

## Article

# Estimating Quantitative Morphometric Parameters and Spatiotemporal Evolution of the Prokopos Lagoon Using Remote Sensing Techniques

Dionysios N. Apostolopoulos <sup>1</sup>, Pavlos Avramidis <sup>2,\*</sup> and Konstantinos G. Nikolakopoulos <sup>1</sup><sup>1</sup> G.I.S. & Remote Sensing Laboratory, Department of Geology, University of Patras, 26504 Rio, Greece; apostolopoulos.dionysios@upatras.gr (D.N.A.); knikolakop@upatras.gr (K.G.N.)<sup>2</sup> Laboratory of Sedimentology, Department of Geology, University of Patras, 26504 Rio, Greece

\* Correspondence: p.avramidis@upatras.gr; Tel.: +30-2610996163

**Abstract:** The Prokopos Lagoon is part of the Kotychi Strofili National Wetlands Park, which is supervised by the Ministry of Environment, Energy and Climate Change of Greece. The lagoon is situated at the northwestern coast of the Peloponnese and is protected by the Ramsar Convention. It is an important ecosystem with ecological services providing habitats for many plants and animals and essential goods and services for humans as well. No previous relevant studies for the wider wetland area are available, and given that lagoons are important ecosystems, their diachronic evolution should be under constant monitoring. Using remote sensing techniques in Geographic Information System (GIS) environment, alterations in critical parameters could be measured and applied for the protection of the area. The present study examines the spatiotemporal changes of the water extent of the Prokopos Lagoon, estimating landscape metrics and several morphometric parameters and indices related to the geomorphological features of the lagoon for the 1945–2021 period. Moreover, the adjacent shoreline was studied for each past decade evolution from 1945 to present, and it is discussed to whether there is a relationship between shoreline changes and the lagoon. High resolution satellite images and air photos at scale 1:30,000 were used to digitize the shorelines and the polygons of the lagoon's surface. Linear Regression Rates (LRR), Net Shoreline Movement (NSM), End Point Rate (EPR) and Shoreline Change Envelope (SCE) provided by the Digital Shoreline Analysis System (DSAS) were used to determine the changes. Finally, future shoreline positions for 2021 and 2031 are estimated, while based on statistic models, we found that in the coastal area, the erosion–accretion cycle is predicted to be completed in 2031, after almost 86 years since 1945.

**Keywords:** coastal and lagoon changes; sedimentation; remote sensing; GIS; DSAS

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## 1. Introduction

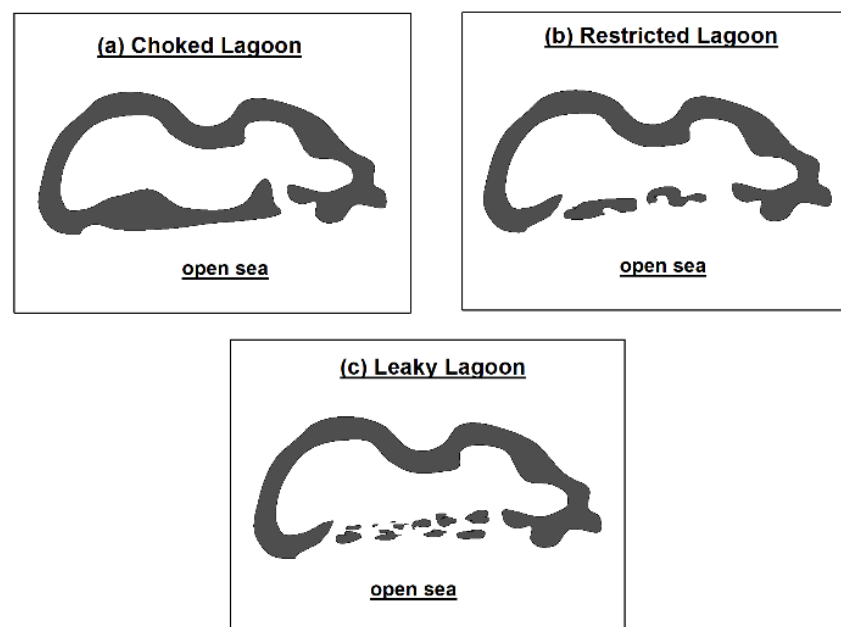
Coastal lagoons are important ecosystems providing a range of ecological services related to the supply of food, protection from floods, groundwater recharge, and sequestration of contaminants. They represent a transitional zone where freshwater and marine ecosystems are linked to each other [1]. They consist of shallow water bodies separated from the sea usually by a sandy barrier, connected at least intermittently to the sea by one or more restricted inlets and usually oriented parallel to the shore [2–4]. The water uses in agriculture have influenced lagoons ecosystems and their ecological status. The Convention on Wetlands is an intergovernmental treaty that provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources [5]. Lagoons are generally formed in topographically low regions behind coasts. By monitoring the seasonal evolution of water boundaries, we can understand, conserve and take advantage of lagoon water volumes. In addition, the connection with the open sea is critical since its type affects the morphological and ecological conditions of the coastline. During the winter months, a large amount discharge of fresh- water through the rivers and

land runoff from the watershed is poured into the lagoon, resulting in a marked change in the lagoons' boundaries, while during the summer months, the water area shrinks. These alterations, in most cases, have a devastating effect on vital natural resources, soil and water volume. For example, there is a significant change in water salinity that affects the balance of the ecosystem, as salinity controls the species of flora and fauna [3]. In addition, large areas of arable land are created or lost with consequences for the local economy.

One of the latest developments in optical remote sensing is the use of the satellite imagery in Earth observation. It has been proven that satellites are useful tools that allow for effective and more efficient monitoring of lagoons water bodies around the world compared to the traditional in situ measurements because of their ability to monitor repeatedly and at multiple scales [6]. Medium- and low-resolution images such as Sentinel-2 [7–10] and Landsat [11–13], although they are valuable sources of images referring to the past, are not suitable for shoreline mapping in high-scale studies due to their high level of uncertainty [14].

Thus, high-resolution satellite images and aerial photography [15,16] have been applied in order to delineate land from water in several studies [17–20], and they should be preferred over any other medium or low-resolution data.

According to a classification proposed by [3,21], lagoons are divided into three types regarding the water exchanged with the sea body: (1) choked, (2) restricted and (3) leaky lagoons (Figure 1). The type of lagoon is determined by the water exchanges with the adjacent coastal sea. Choked lagoons usually connect with a single long narrow entrance channel. This entrance server as a dynamic filter that eliminates currents and water-level fluctuations inside the lagoon. Restricted lagoons consist of a large and wide water body, usually oriented shore-parallel, communicating with two or more inlets. Leaky lagoons are elongated shore-parallel water bodies, are prone to tides, with many entrance channels that can be affected by the wave action and the littoral drift so as to close the channel entrances [3].



**Figure 1.** Coastal lagoons sub-divided into (a) choked, (b) restricted and (c) leaky (remodified after [3]).

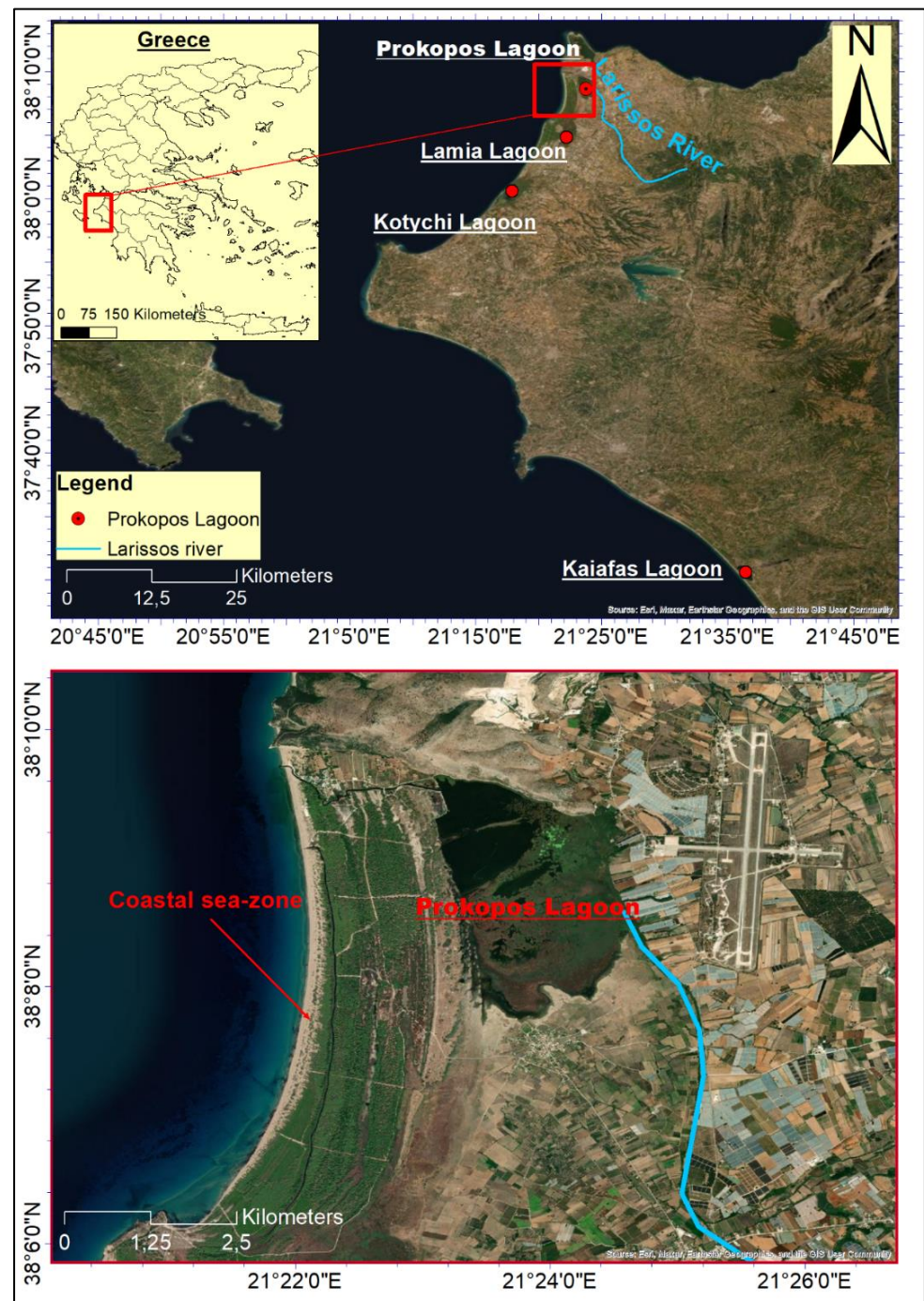
In the present study, we tried to evaluate the spatiotemporal evolution of the Prokopos Lagoon using remote sensing techniques for the 1945–2021 period in order to establish a long-time series dataset of changes in the lagoon area. There are no previous relevant studies for the wider wetland area, and as mentioned before, lagoons are important ecosystems such that their diachronic evolution should be under constant monitoring. Using

remote sensing techniques, it is possible to regularly measure the critical parameters and alterations of which may foretell a significant disturbance in ecosystem balance, and thus, the authorities would be able to act in time.

The landscape metrics of the lagoon, such as area (km<sup>2</sup>), perimeter (km) and several morphometric parameters and indices related to the geomorphologic features, were computed based on the yearly layer of surface water. Moreover, as the lagoon is connected with the littoral zone through a groove in the north, we identify changes in the shoreline by statistical methods, provided by the DSAS tool developed by USGS for ArcGIS software. The Linear Regression Rates (LRR), Net Shoreline Movement (NSM), End Point Rate (EPR) and Shoreline Change Envelope (SCE) were computed, in order to investigate whether there is a relationship between Prokopos Lagoon evolution and the littoral zone. In addition, an attempt to estimate the position of the future shoreline for 10 and 20 years was made.

## 2. Study Area

Coastal depositional environments of Peloponnese are prone to climatic, sea level, tectonic, and human-induced changes. Previous studies in the Peloponnese focused on paleo-environmental [22–24] and palaeoclimatic reconstructions [25], changes in sedimentation [26–28], sea-level changes [29] and high-energy events [30], many of which were in archaeological settings [31]. The area of the northwest Peloponnese is of particular ecological interest, as there are important wetlands such as the Kotychi, Pappas, Lamia, Prokopos and Kaiafas Lagoons, which are protected by the Ramsar convention on Wetlands (Figure 2). The Prokopos Lagoon is part of the Kotychi Strofili National Wetlands Park, which is supervised by the Ministry of Environment, Energy and Climate Change of Greece. It is a network of lagoons, swamps and forests along the northwestern coast of the Peloponnese, situated in the Achaia Prefecture, and it has been protected by the Ramsar Convention since 1971. It covers an area of about 1500 acres with small depths of about 0.5–1.50 m parts of the area recognized as Special Protection Areas (SPAs) for birds, in accordance with the Directive 2009/147/EE, as well as Sites of Community Importance (SCIs) in accordance with the Directive 92/43/EEC, which has led to the establishment of the European NATURA 2000 Network of protected areas (GR2320011, GR2320001, GR2330007) [32]. It separates the forest from the sea and is a natural fish farm with sea bass, mullets and eels. It is surrounded by sand hills, which prevent the waters of the torrents from flowing into the sea, and thus, the lagoon is created. Many aquatic and transient birds arrive there for wintering. There is also a bird observatory. The lagoon is connected to the sea through a groove 2300 m long with a width of 6–7 m and a depth of 0.8 m, while the water of the Larissos river flows into the lagoon (Figure 2). The area is flat with large sections of zero altitude, while it is bordered to the north by hills called “Black Mountains” that are 240 m high (Figure 2). The Prokopos Lagoon is characterized by frequent alterations in depth, thus forming a variety of habitat conditions. During the winter, the seasonal water is collected and acts as a feeding ground for waterfowl, whereas during the summer, it dries off and serves as a breeding ground for rare species. A key feature of the area is the sandy and clayey composition of the soil, as a result of the intense transport and dispersion of sand from the coast to the interior under the influence of westerly winds. The climate is typical Mediterranean without particularly high temperatures in summer or low temperatures in winter, with approximately 300 days of sunshine per year, thus making possible the observation from optical satellites. The water of the lagoon is seasonally stagnant or slowly moving, while their exit to the sea is blocked by the coastal dunes [33]. Summarizing all the above, the Prokopos Lagoon is an important area with unique ecosystems and economical activities, where an evaluation of the spatiotemporal evolution and its future development is required.



**Figure 2.** The major coastal lagoonal ecosystems of western Peloponnese and the location of the study area (Prokopos Lagoon).

### 3. Materials and Methods

#### 3.1. Data Used

In the present study, the long-term spatiotemporal alterations of the surface water of the Prokopos Lagoon are studied. We focused on the summer season (June–August), using a set of aerial images of different years for several decades: 1945, 1960, 1965, 1968, 1975, 1987, 1996, 2000, 2008, 2012, 2014, 2016, 2019 and 2021, with spatial resolution ranging from 0.25 to 5 m. Different high-resolution datasets of satellites, aerial photography, and orthomosaics were combined and used to monitor the coastline's changes in the littoral area of the Prokopos lagoon. Official datasets of orthomosaics for the years of 1945, 2008

and 2016 were acquired through the National Greek Cadastre and Mapping Agency with a spatial resolution of 1.0, 0.5, and 0.25 m, respectively, which are the most accurate datasets for the Greek territory. We did not perform any further processes on it. Moreover, Worldview-2 high-resolution imagery (0.50 m spatial resolution) of the years 2012 and 2014 were used. In addition, two datasets of the Pleiades satellite imagery of the years 2019 and 2021 with spatial resolution of 0.50 m were processed and used. For the years 1960, 1971 and 1987, analogue aerial photographs at 1:30,000 scale, accessed through the Hellenic Military Geographical Service (HMGS) with 60% along the track overlap, were used. For the year 2000, a panchromatic scene of the Indian Remote Sensing satellite (IRS) with spatial resolution of 5 m was used. Finally, CORONA declassified images of the years of 1965, 1968, and 1975 were freely downloaded from the United States Geological Survey (USGS) through Global Visualization Viewer (GLOVIS) site (<http://earthexplorer.usgs.gov/>, accessed on 10 November 2021). Satellite images were in the Universal Transverse Mercator (UTM) projection with zone 34 and WGS 84 datum and were automatically georeferenced to the Hellenic Geodetic Reference System of 1987 (Greek Grid) using the Leica Photogrammetry Suite (LPS) of ERDAS Imagine 2014 software, with root mean square (RMS) error lower than 0.5-pixel size. All images showed 0% cloud cover over the study area, while the tide height throughout the year was estimated at 0.00 to  $\pm 0.10$  m, according to the online platform (<https://www.worldtides.info/>, accessed on 10 November 2021), which quite negligibly affects the shoreline extraction process. All the datasets used in the current study are presented in Table 1.

**Table 1.** Datasets used in the current study.

| Year | Data Type                      | Source                                     | Reference System                                        | Number of Photos | Spatial Resolution |
|------|--------------------------------|--------------------------------------------|---------------------------------------------------------|------------------|--------------------|
| 2021 | Satellite imagery              | Pleiades                                   | No reference system                                     | 1                | 0.50 m             |
| 2019 | Satellite imagery              | Pleiades                                   | No reference system                                     | 1                | 0.50 m             |
| 2016 | Orthomosaic                    | National Greek Cadastre and Mapping Agency | Hellenic Geodetic Reference System of 1987 (Greek Grid) | 1                | 0.25 m             |
| 2014 | Satellite imagery              | World View-2                               | No reference system                                     | 1                | 0.50 m             |
| 2012 | Satellite imagery              | World View-2                               | No reference system                                     | 1                | 0.50 m             |
| 2008 | Orthomosaic                    | National Greek Cadastre and Mapping Agency | Hellenic Geodetic Reference System of 1987 (Greek Grid) | 1                | 0.50 m             |
| 2000 | Satellite imagery              | IRS                                        | No reference system                                     | 1                | 5 m                |
| 1996 | Orthomosaic                    | Ministry of Rural Development & Food       | Hellenic Geodetic Reference System of 1987 (Greek Grid) | 1                | 1 m                |
| 1987 | Analogue aerial photography    | HMGS                                       | No reference system                                     | 8                | 1 m                |
| 1975 | Declassified satellite imagery | USGS                                       | No reference system                                     | 1                | 4 m                |
| 1971 | Analogue air photos            | HMGS                                       | No reference system                                     | 8                | 1 m                |
| 1968 | Declassified satellite imagery | USGS                                       | No reference system                                     | 1                | 2 m                |
| 1965 | Declassified satellite imagery | USGS                                       | No reference system                                     | 1                | 3 m                |
| 1960 | Analogue aerial photography    | HMGS                                       | No reference system                                     | 20               | 1 m                |
| 1945 | Orthomosaic                    | National Greek Cadastre Mapping Agency     | Hellenic Geodetic Reference System of 1987 (Greek Grid) | 1                | 1 m                |

### 3.2. Software Used

In this study, we used the ERDAS IMAGINE 2014 software of Leica Geosystems for image georeferencing and the ArcGIS 10.8 software for vector generation, editing and map composition, while for the statistical analysis, DSAS v5.0 was used [34–36]. The DSAS functionalities have been described in detail in a previous study from our team [37].

## 4. Methodology

In the present study, we developed two models for controlling the evolution of the Prokopos Lagoon. The first concerns the spatiotemporal evolution of the lagoon's shoreline and the multitemporal calculation of several morphodynamical parameters from 1945 to 2021, while the second concerns the change in the sea–coastal zone adjacent to the lagoon boundaries.

### 4.1. Quantitative Morphometric Parameters of the Prokopos Lagoon

We digitized the lagoon's boundaries manually (on-screen method) for all the years in the dataset, in a Geographic Information System (G.I.S) environment, using the wetted boundaries that were visible in the images. A set of quantitative morphometric parameters (Table 2, Figure 3) introduced by [38] and used by [39], which describe the lagoon's orientation and geometry, its horizontal and vertical scales, and the potential sea influence, were determined. Moreover, the landscape metrics of the lagoon, such as area, perimeter and sea entrance length for each year, were computed.

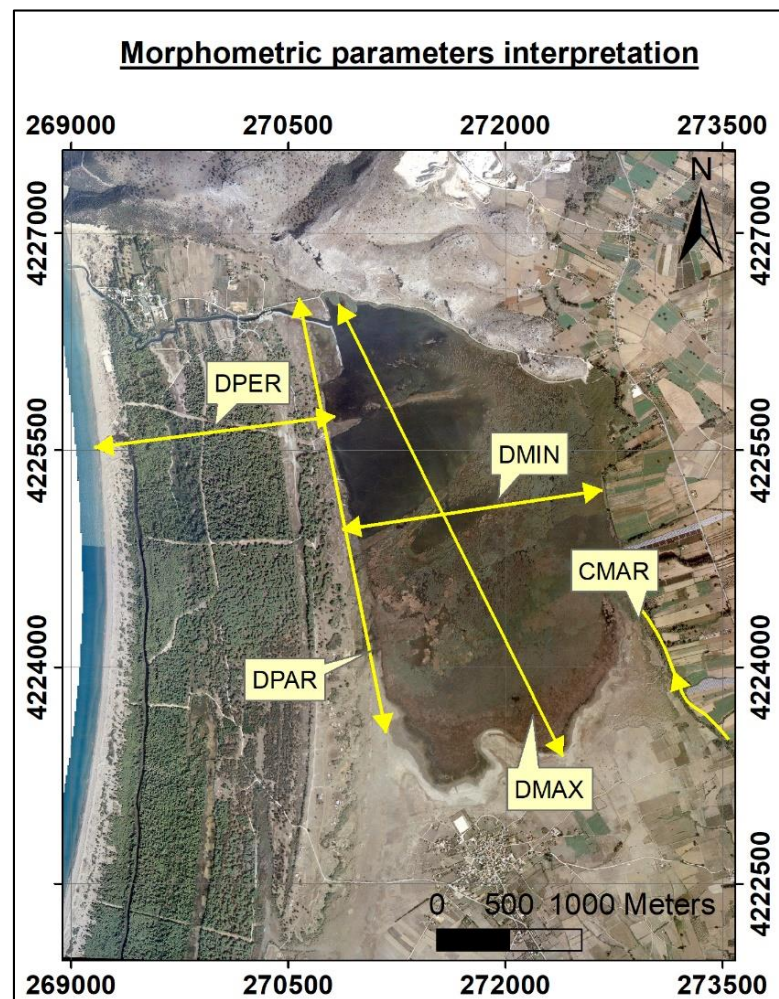


Figure 3. Prokopos Lagoon morphometric parameters interpretation.

**Table 2.** Morphometric lagoon parameters.

| Parameter                               | Description                                                                                                                                                                                                                                                                                                                 |
|-----------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $P_r = \frac{\sum d_i}{b}$ [3,39]       | Restriction ratio ( $P_r$ ) is the ratio between the total width of the lagoon entrance ( $\sum d_i$ ) and the parallel shore direction ( $b$ ), $P_r \in (0, 1)$                                                                                                                                                           |
| $P_{or} = \frac{b}{a}$ [3,39]           | Orientation or anisotropy parameter. The lagoon has orthogonal dimensions of the same order if $P_r \approx 1$ . It is more elongated in the parallel or perpendicular to shore directions if $P_r \geq 1$ or $P_r \leq 1$ , respectively (where ( $a$ ) is the cross-shore length, and ( $b$ ) is the along-shore length). |
| $D_s = l \times (4\pi A)^{-0.5}$ [3,39] | Shoreline development ( $D_s$ ) is the ratio of the length of ( $l$ ) the lagoon's perimeter and ( $A$ ) is the surface area of the lagoon                                                                                                                                                                                  |
| SLAG ( $A$ )                            | Lagoon surface (km <sup>2</sup> )                                                                                                                                                                                                                                                                                           |
| PERI ( $l$ )                            | Lagoon perimeter (km)                                                                                                                                                                                                                                                                                                       |
| DMAX                                    | Maximum diameter of the lagoon (km)                                                                                                                                                                                                                                                                                         |
| DMIN                                    | Minimum diameter of the lagoon (km)                                                                                                                                                                                                                                                                                         |
| DPER                                    | Perpendicular distance to the open sea coastline (km)                                                                                                                                                                                                                                                                       |
| DPAR                                    | Parallel distance to the open sea coastline (km)                                                                                                                                                                                                                                                                            |
| CMAR                                    | Number of inlets or channels                                                                                                                                                                                                                                                                                                |

#### 4.2. Changes in Coastal Sea Zone

Digitizing the shorelines based on multitemporal satellite and aerial images from nine decades (i.e., 1950, 1960, 1970, 1980, 1990, 2000, 2010, and 2020), we estimated the shoreline evolution in the coastal sea zone for the period 1945–2021, using the statistical tools of EPR, NSM, SCE and LRR provided by the DSAS plug-in. Moreover, we estimated the future shoreline position for 2031 and 2041 using the DSAS forecasting beta tool, which is based on the Kalman Filter [40,41]. It initializes with a linear regression rate, which is calculated by using the DSAS. Digital shoreline shapefiles imported in a geodatabase are created in ArcGIS platform, following the DSAS v5.0 requirements such as the acquisition date, identity, shape, length, and uncertainty [34]. A baseline demarcates following the buffering method is the most reliable and accurate method because it takes the same sinuosity shape of the nearest shoreline [42], while transects were set every 30 m along the coastlines. The EPR (m/yr) calculates the distance between the oldest and the most recent shorelines in a given dataset divided by the time elapsed (Equation (1)) and corresponds to the short-term rates of changes, where  $y_1$  and  $y_2$  are the distances separating the shoreline and baseline, and  $t_1$  and  $t_2$  are the dates of the two shoreline positions. Given the one-meter spatial resolution that the images have, and the 90% confidence interval that we have set, 10% equaling to 0.10 corresponds to a frame of uncertainty, and as it is close to 0, the rates between  $-0.10$  and  $+0.10$  m/yr were considered as a stable coast.

$$EPR = \frac{y_1 - y_2}{t_1 - t_2} \quad (1)$$

According to a recent review study from our team [12], this method is the most commonly used method by many coastal researchers [43–46]. Moreover, we computed the LRR (m/yr), which is calculated using a least square regression line from all shoreline positions along each transect and which is used to observe the trend of the shoreline evolution. The inclination of the line is the linear regression rate and corresponds to the long-term rates of coastal changes [47]. The method has the potential to use more than two shorelines and thus to overlap the EPR's disadvantages [48–50]. In addition, the NSM is the net spacing (m) between the old and new shoreline positions for each transect (Equation (2)).

$$NSM = [d_{\text{new}} - d_{\text{old}}] (\pm m) \quad (2)$$

The negative NSM indicates that the lagoon is expanding, the positive NSM indicates that the lagoon is shrinking, while the SCE computes the biggest distance between the

shorelines imported into the geodatabase, representing the highest net of coastal evolution during the study period.

#### 4.3. Shoreline Position Forecasting

Using the integrated forecasting tool of the Digital Shoreline Analysis System (DSAS) v.5 beta software, the future position of the shoreline (forecasted shoreline) for 10 and 20 years since 2021 was estimated [34]. The tool uses the Kalman filter [40] to forecast a future shoreline position as developed by Long and Plant [41]. The results achieved using the forecasting tool are better if the SCE rates of the shorelines used are within a stable low range (lower than 40 m) [51].

We computed the EPR rates to estimate the shoreline future movement for the 2021–2031 (EPR31) and 2021–2041 (EPR41) periods, and the results were compared to the respective LRR rates calculated for the period of 1945–2021 (LRR21).

The results were cross-validated using the R-squared rates, the root mean square error (RMSE), and the mean annual error (MAE) coefficient methods [52–55]. The R-squared represents the proportion of the variance in the dependent variable, which is explained by the linear regression model and reveals how well the data fit the regression model. It can take any value between 0 and 1. The closer to 1, the better the correlation. The MAE represents the average of the absolute difference between the actual and predicted values of the residuals in the dataset. MAE values close to 0 indicate that the model is an accurate predictor [52], while the RMSE measures the standard deviation of residuals [56].

#### 4.4. Uncertainty

Hapke et al. [57] have reported analytical calculations for the shoreline uncertainty estimation using aerial and satellite images. The uncertainty of shoreline position is associated with main sources of error. These errors are georeferencing error, digitizing error, pixel error, and sea level fluctuation error. In the present study, orthomosaics and satellite images of spatial resolution ranging from 1 to 0.50 m were used, while tide rates were negligible. In addition, the georeferencing error for the 1960 and 1987 aerial photographs and satellite images were calculated from the georeferencing and rectifying processes lower than 0.5 pixels. Based on the previous statements, for the estimation of the shoreline change rates uncertainty, we set the predetermined confidence level percentage provided by the DSAS for linear regression (LCI) at 90%. The mean LCI rate is computed at 0.26 m/yr. This means that the band of confidence around the reported rate of change is  $\pm 0.26$  m/yr.

Moreover, regarding the shoreline position forecasting, an uncertainty band automatically created through the respective beta tool of DSAS was displayed as a transparent polygon feature class. The uncertainty band was provided due to past shoreline positions and assumes that future changes will be similar to past changes. These uncertainties cannot account for other factors that may influence the position of the shoreline in the future [3].

## 5. Results

### 5.1. Morphometric Parameters in the Prokopos Lagoon

The vectorized shorelines of the lagoon's boundaries for all the years in the dataset are presented in Figure 4. Using these vectors, we calculated several morphometric parameters (Table 3) for each year, which describe the lagoon's orientation and geometry, its horizontal and vertical scales, and the potential sea influence, while a comparison between them was attempted.

The restriction rate ( $P_r$ ) seems to have a stable value of 0.02 (mean value), showing that the lagoon is isolated from the open sea (Figure 5). It was observed that in the year 1968, a higher value appears. The same happened for the other statistics of the year (SLAG, DMAX, DMIN), which is probably related to seasonal fluctuations in water volumes. The orientation parameter ( $P_{or}$ ) ranges from 1.31 (min) to 2.01 (max), while the mean value is  $1.60 > 1$ , revealing that the lagoon developed as elongated and parallel to the direction of the shore during the study period (Figure 6).

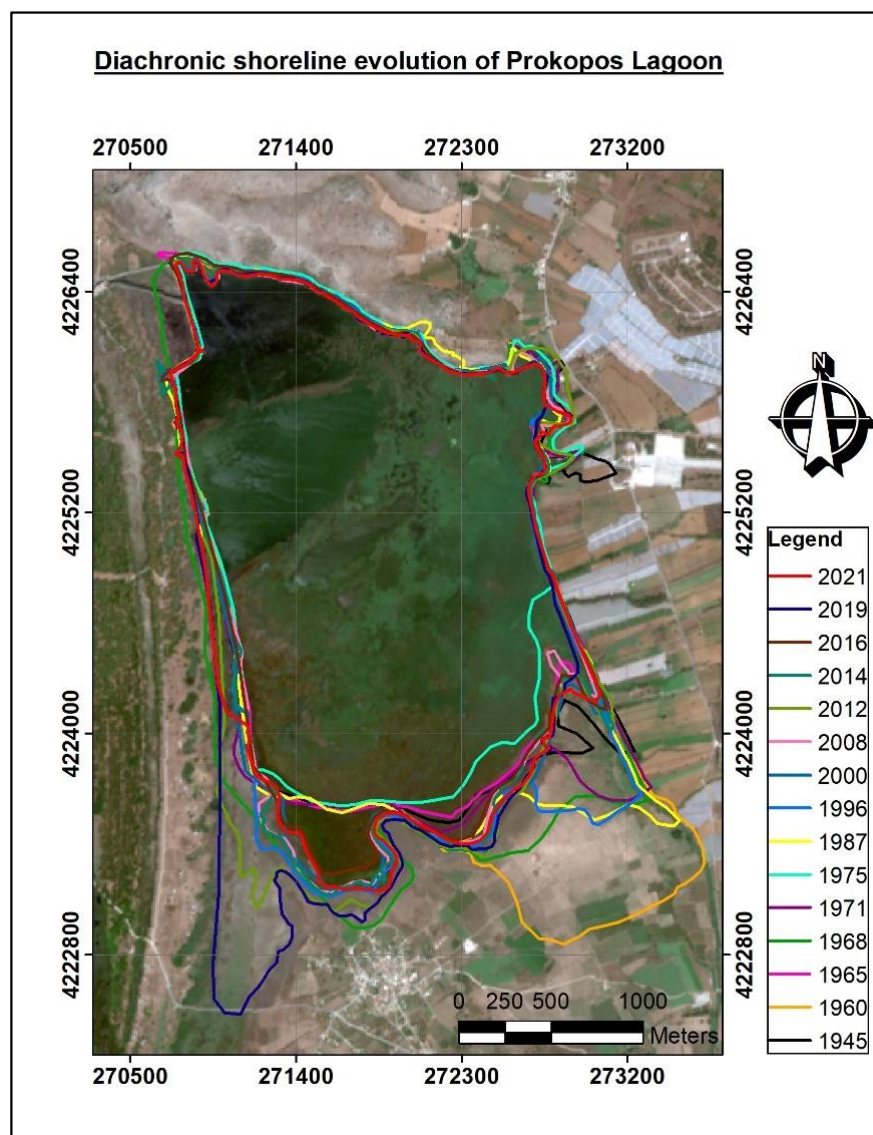


Figure 4. Diachronic shoreline evolution of the Prokopos Lagoon. Basemap of 2021.

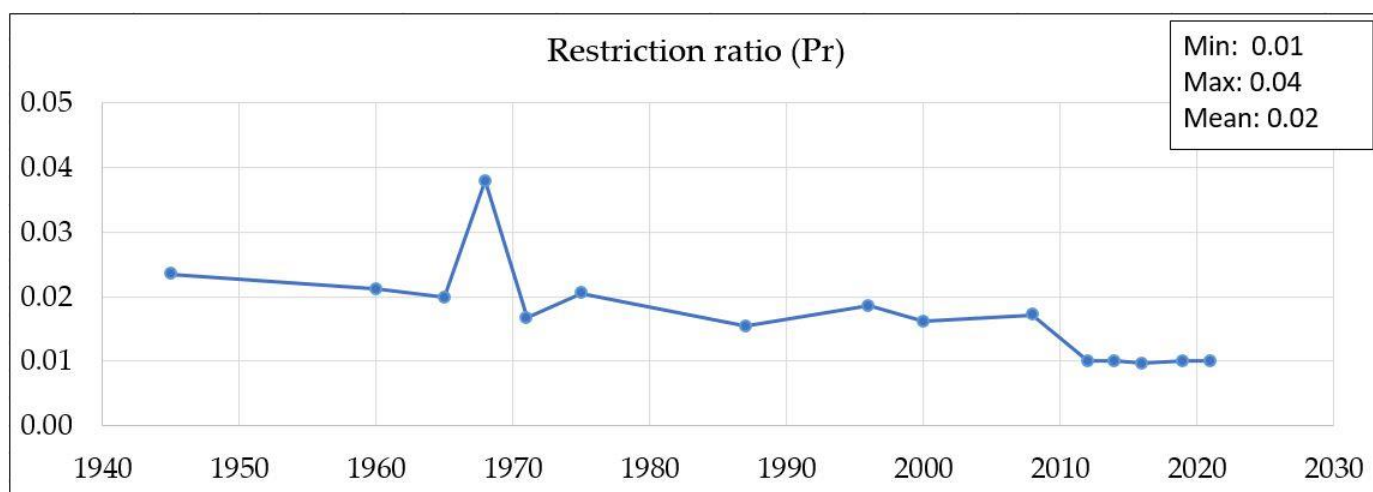
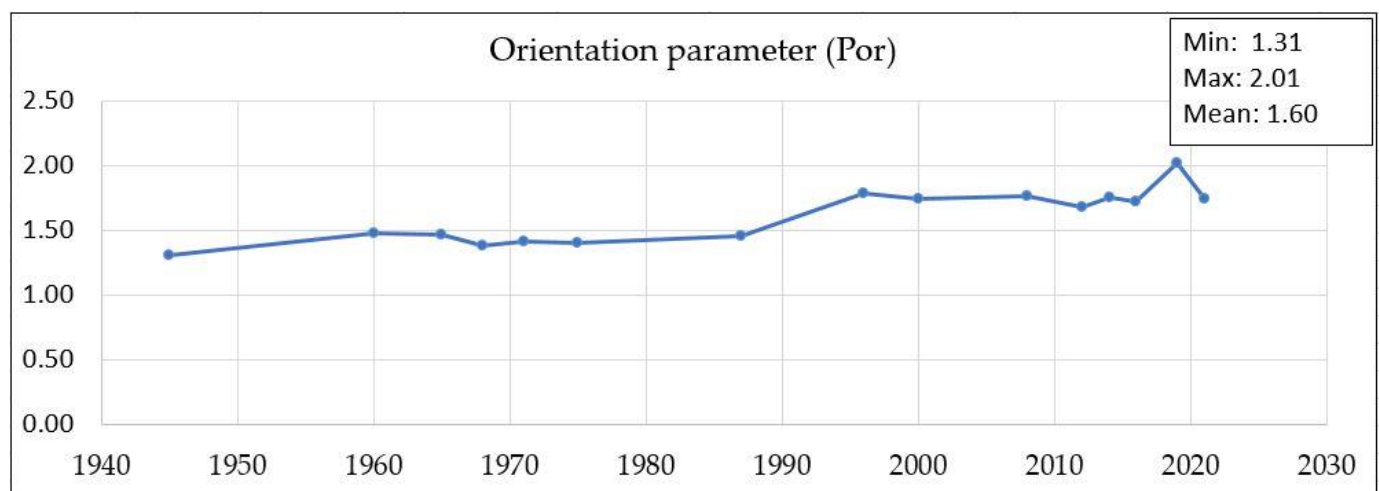


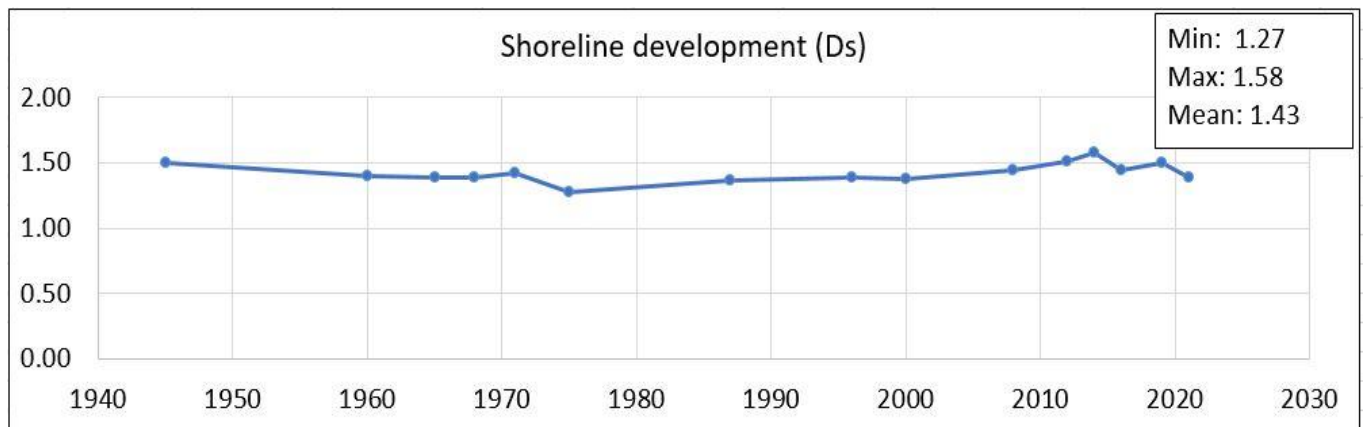
Figure 5. Lagoon restriction ratio index fluctuations during the study period.

**Table 3.** Morphometric parameters of the Prokopos Lagoon.

| Year | P <sub>r</sub> | P <sub>or</sub> | D <sub>s</sub> | SLAG (Sq km) | PERI (km) | DMAX (km) | DMIN (km) | DPER (km) | DPAR (km) | CMAR |
|------|----------------|-----------------|----------------|--------------|-----------|-----------|-----------|-----------|-----------|------|
| 1945 | 0.02           | 1.31            | 1.50           | 4.97         | 11.89     | 3.42      | 2.24      | 1.68      | 2.93      | 3.00 |
| 1960 | 0.02           | 1.47            | 1.40           | 5.90         | 12.09     | 4.34      | 1.98      | 1.70      | 2.92      | 3.00 |
| 1965 | 0.02           | 1.46            | 1.39           | 4.79         | 10.75     | 3.39      | 2.00      | 1.71      | 2.92      | 3.00 |
| 1968 | 0.04           | 1.38            | 1.38           | 6.04         | 12.06     | 3.76      | 2.05      | 1.61      | 2.82      | 3.00 |
| 1971 | 0.02           | 1.41            | 1.42           | 5.13         | 11.41     | 3.42      | 2.08      | 1.67      | 2.93      | 3.00 |
| 1975 | 0.02           | 1.40            | 1.27           | 4.56         | 9.64      | 3.25      | 2.01      | 1.68      | 2.82      | 3.00 |
| 1987 | 0.02           | 1.46            | 1.37           | 5.24         | 11.12     | 3.51      | 2.00      | 1.71      | 2.91      | 3.00 |
| 1996 | 0.02           | 1.78            | 1.39           | 5.44         | 11.51     | 3.58      | 1.99      | 1.72      | 3.55      | 3.00 |
| 2000 | 0.02           | 1.74            | 1.38           | 5.15         | 11.09     | 3.52      | 2.03      | 1.71      | 3.53      | 3.00 |
| 2008 | 0.02           | 1.76            | 1.44           | 5.00         | 11.41     | 3.45      | 1.98      | 1.77      | 3.49      | 3.00 |
| 2012 | 0.01           | 1.68            | 1.51           | 5.52         | 12.61     | 3.61      | 2.10      | 1.75      | 3.52      | 3.00 |
| 2014 | 0.01           | 1.75            | 1.58           | 5.06         | 12.61     | 3.53      | 2.01      | 1.77      | 3.52      | 3.00 |
| 2016 | 0.01           | 1.72            | 1.45           | 4.19         | 10.51     | 3.47      | 1.99      | 1.76      | 3.42      | 3.00 |
| 2019 | 0.01           | 2.01            | 1.50           | 5.69         | 12.69     | 3.65      | 2.01      | 1.69      | 4.05      | 3.00 |
| 2021 | 0.01           | 1.74            | 1.39           | 5.16         | 11.16     | 3.49      | 2.00      | 1.73      | 3.48      | 3.00 |
| Min  | 0.01           | 1.31            | 1.27           | 4.19         | 9.64      | 3.25      | 1.98      | 1.61      | 2.82      |      |
| Max  | 0.04           | 2.01            | 1.58           | 6.04         | 12.69     | 4.34      | 2.24      | 1.77      | 4.05      |      |
| Mean | 0.02           | 1.60            | 1.43           | 5.19         | 11.50     | 3.56      | 2.03      | 1.71      | 3.25      |      |

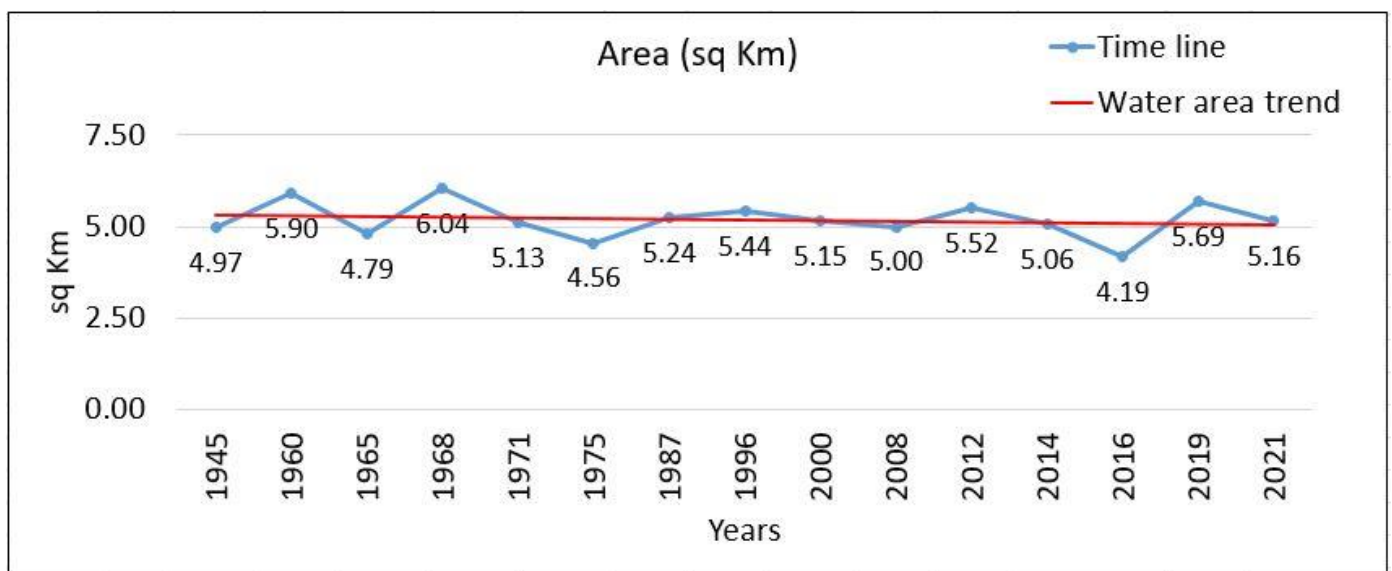
**Figure 6.** Lagoon's orientation parameter fluctuations during the study period.

In addition, the shore development parameter ( $D_s$ ), which indicates the shape of the lagoon's shoreline in comparison to the circumference of a circle whose area  $A$  is equivalent to that of the lagoon's, ranged from 1.27 (min) to 1.58 (max), while the mean value is 1.43 (Figure 7). Rates equal or close to a value of 1 means that the lagoon's shape is closer to a circle.



**Figure 7.** Lagoon's shoreline development index fluctuations during the study period.

Moreover, regarding the lagoon water surface area fluctuations (SLAG-index), the minimum rate is 4.19 sq. km, and the maximum rate is 6.04 sq. km, while the mean rate is 5.19 sq. km. The enhanced lagoon water surface area for the study years shows that this parameter is almost stable and is close to 5 sq. km in general (Figure 8—red line). A similar trend to the lagoon perimeter index (PERI) is observed in Figure 9, where the minimum rate is 9.64 km, and the maximum rate is 12.69 km, while the mean rate is 11.50 km. In addition, the multitemporal ratios of change in the lagoon area (DSLGA) and perimeter (DPERI) during the study period are presented in Figure 10. The statistics reveal that there have been frequent changes over time. For instance, during the periods 1945–1960, 1965–1968, and 2016–2019, the most significant changes in the water surface occurred (SLAG-index) with rates of  $-18.79\%$ ,  $+26.15\%$ , and  $+35.80\%$ , respectively (Figure 10). Moreover, in the periods 1971–1975, 1975–1987, 2014–2016, and 2016–2019, relevant changes to the lagoon's perimeter (DPERI) took place, with rates of  $-15.51\%$ ,  $+15.40\%$ ,  $-16.65\%$  and  $+20.75\%$ , respectively (Figure 10).



**Figure 8.** Water surface area fluctuations during the study period.

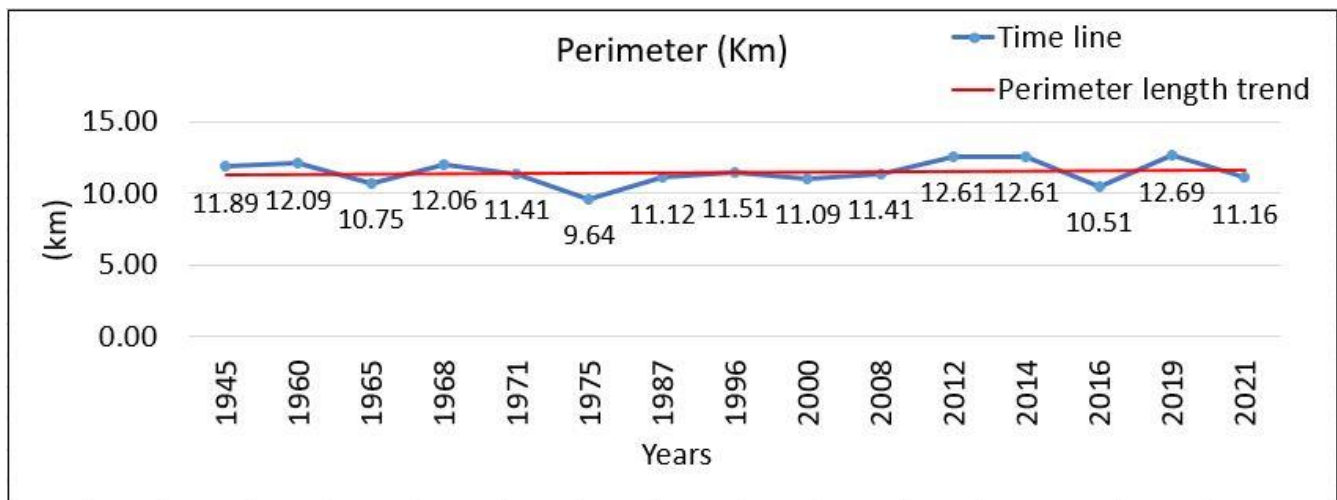


Figure 9. Lagoon's perimeter fluctuations during the study period.

The maximum diameter of the lagoon ranges from 3.25 km (min) to 4.54 km (max), while the mean rate is 3.56 km. The respective rates corresponding to the minimum diameter of the lagoon are 1.98, 2.24 and 2.03 km, respectively. Finally, the rates of the perpendicular distance to the open sea coastline (DPER) range from 1.65 km (min) to 1.77 km (max), while the mean rate is 1.71 km. The respective rates of the parallel distance to the open sea coastline (DPAR) range from 2.82 km (min) to 4.05 km (max), while the mean rate is 3.25 km.

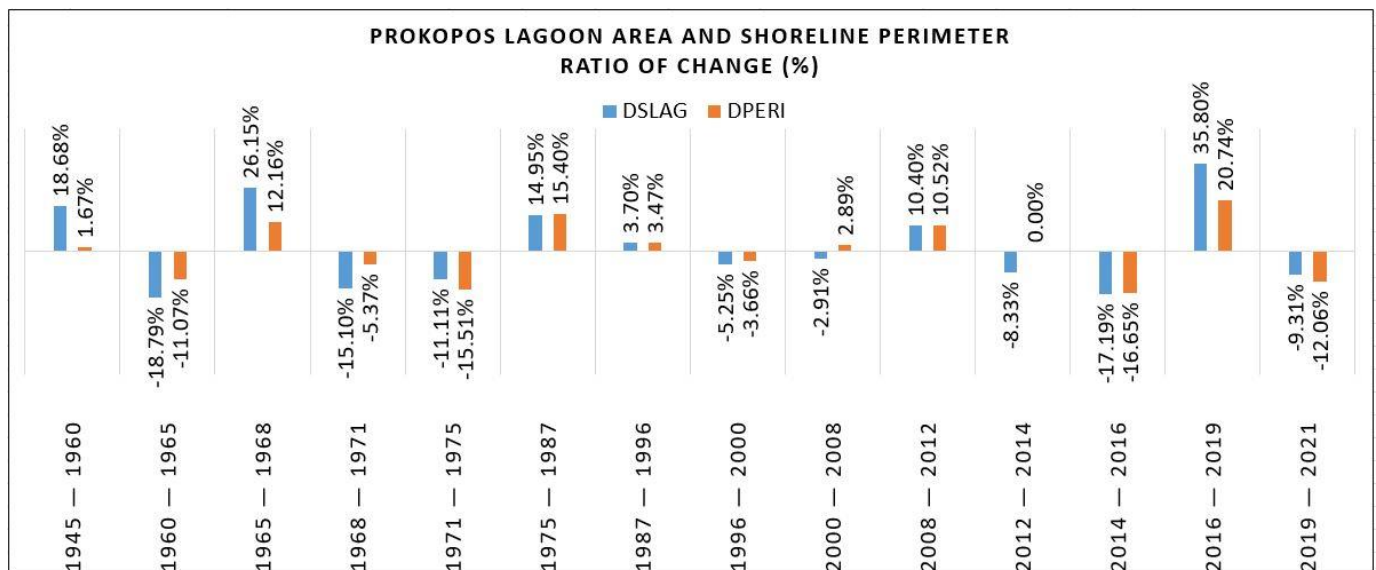
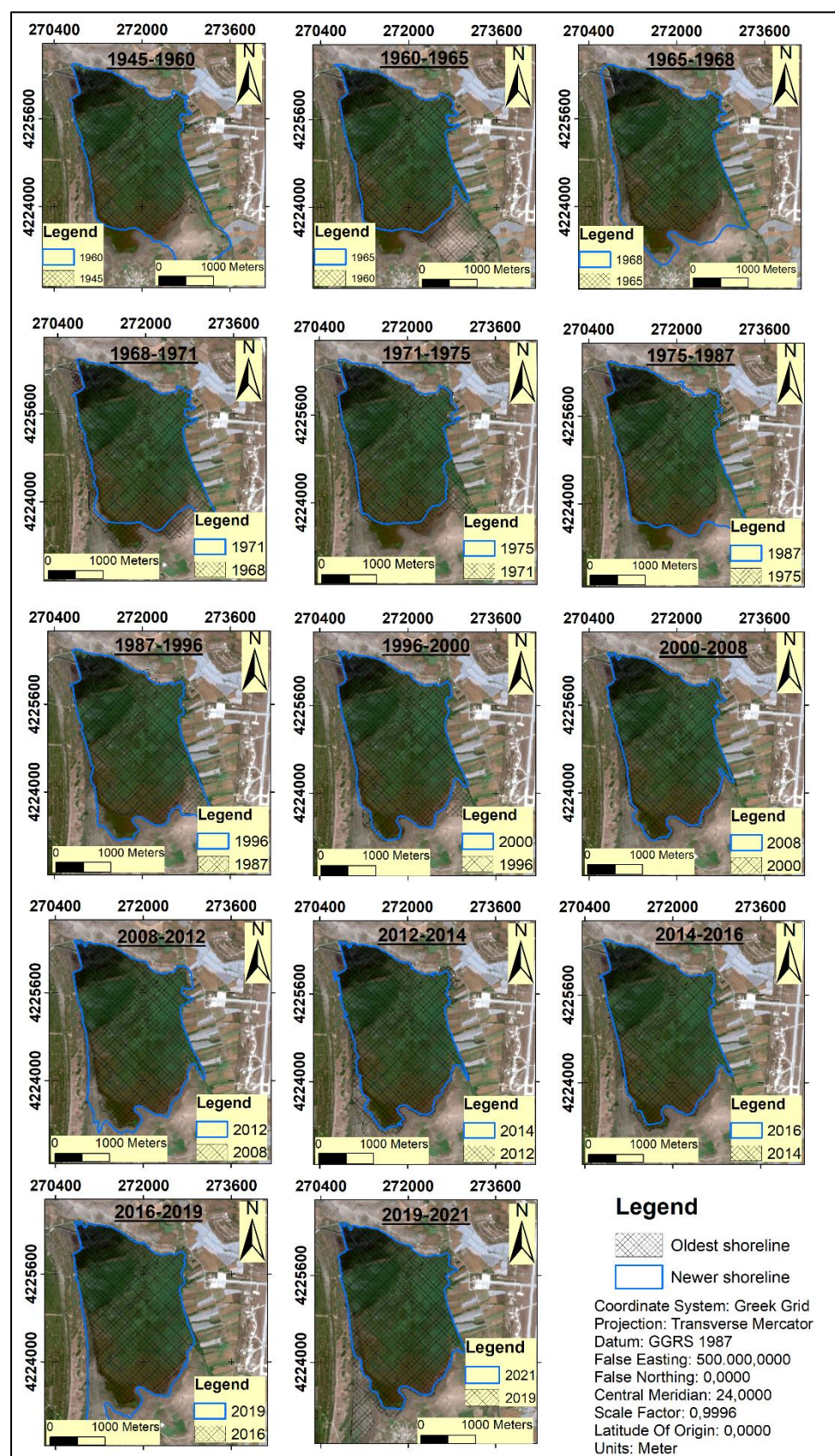


Figure 10. Ratio of change in lagoon area and perimeter during the study period.

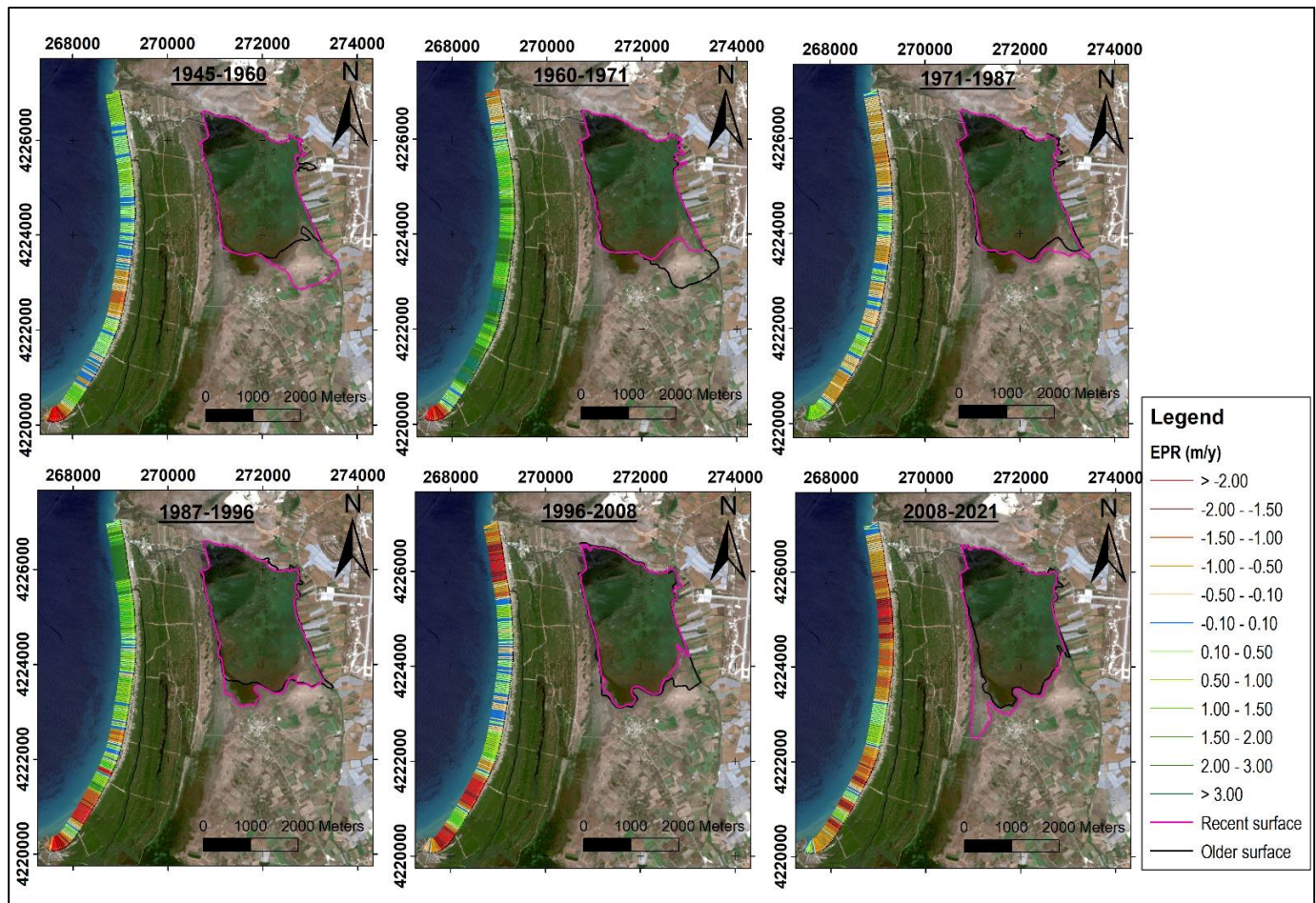
The multitemporal fluctuations in the lagoon morphology related to size, such as surface (SLAG), perimeter (PERI), and diameter (DMAX, DMIN), are presented in Figure 11. It is characteristic of the expansion of the water surface of the lagoon during the period 2016–2019, which corresponds to +35.80% (DSL) and +20.74% (DPERI), and its shrinkage during the last 3 years (2019–2021), corresponding to −9.31% (DSL) and −12.06% (DPERI). In addition, the southern region of the lagoon is constantly shrinking and expanding during the 1945–1987 period, while from 1987 to 2016, it seems that the water surface has been stabilized. From 2016, the fluctuations of the surface began to appear again, proving that the area is in a vulnerable hydrodynamic regime currently.



**Figure 11.** Multitemporal fluctuations in the Prokopos Lagoon. The gridded polygon represents the oldest surface, which is compared to the newer shoreline (blue line) at each time interval. Basemap of 2021.

### 5.2. Littoral Zone Evolution

The shoreline vectors of the coastal zone, extracted from all the available images, show that the coastline adjacent to the Prokopos Lagoon changes considerably during the period from 1945 to 2021. We estimated the rates of change for every past decade (1950, 1960, 1970, 1980, 1990, 2000, 2010, and 2020), based on the respective available data using the EPR method (Figure 12). The shoreline change rate (m/yr) for each past decade is presented in Table 3.



**Figure 12.** Diachronic shoreline changes using the EPR (m/yr) rates. Basemap of 2021.

According to Figure 12 and Table 4, the general pattern of the coastal zone evolution was divided into five stages.

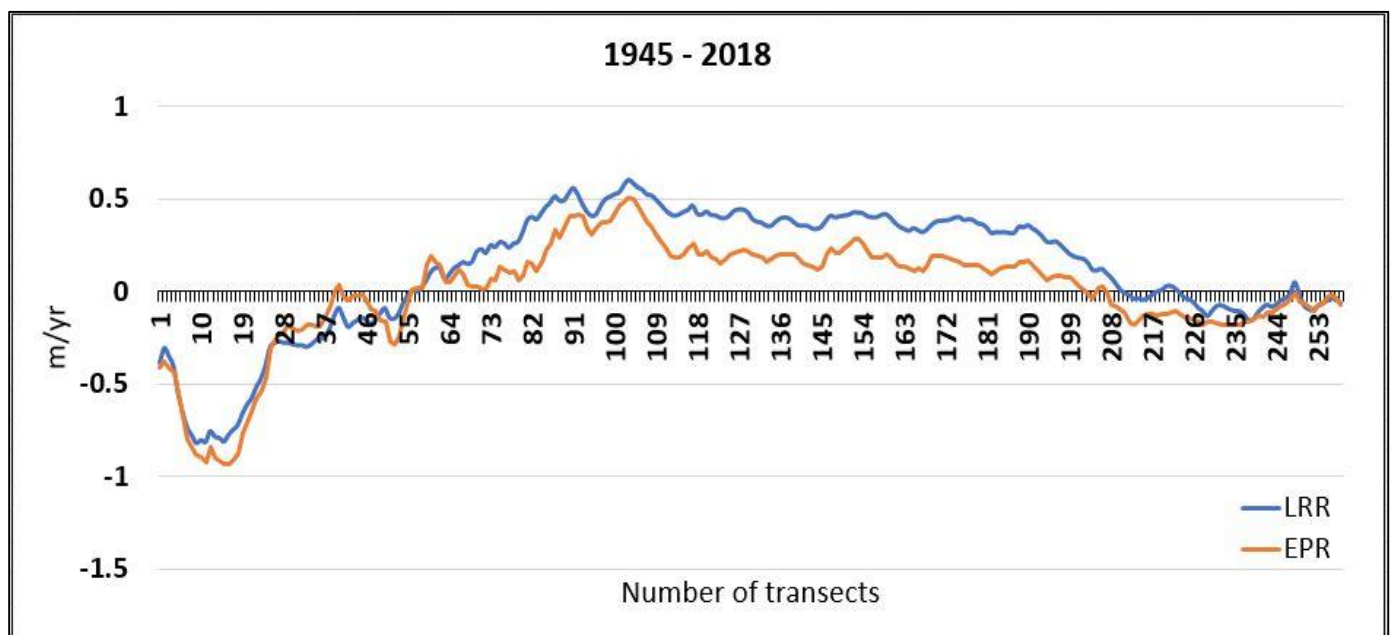
- The stable stage (1945–1960) as well as the mean EPR rate is 0.00 m/yr, while the maximum accretion rate is +1.49 m/yr, and the mean accretion rate is +0.40 m/y, while the maximum and the mean erosion rates are −2.24 and −0.67 m/yr, respectively,
- The rapid accretion stage (1960–1971) shows that the mean EPR rate is +1.13 m/yr, while the maximum accretion rate is +5.00 m/yr and the mean accretion rate is +1.64 m/yr, and the maximum and the mean erosion rates are −4.53 and −1.13 m/yr, respectively.
- The rapid erosion stage (1971–1987), corresponds to a mean EPR rate of −0.14 m/yr and a maximum and mean accretion rate of +2.92 and +0.49 m/yr respectively, while the maximum and the mean erosion rates are −1.43 and −0.50 m/yr, respectively.
- The rapid accretion stage (1987–1996) corresponds to a mean EPR rate of +0.34 m/yr and to a maximum and mean accretion rate of +3.24 and +1.07 m/yr respectively, while the maximum and the mean erosion rates are −2.97 and −1.22 m/yr, respectively.

- (e) The long erosion–accretion stage (1996–2008 and 2008–2021) is still active. During these two seasons, the mean EPR rates are  $-0.52$  and  $-0.71$  m/yr, while the maximum and mean accretion/erosion rates are similar in Table 3. This multiple variation of shoreline movement over time does not appear to be related to the corresponding changes that occurred on the shoreline of the lagoon. For instance, in the stable stage of the 1945–1960 period, the water surface of the lagoon was expanded at  $+19\%$ , while in the rapid accretion stage of the 1960–1971 period, the lagoon’s surface was shrunk at  $-13\%$ . In both cases, the shoreline showed a different trend in stability ( $0.00$  m/y) and accretion ( $+1.13$  m/y), proving that shoreline movement is not related to the lagoon’s water surface volume.

**Table 4.** Multitemporal shoreline change rate EPR (m/yr) in the Prokopos Lagoon.

| Period   | 1945–1960 | 1960–1971 | 1971–1987 | 1987–1996 | 1996–2008 | 2008–2021 |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| max+     | 1.49      | 5.00      | 2.92      | 3.24      | 1.36      | 1.00      |
| average+ | 0.40      | 1.64      | 0.49      | 1.07      | 0.43      | 0.41      |
| average− | −0.67     | −1.13     | −0.50     | −1.22     | −1.12     | −1.02     |
| min      | −2.24     | −4.53     | −1.43     | −2.97     | −3.24     | −2.77     |
| mean     | 0.00      | 1.13      | −0.14     | 0.34      | −0.52     | −0.71     |

For the 1945–2021 period, we estimated the rate of shoreline change (m/yr) using the EPR and the LRR methods. The LRR method considers all 15 years of shoreline-available positions, whereas the EPR considers only the youngest (2021) and the oldest (1945). Thus, the LRR method seems to be more reliable than the EPR (Figure 13).

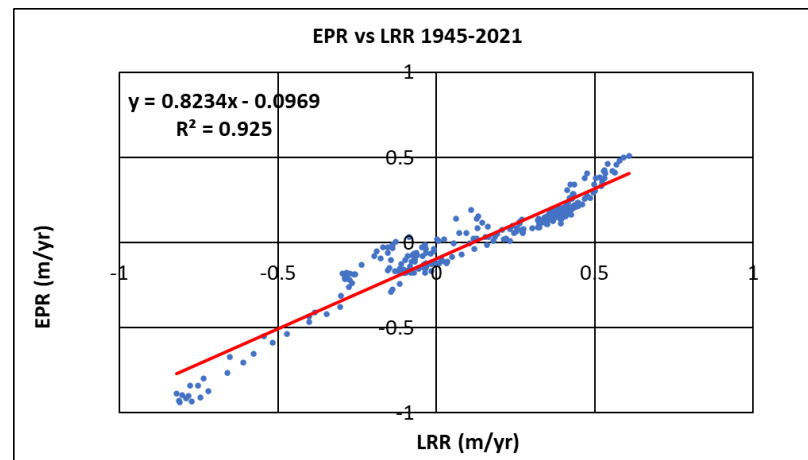


**Figure 13.** Erosion and accretion rates along the Prokopos Lagoon sea zone.

The LRR is a statistical tool and usually tends to show fluctuations regarding the rate of shoreline change relative to the EPR rate, as intermediate coastlines can affect the result. In the study area, significant fluctuations in the mean rate of change have been noticed, which are estimated at  $+0.34$  m/yr (accretion) and  $-0.25$  m/yr (erosion), while the maximum accretion and erosion rates are  $+0.60$  and  $-0.82$  m/yr, respectively.

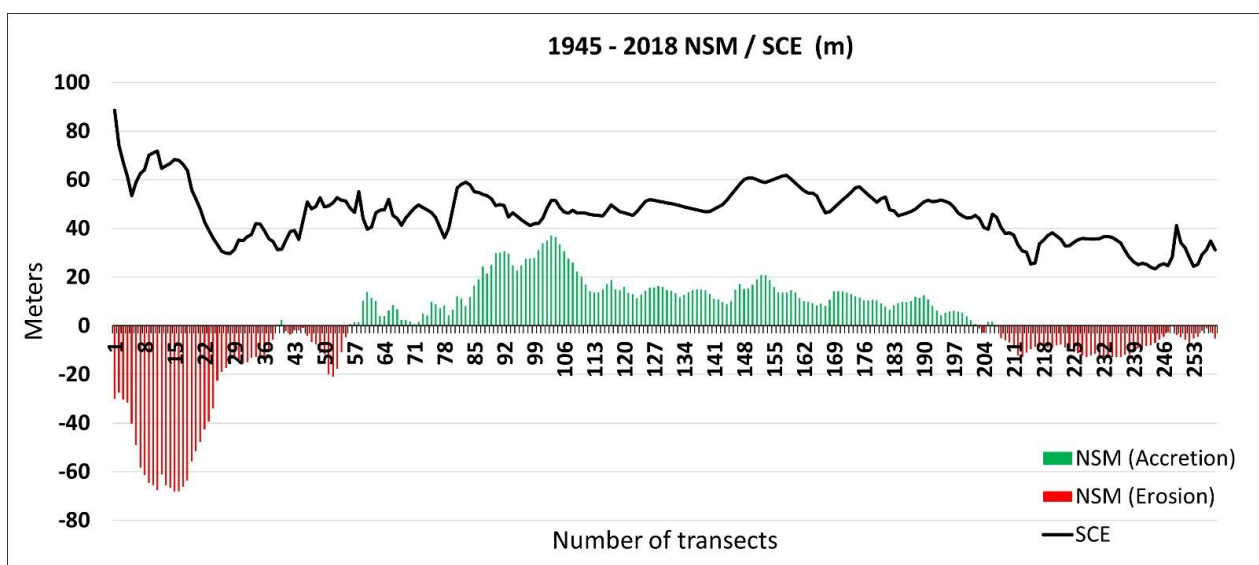
Conversely, the respective rates based on the EPR method are  $+0.18$ ,  $-0.26$ ,  $+0.50$  and  $-0.93$  m/yr. In addition, we tried a linear correlation per transect between the EPR and the LRR methods in order to validate the results (Figure 14). The  $R^2$  value from EPR vs. LRR was obtained to be 0.925, revealing good correlation among the two methods, which proves

that the factors that affect the position of the coastline remain the same as the previous ones, and thus, the statistics follow the facts.



**Figure 14.** Correlation of EPR and LRR change rates for all transects.

The net shoreline movement (NSM), as the EPR, considers only the youngest (2021) and the oldest (1945) shorelines and computes their distance for each transect. It differs from the EPR, as it is not a rate. In Figure 15, the NSM values are plotted with the respective SCE rates, as they are closely related. The NSM shows that the southern (transects 0–60) and the northern (transects 200–260) parts are in a state of erosion while the central segment (transects 60–200) is under accretion. The distance between the two shorelines significantly varies with a mean accretion value of +13.37 m and a mean erosion value of −18.90 m. In addition, the maximum rates of erosion and accretion are −68.25 and +37.13 m, respectively. The shoreline change envelope (SCE) highlights the greatest distance in each transect among all the shorelines imported into the geodatabase representing the highest net of the coast evolution not related to the shoreline's dates. The result reveals that during the study period, the mean SCE value is 46,13 m, while the trend of distance decreases from south to north (transect 1 to 260).

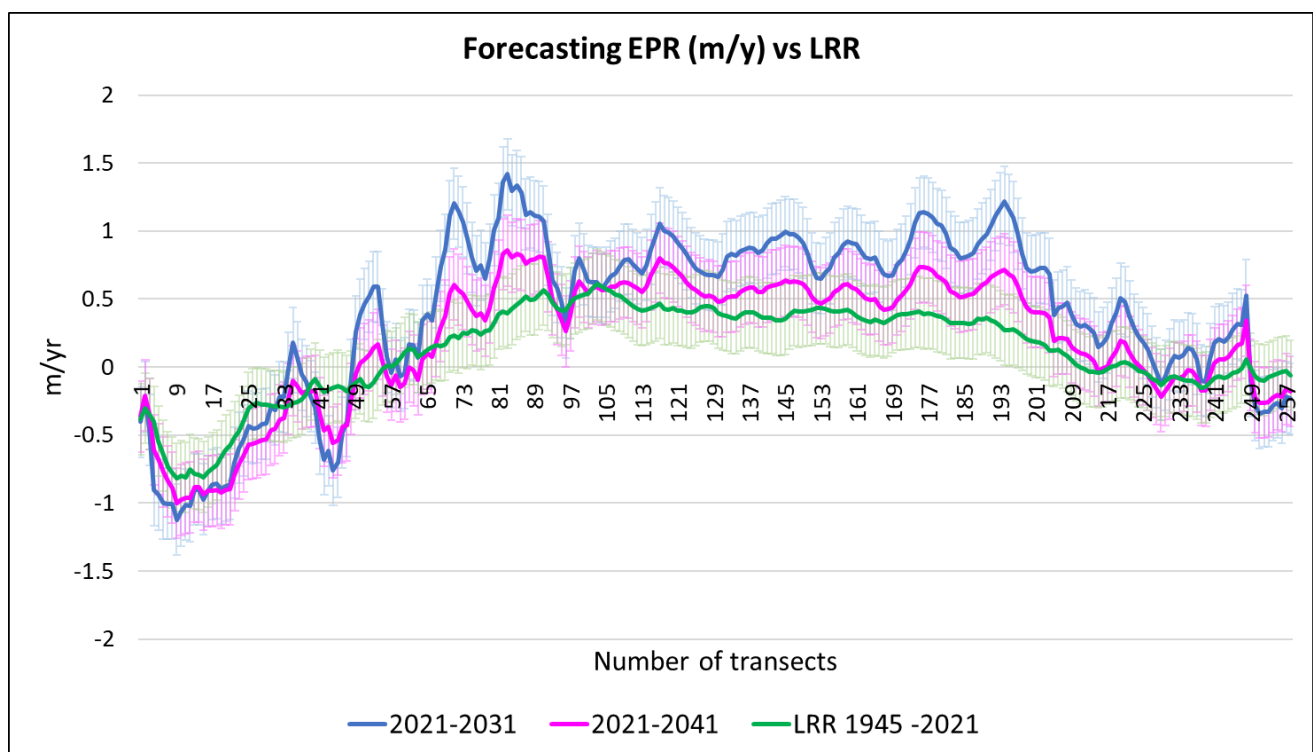


**Figure 15.** NSM rates showing erosion (red color) and accretion (green color) in conjunction with the SCE rates (black line) for the 1945–2021 period.

### 5.3. Shoreline Position Forecasting

As most of the SCE values are in an approximately constant range of 30 to 50 m, the DSAS forecasting method can provide reliable results [51] in conjunction with a high degree of correlation among the EPR and LRR rates [58].

Figure 16 shows that the general trend calculated via the LRR rates of the 1945–2021 period (LRR21—green line) is followed by the forecasted EPR rates of the 2021–2031 and 2021–2041 (EPR31 and EPR41), but at a higher rate of declination. In addition, as the period of 20 years is quite long, there is a more restrained appearance of change rates (purple line) in comparison to the line corresponding to a 10-year period (blue line). The prediction for the 2041 shoreline position is precarious, as there are many interval years without data, and thus, it is taken into account only for statistical reasons and will have to be re-evaluated over the years. In addition, the future shoreline of the 2041 position estimation is an automatic process of the DSAS, and as the coastline is a dynamic ecosystem characterized by frequent environmental disturbances and fluctuations, it is quite difficult for the natural factors that affect the future position of the coastline to remain stable for such a long period starting from 2021.



**Figure 16.** Forecasted EPR for the periods 2021–2031 and 2021–2041 vs. LRR (1945–2021). The prediction interval has been calculated at  $\pm 0.26$  m/yr.

Statistics such as the maximum, minimum, and mean EPR rates based on the forecasting of shorelines revealing erosion and accretion are presented, and they are compared to the respective LRR21 rates (Table 5). We found that the mean rate of change for 2021–2031 is predicted at  $+0.40$  m/yr, while for 2021–2041, it is estimated at  $+0.20$  m/yr. According to the forecast models, it seems that low accretion in general is expected to prevail in the area in the coming years.

In order to validate the results described above, we followed a linear regression analysis, and the statistical rates such as R-squared, RMSE, and MAE were estimated [59].

The R-squared correlation coefficient was 0.82 and 0.92 for the 2021–2031 and 2021–2041 periods, while the RMSE and the MAE were estimated at 0.31, 0.14, 0.19 and 0.09 m/yr, respectively (Table 6).

**Table 5.** Comparison of the forecasted EPR rates and LRR<sub>21</sub>.

| Rates    | EPR <sub>31</sub> (m/yr) | EPR <sub>41</sub> (m/yr) | LRR <sub>21</sub> (m/yr) |
|----------|--------------------------|--------------------------|--------------------------|
|          | 2021–2031                | 2021–2041                | 1945–2021                |
| max+     | 1.42                     | 0.86                     | 0.61                     |
| average+ | 0.69                     | 0.48                     | 0.34                     |
| average− | −0.49                    | −0.38                    | −0.25                    |
| min      | −1.12                    | −1.00                    | −0.82                    |
| mean     | 0.40                     | 0.20                     | 0.12                     |

**Table 6.** The estimated errors of the EPR correlation for the 2021–2031 and 2021–2041 periods compared to the 1945–2021 LRR rates.

| Estimated Errors | EPR <sub>31</sub> /LRR <sub>21</sub> | EPR <sub>41</sub> /LRR <sub>21</sub> |
|------------------|--------------------------------------|--------------------------------------|
| R <sup>2</sup>   | 0.82                                 | 0.92                                 |
| RMSE             | 0.31 m/yr                            | 0.14 m/yr                            |
| MAE              | 0.19 m/yr                            | 0.09 m/yr                            |

## 6. Discussion

In the present study, remote sensing techniques contributed to the computation of several critical parameters that managed the Prokopos Lagoon's water surface fluctuations for the 1945–2021 period. These parameters describe the lagoon's orientation and shape, its horizontal and vertical scales, and the potential sea influence. Moreover, using the statistical tools of the DSAS v5 beta software, an attempt to estimate the position of the future shoreline from 10 to 20 years beyond 2021 was made in order to investigate the impact of the lagoon's fluctuations in the evolution of the shoreline. The specific process was mandatory for the area, as there are no relevant previous studies.

As already mentioned, the Prokopos Lagoon is an important wetland situated in the north Peloponnese, which is protected by the Ramsar convention and significantly influences the local economy. Thus, the diachronic evolution of several critical parameters of the lagoon should be under constant monitoring.

The results reveal that for the last 3 years (2019–2021), the lagoon has yielded significant shrinkage corresponding to −9.31% and −12.06% of the surface and perimeter, respectively. It seems that the ecosystem has started to be destabilized and that it is vital to monitor and measure these parameters in the coming years.

Regarding the evolution of the coastline, its development was studied for each past decade, and it was found that its change is not related to the respective episodes of change of the lagoon's surface, which were expected, as the canal that connects the sea with the lagoon has a length of about 2.5 km.

In addition, the possibility of a correlation between the change in the littoral shoreline and the change in the lagoon's water surface was examined. In Table 7, multitemporal rates of change (%) in the water surface of the Prokopos Lagoon are presented.

**Table 7.** (%) Multitemporal rates of changes in the extension of the Prokopos Lagoon.

| Periods   | Area Change (Sq. km) |
|-----------|----------------------|
| 1945–1960 | 19%                  |
| 1960–1971 | −13%                 |
| 1971–1987 | 2%                   |
| 1987–1996 | 4%                   |
| 1996–2008 | −8%                  |
| 2008–2021 | 3%                   |

During the period of 1945–1960, the lagoon's ecosystem expanded at +19% and the corresponding process in the coastal zone was mainly from the deposition, with a mean

rate of +0.40 m/yr. Moreover, for the 1960–1971 period, the lagoon's water surface shrunk at a rate of −13%, and the deposition remained as the dominant littoral process, with a mean rate of +1.64 m/yr. Furthermore, for the following periods (1971–1987, 1987–1996, 1996–2008, and 2008–2021), the water surface showed several negligible fluctuations of +2%, +4% and −8%, respectively, which are not able to explain the fact that the shoreline revealed erosion and accretion regimes during these periods. It was proven that the adjacent shoreline development from 1945 to present is not related to the respective episodes of change of the lagoon's surface. These changes are due to the prolonged drought observed during this period.

The shoreline future movement for 2021–2031 (EPR31) and 2021–2041 (EPR41) was estimated. The mean rate of change for 2021–2031 is predicted at +0.40 m/yr, while for 2021–2041, it is estimated at +0.20 m/yr. According to the forecast models, we found that it is more possible for the erosion–accretion prediction cycle to be completed in 2031 rather than in 2041, almost 86 years since 1945.

Moreover, it was revealed that the coastal zone followed five stages of evolution: the stable stage (1945–1960) with a mean EPR rate of 0.00 m/yr, the rapid accretion stage (1960–1971) with a mean EPR rate of +1.13 m/yr, the rapid erosion stage (1971–1987) with a mean EPR rate of −0.14 m/yr, the rapid accretion stage (1987–1996), with a mean EPR rate of +0.34 m/yr, and the long erosion–accretion stage (1996–2008 and 2008–2021), which is still active. During these two seasons, the mean EPR rates are −0.52 and −0.71 m/yr.

Conversely, studying the entire period from 1945 to 2021, the NSM values show that the southern and the northern parts are in a state of erosion while the central segment is under accretion. The mean accretion value is +13.37 m, and the mean erosion value is −18.90 m, while the maximum rates of erosion and accretion observed were −68.25 and +37.13 m, respectively. The mean rate of change was estimated at +0.34 m/yr (accretion) and −0.25 m/yr (erosion), while the maximum accretion and erosion rates were +0.60 and −0.82 m/yr, respectively.

Such studies are limited worldwide [60,61], and although there are more than 400 coastal lagoons in the Mediterranean region [62], there are no relevant studies in the literature investigating the impact of the sea to the lagoon surface or vice versa, including the wider area of west Peloponnese. Moreover, there are several studies in the broader area regarding the spatiotemporal changes of the lagoon's sedimentation [26,63,64] but there are no such studies regarding the relationship between the shoreline changes and the Prokopos Lagoon spatiotemporal expansion changes for the 1945–2021 period.

In the future, we aim to apply the current method to the other lagoon ecosystems of western Peloponnese and especially to those that are adjacent to the sea, to thus create a valuable database with spatiotemporal parameters that reveal the alterations of the lagoons' surfaces in order for the authorities to be able to act in time when the ecosystem indicates that it is losing balance.

## 7. Conclusions

This study monitored the spatiotemporal changes of the surface water of the Prokopos Lagoon. Several morphometric parameters and indices related to the geomorphologic features were calculated and analyzed. According to the results, the Prokopos Lagoon is isolated from the open sea (Chocked), elongated in the parallel-to-shore direction. The adjacent shoreline development was studied from 1945 to the present and found that its changes are not related to the respective episodes of change in the lagoon's surface. Moreover, based on statistical models, we found that in the coastal area, the erosion–accretion cycle is active and is predicted to be completed in 2031, almost 86 years since 1945.

Given that lagoons are important ecosystems, their diachronic evolution should be under constant monitoring. Using remote sensing techniques, alterations in critical parameters could be measured and applied for the protection of the area. Remote sensing techniques in conjunction with DSAS v5.0 could provide reliable results regarding the monitoring of the alterations in critical parameters that have affected the long-term shoreline changes at

the Prokopos Lagoon coast as well as an overview of the erosion–accretion that occurred for the last nine decades. In addition, the future seaside shoreline trend could be measured in an efficient way.

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