. This indentation, in turn, causes loss of territory and is considered as a process of coastal erosion.

Portugal is located on the Iberian Peninsula in southwest Europe, facing the Atlantic coast. The Portuguese coast is a highly energetic region, suffering from storms generated in the North Atlantic [13]. Central Portugal is one of Europe's coastal areas that suffers

most from the processes of coastal erosion [7], due to the reduction in the delivery of sediments to the coast, sea level rise, the increase in the frequency of storms, and changes of human origin [11,14,15]. Several studies have shown that the Espinho-Mira section is one of the areas most vulnerable to coastal erosion [14,16,17,18,19,20,21]. This area has a variety of beaches, including Vagueira Beach – a small Portuguese village situated in the district of Aveiro and that annually receives a large inflow of tourists. Vagueira Beach has suffered about 160 meters of coastline retreat over the period 1948 to 2001 [7].

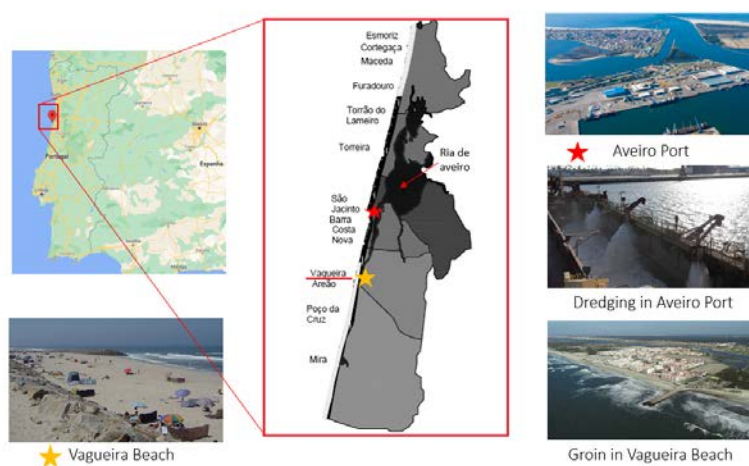
With the purpose to understand what is aggravating coastal erosion in Central Portugal, the objective of this study is to assess the key anthropogenic and natural factors that influence the rate of coastline retreat. To this end, correlation and regression analyses are performed, relating coastline retreat to anthropogenic and natural factors. This study contributes to previous studies [14,20,21], that mostly used monitoring and modeling approaches to assess the causes and impacts of coastal erosion. Hence, this study developed a correlation and regression analysis to assess the key anthropogenic and natural factors that influence the rate of coastline retreat and, thus, may contribute to the development of coastal erosion adaptation strategies in Central Portugal.

The remainder of this paper is structured as follows. Section 2 (Materials and methods) provides the definition and sources of data, a characterization of the study area and a description of statistical analyses performed. In Section 3 (Results and discussion) results from the correlation and regression analyses are presented, and the influence of the various anthropogenic and natural factors on coastline retreat are discussed. Finally, concluding remarks and observations are provided in Section 4.

## 2. Materials and Methods

### 2.1. Characterization of the study area

Vagueira Beach is located on the Central Portuguese Coast, between Costa Nova and Areão Beaches (see Figure 1). This region suffers strong urbanization pressure, widespread sedimentary deficit, and frequent wave attack from energetic storm events [20]. This coastal stretch, marked by the presence of extensive and fragile dunes, sandy beaches of low quotas and developments parallel to the Ria de Aveiro lagoon, is considered one of the most dynamic types of coast [21].



**Figure 1.** Vagueira Beach study area location in the Ria de Aveiro Region [21,33].

Vagueira Beach shows an increase in coastal erosion – with rates of coastline retreat increasing from 1.6 m/year during the late 1950s to 7.1 m/year over the period 1996–2001 (see Table 1). Note that rates of coastal erosion are grouped into 4 different periods of time due to scarcity of specific information and, thus, coastline retreat data is based on the best available information.

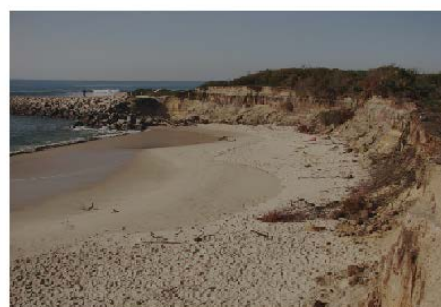
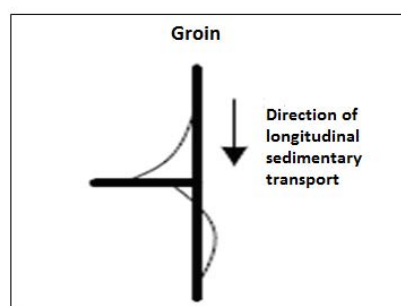
**Table 1.** Average rates of the coastline retreat in Vagueira Beach over the period 1958 to 2001 [7,21,22].

| Period<br>(years)    | Coastline retreat |           |
|----------------------|-------------------|-----------|
|                      | Annual (m/year)   | Total (m) |
| 1958-1969 (12 years) | 1.6               | 19.2      |
| 1970-1979 (10 years) | 2.4               | 24.0      |
| 1980-1990 (11 years) | 3.9               | 42.9      |
| 1991-1995 (5 years)  | 5.5               | 27.5      |
| 1996-2001 (6 years)  | 7.1               | 42.6      |
| Total                | -                 | 156,2     |

In case the sediment available for littoral drift is equal to the potential sediment transport capacity, the coastline would be in dynamic equilibrium and the sediment transport along this coastal stretch would forward the sediments downdrift [21]. In the past, the Douro river would be able to practically alone provide the amount of sediment needed to balance sediment losses [23]. However, with the construction of dams (between 1972 and 1985) this supply of sediment decreased dramatically [9, 34]. In addition, the construction of the breakwater at the Aveiro Port entrance in 1942 resulted in the trapping of sediments from the northern part of the considered coastal stretch [33]. Another factor related to the coastline retreat is the dredging that occurs at the Aveiro Port entrance, in which part of this material was, in the past, commercialized for other uses (such as construction and industrial use) – further reducing sediment supply from the north and, thus, accentuating coastline retreat in Vagueira Beach [21]. Only after 2000, the dredging operations performed for navigation purposes at Aveiro port were used for beach and landfill nourishment (when the sediments present the required quality), with only a part deposited at sea, to the south of breakwater, trying to mitigate coastal erosion.

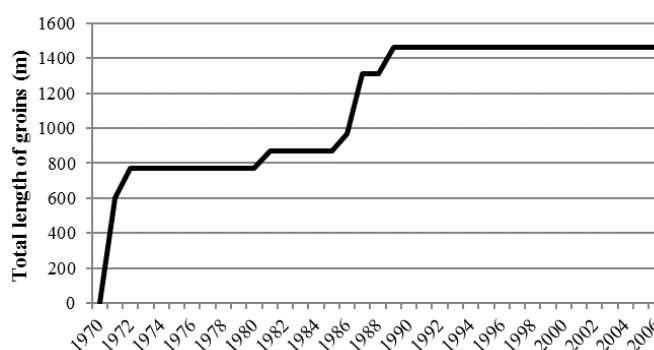
Anthropic interventions and impacts can be even more severe due to the destruction of natural coastal defense structures, in particular the beach and the frontal dune system, first natural barriers to the wave action. Beach tourism, the advance of urbanization and the construction of industrial areas are the main activities that have resulted in the creation of wind runners, changes of the floodplain and the extraction of sediments [24]. The rate of urbanization in the Ria de Aveiro region increased from 5% in 1975 to 12% in 2006 [11]. This occupation of the coastal area led to the destruction of dunes that provide large volumes of sand for the dynamic interaction with and natural defense against the sea [23].

Due to the increase in coastal erosion, the vulnerability of human settlements to losses and damages has increased. This resulted in the construction of heavy engineering structures (groins, rocky revetments and dikes) as to protect these settlements against the sea. The main structures found along the Central Portuguese Coast are groins. However, these types of interventions cause an imbalance in the natural circulation of sediments along the coast, having as main effect the accumulation of sediments north of the structure and the aggravation of erosion south of the structure (Figure 2). This is explained by a predominance of currents from the north-west along the considered coastal stretch [24].



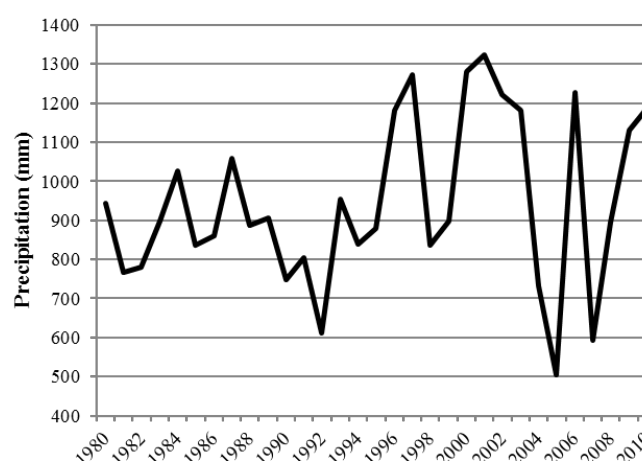
**Figure 2.** Scheme of the consequences resulting from the construction of groins on the coast and effects of erosion immediately south of the groin in Cortegaça Beach, Portugal [24].

The number of groins built between Esmoriz Beach and Vagueira Beach increased from none in 1970 to nine in 2006. In 2006 there are nine groins of various lengths (between 100 and 200 meters, each) in this section – totaling 1460 meters of groins (see Figure 3). Built with the objective of protecting the areas north of where they are located, they tend to further aggravate coastline retreat in Vagueira Beach.



**Figure 3.** Total length of groins built in the Espinho-Vagueira section over the period 1970 to 2006 [7].

Storm events contribute to the coastline retreat, changing the beach morphology, including the response to the direct action of waves, winds, tides, and surges, as well as seasonal changes in the surf zone between storms and calm periods [25]. Storms generated in the North Atlantic are frequent in winter and can persist for up to 5 days, with significant wave heights as high as 8 m [26]. However, wave records during storm events are unreliable (incomplete), as during these events measuring equipment frequently fails due to the high wave energy. A proxy for storm events is precipitation, as periods of intense rainfall (mainly during autumn and winter) are, generally, accompanied by storm events (Figure 4; see also Section 3.1). Over the period 1980-2010 the median annual precipitation was about 950 mm, with a standard deviation in annual precipitation of about 175 mm.



**Figure 4.** Annual precipitation in Aveiro district over the period 1981 to 2011 [27].

## 2.2. Data collection

As to allow for the assessment of the key anthropogenic and natural factors that explain the rate of coastline retreat, corresponding time series data were collected from government bodies and publications for the Espinho-Mira case study area. For this analysis it

was adopted data over the period 1980 to 2001 (21 years), for which information on all considered variables was available. In particular:

- a) Annual coastline retreat (in meters/year) in Vagueira Beach for the period 1980 to 2006 (obtained from the EUROSION project) [7];
- b) Annual dredging (in m<sup>3</sup>/year) at the Aveiro Port entrance for the period 1980 to 2010 (data provided by the Port of Aveiro);
- c) Total length of groins built (in meters) in the Espinho-Vagueira section for the period 1980 to 2001 (obtained from the EUROSION project) [7];
- d) Annual precipitation (in mm/year) in the Aveiro district for the period 1980 to 2010, as a proxy for storm events (obtained from the Instituto Português do Mar e da Atmosfera) [27].

### 2.3. Statistical analysis

In seeking to determine which anthropogenic and natural factors influence coastal erosion in Vagueira Beach, a series of correlation and regression analyses were performed with the statistical software SPSS (Statistical Package for Social Science; version 15.0).

Correlation analysis was applied to assess the correlation between the independent variables (dredging; length of groins; annual precipitation) and the dependent variable (coastline retreat). The coefficient of correlation ( $r$ ) is a measure of the degree of linear relationship between two quantitative variables (where -1 indicates there is a perfect negative linear relationship, 0 indicates that there is no linear relationship, and +1 indicates a perfect positive linear relationship). The closer the correlation coefficient is to -1 or +1, the stronger is the linear association between the two variables [28,29]. The Pearson's correlation coefficient ( $r$ ) is given by:

$$r = \frac{\sum(x_i - \bar{x}) \times (y_i - \bar{y})}{\sqrt{(\sum(x_i - \bar{x})^2) \times (\sum(y_i - \bar{y})^2)}} \quad (1)$$

where  $r$  is the Pearson correlation coefficient of a group of variables  $x$  with another group of variables  $y$ .

In turn, a multiple linear regression analysis was performed. The dependent variable is annual coastline retreat, and the independent variables are annual dredging, total length of groins and annual precipitation. The goal of multiple linear regression analysis is to find a regression equation that provides a better perception of the sign and the extent to which independent variables determine values of the dependent variable – thus, aiming to find regression coefficients  $\beta$  that best fit the dependent variable  $y$  [30]:

$$y = \beta_0 + \beta_1 x_1 + \dots + \beta_n x_n + \varepsilon \quad (2)$$

where  $y$  is the dependent variable,  $x$  are the independent variables,  $\beta$  are the regression coefficients, and where  $\varepsilon$  is the residue error of prediction. The latter is the difference between the actual values and those predicted by the regression model, and is assumed normally distributed with zero mean and constant variance ( $\sigma^2$ ) [29,30].

In seeking to determine the extent to which anthropogenic and natural factors explain coastline retreat in Vagueira Beach, the following multiple linear regression model was developed:

$$Retreat = \beta_0 + \beta_1 Groin5 + \beta_2 Dred3 + \beta_3 Precp \quad (3)$$

where *Retreat* is the annual coastline retreat in Vagueira Beach (in m/year), *Groin5* the total length of groins built for the Espinho-Vagueira section at  $t+5$  (in m), *Dred3* the annual dredging volume at the Aveiro Port entrance at  $t+3$  (in 100,000 m<sup>3</sup>/year), and where *Precp* is the annual precipitation (in mm/year). It was adopted a time lag of  $t+5$  years for total length of groins and  $t+3$  years for dredging volume, as the lack of sediments in Vagueira Beach is noticed in about this time scale [14,16,21,23].

Finally, the estimated regression model was validated using the Student  $t$ -test, the determination coefficient ( $R^2$ ), the ANOVA F-test, and the variance inflation factor (VIF).

The Student *t*-test was used to check whether signs and magnitude of the regression coefficients make sense in the context of the phenomenon being studied [29]. Furthermore, tests and confidence intervals (*t*-test and *F*-test) allow to obtain an indirect idea of the regression quality and confirm hypotheses of particular values for the parameters established by theoretical means.

The determination coefficient ( $R^2$ ) represents a measure of adjustment of a statistical model in relation to the observed values, i.e., it indicates, in percentage terms, the extent to which the regression model explains the observed values. The closer the  $R^2$  to 1, the larger the explanatory power or fit of the model [30].

The ANOVA *F*-test allows to evaluate the overall model, which in general is the statistical testing of the confidence of the coefficient of determination. Thus, if the *F*-test indicates a low level of significance (less than 5%), the data estimated by the regression model are close to those of the initially observed data.

Multicollinearity occurs when independent variables are strongly correlated, such that the interpretation of the contribution of predictors becomes difficult and the estimation of the regression coefficients is flawed. To test whether this occurs, the variance inflation factor (*VIF*) was calculated. A *VIF* > 10 indicates that the regression model shows problems of multicollinearity. The *VIF* is given by [31]:

$$VIF = \frac{1}{1 - R^2} \quad (4)$$

where *VIF* is the variance inflation factor of the regression model with a coefficient of determination  $R^2$ .

### 3. Results

#### 3.1. Analysis of correlation between the factors related to coastline retreat

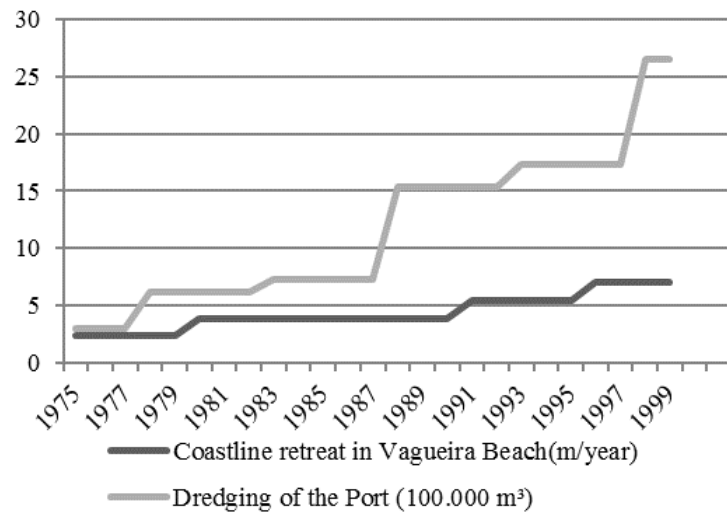
The retreat rate of the coastline is one of the best indexes of coastal erosion. It is a unique index and of exceptional value for the evaluation of coastline evolution tendencies as well as for the assessment of the real impacts of disruptive factors on coastal sediment dynamics [23]. In order to assess the relationship between the factors that can contribute to coastal erosion, correlation analysis was used to correlate the annual coastline retreat at Vagueira Beach with variables that are considered to influence coastal erosion – namely (Table 2): annual dredging, total length of groins and annual precipitation (as a proxy for storm events).

**Table 2.** Correlation analysis between coastline retreat and possible factors that influence coastal erosion in Vagueira Beach.

| Coastline retreat in Vagueira Beach |                       |   |
|-------------------------------------|-----------------------|---|
| Factors                             | Pearson's Correlation | Nº of Observations<br>(evaluated years) |
| Dredging <i>t</i> +3                | 0.931***              | 27                                      |
| Total length of groins <i>t</i> +5  | 0.891***              | 27                                      |
| Precipitation                       | 0.521***              | 22                                      |

Significant at the 1% (\*\*\*) level.

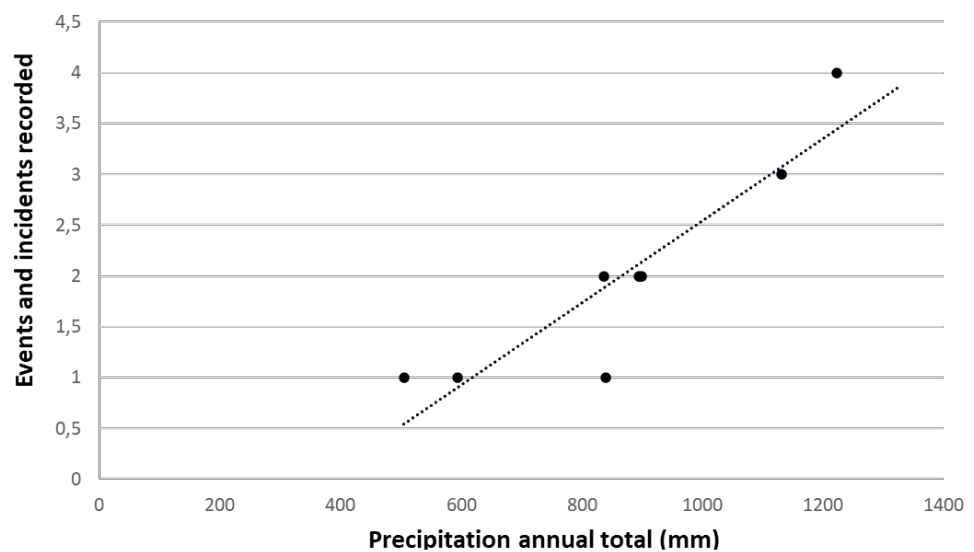
A high correlation was obtained between coastline retreat and the dredging at the Aveiro Port entrance (0.931), even though the port entrance is located around 10 km north of Vagueira Beach. The sediment dredged from the port entrance creates a deficit of sediment along the coastal stretch to the south. This lack of sediments is noticed in Vagueira Beach about 3 years after dredging (*t*+3) at the Aveiro Port entrance (see Figure 5).



**Figure 5.** Cumulative annual volume dredged at the Aveiro Port entrance and cumulative annual coastline retreat at Vagueira Beach over the period 1975 to 2000 [7].

The total length of groins also presents a high correlation with coastline retreat (0.891). Coastal protection measures are generally established in front and just south of urbanized areas [14]. As with the dredging process, groins reduce sediment transport along the coast that, according to the correlation analysis, takes 5 years to be transported to Vagueira Beach (t+5).

Finally, the coastal area is influenced by oceanic, continental and atmospheric agents and, hence, its sensitivity to climate conditions [32]. Even though the correlation between coastline retreat and precipitation is relatively low (0.521), it seems annual precipitation (and associated storm events) are a reasonable proxy for energetic actions of the sea (see Figure 6). These actions have generated events of great impact, destroying works of containment and coastal defense – leading to the relocation of sediments confined by coastal defense structures [21].



**Figure 6.** Annual precipitation and number of recorded events & incidents of wave actions in Vagueira Beach [21,27].

### 3.2. Assessment of factors related to coastal erosion through multiple linear regression

Regression simulation results (see Table 3) show that the model has a very good fit ( $R^2 = 0.91$ ). The ANOVA F-test (significant at 1%) indicates that values estimated by the regression model are close to the initial data of annual coastline retreat in Vagueira Beach, while the variance inflation factor (VIF) indicates that there is no problem of multicollinearity ( $VIF < 10$ ).

**Table 3.** Results for the multiple linear regression model of coastline retreat in Vagueira Beach.

| Explanatory Variables       | Coefficients |        |                        | VIF   |
|-----------------------------|--------------|--------|------------------------|-------|
|                             | Estimate     | Weight | Student <i>t</i> -test |       |
| Constant ( $\beta_0$ )      | 0.615        |        | 0.912                  |       |
| <i>Groin5</i> ( $\beta_1$ ) | 0.002        | 0.526  | 3.074 ***              | 5.773 |
| <i>Dred3</i> ( $\beta_2$ )  | 0.009        | 0.384  | 2.171 **               | 6.165 |
| <i>Precp</i> ( $\beta_3$ )  | 0.001        | 0.130  | 1.611 *                | 1.280 |
| $R^2$                       |              |        | 0.91                   |       |
| ANOVA F-test                |              |        | 59.79 ***              |       |

Significant at the 1% (\*\*\*) , 5% (\*\*) and 10% (\*) level.

The analysis of the factors that explain annual coastline retreat allow a series of interpretations (Table 3). All factors have a positive sign, indicating that they are directly proportional to coastline retreat. The contribution of the total length of groins is the main factor responsible for coastline retreat in Vagueira Beach (*Groin5* with a weight of 53%), followed by the volume dredged at the Aveiro Port entrance (*Dred3* with a weight of 38%) and precipitation (*Precp* with a weight of 13%). Several authors argue that the weakening of sedimentary sources in the region is the biggest cause of coastal erosion problems [14,16,21,23]. The reduction of sedimentary sources can explain the rates of coastline retreat observed in the region. This is in line with the obtained results, which show that groins and dredging reduce the transport of sediments that over the years (after five and three years, respectively) would settle on the coast in front of Vagueira Beach [21].

The Student *t*-test reveals that the total length of groins (*Groin5*) is the most significant factor (significant at the 1% level), followed by the volume dredged at the Aveiro Port entrance (*Dred3*; significant at the 5% level) – proving, once again, the importance of sediment removal in explaining coastline retreat and confirming that human interventions lead to environmental changes. Finally, precipitation (*Precp*) is the least significant factor explaining coastline retreat (significant at the 10% level), indicating that annual precipitation, and associated storm events, only have a limited impact on shoreline retreat – albeit storm events cause significant damages to coastal infrastructures (see e.g. [21,23,26]).

## 4. Conclusions and Recommendations

This study assessed the influence of anthropogenic and natural factors on coastline retreat in Vagueira Beach (Central Portugal). To this end, correlation and multiple linear regression analyses were applied. The main variables correlated with coastline retreat in Vagueira Beach were total length of groins, annual dredging, and, to a minor extent, annual precipitation (as a proxy for storm events). These results are in line with other authors that highlighted the influence of sediment deficits on downdrift coastline retreat [21] associated with human interventions (such as dredging) and coastal structures (such as groins) [24] as well as the influence of climatic factors [14,23].

Through the temporal distribution of several factors in the analysis it can be concluded that coastline retreat in Vagueira Beach has increased and is expected to maintain this trend in the near future, if no other mitigation measures are considered. In particular, this is observed because of the groins constructed along the coastal stretch north of Vagueira Beach and the volume of material dredged at the Aveiro Port entrance, that show an increasing trend [21]. In addition, climate change is expected to lead to an increase in storm events over the next century [8,12,20,23]. Hence, construction of groins

along the coastal stretch north of Vagueira Beach should be carefully deliberated, while recharge of the material dredged at the Aveiro Port entrance to beaches located south of it may be considered and are increasingly being considered to mitigate coastal erosion on this coastal stretch [20-23]. In the meantime, local solutions in front of Vagueira Beach are assessed to halt and reverse coastline retreat in Vagueira Beach [8,11,17,35].

Some caveats remain. First, the use of annual precipitation as proxy for storm events and associated wave actions, has proven to work only reasonably well. A complete time series of actual wave action would be preferred, though the maritime wave records were too incomplete to be used for this purpose. Second, river sediment recharge from the main river to the north of Vagueira Beach (in particular from the Vouga river) would be an additional explanatory variable of importance, albeit that most of the sediments from the Vouga river are trapped in the Aveiro Lagoon and Aveiro Port entrance. Finally, unlike other studies in the area, which focus on monitoring and modeling, this study provided an innovative statistical approach, based on correlation and regression analysis, to assess the causes and impacts of coastal erosion and that can be easily replicated in similar coastal zones.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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