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Applying the kalman filter model to forecast shoreline positions: A case study in Şile, İstanbul

Kıyı çizgisi pozisyonlarını tahmin etmek için kalman filtresi modelinin uygulanması: Şile, İstanbul örneği

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ABSTRACT/ÖZ

Coastal zones are remarkably productive and diverse environments on Earth, yet they are also highly vulnerable ecosystems. Therefore, examining both temporal and spatial variations in shorelines, as well as forecasting future shoreline position, is critical for ensuring the sustainability of coastal zones. In this study, historical shoreline change of the Şile (between western part of Şile port and eastern part of the Kumbaba Beach) was analyzed using End Point Rate (EPR), Net Shoreline Movement (NSM), and Linear Regression Rate (LRR) statistics of Digital Shoreline Change Analyses System (DSAS). Future shoreline forecasting was estimated using Kalman Filter method within DSAS tool. To analyze the historical shoreline changes in Şile, 18 shoreline data sets were generated from Google Earth Pro spanning the period from 2002 to 2021. The statistical result of the study indicates that the maximum shoreline progression of Şile between 2002 and 2021 was 41.3 m for NSM and 2.6 m/yr for LRR, while the maximum shoreline regression was -26.2 m for NSM and -1.3 m/yr for EPR. The projected future shoreline for Şile suggests that the most substantial shoreline advancement is anticipated to occur between 2031 and 2041, particularly in designated areas such as zone I, zone II, and zone III. Conversely, significant shoreline regression is forecasted to transpire in zone IV during the same periods. As a result, the shoreline of Şile has witnessed notable shoreline alterations throughout its history, and it is expected to continue experiencing significant changes in the future.

Kıyı bölgeleri, yeryüzünün en verimli ve çeşitli alanlarıdır, fakat aynı zamanda oldukça kırılgan bir ekosisteme sahiptir. Bu nedenle, kıyı şeritlerindeki hem zamansal hem de mekânsal değişimlerin incelenmesi ve gelecekteki kıyı şeridi konumunun tahmin edilmesi, kıyı bölgelerinin sürdürülebilirliğinin sağlanması açısından kritik öneme sahiptir. Bu çalışmada Şile'nin tarihsel kıyı şeridi değişimi (Şile limanın batısı ve Kumbaba Plajının doğu kıyısı), Dijital Kıyı Şeridi Değişim Analiz Sisteminin (DSAS), Uç Nokta Oranı (EPR), Net Kıyı Şeridi Hareketi (NSM) ve Doğrusal Regresyon Oranı (LRR) istatistikleri kullanılarak analiz edilmiştir. Gelecekteki kıyı şeridi tahmini, DSAS aracındaki Kalman Filtresi yöntemi ile belirlenmiştir. Çalışma sahasının tarihsel kıyı çizgisi değişiminin belirlenmesinde, 2002 ve 2021 yılları arasında Google Earth pro uydu görüntülerinden üretilmiş 18 veri setinden yararlanılmıştır. Çalışmanın istatistiksel sonucu Şile'nin 2002–2021 yılları arasında maksimum kıyı şeridi ilerlemesinin NSM için 41.3 m ve LRR için 2.6 m/yıl olduğunu, maksimum kıyı şeridi gerilemesinin ise NSM için -26.2 m ve EPR için -1.3 m/yıl olduğunu göstermektedir. Şile için öngörülen gelecekteki kıyı şeridi, en önemli kıyı şeridi ilerlemesinin 2031 ile 2041 yılları arasında, özellikle bölge I, bölge II ve bölge III gibi belirlenmiş alanlarda gerçekleşecektir. Tersine, aynı dönemlerde IV. bölgede kıyı şeridinde önemli bir gerilemenin meydana geleceği tahmin edilmektedir. Sonuç olarak, Şile kıyı şeridi tarihi boyunca önemli kıyı şeridi değişikliklerine sahne olmuştur ve gelecekte de önemli kıyı değişikliklerinin yaşanmaya devam etmesi beklenmektedir.

1. Introduction

Coasts are highly dynamic natural formations, subject to constant change driven by a combination of natural forces and human activities (Aydın & Uysal, 2014). Throughout history, human societies have frequently gravitated to coastal areas due to their favorable conditions for industrial, agricultural and recreational activities (Ferreira et al., 2021; Özyurt & Ergin, 2009). Currently, over 2 billion individuals, constituting 25% of the global population, live within 100 kilometers of coastlines, which is three times greater than the world's average population density (Ferreira et al., 2021). The world's multifunctional, dynamic coastal ecosystems are under severe stress due to population growth, urbanization, sea level rise and climate change (Jangir et al., 2016; Santos et al., 2021; Shailesh Nayak, 2002).

The shoreline is one of the most dynamically evolving features of the coastal region (Saranathan et al., 2011). The natural factors effecting shoreline change are waves, winds, tides, sea level change, tsunamis, periodic storms, (Anthony, 2015; Deepika et al., 2014; Di Stefano et al., 2013; Muskananfola & Febrianto, 2020; Nazeer et al., 2020; Selvavinayagam, 2008) while the anthropogenic factors are construction of breakwaters, groins, sand mining, domestic and industrial effluents, dredging of navigation channels, jetties, and recreational activities (Deepika et al., 2014; Di Stefano et al., 2013; Muskananfola & Febrianto, 2020). Both natural and anthropogenic factors have contributed to the erosion and accretion process in the coastal area, resulting in shoreline changes over short and long time periods (Muskananfola & Febrianto, 2020).

Shoreline analyses play a crucial role in understanding the morpho-dynamics of coastal zones by detecting erosion and accretion (Armenio et al., 2019; Chrisben Sam & Gurugnanam, 2023). The use of remote sensing techniques, such as satellite images, and Geographic Information System (GIS) integrated with Digital Shoreline Analysis System (DSAS), improves the accuracy and effectiveness of delineating both long-term and short-term shoreline changes (Chrisben Sam & Gurugnanam, 2022; Mahapatra et al., 2014; Roy et al., 2018; Yan et al., 2021) and predicting future shoreline positions. The DSAS technique is widely employed for estimating shoreline changes due to its use of statistical data (Acharyya et al., 2023; Bheeroo et al., 2016; Chrisben Sam & Gurugnanam, 2022; Nassar et al., 2019; Obiene et al., 2022; Siyal et al., 2022; Uzun, 2023). DSAS is an accessible software application that operates within GIS software and computes rate-of-change statistics using a time series of shoreline vector data (Himmelstoss et al., 2021). Furthermore, the beta forecast within DSAS provides insights for predicting future shorelines using the Kalman filter method (Himmelstoss, et al., 2018; Himmelstoss et al., 2021).

In recent years, numerous studies have been conducted to predict future shorelines (Chrisben Sam & Gurugnanam, 2022; Farris et al., 2023; Kazı & Karabulut, 2023; Kılar & Çiçek, 2019; Koç & Baş, 2023; Mishra et al., 2023; Natarajan et al., 2021; Nijamir et al., 2023; San & Ulusar, 2018). For example, Chrisben Sam & Gurugnanam (2022) used the DSAS tool to analyze shoreline change along India's southern coast from 1980 to 2020 and forecast shoreline for 2030 and 2040. The study indicates that Inayam, Periyakattuthurai, and Kodimunai are projected to shift inland by 170 m, 157 m, and 145 m respectively by 2030. By 2040, these shifts are anticipated to increase to 194 m, 182 m, and 165 m for Inayam, Periyakattuthurai, and Kodimunai respectively. Farris et al. (2023) used sparse data to test two methods for forecasting shoreline change over decadal time scales: extrapolation of linear regression (ELR) and Kalman filter. At the end of the study, both methods produced similar results, with regionally averaged forecast accuracies ranging from 5 to 16 meters. Furthermore, Mishra et al. (2023) examined the short-term and long-term shoreline changes along the Odisha coast and predicted the future shoreline position for 2050. According to the statistical findings of the study, approximately 55.85% of the transects will exhibit accretion by 2050, with the remaining 44.15% expected to experience erosion or maintain a constant trend.

The objective of this study is to analyze the historical shoreline changes of Şile and forecast the future shoreline position using the Beta Shoreline Forecasting within DSAS tool. The historical shoreline change of the Şile from 2002 to 2021 was analyzed by using End Point Rate (EPR), Net Shoreline Movement (NSM), and Linear Regression Rate (LRR) statistics from the DSAS tool. The future shoreline forecasting for Şile was estimated using the Beta Shoreline Forecasting tool within the DSAS software, employing the Kalman Filter model. This research aimed to address the existing gap in the literature concerning the spatial and temporal changes in the shoreline of Şile. Moreover, the shoreline of Şile has undergone notable natural and anthropogenic alterations in recent years. As a result, conducting historical shoreline analyses and predicting future changes is essential to bridge this gap in the literature and enhance the sustainability of the coast.

2. Study Area

Şile is located in northwest Turkey, 71 kilometers from Istanbul, and covers an area of 735 km^2. Şile has a maximum elevation of 357 meters and 90% of its area is covered by forests and shrubs (Tuzlacı & Tolon, 2000). The study area is located in the western side of Şile port, stretching from the eastern part of Kumbaba Beach, covering a shoreline distance of 3 kilometers between coordinates 41°10'31.11"N-29°36'13.50"E and 41°10'21.94"N-29°34'11.32"E (Figure 1). The Türnil River is an important water resource in the study area, shaping and effecting the coastal morphology. Furthermore, the study area has transitional climatic characteristics, combining aspects of the Mediterranean climate, which is distinguished by hot, dry summers and mild, rainy winters, with elements of the Black Sea climate, which is known for its humid and mild conditions throughout the year. The coast of Şile is exposed to north sectoral winds, such as those from the Northeast, Northwest, and due North, with the prevailing wind direction being Northeast. In Şile, the annual average temperature is 13.6°C, with 788.8 mm of precipitation (İncekara, 2001). The coast of Şile was characterized by ecologically rich yet fragile ecosystem. Hence, natural and anthropogenic factors leading shoreline change will profoundly affect coastal morphology. In recent years, numerous natural and anthropogenic factors were observed along the coast of Şile. Therefore, determining the temporal and spatial changes of the shoreline in Şile, as well as identifying the factors causing these changes, is crucial for the sustainability of the study area.

Figure 1. Study area location map.

3. Data and Methodology

3.1. Shoreline Data

The shoreline of the Şile was extracted from the Google Earth pro, which is increasingly utilized in various studies for shoreline extraction purposes (Awad & El-Sayed, 2021; Dang et al., 2022). Google Earth is a valuable data source that provides easy access to high-resolution images at resolutions of up to 0.3 m-1 m (Awad & El-Sayed, 2021; Dang et al., 2022; Malarvizhi et al., 2016). This study examined spatial and temporal shoreline change along the coast of Şile spanning from 2002 to 2021, employing 18 sets of historical shoreline data (Table 1). The historical shoreline data of the study area was acquired from Google Earth Pro using digitization techniques, and subsequently, it was transferred to the ArcGIS 10.4 program as a KMZ file. The historical image archive of Google Earth Pro offers 18 high-quality images of the coast of Şile, covering the period from 2002 to 2021. By delineating the historical shoreline of the study area, the datasets were prepared following the guidelines of DSAS 5.0 version.

In this section of the study, the initial baseline layer was created on the landward side of the study area, followed by the generation of transect layers at 5-meter intervals intersecting shoreline data. In the final segment of the study, the historical shoreline of the study area was examined using the EPR, NSM, and LRR statistics provided by the DSAS program.

Additionally, projections for the future shoreline of the study area were interpreted for 2031 and 2041 utilizing the Kalman Filter method within the DSAS tool.

Table 1. Shoreline date.

Shoreline acquisition date	
09/29/2002	09/20/2017
03/31/2009	08/10/2018
08/24/2011	09/18/2018
10/25/2012	05/29/2019
12/26/2012	07/29/2019
10/21/2013	02/26/2020
08/14/2015	07/24/2020
06/01/2016	06/04/2021
04/25/2017	08/27/2021

3.2. Shoreline Data

The shoreline of Şile was analyzed by using EPR, NSM and LRR statistics of DSAS tool. DSAS is a free software application that integrates with GIS. DSAS can calculate rate-of-change statistics from a time series of shoreline vector data (Himmelstoss et al., 2018; Himmelstoss et al., 2021). EPR is determined by dividing the distance of shoreline movement by the time elapsed between the oldest and the most recent shoreline (Himmelstoss et al., 2021). The formula for the EPR can be described as:

$$EPR = \left\{\frac{d_{2021} - d_{2002}}{t_{2021} - t_{2002}}\right\}$$

NSM refers to the distance between the oldest and youngest shorelines observed for each transect (Himmelstoss et al., 2018; Himmelstoss et al., 2021). The formula for NSM is:

$$NSM = \{d_{2021} - d_{2002}$$

A linear regression rate of change statistic can be calculated by fitting a least-squares regression line to all shoreline points along a transect (Himmelstoss et al., 2021). After computing the historical shoreline changes along the coast of Şile, shoreline forecasting calculations are performed using the Kalman filter. A new feature introduced in DSAS v5 allows for the calculation of a forecasted shoreline position, projecting either 10 or 20 years into the future, based on historical shoreline position data. The DSAS Kalman filter approach starts with the linear regression rate calculated by DSAS and then estimates shoreline position and rate of change every tenth of the year, providing an estimate of spatial uncertainty at each time step (Himmelstoss et al., 2021).

The Kalman filter computes the shoreline position at the next time step using the following formula (Farris et al., 2023).

$$Y(t + dt) = Y(t) + m \cdot dt$$

In the equation, Y(*t*) represents the shoreline position at time *t*, and *t* denotes the shoreline change rate in meters per year. The timestep, *dt*, is set to 0.1 years (Farris et al., 2023).

4. Result and Discussion

4.1. Historical Shoreline Change Analysis

The shoreline dynamics of the Şile was analyzed by EPR, NSM and LRR statistics of DSAS tool, spanning from 2002 to 2021. The statistical results of the study indicate that the maximum shoreline progression in the Şile was 41.3 m for NSM, 2.1 m/yr for EPR and 2.6 m/yr for LRR, whereas the maximum shoreline regression was -26.2 m for NSM, -1.3 m/yr for EPR and -1.03 for LRR (Table 2). Moreover, over the 19-year period, the most significant shoreline erosion was observed on the western side of Şile port, whereas the greatest shoreline accumulation occurred along the Türknil River coast (Figure 2). In Figure 3, shoreline changes along the coast of Şile were indicated based on transect numbers, which were created in 5 meter intervals. Transects numbers 1–100, situated in the western section of Şile Port, exhibit a notable shoreline regression trend, marked by an average rate of -14.8 m for NSM and 0.7 m/yr for EPR. Additionally, transects numbers 354–654, tracing the Türknil River shoreline, demonstrate an average shoreline progression rate of 22.6 m for NSM and 1.1 m/yr for LRR (Figure 3). As a result, between 2002 and 2021, the western part of Şile port and the mouth of the Türknil River experienced the most significant shoreline changes. The sediment transported by the Turknil River caused accumulation and leading to shoreline advancement on the coast of Şile. Conversely, regions with lower sediment deposition, like the western part of the Şile port, underwent erosion. Another significant factor influencing coastal erosion on the eastern side of the study area is the construction of the Şile port. The coastal structure along shoreline disrupt natural processes in the study area and contribute to coastal erosion. Furthermore, Şile boasts a distinctive natural landscape with its Neogene formation sand dunes. The coastal sand dunes located between Ağva and Şile, around Kurfallı, Sofular, Karacaköy, Teke and on the hills between Şile-Çayırbaşı, Sofular-Avcıkoru villages, Şile-Ömerli. In recent years, sand and clay quarry operations have degraded Neogene sand deposits, causing anthropogenic changes on the coast and disrupting coastal ecology (Ertek, 2016).

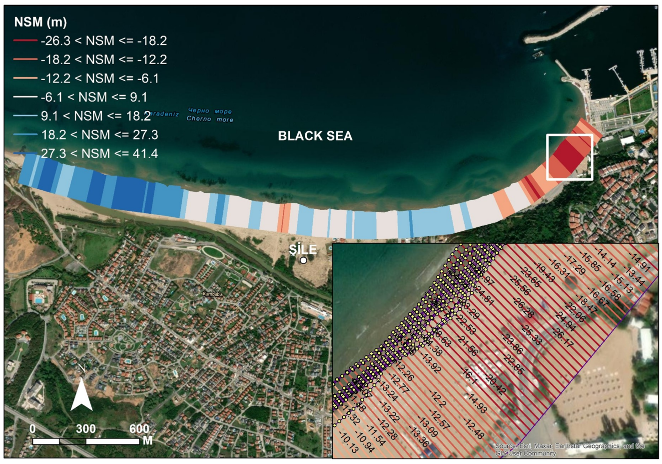

Figure 2. Net Shoreline Movement (NSM) statistics for 2002 and 2021.

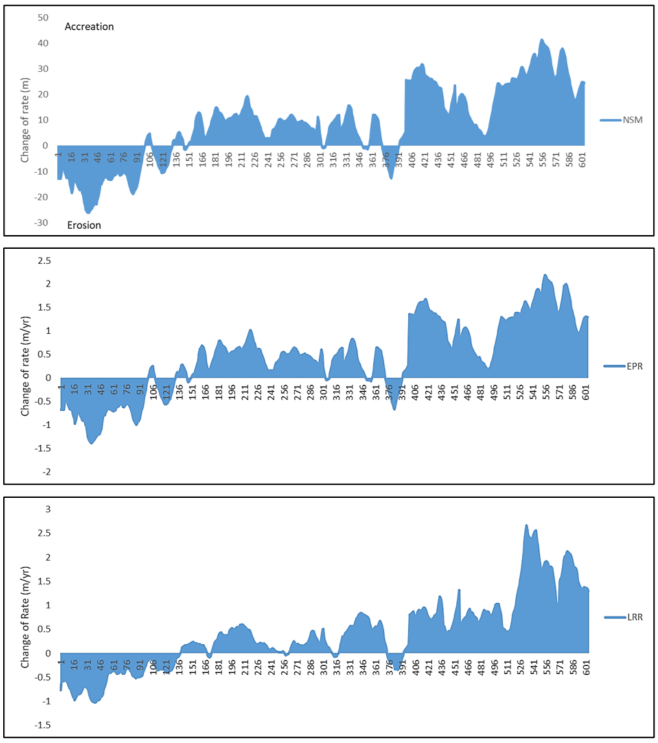

Figure 3. Shoreline change statistics for 2002 and 2021.

4.2. Future Shorelines Forecasting of Şile for 2031 and 2041

The future shoreline prediction of the Şile was determented by the Kalman filter method held in DSAS version 5.0 (Himmelstoss et al., 2021). The shoreline prediction analyses for the Şile highlight that the most substantial regression and progression will be observed at four specified locations, labeled as:

Table 2. Shoreline change statistics from 2002 to 2021.

Statistics	EPR			NSM			LRR		
	Average	Max.	Min.	Average	Max.	Min.	Average	Max.	Min.
2002–2021	0.4	2.1	-1.3	8.2	41.3	-26.2	0.3	2.6	-1.03

Figure 4. Future shoreline prediction for 2031 and 2041.

zone I, zone II, zone III, and zone IV. Additionally, the analysis indicates that within the designated zones, zone I, zone II, and zone III will undergo notable shoreline advancement, while zone IV is expected to experience significant shoreline regression between 2031 and 2041. By 2031, the maximum shoreline advancement is projected to reach 36.7 meters for zone I, 45.6 meters for zone II, and 9.9 meters for zone III, while the maximum shoreline recession is anticipated to be -14.1 meters for zone IV. By 2041, the maximum shoreline advancement is forecasted to reach 55.8 meters for zone I, 75.7 meters for zone II, and 16.5 meters for zone III, whereas the maximum shoreline recession is expected to be -26.1 meters for zone IV (Figure 4). As a result, the shoreline forecasts for Şile in 2031 and 2041 indicate that the most significant shoreline changes will occur along the mouth of the Türknil River and the western section of the Şile Port. Additionally, the future shoreline morphology of the Şile will be shaped by sediment, currents, and coastal structures.

5. Conclusion

The historical shoreline changes in Şile were examined spanning from 2002 to 2021, with future forecasts projected up to 2031 and 2041. The historical shoreline analysis was conducted utilizing EPR, NSM, and LRR statistics provided by DSAS, which operates within GIS software. Moreover, the future forecasting of the shoreline was conducted using the Beta Shoreline Forecasting within DSAS, utilizing the Kalman Filter method. The statistical findings of the study are as follows:

- Between 2002 and 2021, the maximum shoreline progression in Şile was recorded at 2.1 m/yr for EPR and 41.3 m for NSM. Conversely, the maximum shoreline recession during this period was -26.2 m for NSM and -1.03 m/yr LRR.

- For the shoreline forecasting of 2031 and 2041, the maximum shoreline progression was observed in zone I, zone II, and zone III, while the maximum shoreline recession was observed in Zone IV.

Consequently, the shoreline of Şile is highly dynamic, having experienced significant changes throughout its history and continuing to do so in the future. The temporal and spatial shoreline changes in the study area are caused not only by natural factors but also, to a greater extent, by anthropogenic issues. For example, the construction of the Şile harbor is among the most significant factors affecting the wave and current processes of the study area. Additionally, changes in flow and sediment rates due to anthropogenic practices are another factor affecting the coastal processes of Şile. Furthermore, the operation of sand quarries in the study area also contributes to the anthropogenic changes in the shoreline. As a result, analyzing spatial and temporal shoreline change of Şile and forecasting its shoreline position are essential for making effective decisions and contributing to its sustainability.

Conflict of Interest/ *Çıkar Çatışması:* : Yazarlar arasında herhangi bir çıkar çatışması bulunmamaktadır. *The authors declare that there is no conflict of interest.*

Author contribution/ *Yazar Katkısı:* Conceptualization, data curation, methodology, software, writing original draft preparation were done by H. K.; conceptualization, visualization, evaluation, reviewing and editing, arrangement were done by O. A. *Bu çalışmanın kavramsallaştırma, veri küratörlüğü, metodoloji, yazılım, özgün taslak hazırlaması H. K tarafından; kavramsallaştırma, görselleştirme, değerlendirme, gözden geçirme ve düzenleme ise O. A. tarafından yapılmıştır.*

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