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Satellite-Based Monitoring of Surface Coastal Water Quality Using Sentinel-2 Images from OCEANIDS Data Cubes: A Case Study of the Coastal Zone of Heraklion, Crete

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Highlights

What are the main findings?

- The spatiotemporal analysis of the NDCI and NDTI revealed strong seasonal variability regarding water quality in the Heraklion coastal zone, with higher index values in winter and close to river estuaries and the port.
- The Karteros zone presented the highest seasonal variability and hotspot-persistent areas with the highest NDCI values, emerging as a priority area for further environmental monitoring and management.

What are the implications of the main findings?

- The satellite-derived spectral indices (NDCI, NDTI) proved useful relative indicators for identifying seasonal and spatial patterns of surface coastal water quality variability in a data-limited area.
- Hotspot persistence analysis and spatial correlation could support prioritization of coastal areas with environmental pressures and decision-making for sustainable coastal zone management.

Abstract

Coastal waters are vulnerable ecosystems that are increasingly affected by sediment and nutrient inputs, as well as pollution resulting from both natural processes and anthropogenic pressures. Monitoring the pattern of chlorophyll-a and turbidity is essential for understanding the dynamics of coastal ecosystems and supporting environmental management. This study investigates the spatial and seasonal patterns of water quality in the coastal zone of Heraklion, Crete (Greece), for the period 2016–2024 using OCEANIDS Data Cube products (GA 101112919). Water quality variability was assessed using satellite-derived spectral indices, including the Normalized Difference Chlorophyll Index (NDCI) and the Normalized Difference Turbidity Index (NDTI). Monthly observations were analyzed using a GIS-based workflow to assess seasonal spatiotemporal variability. The results revealed strong seasonal variability, with higher winter NDCI values in all coastal zones and persistent hotspots concentrated near river estuaries and waters influenced by port activities. Meanwhile, the analysis was used to prioritize the region for further monitoring and to support decision-making for stakeholders. In summary, this study demonstrates the potential of OCEANIDS Data Cube products (NDCI, NDTI) for long-term monitoring of surface coastal water quality in a Mediterranean environment with limited data and supports evidence-based coastal management.

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1. Introduction

Coastal zones are highly dynamic and environmentally sensitive ecosystems in which natural and anthropogenic processes interact across various spatiotemporal scales [1]. Coastal water quality is influenced by multiple factors, such as river runoff, urban runoff, port activities, and, more specifically, nutrient inputs from agriculture, the transport of suspended particulate matter (SPM) from rivers, and climate variability. Industrial development, increasing urbanization, and the intensification of anthropogenic pressures on coastal areas often lead to the degradation of water quality and increased environmental risk for marine ecosystems as well as humans [2]. Seasonal precipitation and riverine runoff strongly influence nutrient delivery, phytoplankton dynamics, and total suspended solids transport in coastal waters [3,4]. As a result, this degradation directly affects biodiversity, fishing activities, tourism, and the ecosystem services provided by coastal ecosystems, while simultaneously increasing the costs of managing and restoring degraded waters [1,2].

The assessment of coastal water quality is typically conducted using a combination of physicochemical and biological variables, such as turbidity, suspended sediment concentrations, dissolved oxygen, nutrients, and chlorophyll-a concentration [2,5]. Among these variables, chlorophyll-a is widely used as an indicator of phytoplankton biomass and relates to the phenomenon of eutrophication, while turbidity reflects sediment transport and suspended particulate matter dynamics [6]. Continuous and effective monitoring of water quality is a fundamental prerequisite for the sustainable management of coastal areas and ecosystems, according to European Commission Directive 2008/56/EC [7].

The development of Earth Observation (EO) satellite missions has contributed significantly to the monitoring of coastal ecosystems [8]. Specifically, the Copernicus Program's Sentinel-2 mission provides high-resolution (10 m) multispectral data with high revisit frequency and is suitable for coastal monitoring applications [2,9]. Sentinel-2 data have been used to analyze the spatial distribution of water quality parameters, estimating chlorophyll-a and suspended particulate matter (SPM) concentrations through empirical or semi-analytical algorithms, which typically require calibration and validation using concurrent in situ measurements to ensure the accuracy and reliability of the retrieved products [10,11]. In addition, Sentinel-2 includes "red-edge" bands specifically designed to capture subtle variations in vegetation and aquatic reflectance [2,9]. At the same time, Sentinel-2's capability to analyze long time series of satellite data allows for the investigation of long-term trends in water quality parameters as well as the identification of areas experiencing persistent environmental stress [12].

One approach to assessing water quality through remote sensing is the use of spectral indices designed to detect water quality parameters based on their spectral properties [2,13]. These indices exploit the different spectral responses of water constituents to provide information on chlorophyll concentration, turbidity, and other water quality parameters and are preferred due to their simplicity and operational applicability [13,14]. One of the spectral indices used in this paper is the Normalized Difference Chlorophyll Index (NDCI), which was proposed by [13] and has proven effective for detecting chlorophyll-related variability in turbid and productive coastal waters. On the other hand, the Normalized Difference Turbidity Index (NDTI), proposed by [14], is widely used as an indicator of turbidity and total suspended solids dynamics in coastal and estuarine environments. The NDCI and NDTI were selected because they can be calculated directly from Sentinel-2

reflectance bands without requiring local calibration datasets for their calculation, making them particularly suitable for coastal environments with limited in situ data [9,14,15]. Nevertheless, field observations are important for validating the interpretation of these spectral indices whenever such measurements are available.

In recent years, the rapid increase in the volume of EO data has led to the development of new infrastructure for managing and processing large geospatial time series [16]. Compared to conventional scene-by-scene processing, geospatial "data cubes" facilitate scalable analysis of long-term satellite records through harmonized and analysis-ready datasets, enabling the rapid and reproducible execution of large-scale spatiotemporal analysis [16,17]. The EU OCEANIDS (GA 101112919) project has developed a data infrastructure for coastal environments, providing harmonized Sentinel products as well as calculated environmental indicators in a format suitable for operational use and long-term analysis [17,18]. The project's objective was to develop technological tools tailored to the needs of end users to support relevant agencies in making decisions regarding the sustainable management of coastal and port areas [17,18].

Additionally, one of the pilot areas of the OCEANIDS project was the coastal zone of Heraklion, in Crete, which is a suitable case study for monitoring surface coastal water quality via satellite due to the combination of multiple anthropogenic pressures and complex hydrodynamic processes. The area is affected by urban runoff, port activities, river inflows, and heavy tourism, while previous studies have highlighted instances of eutrophication and hydrocarbon pollution linked to long-term anthropogenic pressures [19]. These characteristics make the area particularly suitable for monitoring and assessing coastal water quality to identify areas under persistent environmental stress.

Despite the routine water quality monitoring activities conducted by the responsible authorities according to European Commission Directive 2008/56/EC [7], the use of EO data cubes and spectral indices for operational coastal water quality monitoring remains relatively limited in the Eastern Mediterranean and, more specifically, in Greece. Most previous studies focus on retrieving individual water quality parameters through empirical or semi-analytical algorithms that require calibration and validation using in situ measurements [19,20]. Although spectral indices such as the NDCI and NDTI have been successfully applied in several coastal environments to assess chlorophyll-related variability and turbidity patterns [2,4,21], their combined use within an EO data cube framework for long-term coastal monitoring has not yet been reported for Greece and the Eastern Mediterranean. To the best of our knowledge, no published study has combined EO data cube products, long-term Sentinel-2 spectral indices (NDCI and NDTI), hotspot persistent mapping, and spatial hotspot statistics within a framework designed to prioritize coastal areas for targeted environmental monitoring. This represents an important gap, particularly in coastal regions where field observations are spatially and temporally limited.

This paper examines the spatial and seasonal variability of surface coastal water quality in the coastal zone of Heraklion, Crete, using satellite-based water quality indicators through the OCEANIDS Data Cubes. Rather than replacing conventional field monitoring, the proposed framework is intended as a complementary screening tool that can identify areas exhibiting persistent environmental stress and support the prioritization of targeted in situ sampling and monitoring activities. This study includes long-term spatiotemporal analysis (2016–2024), mapping of hotspot persistence, and spatial hotspot statistics within an integrated coastal monitoring framework aimed at prioritizing areas experiencing environmental stress and requiring complementary monitoring by the responsible authorities, supporting decision-making through OCEANIDS.

Specifically, this study aims to (i) assess the seasonal variability of the NDCI and NDTI during the 2016–2024 period; (ii) quantify the winter–summer differences in NDCI and NDTI

patterns; (iii) assess the relationship between rainfall and the variability of the NDCI and NDTI; (iv) identify persistent areas with high index values (hotspots); and (v) analyze the spatial clustering of these patterns using the Getis-Ord Gi* statistical method, thus contributing to the development of effective environmental monitoring strategies in coastal areas. This paper demonstrates the potential of OCEANIDS Data Cube products (NDCI and NDTI) as an operational and reproducible framework for identifying spatiotemporal patterns of coastal water quality variability, prioritizing areas for targeted field investigations, and supporting coastal management in regions with limited in situ observations.

2. Materials and Methods

2.1. Study Area

The study area is located along the northern coastline of Crete, Greece, covering the coastal zone of Heraklion between approximately 35.3147° N–35.3690° N and 25.1057° E–25.2210° E (Figure 1). This coastal area includes the port of Heraklion as well as the estuarine systems of the Giofyros and Karteros rivers, which play an important role in providing nutrients and suspended sediments in the coastal environment. The Giofyros estuary is particularly sensitive because it receives discharges from the Heraklion Wastewater Treatment Plant (WWTP), while the Karteros river contributes significant sediment and nutrient loads to coastal waters [22].

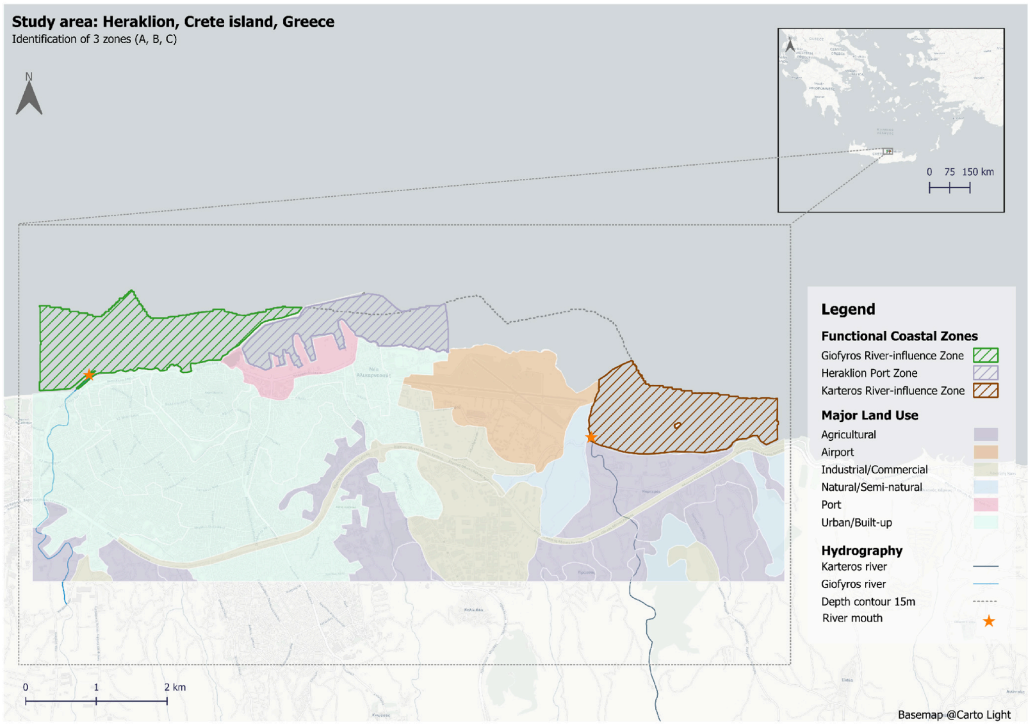


Figure 1. The study area in Heraklion, Crete, Greece, illustrating the delineation of the three functional coastal zones in this study.

The coastal zone of Heraklion is characterized by a Mediterranean climate of type Csa (Köppen–Gieger classification, C—Temperate, s—Dry Summer, a—Warm Summer), with hot, dry summers and relatively mild, wet winters. Precipitation is strongly seasonal, with most rainfall occurring in winter, while the summer months are generally characterized by prolonged dry conditions [23]. In addition, the coastal zone is often affected by strong northerly and northwesterly winds, especially during the summer (annual winds), which enhance the processes of water column mixing and sediment resuspension [24]. These

factors influence freshwater inputs, nutrient loading, and the distribution of suspended sediments in the coastal environment.

The port of Heraklion is one of the most active ports in the Eastern Mediterranean, supporting a wide range of activities, including passenger transport, cargo operations, cruise tourism, and shipyard services [19]. Previous studies have identified elevated nutrient concentrations, elevated chlorophyll-a levels, and local eutrophic conditions in the port associated with historical sewage discharges and urban runoff [25]. In addition, hydrocarbon pollution and recurrent oil spills associated with maritime activities have been recorded in the area [19,26]. Seasonal tourism, which is intense during summer, constitutes an additional source of environmental pressure on the coastal ecosystem [27].

Finally, the interaction of river inflows, port-related activities, urban development, tourism pressures and hydrodynamic processes lead to significant spatiotemporal variability in environmental conditions across the study area. Therefore, there is a need for further investigation of water quality and detection of degraded areas to support effective coastal management.

2.2. Datasets

The analysis was based on the satellite-derived spectral indices from Sentinel-2 A/B imagery for the period 2016–2024 and made available through OCEANIDS Data Cube infrastructure [17,18]. OCEANIDS Data Cube infrastructure provides harmonized Sentinel-2A/B Level-2A surface reflectance datasets with standard preprocessing and atmospheric correction procedures, ensuring consistency and comparability across long-term environmental analysis. Therefore, atmospheric correction had already been applied within the OCEANIDS preprocessing workflow before the products were incorporated into the data cube [17].

For the study period, 108 monthly Sentinel-2 observations were available for each indicator (NDCI, NDTI), corresponding to one monthly Sentinel-2 product representing one specific date within each month provided through the OCEANIDS Data Cubes for each month (twelve observations per year) at a spatial resolution of 10 m (Table 1). The NDCI and NDTI were extracted from the corresponding bands of these products. All datasets were stored in NetCDF format and organized within a common spatial and temporal reference framework [17].

Table 1. A description of the datasets used for the analysis, including data sources and spatial and temporal characteristics.

Dataset	Source	Spatial Resolution	Temporal Resolution	Period
Sentinel-2 NDCI & NDTI products	Geosystems Hellas S.A. [28]	10 m	Monthly	2016–2024
Bathymetry points	Region of Crete [29]	Point observations	Static	-
Rainfall records	HNMS [30]	Point observations (meteorological station)	Monthly	2017–2023

Within the OCEANIDS processing workflow, Sentinel-2 observations with cloud cover below 60% were retained for further processing. The OCEANIDS Data Cube consists of harmonized, analysis-ready NetCDF products generated from Sentinel-2 imagery through preprocessing steps including clipping, resampling, reprojection and the calculation of multiple spectral indices. Each monthly NetCDF product contains both the original Sentinel-2 spectral bands and a set of pre-computed environmental indicators (e.g., NDCI, NDTI, NDVI, NDWI) [28]. In the present study, the NDCI and NDTI datasets were extracted

directly from the corresponding bands of these analysis-ready products for the subsequent spatiotemporal analysis.

In addition, to complement the satellite-based analysis, bathymetric point data provided by the Region of Crete [29], were used to develop bathymetric contours, which were significant for delineating functional zones in the study area. Furthermore, monthly precipitation records for the period 2017–2023 obtained from the Hellenic National Meteorological Service (HNMS) [30] were incorporated to examine possible relationships between hydroclimatic conditions and the temporal variability of the NDCI and NDTI.

2.3. Methods

The methodological framework adopted in this study comprises four main stages: data acquisition, processing, analysis, and application, as summarized in Figure 2.

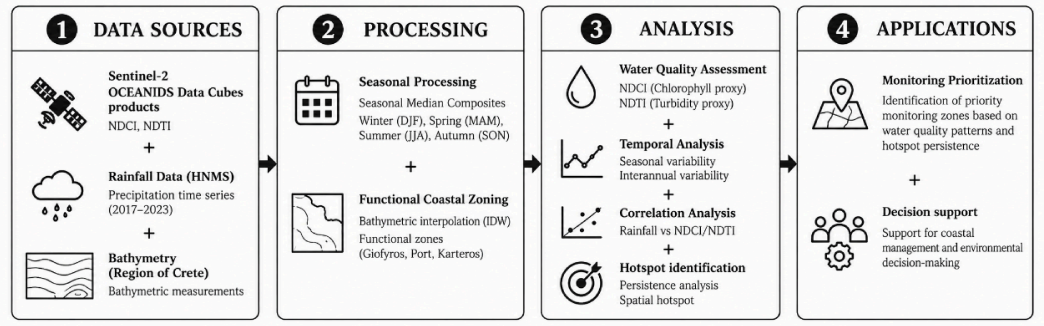


Figure 2. An overview of the methodological study workflow, including data acquisition, processing, analysis and applications.

All geospatial analyses were performed using QGIS (version 4.0.2), GRASS 8 GIS (version 2.12.99), and R (version 4.6.0).

2.3.1. Water Quality Indices

The NDCI (Normalized Difference Chlorophyll Index) and NDTI (Normalized Difference Turbidity Index) products were obtained directly from the OCEANIDS Data Cubes, where they were generated from harmonized Sentinel-2 A/B Analysis Ready Data (ARD) using the standard OCEANIDS processing workflows. Within this workflow, Sentinel-2 bands with different native spatial resolutions were harmonized to a common spatial grid through reprojection and resampling prior to the generation of the analysis-ready products and the calculation of the spectral indices [17,18].

The NDCI was used as a proxy for the variability associated with chlorophyll and phytoplankton biomass. The index exploits the spectrum of chlorophyll-a in the red and red-edge regions and is calculated from the Sentinel-2 bands B4 (664.5 nm) and B5 (703.9 nm) according to Equation (1):

$$\mathrm{NDCI} = \frac{\mathrm{B5} - \mathrm{B4}}{\mathrm{B5} + \mathrm{B4}} \quad (1)$$

NDCI values theoretically range from −1 to +1, with higher positive values indicating increased phytoplankton biomass [13]. The index has been widely applied to optically complex coastal waters due to its reduced sensitivity to suspended sediments and colored dissolved organic matter (CDOM) compared to conventional chlorophyll retrieval approaches [13,15].

Furthermore, the NDTI was used as an indicator of turbidity and suspended sediment dynamics. It is calculated from the green (B3, 560 nm) and red (B4, 665 nm) bands of Sentinel-2 according to Equation (2) and is based on the increase in water reflectivity associated with higher suspended particle concentrations.

$$\mathrm{NDTI} = \frac{\mathrm{B4} - \mathrm{B3}}{\mathrm{B4} + \mathrm{B3}} \quad (2)$$

The NDTI's values range from −1 to +1, with higher values corresponding to increased turbidity and suspended sediment loads [14]. The NDTI has been widely used in coastal and estuarine environments to monitor spatial and temporal variations in water clarity and sediment transport [14,31].

The combined use of the NDCI and NDTI enables simultaneous information on biological productivity and sediment-related processes in coastal waters. Both indices can be derived directly from Sentinel-2 surface reflectance products without requiring extensive local calibration datasets, which makes them particularly suitable for long-term monitoring in data-limited areas. The use of harmonized OCEANIDS products further ensured consistency and comparability throughout the study period, thereby supporting reproducible spatiotemporal analysis of surface coastal water quality dynamics.

2.3.2. Seasonal Composite Generation

Seasonal median composites were generated for the four meteorological seasons: winter (DJF), spring (MAM), summer (JJA), and autumn (SON), to minimize the effects of outliers, residual cloud contamination, and short-term environmental variability.

For each index (NDCI and NDTI), annual seasonal median rasters were generated for the period 2017–2024. Furthermore, long-term seasonal composites were also generated using the full 2016–2024 dataset. These products were obtained by first computing the monthly climatological median rasters for each calendar month and then aggregating them into seasonal median composites.

The seasonal analysis was conducted for the 2017–2024 period due to the limited number of available observations for 2016. All raster datasets were reprojected to WGS84/UTM Zone 35N (EPSG: 32635) and a sea mask was applied to exclude land pixels.

Median values were used instead of arithmetic means because they are less affected by outliers, residual cloud effects, and uncertainties associated with atmospheric correction, providing a more robust representation of seasonal conditions [32]. The resulting seasonal composite variables were used to examine and map the spatial distribution of the NDCI and NDTI across the study area.

2.3.3. Bathymetric Analysis and Functional Coastal Zoning

The bathymetric point data provided by the Region of Crete was imported into QGIS (version 4.0.2) and projected to the WGS84/UTM Zone 35N reference system. A bathymetric surface with a spatial resolution of 10 m was created using the Inverse Distance Weighting (IDW) interpolation method, using the depth values as the interpolation variable and a distance coefficient of 2. The distance coefficient 2 was preferred because it represents the most commonly adopted compromise between local detail preservation and surface smoothness [33].

The IDW method was chosen because the available bathymetric measurements were sparse and irregularly distributed, making more complex geostatistical approaches less suitable [31]. The objective of interpolation was the extraction of bathymetric contours required for the delineation of the study area's boundary and the functional zones. This process generated bathymetric contours at 5 m intervals, while the 15 m isobath was adopted as the offshore boundary of the functional zones. The selected 15 m isobath represents the shallow nearshore environment, where land–sea interactions and coastal processes are expected to be most pronounced.

The study area was subdivided into three functional zones: (i) Giofyros river-influenced zone, (ii) Heraklion Port zone, and (iii) Karteros river-influenced zone. The

functional coastal zones were developed to define marine assessment units affected by different terrestrial and coastal pressure sources within the nearshore marine environment and were therefore not intended to represent hydrological watershed boundaries. In particular, the locations of the Giofyros and Karteros river mouths were considered, as they represent the main pathways through which freshwater, sediment, and nutrient inputs may reach the adjacent coastal waters. These functional zones were defined to facilitate comparisons between coastal sectors influenced by different environmental pressures, including riverine inputs and sewage discharges (Giofyros) and port-related activities (Port), as well as freshwater inflows and fluvial sediment deposition (Karteros).

Furthermore, the lateral boundaries were determined considering shoreline geometry, the infrastructure of Heraklion Port, the locations of Giofyros and Karteros river mouths, the spatial extent of the available OCEANIDS analysis grid, and the dominant adjacent land use patterns derived from the CORINE Land Cover (CLC) 2018 dataset available through the Region of Crete GIS platform [32,34]. The original CLC 2018 classes were aggregated into six generalized land use categories (Agricultural, Industrial/Commercial, Natural/Semi-natural, Port, Urban/Built-up and Airport) to highlight the dominant terrestrial pressure sources adjacent to each functional coastal zone (Figure 1).

The functional zones were incorporated into the study area framework (Figure 1) and subsequently used for zonal statistics described in Section 2.3.4.

2.3.4. Zonal Statistics and Temporal Analysis

For each seasonal composite index (NDCI, NDTI), the pixel values within the three functional zones were extracted and summarized using zonal statistics for each zone. Descriptive statistics such as the mean and median were calculated to characterize the spatial distribution of the indices within each zone. Emphasis was placed on seasonal mean values, which were used to compare water quality conditions across zones and to assess temporal variability [11].

The temporal variability was assessed by analyzing interannual fluctuations in mean NDCI and NDTI values for the period 2017–2024. The seasonal patterns and differences between winter and summer were analyzed separately for each functional zone, and the results were visualized using line graphs created in R (version 4.6.0).

The winter and summer seasons were selected for detailed comparison, as they are the two contrasting hydroclimatic conditions of the Mediterranean region [33]. The wet season (winter) is associated with increased precipitation and river runoff, while summer is characterized by prolonged dry conditions. These seasonal contrasts can significantly affect nutrient loads, phytoplankton productivity, and the dynamics of suspended sediments in coastal waters [4,23].

2.3.5. Rainfall Analysis and Correlation Assessment

Monthly precipitation data from the Hellenic National Meteorological Service (HNMS) were used to examine possible relationships between hydroclimatic conditions and satellite-derived water quality indices.

Correlation analysis was conducted for each functional zone, using the monthly precipitation data and the corresponding monthly mean values of the NDCI and NDTI for the period 2017–2023, which corresponds to the period for which monthly precipitation records were available [4].

The relationships between precipitation and water quality indices were evaluated using Spearman's rank correlation coefficient (ρ), while statistical significance was assessed using the corresponding p values [35]. The analysis was based on 84 monthly observations (n = 84) for each functional zone. Spearman's correlation coefficient was chosen because it

is suitable for small sets of environmental data and does not require normally distributed data [36].

To facilitate the interpretation of the temporal relationship between precipitation and the spectral indices, the corresponding monthly mean NDCI and NDTI values and the monthly rainfall are presented as time series for each functional zone.

2.3.6. Hotspot Persistence Analysis

The hotspot persistence sites were assessed using the annual seasonal median of NDCI values for winter and summer. The seasonal thresholds for hotspots were derived from the corresponding long-term seasonal composite median values through *r.quantile* analysis in GRASS GIS. Pixels exceeding the 92nd percentile of the NDCI distribution (NDCI > 0.2315 for winter and NDCI > 0.186 for summer) were classified as hotspots. The hotspot threshold was selected empirically after testing alternative percentile thresholds. The 92nd percentile produced the most spatially coherent hotspot patterns while limiting background variability. Higher thresholds resulted in fragmented hotspots, whereas lower thresholds included broader areas with moderate NDCI values. Therefore, the 92nd percentile was used in all persistence analysis.

Furthermore, the annual seasonal median values of indices (2017–2024) were converted into binary maps of hotspots (1 = hotspot, 0 = non-hotspot). These maps were aggregated to create persistence hotspot layers, where persistence was defined as the percentage of years in which a pixel was classified as a hotspot [37]. Persistence was expressed both as frequency of occurrence and as a persistence rate over the study period. To compare the patterns of hotspots across the study areas, the mean persistence values, the standard deviation, and the maximum values were calculated for the functional zones of Giofyros, Heraklion Port, and Karteros.

2.3.7. Spatial Hotspot Analysis

The analysis of spatial hotspots was conducted based on long-term, winter median composite NDCI and NDTI values, as winter conditions had the strongest influence of precipitation and river inflows on surface coastal water quality.

A regular 100 × 100 m grid was created in the WGS84/UTM Zone 35N coordinate system, and land cells were excluded using a sea mask. The 100 m grid resolution was selected to balance spatial detail and computational efficiency [38]. The mean values of the NDCI and NDTI indices were calculated for each grid cell and used as input data for the spatial analysis. Spatial clustering patterns were identified using the Getis-Ord Gi* statistic [39,40]. A 300 m distance band was applied to define neighborhood relationships, following an exploratory spatial analysis to ensure that each cell had enough neighboring observations while preserving the local character of spatial clustering [39,40].

Statistically significant hotspots were identified at 95% and 99% confidence levels, and their spatial extent was quantified within each functional zone to assess the distribution and coverage of the hotspots.

3. Results

3.1. Seasonal Composite Generation

This section examines the seasonal variability of the NDCI and NDTI in the coastal zones of Giofyros, Heraklion Port, and Karteros, using long-term seasonal median composites and zonal statistics.

The NDCI exhibited strong seasonal variability throughout the study area (Figure 3). The highest values were observed along the coastline of the Karteros zone (0.35), while in spring and summer, lower values were recorded across all functional zones (0.25–0.30).

During autumn, NDCI values increased again (0.30–0.35) in several coastal areas, reflecting the transition towards winter conditions.

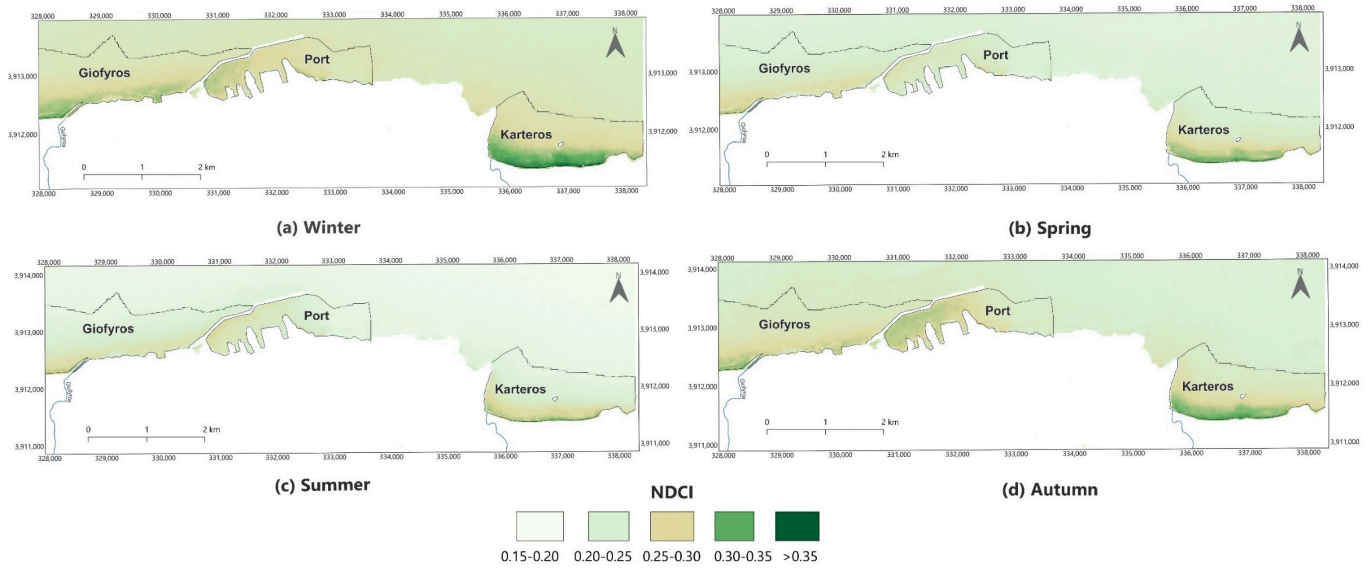


Figure 3. The seasonal spatial distribution of median NDCI values for winter (**a**), spring (**b**), summer (**c**), and autumn (**d**) within the Giofyros, Heraklion Port, and Karteros functional coastal zones.

The mean values ranged from 0.19 to 0.25, with the highest values consistently observed during winter and the lowest during summer (Figure 4a). The Karteros zone exhibited the highest NDCI values in all seasons, reaching a winter average of 0.25, while the Port zone generally exhibited the lowest values. In all zones, a gradual decline from winter to summer was evident, reaching minimum values of 0.21 (Karteros) and 0.20 (Port, Giofyros), followed by a recovery during the fall, when NDCI values approached winter levels.

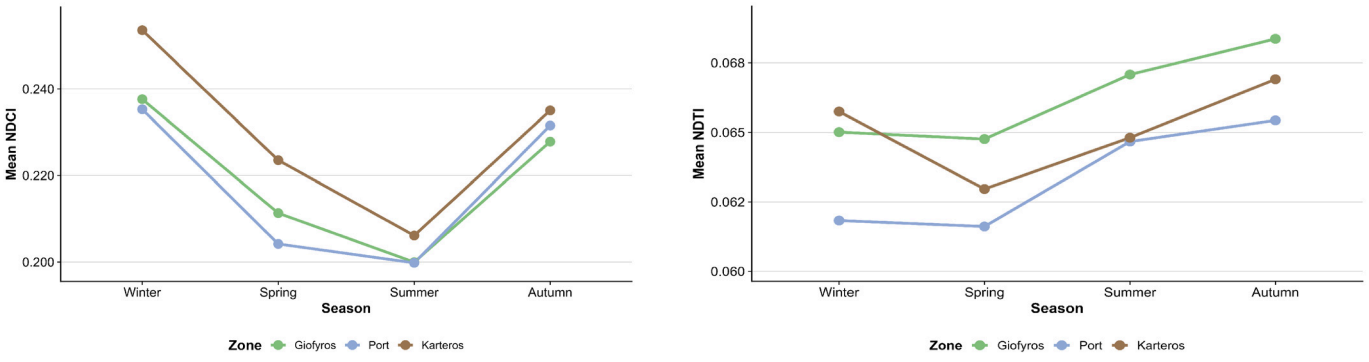


Figure 4. The seasonal variability of mean spectral index values across the Giofyros, Heraklion Port, and Karteros coastal zones. (**a**) Mean NDCI values by season for the three study zones; (**b**) mean NDTI values by season for the three study zones.

Compared to the NDCI, the NDTI exhibited less seasonal variability, with mean values ranging between 0.061 and 0.069 (Figure 4b). The highest values of the NDTI (0.09–0.15) were concentrated mainly in coastal areas affected by the Giofyros estuary, the Port of Heraklion, and the Karteros coastline, while open waters were generally characterized by lower values (<0.07). Seasonal maps showed a broader distribution of elevated NDTI values during the summer and fall, particularly around the coastal zone of Giofyros and the port facilities, while winter and spring conditions exhibited a more localized spatial pattern (>0.15) (Figure 5).

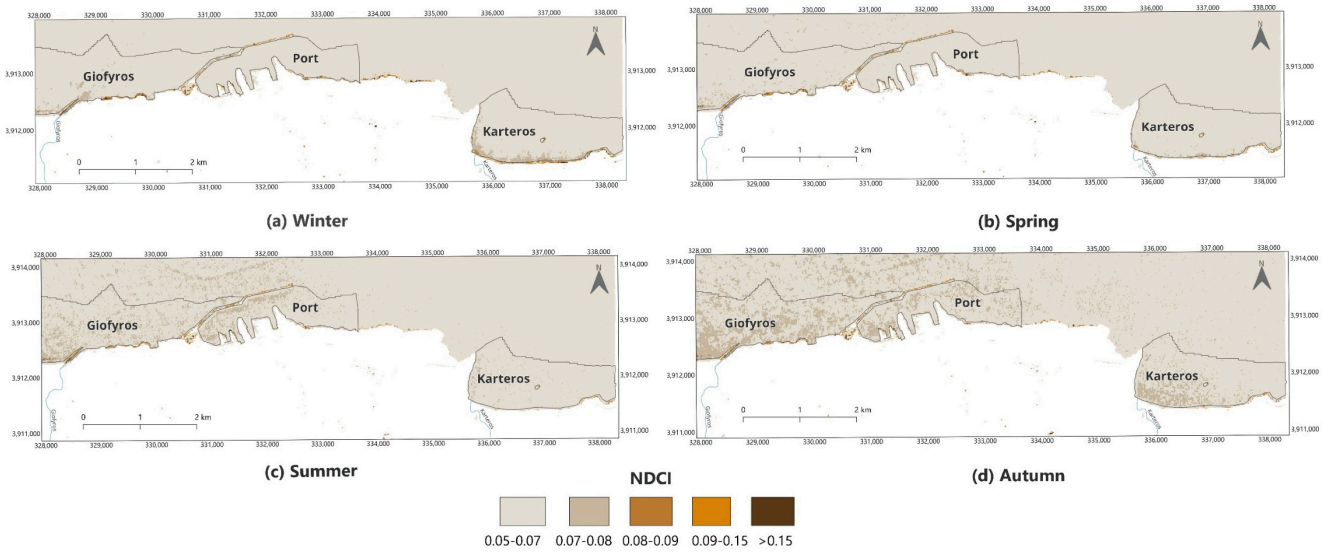


Figure 5. Seasonal spatial distribution of median NDTI values in Giofyros, Heraklion Port, and Karteros coastal zones for winter (**a**), spring (**b**), summer (**c**), and autumn (**d**).

The mean NDTI values increased from spring to fall in all zones, with the highest value recorded in the Giofyros zone during the fall (0.069), followed by the Karteros (0.067) and Port zone (0.066) (Figure 4b). In contrast to the NDCI, seasonal differences between zones were relatively small, suggesting a more homogeneous spatial distribution of turbidity-related variability across the entire study area.

Overall, the Karteros zone consistently exhibited the greatest variability of NDCI values, as reflected in the seasonal pattern of chlorophyll distribution, while the Giofyros zone generally exhibited the highest NDTI values in the long-term seasonal composites.

3.2. Zonal Statistics and Temporal Analysis

The temporal variability of the NDCI was assessed based on the mean values per functional zone, which were derived from the annual seasonal median composites for winter and summer for the period 2017–2024 (Figure 6). In all three functional zones, winter NDCI values were consistently higher than summer values, indicating a strong seasonal signal throughout the study period.

The Karteros zone exhibited the strongest contrast between winter and summer, with winter values peaking in 2022 (0.28), while summer values remained relatively stable and significantly lower (0.20) (Figure 6a). A similar pattern was observed in the Giofyros zone, where winter values consistently exceeded summer values and peaked in 2019 (0.260) (Figure 6b). In contrast, summer NDCI values in Giofyros showed a gradual decline after 2018, reaching their lowest levels in 2024.

The Port zone also exhibited higher NDCI values during winter compared to summer, although the seasonal differences were less pronounced than those observed in the Karteros zone. The winter NDCI peaked in 2022 (0.27), while summer values remained relatively stable for most of the study period before declining slightly in 2024 (0.18) (Figure 6c).

Overall, the three zones exhibited comparable temporal patterns characterized by higher NDCI values in winter and lower values in summer. However, the pattern of seasonal variability differed among the zones, with Karteros exhibiting the strongest seasonal contrast and the Giofyros and Port zone showing more moderate temporal fluctuations.

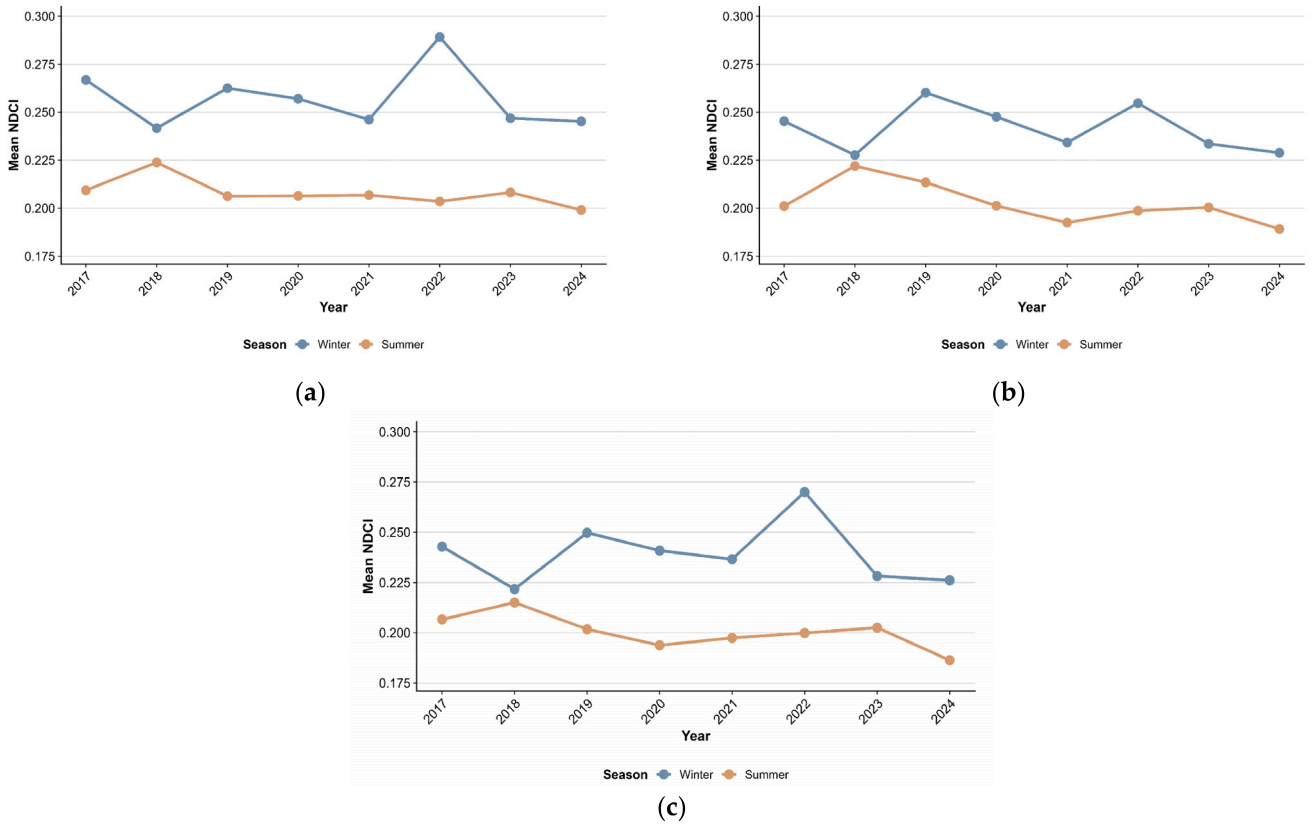


Figure 6. Interannual winter–summer variability of mean NDCI values during 2017–2024. (**a**) Karteros; (**b**) Giofyros; (**c**) Port. Seasonal mean NDCI values for winter and summer are presented for each study zone.

The temporal patterns of the NDTI differed from those observed for the NDCI, exhibiting weaker seasonal contrasts and lower overall variability across the entire study area (Figure 7). In the Karteros zone, the NDTI exhibited moderate temporal variations during the 2017–2024 period, with winter values generally exceeding summer values (Figure 7a). The highest winter value of the NDTI was recorded in 2022 (0.083), while both seasonal series (summer, winter) showed a substantial decline in 2024 (0.057).

A similar pattern was observed in the Giofyros zone, where winter NDTI values were usually higher than summer values, although seasonal differences varied from year to year. The most pronounced winter–summer contrast occurred in 2022, when winter values reached their peak (0.076), compared with summer values (0.068) (Figure 7b). Both seasonal series declined significantly in 2024, reaching their lowest levels during the study period.

The Port zone exhibited the lowest overall NDTI values and showed less stable seasonal behavior compared to the other zones (Figure 7c). In several years, including 2018, 2019, and 2023, summer values exceeded winter values (0.066–0.068). However, both seasonal series followed the general downward trend observed in 2024.

The NDTI exhibited a smaller range of variation and weaker seasonal differences compared to the NDCI in all three functional zones. A common feature across the study area was the peak in winter NDTI values in 2022, which was followed by a substantial decline in both winter and summer conditions in 2024.

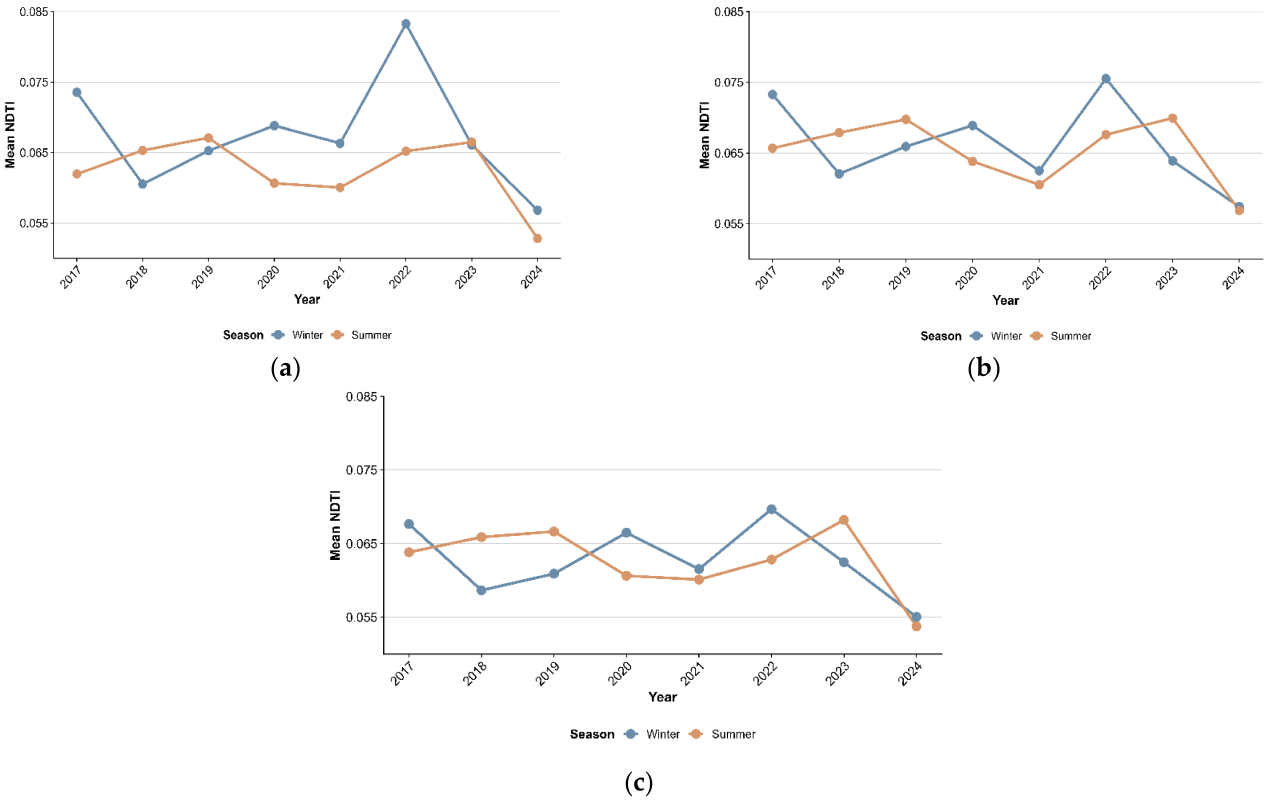


Figure 7. Interannual winter–summer variability of mean NDTI values during 2017–2024. (**a**) Karteros; (**b**) Giofyros; (**c**) Port. Seasonal mean NDTI values for winter and summer are presented for each study zone.

3.3. Rainfall Analysis and Correlation Assessment

The relationships between precipitation and the satellite-derived indices (NDCI and NDTI) were investigated using monthly observations for the 2017–2023 period.

The temporal variability of monthly precipitation and the monthly mean NDCI values for each functional zone are presented in Figure 8. Interannual variability was evident, with similar temporal patterns observed across all three functional zones. Although the monthly peaks of precipitation and the NDCI did not always coincide, periods of increased rainfall generally corresponded to higher NDCI values, indicating an overall positive relationship between precipitation and NDCI. The Karteros zone exhibited the highest NDCI values (0.2–0.4) among the three functional zones. The most pronounced increase in NDCI values was observed in early 2022 (0.36–0.39) for each functional zone. Following this peak, NDCI values gradually declined during the subsequent months.

This relationship was confirmed by Spearman's correlation analysis, which revealed moderate and statistically significant positive correlations between monthly precipitation and the NDCI in all three functional zones (Table 2). Correlation coefficients ranged from $\rho = 0.343$ in the Port zone to 0.494 in the Giofyros zone and 0.445 in the Karteros zone ($p = 0.002$ to $p < 0.001$), suggesting that precipitation-driven processes may have contributed substantially to the observed variability of the NDCI in the study period.

In contrast, the temporal variability of the NDTI showed a less consistent relationship with precipitation (Figure 9). Monthly NDTI values remained stable during most of the study period, with only a few isolated peaks, the most notable occurring in early 2022 (0.25) in all three functional zones. However, similar increases were not observed during other periods of high rainfall, indicating that precipitation could not explain the temporal variability of the NDTI.



Figure 8. The temporal relationship between monthly mean NDCI values and monthly precipitation (HNMS) for the Giofyros, Port and Karteros functional zones during the 2017–2023 study period. The upper panel shows monthly rainfall, while the lower panels present corresponding monthly mean NDCI values for each functional zone.

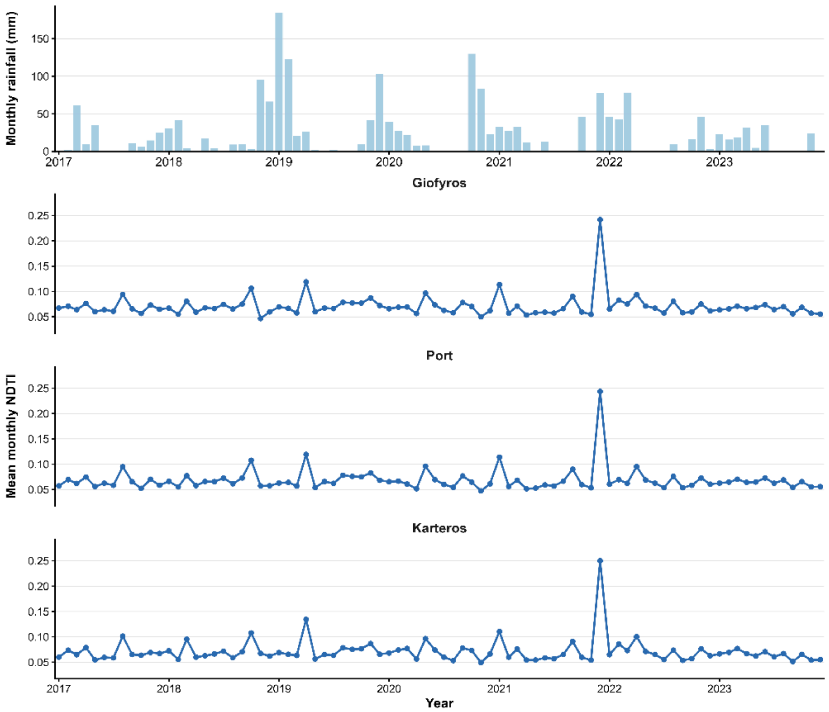


Figure 9. The temporal relationship between monthly mean NDTI values and monthly precipitation for the Giofyros, Port, and Karteros functional zones during 2017–2023 study period. The upper panel shows monthly rainfall, while the lower panels present corresponding monthly mean NDTI values for each functional zone.

Table 2. Spearman correlation analysis between monthly precipitation and the monthly mean NDCI and NDTI values for the Giofyros, Heraklion Port, and Karteros functional coastal zones (2017–2023).

Zone	Index	*n*	Spearman_r	*p*_Value
Giofyros	NDCI	84	0.494	<0.001
Port	NDCI	84	0.343	0.002
Karteros	NDCI	84	0.445	<0.001
Giofyros	NDTI	84	−0.012	0.912
Port	NDTI	84	−0.065	0.556
Karteros	NDTI	84	0.093	0.400

Spearman's correlation analysis confirmed the absence of statistically significant relationships between precipitation and the NDTI in any of the three zones, with correlation coefficients ranging from ρ = −0.065 to 0.093 and *p*-values from 0.400 in the Karteros zone to 0.912 in the Giofyros zone (Table 2).

Overall, the results suggest that the temporal variability of the NDCI may be influenced by interannual precipitation patterns, whereas the temporal variability of the NDTI was likely influenced by additional environmental and hydrodynamic factors beyond precipitation alone.

3.4. Hotspot Persistence Analysis

An analysis of the persistent hotspots was conducted to identify regions with recurring high NDCI values during the 2017–2024 period. Separate persistence maps were created for winter and summer to assess the spatial distribution and temporal stability of NDCI hotspots in Giofyros, the port of Heraklion, and Karteros coastal zones (Figure 10).

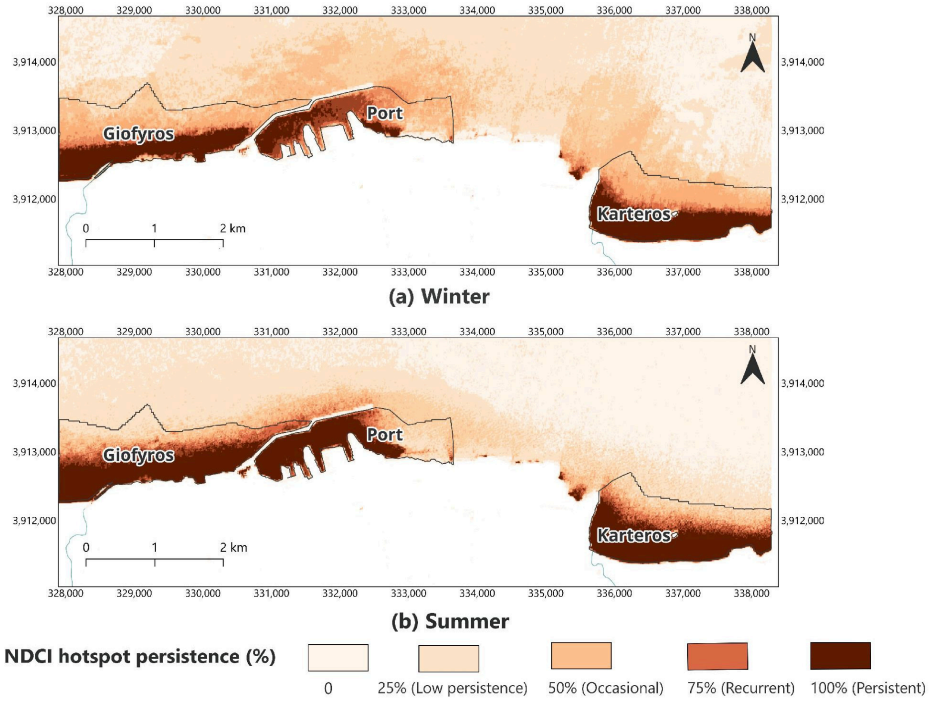


Figure 10. Seasonal NDCI hotspot persistence maps derived from winter (**a**) and summer (**b**) median NDCI composites for the period 2017–2024. Persistence values represent the percentage of years in which a pixel was classified as a hotspot.

During winter, persistent hotspots were widely distributed across all three zones, with the highest persistence observed in the coastal area of Karteros (Figure 10a). Mean persistence values exceeded 60% in all zones, reaching a maximum of 73.1% in Karteros,

indicating the recurring occurrence of hotspot conditions with elevated NDCI throughout the study period (Table 3). Locations exhibiting 100% persistence were identified in all zones, although the occurrence of hotspots showed significant spatial variability.

Table 3. Descriptive statistics of winter and summer hotspot persistence (%) for the NDCI in the Giofyros, Heraklion Port, and Karteros functional coastal zones the during 2017–2024 study period.

Zone	Index	Season	Count	Mean	St. Deviation	Max
Giofyros	NDCI	Winter	22,314	62.90	29.71	100
Port	NDCI	Winter	13,254	64.08	30.12	100
Karteros	NDCI	Winter	19,549	73.11	27.52	100
Giofyros	NDCI	Summer	22,314	71.85	32.50	100
Port	NDCI	Summer	13,254	68.10	36.40	100
Karteros	NDCI	Summer	19,549	75.50	31.48	100

A similar pattern was observed during summer, with recurring "hotspots" concentrated mainly in the coastal areas of the Karteros and Port zones (Figure 10b). Mean persistence ranged from 68.1% to 75.5%, with Karteros again exhibiting the highest persistence, followed by Giofyros and the Port zone (Table 3). Areas with 100% persistence were also identified in all zones, highlighting locations that consistently exhibited "hotspot" conditions throughout the study period. Standard deviation values varied between 31.5% and 36.4%, suggesting substantial spatial variability in hotspot persistence.

Overall, the hotspot persistence maps revealed that recurring NDCI hotspots were primarily associated with coastal environments influenced by river inflows and anthropogenic pressures. Karteros consistently exhibited the highest persistence values in both seasons, while Giofyros and the Port area also showed significant hotspot occurrence over time.

3.5. Spatial Hotspot Analysis

The Getis-Ord Gi* analysis of the mean NDCI values during the winter season identified extensive and spatially coherent "hotspot" clusters in all three coastal zones (Figure 11a). The hotspots were concentrated mainly in coastal areas influenced by river inflows and coastal processes. The most extensive cluster of hotspots was identified in the Karteros zone, while Giofyros exhibited a continuous zone of hotspots. In contrast, the clusters of hotspots within the Port zone were smaller and more fragmented, occurring mainly around the harbor basin and the adjacent coastal waters.

The Karteros zone exhibited the highest concentration of statistically significant hotspots, with hotspots at a 99% confidence level covering 2.04 km^2 (91.1% of the zone's area) (Table 4). Extensive coverage by hotspots was also observed in Giofyros, where extremely significant hotspots covered 1.69 km^2 (66.0%). The Port zone had a smaller area of hotspots, with 0.33 km^2 (21.9%) classified at a 99% confidence level. The areas identified with a 95% confidence level accounted for a smaller percentage in each zone.

In contrast, the Getis-Ord Gi* analysis of the mean NDTI values during the winter season revealed a much more localized pattern of hotspots (Figure 11b). Significant accumulations were largely confined to the Karteros zone, where hotspot areas with 95% and 99% confidence levels covered 0.12 km^2 (5.6%) and 0.09 km^2 (4.0%) of the zone's total area, respectively (Table 4). Only one very limited area of high concentration was identified in Giofyros, while no statistically significant areas of high NDTI concentration were detected within the Port zone.

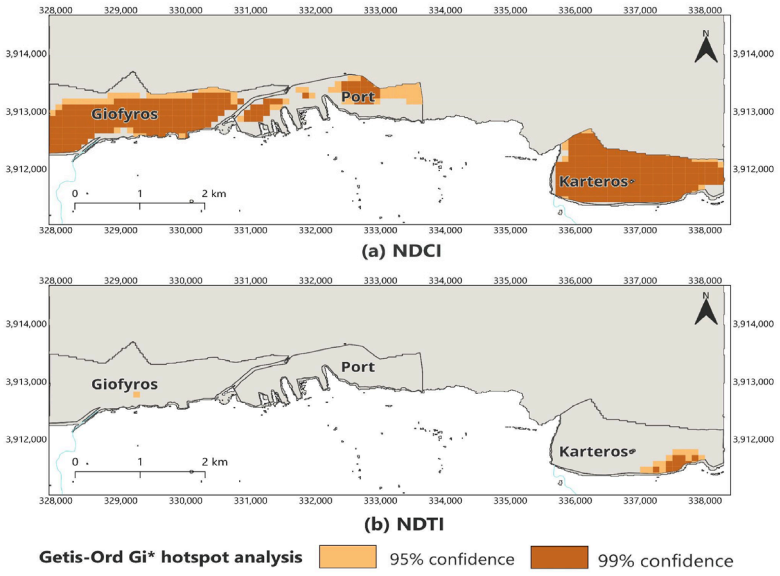


Figure 11. Getis–Ord Gi* hotspot analysis of winter median (**a**) NDCI and (**b**) NDTI values for the period 2017–2024. Colored cells indicate statistically significant hotspot clusters at 95% and 99% confidence levels.

Table 4. Area and percentage coverage of statistically significant Getis–Ord Gi* hotspots (95% and 99% confidence levels) for the NDCI and NDTI in the Giofyros, Port, and Karteros functional coastal zones during the winter season (2017–2024).

Zone	Index	Zone Area (km^2)	95% Hotspot Area (km^2)	99% Hotspot Area (km^2)	95% Coverage	99% Coverage
Giofyros	NDCI	2.56	0.30	1.69	11.9	66.0
Port	NDCI	1.52	0.32	0.33	21.4	21.9
Karteros	NDCI	2.24	0.08	2.04	3.40	91.1
Giofyros	NDTI	2.56	0.01	0.00	0.40	0.00
Port	NDTI	1.52	0.00	0.00	0.00	0.00
Karteros	NDTI	2.24	0.12	0.09	5.60	4.00

The hotspot areas of NDCI concentration exhibited broader spatial coverage and stronger concentration patterns compared to those of the NDTI. While hotspot areas related to chlorophyll were widespread in all three coastal zones, the hotspot areas associated with turbidity were limited to a small number of local areas, mainly within the coastal sector of Karteros.

4. Discussion

4.1. Seasonal and Interannual Variability of NDCI and NDTI

The analysis of the spectral indices revealed clear seasonal differences in surface coastal water quality variability across the Heraklion coastal zone. Specifically, the NDCI exhibited a pronounced seasonal cycle, with consistently higher values during winter and lower values during summer across all functional zones. The strongest seasonal contrast was observed in the Karteros zone, where winter NDCI values reached their highest levels and persistent hotspots indicated recurrent chlorophyll-related variability. These patterns suggest enhanced chlorophyll-related variability in areas influenced by riverine and coastal processes.

The observed winter enhancement in the NDCI is likely associated with the combined effects of increased nutrient-rich freshwater runoff, enhanced vertical mixing of the water column, and winter hydrodynamic processes that replenish nutrients during the wet season. These findings are consistent with those reported by Yilmaz et al. [2], who observed elevated NDCI values in nearshore areas of Izmir Bay affected by urban and anthropogenic pressures, highlighting the usefulness of the NDCI for identifying chlorophyll-related

variability in coastal environments. Seasonal rainfall promotes runoff-driven transport of nutrients from terrestrial environments to coastal waters [6], stimulating phytoplankton growth and contributing to stronger chlorophyll-related optical signals detected by satellite observations. The spatial patterns showed that elevated NDCI values were mainly concentrated in nearshore waters and in river-influenced areas, particularly around the Karteros estuary and, to a lesser extent, the Giofyros river-influenced area. This spatial distribution agrees with previous studies demonstrating that river estuaries, due to nutrient enrichment, often can enhance biological productivity [2,41].

Although increased solar radiation during spring generally favors phytoplankton growth, seasonal phytoplankton dynamics in the ultra-oligotrophic Eastern Mediterranean are primarily controlled by nutrient availability rather more than light [42]. During winter, enhanced vertical mixing of water column, stronger wind-driven circulation, and increased freshwater inputs replenish surface waters with nutrients, which may stimulate phytoplankton growth despite lower solar irradiance [42]. Therefore, the consistently higher NDCI values in the winter period observed across all three functional zones are likely the combined results of winter nutrient replenishment and riverine inputs rather than solar radiation alone.

In contrast, the NDTI exhibited significantly weak seasonal variability with some modest increases during summer and autumn. A comparable influence of local hydrodynamic processes was reported by Ningwuri et al. [4], who identified increased turbidity during periods of limited rainfall and attributed these patterns to sediment resuspension in shallow coastal waters rather than precipitation alone. The narrow range of NDTI values and the limited spatial extent of areas with elevated values suggest that suspended solids dynamics are influenced by localized and short-term processes rather than by the broader seasonal drivers affecting chlorophyll-a-related variability [21]. Similar observations have been reported in other coastal environments where sediment resuspension is largely controlled by local hydrodynamic conditions, such as coastal circulation and wave action, rather than solely by seasonal nutrient inputs or freshwater runoff [9,14,21].

The interannual analysis further highlighted the distinct behavior of the two indices. Both the NDCI and the NDTI reached their highest winter values in 2022, indicating a period characterized by enhanced coastal environmental variability. Consequently, further analysis was conducted to investigate the relationship between precipitation and index variability during the 2017–2023 period, with the aim of evaluating the potential influence of hydrological conditions on the observed temporal variability.

4.2. Influence of Rainfall and Hydrological Processes

The precipitation analysis demonstrated moderate and statistically significant positive correlations between rainfall and NDCI variability across all study zones. Spearman correlation coefficients ranged from 0.343 in the Port zone ($p = 0.002$) to 0.494 in the Giofyros zone ($p < 0.001$), while the Karteros zone exhibited a correlation coefficient of $\rho = 0.445$ ($p < 0.001$). These findings suggest that precipitation contributed to the temporal variability of the NDCI, likely associated with enhanced nutrient inputs delivered to coastal waters by rainfall-driven runoff. Although precipitation appears to be an important driver of chlorophyll-related variability, the moderate correlation coefficients indicate that additional environmental processes also influence the observed temporal patterns in the coastal zone of Heraklion.

Additional factors, including antecedent hydrological conditions, nutrient availability, coastal circulation patterns, water residence time, and anthropogenic inputs, could also influence the dynamics of biological productivity [6,41].

In contrast, the NDTI exhibited weak and statistically insignificant relationships with precipitation across all functional zones ($\rho = -0.012$ to 0.093, $p > 0.05$), indicating that suspended particulate matter dynamics are not directly controlled by monthly precipitation during the study period. Unlike the findings reported by Ningwuri et al. [4], who observed a strong positive relationship between precipitation and the NDTI ($\rho = 0.63$) in Jepara coastal waters, no statistically significant correlation was identified in the present study. This difference is likely related to differences in local hydrological, geomorphological and coastal circulation conditions between the two study areas. Instead, turbidity patterns likely reflect the combined influence of factors such as sediment resuspension, wave action, coastal currents, port activities, and local hydrodynamic processes [21]. The absence of a significant relationship with rainfall suggests that these processes may play a more important role than precipitation in controlling turbidity variability within the study area. Similar findings have also been reported in other coastal environments where turbidity variability is governed by short-term natural stresses rather than seasonal precipitation patterns [4,21].

4.3. Persistent and Spatial Hotspots of Surface Coastal Water Quality Variability

The hotspot persistence analysis was conducted for the winter and summer seasons of the time series (2017–2024) using the NDCI, with the aim of investigating the temporal stability and seasonal behavior of chlorophyll-related hotspot areas. The spatial analysis of the persistence hotspots revealed that recurrent NDCI hotspots were concentrated in the coastal areas of the Karteros, Giofyros, and Port coastal zones throughout the study period. Similarly, Yilmaz et al. [2] demonstrated that elevated NDCI values were concentrated in specific sectors of Izmir Bay rather than being uniformly distributed, supporting the usefulness of satellite derived chlorophyll indices for identifying localized coastal hotspots. Particularly high persistence values were observed in the Karteros zone under both winter and summer conditions, indicating that elevated NDCI variability represents a consistent long-term characteristic of this region. The persistence of hotspot conditions near the Karteros estuary further suggests a sustained influence of riverine inputs and associated nutrient delivery on surface coastal water quality dynamics over time.

To further investigate the spatial distribution of elevated index values within the functional zones, a Getis–Ord Gi* hotspot analysis was performed for the NDCI and NDTI using the winter composites for the 2017–2024 period. The results confirmed the existence of statistically significant spatial clustering of high NDCI values within the Karteros zone. Meanwhile, an elongated hotspot pattern was identified in the Giofyros zone, indicating that high NDCI values are not randomly distributed but are concentrated in specific coastal sectors, which are influenced by riverine input and coastal processes.

In contrast, NDTI hotspots were significantly more restricted, both spatially and statistically, during the 2017–2024 winter period. Statistically significant clusters of elevated NDTI values were identified mainly in a small part of the coastline within the Karteros zone. At the same time, only very limited or no significant hotspot areas were detected in the Giofyros and Port zones. These findings suggest that turbidity-related variability is influenced by localized processes operating at smaller spatial scales, such as sediment resuspension and short-term hydrodynamic conditions, rather than by broader environmental drivers affecting the study area.

The combined use of hotspot persistence mapping and the Gi* statistics provided a more comprehensive assessment of the spatial patterns observed in the study area. Together, these approaches enabled the identification of areas characterized by recurrent elevated index values and statistically significant spatial clustering. The results highlighted the Karteros coastal sector as the most environmentally dynamic area within the study region,

exhibiting persistent chlorophyll-related hotspots and the strongest spatial concentration of elevated NDCI values.

4.4. Implications for EO-Based Coastal Monitoring

This study highlights the utility of satellite-derived spectral indices for monitoring coastal environmental variability in data-limited environments. The use of analysis-ready data (ARD) products from the OCEANIDS Data Cubes enabled the development of consistent long-term time series suitable for seasonal, interannual, and spatial analysis while significantly reducing preprocessing requirements.

In addition, the combined application of the NDCI and NDTI, together with hotspot persistence mapping and Getis-Ord Gi* spatial statistics, provided valuable information for the temporal dynamics and spatial distribution of coastal environmental variability. These approaches facilitated the identification of areas characterized by recurrent elevated index values and significant spatial clustering, supporting the prioritization of monitoring efforts and contributing to more informed coastal management and decision-making processes. This is in agreement with the study of Yilmaz et al. [2], who highlighted the value of long-term Sentinel-2 NDCI time series for operational coastal monitoring and early identification of environmental degradation.

The results highlight the potential of EO data cubes and satellite-derived spectral indices to support operational monitoring of surface coastal water quality and environmental management in Mediterranean coastal systems. Identifying areas with persistent hotspots might assist coastal managers in prioritizing monitoring efforts and targeting areas that are potentially more vulnerable to environmental and anthropogenic pressures. Such approaches are particularly important in areas where regular in situ monitoring remains limited or spatially fragmented.

4.5. Prioritization of Monitoring Areas and Decision Support Applications

In addition to characterizing patterns of surface coastal water quality variability, the results also provide a practical framework for supporting monitoring prioritization and coastal management. The combination of seasonal variability analysis, precipitation-driven dynamics, hotspot persistence mapping, and spatial hotspot statistics enabled the identification of coastal sectors with distinct environmental sensitivity and monitoring requirements. Such information could contribute to the development of targeted monitoring strategies and support evidence-based decision-making in coastal environments.

Among the three functional zones, the Karteros coastal sector emerged as the highest-priority area for environmental monitoring. This zone consistently exhibited the highest NDCI values, the strongest winter-summer contrasts, the highest hotspot persistence, and the largest spatial extent of statistically significant NDCI hotspots. Furthermore, the rainfall–NDCI relationship indicates that the area is particularly sensitive to hydrological forcing and potential nutrient inputs provided through river runoff. These features suggest that Karteros represents a persistent hotspot of chlorophyll-related variability and should, therefore, be considered a priority area for regular seasonal monitoring.

The Giofyros zone represents a secondary monitoring priority. Although the persistence and spatial clustering of hotspots were less pronounced than in Karteros, elevated NDCI values were repeatedly observed near the estuarine region. The influence of wastewater treatment plant discharges and river inflows may contribute to local water quality variability, highlighting the need for continuous environmental surveillance. In contrast, the Port zone presented lower NDCI values, weaker persistence, and more spatially fragmented hotspot patterns. Nevertheless, the presence of port activities, maritime traffic, and

local anthropogenic pressures suggests that operational monitoring remains important for detecting potential environmental disturbances associated with port operations.

These findings demonstrate how the OCEANIDS Data Cube products could be translated into decision support information for coastal stakeholders (Table 5). The ability to identify priority monitoring areas and characterize the dominant environmental pressures provides a practical basis for optimizing monitoring resources, supporting early warning strategies, and improving evidence-based coastal management.

Table 5. Proposed monitoring priorities and decision support framework derived from EO-based coastal water quality assessment.

Zone	Main Pressure	Monitoring Priority	Recommended Action
Karteros	River runoff/nutrients	High	Seasonal monitoring
Giofyros	WWTP influence	Medium-High	Water quality surveillance
Port	Harbor activities	Medium	Operational monitoring

4.6. Limitations and Future Work

In the present study, the objective was not to estimate chlorophyll-a or suspended sediment concentrations, but to investigate the spatial and temporal variability of surface coastal water quality using the NDCI and NDTI as relative spectral indicators. Consequently, no local calibration or validation with concurrent in situ measurements was possible, and the uncertainty associated with derived index values could not be quantified through site-specific error estimates or confidence bands. The indices were therefore interpreted as relative indicators of the spatial and temporal variability of surface coastal water quality rather than direct estimates of constituent concentrations.

Previous studies have demonstrated the potential application of the NDCI, the NDTI, and related spectral indices in coastal, estuarine, and inland water environments [2,4,9,12,21]. However, their performance and uncertainty are strongly dependent on local optical conditions, atmospheric correction, sensor characteristics, water depth, and the relative contribution of optically active constituents [43]. Therefore, uncertainty ranges or error bands reported for other study areas cannot be directly transferred to the present coastal environment without local calibration and validation.

The performance of optical indices may also be affected by the optical complexity of coastal waters, where phytoplankton, suspended sediments, colored dissolved organic matter (CDOM) and atmospheric residuals may simultaneously influence water reflectance [15,43]. In shallow coastal areas, an additional source of uncertainty is bottom-reflectance interference [43,44]. As a result, variations in the NDCI and NDTI in shallow or optically clear waters may partly reflect changes in water depth or benthic cover, and this limitation is particularly relevant close to the shoreline and should be considered when interpreting localized index anomalies [43]. Although shallow-water effects were not explicitly corrected or modeled in the present analysis, the indices were primarily used to identify broad, recurring spatial and temporal patterns rather than isolated pixel-level variations.

Despite these limitations, the long-term Sentinel-2 time series and the use of OCEANIDS Data Cube products allowed for the identification of consistent spatial and temporal patterns of surface coastal water quality variability. The recurrence and spatial coherence of these patterns provide useful evidence of environmental variability, although their interpretation remains qualitative in the absence of field-based validation.

Future research should combine satellite observations with targeted field measurements and existing water quality monitoring programs to improve the calibration and validation of satellite-derived indicators. The spatial and temporal patterns identified in the present study may also support the design of more efficient field sampling strategies

by prioritizing areas and periods with persistent environmental variability. The integration of EO data cubes, spectral indicators, in situ observations, and advanced analytical approaches could further improve operational monitoring of surface coastal water quality in the Eastern Mediterranean.

5. Conclusions

This paper assessed the spatial and seasonal variability of surface coastal water quality in the Heraklion coastal zone for the period 2016–2024, using Sentinel-2-derived NDCI and NDTI products from the OCEANIDS Data Cubes.

The results revealed clear seasonal patterns, with higher NDCI values during winter and lower values during summer, indicating strong chlorophyll-related variability likely associated with hydrological processes and nutrient load transport in coastal areas.

Among the three functional zones, the Karteros zone consistently showed the highest NDCI values, the strongest winter–summer contrasts, and the most persistent hotspot patterns, identifying it as a priority area for further monitoring.

The NDTI showed weaker seasonal variability and more localized hotspot patterns, suggesting that turbidity-related variability is influenced by additional local factors such as sediment resuspension, wave action, coastal circulation, and port-related activities. The exploratory rainfall analysis for 2017–2023 period, showed moderate and statistically significant positive correlations between monthly precipitation and the NDCI, while no statistically significant relationship was observed between precipitation and the NDTI.

Overall, this study confirmed that OCEANIDS Data Cube products and satellite-derived spectral indices can provide useful relative indicators for long-term EO-based monitoring of coastal water quality variability. This approach could complement conventional monitoring programs by supporting the identification of priority areas, the detection of persistent environmental patterns, and evidence-based coastal management. Future work should integrate satellite observations with in situ chlorophyll-a, turbidity, and suspended sediment measurements to improve calibration, validation, and operational applicability.

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Conflicts of Interest: Author Eirini Marinou is employed by Geosystems Hellas S.A., a private company participating in the OCEANIDS project, while author Betty Charalampopoulou serves

as President and Chief Executive Officer (CEO) of the company. Through the OCEANIDS project, Geosystems Hellas S.A. provided access to the Data Cube products used in this study and contributed to the study design. The remaining authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EO	Earth Observation
GIS	Geographic Information System
ARD	Analysis Ready Data
NDTI	Normalized Difference Turbidity Index
NDCI	Normalized Difference Chlorophyll Index
DC	Data Cubes
SPM	Suspended particulate matter
TSS	Total suspended solids
WWTP	Wastewater Treatment Plant

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