Estuarine, Coastal and Shelf Science 331 (2026) 109722

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Long-term changes in the Adriatic Sea (1971–2023): river influence, climate impacts, and biogeochemical shifts in coastal bottom waters

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ARTICLE INFO

Keywords:
Adriatic sea
Climate change
River runoff
Long-term trends
Bottom waters
Coastal waters

ABSTRACT

This study analyses long-term (1971–2023) trends in physical (temperature and salinity) and biogeochemical (chlorophyll-*a* and nitrate concentration) properties of bottom coastal waters in the Western Adriatic Sea. Results reveal complex patterns driven by a combination of regional hydrological shifts and broader climate change impacts. The basin was divided into North and Central-South sub-basins, focusing on winter and summer data. Over the last 53 years, Po River flow has progressively decreased especially during summer, altering hydrography and nutrient dynamics. Marked regional and seasonal divergences were observed. The North Adriatic showed summer warming (+1.05 % yr^{-1}), slight winter cooling (−0.27 % yr^{-1}), and decreased salinity in winter with a slight increase in summer. In contrast, the Central-South Adriatic exhibited stronger winter warming (+0.43 % yr^{-1}), weaker summer warming (+0.08 % yr^{-1}), increased salinity in winter and a decline in summer. Biogeochemical trends revealed strong regional and seasonal contrasts in chlorophyll-*a* and nitrate concentrations, with declining summer chlorophyll-*a* across the basin and decreases in both chlorophyll-*a* and nitrate in the Central-South Adriatic, consistent with a long-term, phosphorus-driven reduction in trophic conditions. This research helps to fill a critical knowledge gap concerning increasingly vulnerable and impacted coastal and bottom environments, underscoring the importance of sustained basin-wide monitoring to ensure uniform spatial and temporal coverage.

1. Introduction

Extending to 45°47′N with complex bathymetric asymmetries, the Adriatic Sea is the Mediterranean's northernmost basin (Cushman-Roisin et al., 2001). This basin extends approximately 800 km along a northwest-southeast axis and exhibits distinct bathymetric regions conventionally classified as northern, central, and southern sub-basins (Artegiani et al., 1997). The northern Adriatic is a shallow region, with an average depth of about 35 m, a gentle bathymetric slope, and a substantial contribution of freshwater from rivers, primarily those flowing from the Italian mainland (Cushman-Roisin et al., 2001; Totti et al., 2019). Conversely, the central Adriatic reaches depths of up to 270 m in the Jabuka Pit and is separated from the southern basin by the Palagruža Sill (170 m). The maximum depth is reached in the southern Adriatic, where the seafloor plunges to around 1200 m in the South Adriatic Pit (Cushman-Roisin et al., 2001). The Central-South Adriatic displays reduced primary productivity compared to the northern region (Cibic et al., 2022), reflecting both diminished continental nutrient inputs and benthic-pelagic interactions of lesser importance (Batistić et al., 2019). The Adriatic Sea receives substantial freshwater inputs (~5700 m^3/s), dominated by the Po River which contributes approximately 30 % of the total discharge (Cozzi and Giani, 2011). Its dominance is even more pronounced in the northwestern sector, where it accounts for >70 % of the total freshwater runoff (Cozzi and Giani, 2011; Mikhailova, 2002; Falcieri et al., 2014; Vona et al., 2025; Brando et al., 2015). Moreover, the Adriatic collects, in total, one-third of the freshwater

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https://doi.org/10.1016/j.ecss.2026.109722
Received 17 September 2025; Received in revised form 15 January 2026; Accepted 18 January 2026

flowing into the Mediterranean Sea (Campanelli et al., 2011; Raicich and Colucci, 2019; Sani et al., 2024). Due to these runoff characteristics, the Adriatic Sea is considered as a dilution basin (Cushman-Roisin et al., 2001). River runoff drives critical density gradients in the shallow northwestern Adriatic, modulating stratification and circulation patterns (Marini et al., 2008; Cozzi et al., 2020). Although the Adriatic Sea has a positive water budget, with precipitation and river runoff exceeding evaporation, excessive freshwater input from the Po River can alter salinity-driven density gradients enhancing stratification that weakens dense water formation and reduces vertical circulation in the overturning system (Bonaldo et al., 2016; Verri et al., 2018).

The Adriatic Sea is a crucial site for dense water formation that drives its deep circulation and ultimately feeds the Eastern Mediterranean (Martellucci et al., 2025). North Adriatic dense Water (NAddW), the densest water mass in the Mediterranean (Robinson et al., 1992), forms on the broad northern shelf through intense winter surface heat losses driven by cold, dry Bora winds (Vilibić and Supić, 2005; Beg Paklar et al., 2001) and large rivers flooding the surface layers. Once formed, this dense water sinks and propagates southward along the western Adriatic shelf as a bottom-trapped density current, eventually cascading into the southern Adriatic Pit (Vilibić and Supić, 2005; Manca et al., 2002; Vilibić et al., 2023). The formation of NAddW is a result of three interconnected processes: buoyancy-driven circulation from river runoff, surface cooling during intense Bora wind events, and wind-driven circulation with enhanced vertical mixing (Vilibić and Supić, 2005). Thus, river discharge is a key modulator in the chain linking surface processes to deep-water renewal.

These dynamics profoundly impact thermohaline processes. Several studies confirmed that river discharges alter basin-scale buoyancy potentially reversing overturning circulation (Verri et al., 2018; Kourafalou, 1999; Aragão et al., 2024) and regulate dense water volume through salinity-mediated processes (Vodopivec et al., 2022). Due to these characteristics, the Adriatic Sea can be a natural laboratory in which to study land-sea interactions and climate change impacts on coastal ecosystems.

River runoff, combined with the cyclonic circulation, predominant in the Adriatic Sea, drives the distribution of nutrients and sediments loading along the western Italian coast. Since the 1800s, the Po River has delivered elevated nutrient loads (N range: 1–300 μM; P range: 0.01–4 μM) (Grilli et al., 2020), initiating periodic occurrences of algal, diatom, and dinoflagellate blooms (Tedesco et al., 2007; Viaroli et al., 2005; Marini et al., 2002; Boldrin et al., 2009). Starting in the 1960s, significant eutrophication and hypoxia events were documented in coastal areas of the Adriatic Sea (Viaroli et al., 2005; Marini et al., 2015; Marini and Grilli, 2023). Their frequency increased exponentially until the 1990s, driven by the intensive release of inorganic nutrients, particularly nitrogen and phosphorus, from agricultural practices, continental emissions, and river runoff (Soana et al., 2024; Viaroli et al., 2018). Data from the Po River, indicate that the transport of total nitrogen has increased about two times since the 1980s, peaking at an estimated 173 × 103 t N yr^{-1} between 1996 and 2000 due to increased anthropogenic activity. Conversely, the transport of total phosphorus has decreased from 15.6 to 8.1 × 103 t P yr^{-1} since 1978, as a direct result of Italian regulations enacted in 1986 that required the reduction of phosphates in detergents (Bressan, 1986). While much of the attention has been devoted to surface manifestations such as phytoplankton blooms, riverine inputs also exert profound effects on the seabed of the shallow coastal Adriatic. The excess of nutrients can cause an overgrowth of phytoplankton and macroalgae, which reduces light and oxygen penetration in the water, harming marine life (Viaroli et al., 2005; Glibert, 2017). These processes are particularly pronounced in the northern Adriatic, where limited depth (~35 m on average) enhances the direct connectivity between riverine discharge, surface production, and bottom-water biogeochemistry. Coastal bottom waters therefore, represent one of the most sensitive compartments of the basin to land-sea interactions, yet they remain less investigated compared to surface dynamics.

Despite several localized studies documenting Adriatic subregional dynamics (e.g., Po River plume biogeochemistry (Campanelli et al., 2004; Babagolimatikolaei et al., 2025; Ricci et al., 2024), Southern Adriatic gyre variability (Branislav et al., 2021)), comprehensive basin-wide assessments of spatiotemporal trends remain scarce. A critical knowledge gap persists not only because of the disproportionate research focus on the northern Adriatic, heavily influenced by river runoff, compared to the oligotrophic southern basin, but also because most studies are limited to surface-layer dynamics, neglecting nearshore coastal zones that are fundamental for benthic processes (Grilli et al., 2020). These latter areas, although shallower, are highly dynamic and ecologically crucial, but they remain poorly characterized in terms of long-term variability and changes. The pronounced spatial heterogeneity challenges the identification of how processes like nutrient transfer efficiency and thermohaline feedback function across the entire basin. Moreover, the lack of harmonized long-term datasets has hindered robust analysis of seasonal patterns, interannual variability, and climate-driven shifts. Assessing how much river discharges and abiotic factors in the Adriatic Sea have changed in the past five decades and which areas were most influenced is essential to understanding the current freshwater and biogeochemical dynamics. In this contest, integrating bottom-layer observations with coastal-scale perspectives is essential to move beyond surface-focused approaches and to achieve a more complete understanding of basin functioning. Our study addresses these spatial and depth-related knowledge gaps through the analysis of a 53-year dataset (1971–2023) of bottom measurements (≥4 m depth) of temperature, salinity, chlorophyll-*a*, and nitrate concentrations. Data were extracted from the EMODnet Chemistry Ocean Browser and from the Regional Environmental Protection Agencies (Agenzie Regionali per la Protezione dell'Ambiente, ARPA) of Emilia-Romagna (ARPAE); Marche (ARPAM); Abruzzo (ARTA) and Puglia (ARPA Puglia). By applying spatial interpolation techniques (DIVA) and a comparative subregional framework, we resolved seasonal (winter/summer) spatial patterns and quantified long-term trends across northern river-influenced areas and central-southern zones. This approach allowed us to assess interannual variability in response to changing runoff regimes and to provide a robust benchmark for ecosystem management under evolving hydrological and climatic conditions.

2. Materials and methods

2.1. Study site

The Adriatic Sea is a semi-enclosed sub-basin of the eastern Mediterranean Sea, extending in a northwest-southeast direction for approximately 800 km. It is bordered along its longitudinal axis by the Apennine and Balkan mountain ranges and is enclosed at its northern end by the Padan-Venetian-Friulian plain (Artegiani et al., 1997). The Adriatic is conventionally subdivided into northern, central, and southern sub-basins (Artegiani et al., 1997); however, the basin is often described in term of a shallow northern sector, characterized by an extensive continental shelf, and a deeper southern sector, where water depths gradually increase southward, reaching approximately 1200 m in the Southern Adriatic Pit (SAP) (Bonaldo et al., 2016). This bathymetric configuration makes the Adriatic a highly heterogeneous basin from both geomorphological and oceanographic perspectives. In this study we focused on the Adriatic Sea between latitudes 41.8872°N and 45.5000°N, encompassing the northern and central sectors. Sampling stations were grouped into two subregions, a North Adriatic and Central-South Adriatic, using the area near Ancona as a geographic boundary (Fig. 1). This subdivision represents a study-specific methodological choice, adopted to reflect similarities in bathymetry, circulation patterns, and data availability, rather than a canonical basin classification. Only coastal and bottom water data were included in the analysis, reflecting our emphasis on seabed dynamics and shallow

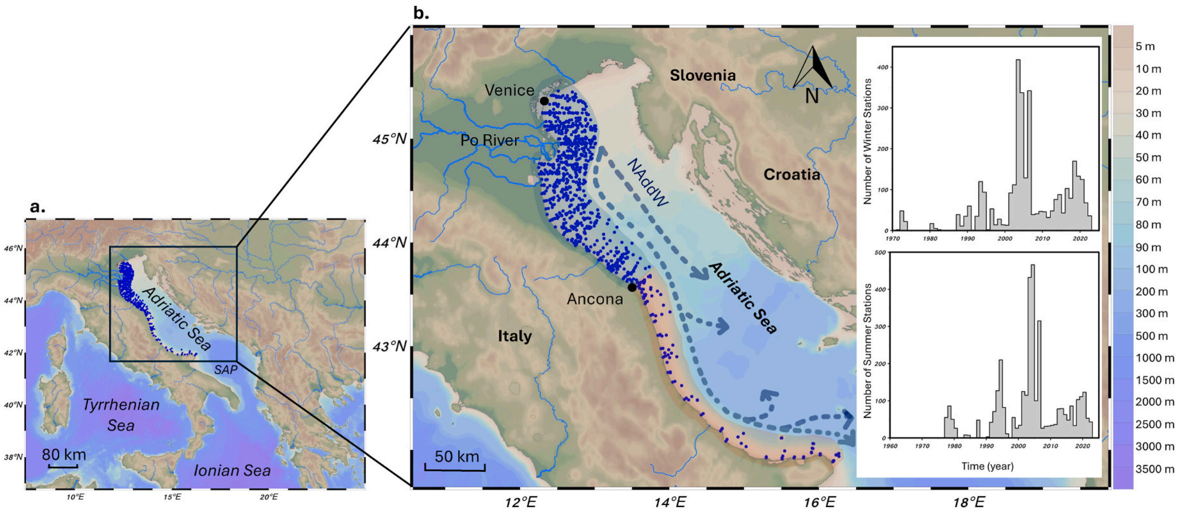

Fig. 1. (A) Location of the Adriatic Sea within the Mediterranean Sea (SAP, Southern Adriatic Pit). (b) Geographical distribution of sampling stations (1971–2023), with the northern (blue) and central-southern (red) subregions indicated. The blue dashed line represents the pathway of the North Adriatic dense Water (NAddW). Inset: Number of stations per year. Maps generated using Ocean Data View (ODV v5.8.1, 64-bit macOS ARM, build 3.2 – April 2023). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

coastal processes. These areas are particularly sensitive to riverine inputs, which strongly influence benthic–pelagic interactions, nutrient accumulation, and local ecosystem functioning.

2.2. Data inventory and processing

Variations in river discharge have long been directly linked to changes in environmental parameters and nutrient loads across the Adriatic Sea (Vona et al., 2025; Sani et al., 2024; Verri et al., 2024). To investigate these long-term trends and their impacts on the marine environment, consistent and continuous time series of river discharge are essential. Daily discharge data for the Po River covering the period 1970–2023 were sourced from the ARPAE Emilia-Romagna's DEXT3R repository (https://simc.arpae.it/dext3r/; accessed on June 18, 2025). The dataset provides complete daily records organized by hydrological years (October–September) from the Pontelagoscuro monitoring station (44°53′N, 11°36′E), which captures >90 % of the total Po River basin drainage.

Long-term oceanographic time series represent a valuable resource for identifying persistent seasonal patterns and detecting significant changes in response to local or global pressures. For this study, a comprehensive dataset was meticulously assembled by integrating multiple data sources. Oceanographic data were extracted from the Ocean Browser EMODnet Chemistry portal (European Marine Observation and Data Network, URL: https://www.emodnet-chemistry.eu; accessed in July 2023) and from the Regional Environmental Protection Agencies (Agenzie Regionali per la Protezione dell'Ambiente, ARPA) of Emilia-Romagna (ARPAE), Marche (ARPAM), Abruzzo (ARTA) and Puglia (ARPA Puglia). The EMODnet Chemistry portal provides free access to validated marine chemistry datasets, collected from environmental monitoring programs and scientific research activities. Quality Assurance and Quality Control (QA/QC) procedures follow the international standard ISO/IEC 17025:2005 and complete metadata are made available through the Common Data Index (CDI) data portal (https://csr.seadatanet.org). Data from the ARPAs underwent internal QA/QC procedures prior to dissemination, including calibration verification and consistency checks. Historical data (1970s–1990s) were collected following classical oceanographic protocols (e.g., Strickland and Parsons, 1968 (Strickland et al., 1972);), while from the late 1990s onward, national and regional monitoring programs adopted standardized analytical procedures including APHA/AWWA/WEF standards and more recently IRSA-CNR methodologies. Only data passing all QC levels were included in the final harmonized dataset.

To ensure harmonization across the combined dataset, we applied additional screening criteria, such as range checks, removal of duplicates, unit standardization, and spatiotemporal consistency validation. Given the multi-decadal span and methodological evolution, a structured data harmonization process was implemented to ensure internal consistency, traceability, and interpretability. For each variable, the potential influence of evolving analytical methods over time was evaluated. Temperature and salinity data derived from discrete sampling and CTD (Conductivity-Temperature-Depth) profiles were used without correction, as no systematic biases were detected. Chlorophyll-*a* and nitrate concentrations, measured using different chromatographic and colorimetric techniques over the decades, were harmonized through the standardization of units and detection limits, with analytical method information preserved in the metadata. The metadata reconciliation involved standardizing variable names, units, station identifiers, geographic coordinates, and temporal references. Records with incomplete and irreconcilable metadata were excluded.

The final dataset comprises approximately 6693 sampling stations and includes measurements of seawater temperature (°C), salinity, chlorophyll-*a* ($\mu g\ L^{-1}$) and nitrate (μM) collected in 1971–2023 using CTD probes, bottle sampling, and autonomous monitoring systems. The analysis was restricted to coastal bottom water defined as discrete water samples collected at the deepest depth of each vertical profile within a depth range from 4 to 50 m. This selection ensures a consistent and comparable analysis of near bottom coastal conditions across the North and Central-South Adriatic. Focusing on the bottom layer is ecologically significant, as it represents the habitat where benthic organisms (e.g., seagrasses, mollusks, demersal fish) interact directly with their environment.

2.3. Spatial interpolation

Spatial interpolation was performed using Data-Interpolating Variational Analysis (DIVA), a gridding software developed at the University of Liège (Marini et al., 2002) and implemented as a package within Ocean Data View (ODV). DIVA is specifically designed for irregularly distributed marine datasets and accounts for coastline geometry and bathymetric constraints. Compared to conventional weighted-averaging methods, it offers improved performance by incorporating spatial error covariance and topographic limitations. The interpolation was performed using manually tuned anisotropic spatial correlation length scales (17 ‰ along x-axis and 13 ‰ along y-axis). This anisotropy reflects the strong northwest–southeast elongation of the Adriatic Sea and its dominant circulation patterns, which promote along-basin coherence substantially larger than cross-basin coherence. Isopycnal constraints were not applied, as this study focuses on long-term patterns in coastal bottom waters. In shallow areas, density surfaces frequently intersect the seabed and are strongly influenced by seasonal vertical mixing and riverine inputs. The interpolation achieved a signal-to-noise ratio (SNR) of 50, confirming robust separation of environmental signals from noise. Following the interpolation, a quality control step was applied to mask grid points where the normalized error estimate exceeded a threshold of 3.0. This dimensionless error metric, computed by DIVA, reflects the confidence of the interpolation relative to the background data error. This threshold is a standard conservative choice for identifying and masking areas where field reconstruction relies primarily on extrapolation from the *a priori* covariance function (due to very low data density) rather than being constrained by direct observations.

The results were visualized with color shading and overlaid isolines to improve the physical interpretability of spatial gradients. All statistical analyses were performed using RStudio (v2023.06.2 + 561; RStudio Team, 2023) within the R programming environment (v4.3.1; R Core Team, 2023). Overall long-term temporal trends were assessed by Generalized Linear Model (GLM) regression, using Gamma as a statistical distribution and a log-link function (Grilli et al., 2020), which appropriately handles the continuous, non-negative nature of the response variables and reduces the influence of outliers.

3. Results

Oceanographic properties (temperature, salinity), chlorophyll-*a*, and nitrate concentrations were analyzed across spatial and temporal scales to resolve seasonal variability in spatial patterns and quantify long-term trends throughout the Adriatic Sea. Trends were compared between the river-influenced North Adriatic (Fig. 1, blue) and the Central-South Adriatic (Fig. 1, red). Interannual variability was assessed for both seasonal periods and subregions to identify potential differences in the temporal evolution.

3.1. Po River hydrological trends

Over the period 1970–2023, the Po River exhibited pronounced seasonal discharge variability, with mean (±SE) daily flows of 1395.098 ± 11.17 $m^3 s^{-1}$ during the winter (January–March) and 1068.12 ± 9.78 $m^3 s^{-1}$ during summer (July–September). Daily discharge exhibited statistically significant long-term declines in both seasons, as quantified using a Generalized Linear Models (Gamma distribution, log-link). During winter, the model revealed an annual percent decrease of 0.46 % yr^{-1} ($p < 0.001$). In summer, an annual percent decrease of 1.00 % yr^{-1} was observed ($p < 0.001$) (Fig. 2). These trends are consistent with the findings of Grilli et al. (2020), who documented comparable seasonal patterns during 1993–2015, characterized by higher baseline discharge (winter: 1850 ± 24 $m^3 s^{-1}$; summer: 1126 ± 12 $m^3 s^{-1}$) and lower annual multiplicative decline rates of −0.25 % in winter and −0.89 % in summer. Our extended analysis confirms the persistence of these declining trends while revealing an acceleration in discharge reduction over the full 1971–2023 period, indicating a progressive reduction in freshwater input to the Adriatic Sea. These findings are further supported by Cozzi et al. (2018), and Marini & Grilli (Marini and Grilli, 2023), who documented historical alternations between high-runoff (e.g., years 1975–2002) and low-runoff (e.g., years 1942–1974) phases. The post-2003 period has been identified asthe most severe drought of the last century, characterized by a decrease in annual discharge of approximately 567 $m^3 s^{-1}$, followed by a phase of high and variable regime in 2010–2015 (Grilli et al., 2020; Cozzi et al., 2018). Despite natural oscillations in runoff, driven by natural climate variability (Cozzi et al., 2018), the discharge decline that occurred after 2003 has persists (Marini and Grilli, 2023), reflecting a broader drying trend associated with anthropogenic climate forcing. Reduced freshwater input has multi-level impacts on Adriatic ecosystems, including prolonged salinity intrusion in coastal zones, amplified benthic hypoxia due to stronger stratification and reduced oxygen renewal, shifts in plankton community's structures driven by altered nutrient stoichiometry and reorganization of macrobenthic assemblages (Giani et al., 2012; Mozetič et al., 2019). Together, these changes may facilitate non-indigenous species establishment while reducing total biomass, thereby threatening the biogeochemical stability and ecological resilience of the Adriatic Sea (Cabrini et al., 2019; Petrocelli et al., 2019; Azzurro et al., 2019).

3.2. Spatial distribution patterns

The hydrography and biogeochemistry of the Adriatic Sea are profoundly influenced by the freshwater and nutrient inputs of the Po River, particularly in the northern and western coastal sectors.

Bottom water temperatures (Fig. 3a) exhibited a clear seasonal cycle with the largest amplitude between winter and summer observed in shallow coastal areas. Here, temperatures ranged from approximately 6 °C in winter to 25 °C in summer, while smaller seasonal changes occurred offshore. A pronounced north-south gradient was also evident, with colder waters prevailing in the northern part of the basin, particularly during winter. The coastal area, directly influenced by the Po River discharge, displayed distinct thermal properties, with lower temperatures in winter and warmer temperatures in summer compared to offshore bottom waters.

Bottom salinity distributions (Fig. 3b) revealed a strong cross-shelf gradient within the western Adriatic Sea, particularly in the northern

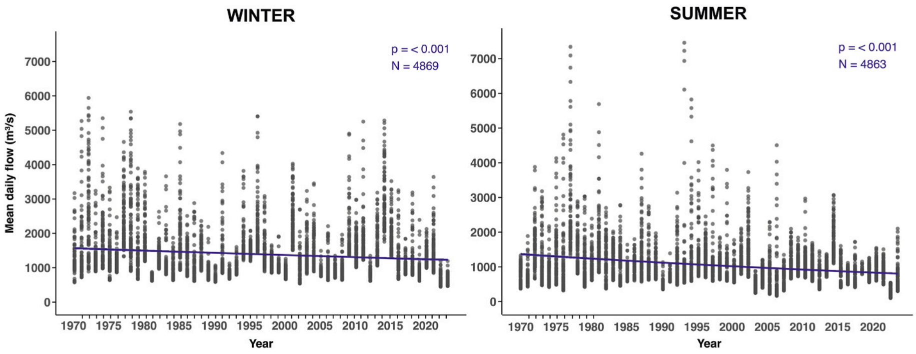

Fig. 2. Long-term trends in daily Po River discharge ($m^3 s^{-1}$) for winter (left) and summer (right) from 1970 to 2023. The blue line represents the fitted trend from a Generalized Linear Model (Gamma distribution, log-link). Data were provided by the Pontelagoscuro monitoring station, ARPAE Emilia-Romagna's DEXT3R repository (https://simc.arpae.it/dext3r/). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

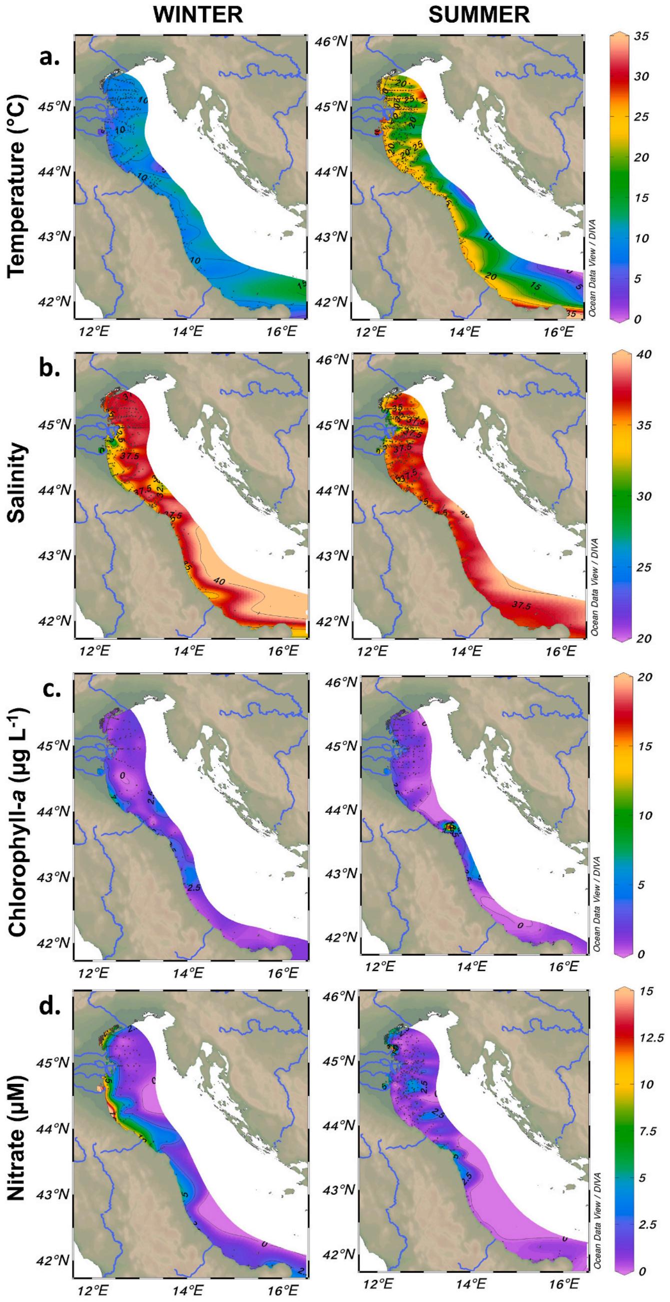

Fig. 3. Bottom-water patterns of (a) seawater temperature (°C), (b) salinity, (c) chlorophyll-*a* (μg L^{-1}), and (d) nitrate (μM) concentrations during winter (left) and summer (right). Maps show seasonal climatologies for the period 1971–2023, reconstructed with the DIVA interpolation method.

part of the basin. Along the coast seafloor, low-salinity waters associated withthe Po River formed a well-defined bottom plume. The spatial extent and orientation of this plume exhibited a clear seasonal shift: during winter, enhanced river discharge and prevailing circulation drove the plume southward along the Italian coast, while in summer the freshwater signal became more radially distributed, extending eastward toward the center of the basin. Consistent with this pattern, mean bottom salinity in the North Adriatic was significantly lower than in the Central-South sub-basin during winter (Table 1).

Bottom chlorophyll-*a* concentrations (Fig. 3c) were highest close to the Po River delta in both seasons, with a pronounced maximum during winter (Table 1). This seasonal peak in biomass was accompanied by a notable southward extension of the high-chlorophyll-*a* values along the western coastal shelf.

Table 1
Statistics of the seasonal dataset in bottom seawater of temperature (°C), salinity, chlorophyll-*a* (μg L^{-1}), and nitrate (μM) from 1971 to 2023.

Sub-basin	North Adriatic		Central-South Adriatic	
Season	Winter	Summer	Winter	Summer
Temperature (°C)				
No. data	45249	54850	5721	3227
Mean	8.64	23.34	9.02	25.51
Standard Error	0.01	0.02	0.02	0.03
Minimum	3.32	8.76	4.11	12.68
Maximum	14.70	30.40	15.90	29.10
Salinity				
No. data	45220	54831	6270	3225
Mean	35.35	36.22	36.48	36.21
Standard Error	0.01	0.01	0.02	0.02
Minimum	6.64	2.76	22.66	30.69
Maximum	38.74	39.81	39.74	39.12
Chlorophyll-*a* (μg L^{-1})				
No. data	9518	9652	6009	3157
Mean	2.86	1.67	1.98	0.74
Standard Error	0.04	0.03	0.04	0.02
Minimum	0.03	0.02	0.05	0.04
Maximum	28.62	39.74	29.19	32.15
Nitrate (μM)				
No. data	3972	4319	535	296
Mean	4.44	1.85	2.24	0.55
Standard Error	0.11	0.06	0.09	0.09
Minimum	0.01	0.01	0.08	0.00
Maximum	40.44	37.58	16.15	13.16

Bottom nitrate concentrations (Fig. 3d) exhibited a strong inverse relationship with salinity, with the highest values closely associated with the low-salinity Po River plume along the western coast. This created a marked cross-shelf gradient, with concentrations declining sharply towards the offshore and southern regions. A clear seasonal pattern was evident, characterized by elevated nitrate concentrations and a south-eastward extension of the nutrient-rich plume during the high-discharge winter season. In contrast, summer conditions were marked by generally lower and more spatially uniform nitrate levels across the basin.

3.3. *Long-term interannual trends*

We analyzed multi-decadal variability (1971–2023) in physical (temperature, salinity) and biogeochemical (chlorophyll-*a*, nitrate) parameters using a GLM with a Gamma distribution and a log-link function. This approach revealed significant long-term changes, characterized by pronounced regional and seasonal contrasts.

In the North Adriatic, bottom temperature exhibited a slight negative trend during winter, with an annual rate of change of −0.28 % yr^{-1} ($p < 0.001$; Table 2; Fig. 4a) and a mean value of 8.64 ± 0.01 °C (Table 1). In contrast, summer temperatures showed a more pronounced positive trend of +1.05 % yr^{-1} ($p < 0.001$; Table 2; Fig. 4a), with a mean temperature of 23.34 ± 0.02 °C (Table 1). In the Central-South Adriatic, bottom temperature showed marked seasonal differences in warming rates, with pronounced warming during winter (+0.43 % yr^{-1}, $p < 0.001$; Table 2; Fig. 5a), corresponding to a mean temperature of 9.02 ± 0.02 °C (Table 1), and a weaker but still warming trend in summer (+0.08 % yr^{-1}, $p < 0.001$; Table 2; Fig. 5a), with a mean temperature of 25.51 ± 0.03 °C; Table 1).

Salinity trend also reflected the influence of large-scale drivers. In the North Adriatic, salinity exhibited a decrease in winter (−0.28 % yr^{-1}, $p < 0.001$; Table 2; Fig. 4b) and a slight increase in summer (+0.02 % yr^{-1}, $p < 0.001$; Table 2; Fig. 4b), with mean values of 35.35

Table 2
Variation (% yr^{-1}) of bottom-water physical and biogeochemical properties in the North and Central-South Adriatic Sea for winter and summer seasons (1971–2023). Values represent the estimated trend with 95 % confidence intervals shown in parentheses. Statistically non-significant trends ($p > 0.05$) are indicated as "NS". Significance levels: *** = $p < 0.001$.

Parameter	North Adriatic		Central-South Adriatic	
	Winter	Summer	Winter	Summer
Temperature (°C)	−0.27 *** (−0.29; −0.25)	+1.05 *** (1.04; 1.08)	+0.43 *** (0.37; 0.49)	+0.08 *** (0.05; 0.11)
Salinity	−0.28 *** (−0.29; −0.27)	+0.02 *** (0.01; 0.02)	+0.10 *** (0.09; 0.11)	−0.09 *** (−0.11; −0.07)
Chlorophyll-*a* (µg L^{-1})	+0.88 *** (0.68; 1.11)	−1.97 *** (−2.21; −1.66)	−3.83 *** (−4.18; −3.19)	−3.63 *** (−4.29; −2.70)
Nitrate (µM)	+3.91*** (3.25; 4.88)	NS	−2.69 *** (−5.09; −0.08)	−10.35 *** (−11.96; −6.72)

± 0.01 and 36.22 ± 0.01, respectively. Conversely, the Central-South sub-basin showed the opposite pattern, with an increasing trend in winter (+0.10 % yr^{-1}, $p < 0.001$; Table 2; Fig. 5b) and a decreasing trend in summer (−0.09 % yr^{-1}, $p < 0.001$; Table 2; Fig. 5b). Corresponding mean salinity values were 36.48 ± 0.02 in winter and 36.21 ± 0.02 in summer.

Distinct long-term trends in chlorophyll-*a* were observed between the two sub-basins. In the North Adriatic, chlorophyll-*a* concentrations increased in winter (+0.88 % yr^{-1}, $p < 0.001$; Table 2; Fig. 4c) but showed a marked decline in summer (−1.97 % yr^{-1}, $p < 0.001$; Table 2; Fig. 4c). In the Central-South Adriatic, chlorophyll-*a* concentrations decreased in both seasons with rates of −3.83 % yr^{-1} ($p < 0.001$; Table 2; Fig. 5c) during winter and −3.63 % yr^{-1} ($p < 0.001$; Table 2; Fig. 5c) during summer.

Nitrate concentrations increased in the North Adriatic during winter (+3.91 % yr^{-1}, $p < 0.001$; Table 2; Fig. 4d). In contrast, in the Central-Southern sub-basin, nitrate concentrations decreased in both seasons (−2.69 % yr^{-1} in winter and −10.35 % yr^{-1} in summer, $p < 0.001$; Table 2; Fig. 5d).

4. Discussion

The spatial distribution patterns of bottom temperature, salinity, and biogeochemical parameters presented in this study refers exclusively to the western Adriatic Sea, as only coastal data were analyzed. Consequently, the observed north-south and coastal-offshore gradients are discussed within this defined western domain. The seasonal distribution maps (Fig. 3) reveal that the influence of the Po River extends southwestward along the Italian coast, with a particularly pronounced signal in winter. This influence is clearly indicated by a distinct low-salinity plume associated with elevated concentrations of chlorophyll-*a* and nitrate. Interestingly, the Po River signature is detectable even in bottom-water fields, although freshwater inputs are typically expected to remain confined to surface layers. This bottom water imprint suggests the occurrence of vertical propagation and mixing processes, as well as benthic-pelagic coupling driven by riverine inputs. This combination of high nutrient availability and enhanced productivity makes the northwestern Adriatic Sea a highly productive region but also one potentially vulnerable to eutrophic and dystrophic conditions.

The distinct thermal properties of the coastal bottom waters can also be explained by the influence of the Po River. During winter, the input of colder continental runoff contributes to lower coastal temperatures. In summer, by contrast, the river freshwater forms a distinct, shallow surface layer that is rapidly heated by the sun. Due to the shallowness of the coastal area, this surface warming can be transferred downward through vertical mixing, resulting in warmer bottom waters compared to offshore areas, which are deeper and less affected by surface heat fluxes (Boldrin et al., 2009). The seasonal shift in the direction and extent of the Po River plume is driven by changes in physical forcing. Southward transport in winter is facilitated by prevailing winds and basin-scale circulation patterns (Kourafalou, 1999; Boldrin et al., 2009; Lee et al., 2005). In summer, reduced wind-driving mixing and enhanced stratification allow the plume to spread more radially confining freshwater to a thin surface layer and enabling pronounced offshore propagation despite lower river discharge (Cozzi et al., 2020; Grilli et al., 2020)

The higher chlorophyll-*a* concentrations observed in proximity to the Po River delta, particularly during winter, suggest a dominant bottom-up control driven by river-borne nutrient inputs at a sub-regional scale, whereas spatial variability observed farther from the river mouth is likely influenced by local processes (Cozzi et al., 2020; Cavallini et al., 2024). Similarly, the seasonal patterns observed in bottom nitrate concentrations, characterized by high winter values and widespread depletion in summer, indicates significant biological uptake by phytoplankton following the spring bloom, which consumes the riverine nutrient inputs (Cavallini et al., 2024).

Overall, the analysis of seasonal distribution provides essential background for deepening the interannual variability and long-term trends within the Adriatic Sea system. While seasonal patterns are largely forced by recurring atmospheric and hydrological cycles, interannual variability and log-term trends may often reveal the influence of broader environmental changes. The pronounced summer warming observed in both sub-basins is consistent with the Mediterranean Sea being recognized as a climate change hotspot and is consistent with future projections (Tojčić et al., 2023, 2024). In winter, however, the temperature trends exhibit a contrasting behaviour between regions: while the Central-South Adriatic Sea shows a positive trend, the North Adriatic is characterized by a slight but statistically significant cooling. This seasonal and spatial asymmetry suggests the involvement of distinct regional processes that locally modulate the large-scale warming signal. Future projections for the end of the century suggest intense warming in parts of the basin like the Otranto Strait, but also a strong reduction in warming rate and even contrasting patterns between sub-basins, particularly at a bottom level (Cozzi et al., 2020). This heterogeneity in projected responses is consistent with our observations and may, in the North Adriatic, point to changes in dense water formation (DWF) dynamics. One plausible mechanism is suggested by the far-future modelling study of Denamiel et al. (2025), which shows that despite a projected weakening of the Bora wind, enhanced surface buoyancy losses associated with increased evaporation may allow NAddW properties to remain comparable to present conditions, even under extreme warming scenarios. This mechanism could be further modulated by the projected reduction in river discharge described by Verri et al. (2024), which would reduce stratification in the northern basin. Reduced stratification may enhance vertical mixing and bottom water ventilation, potentially favouring dense water formation under conditions of sufficient surface buoyancy loss, rather than directly increasing bottom water density. In this framework, the observed winter cooling in the northern Adriatic may reflect a regional-scale response in which coupled atmospheric and hydrological changes partially counteract the broader warming signal through enhanced renewal of the bottom layer.

Salinity trends exhibit a marked seasonal and regional contrast, with opposite behaviour between the two sub-basins. In the North Adriatic, salinity shows a decreasing trend during winter and a slight increase during summer, whereas in the Central–South Adriatic the opposite pattern is observed, with increasing salinity in winter and decreasing salinity in summer. This seasonal inversion suggests that salinity variability cannot be explained by Po River discharge alone, which has exhibited a long-term decline over the study period. Previous studies focusing on surface waters have similarly indicated that interannual and decadal-scale processes, rather than local riverine inputs, play a

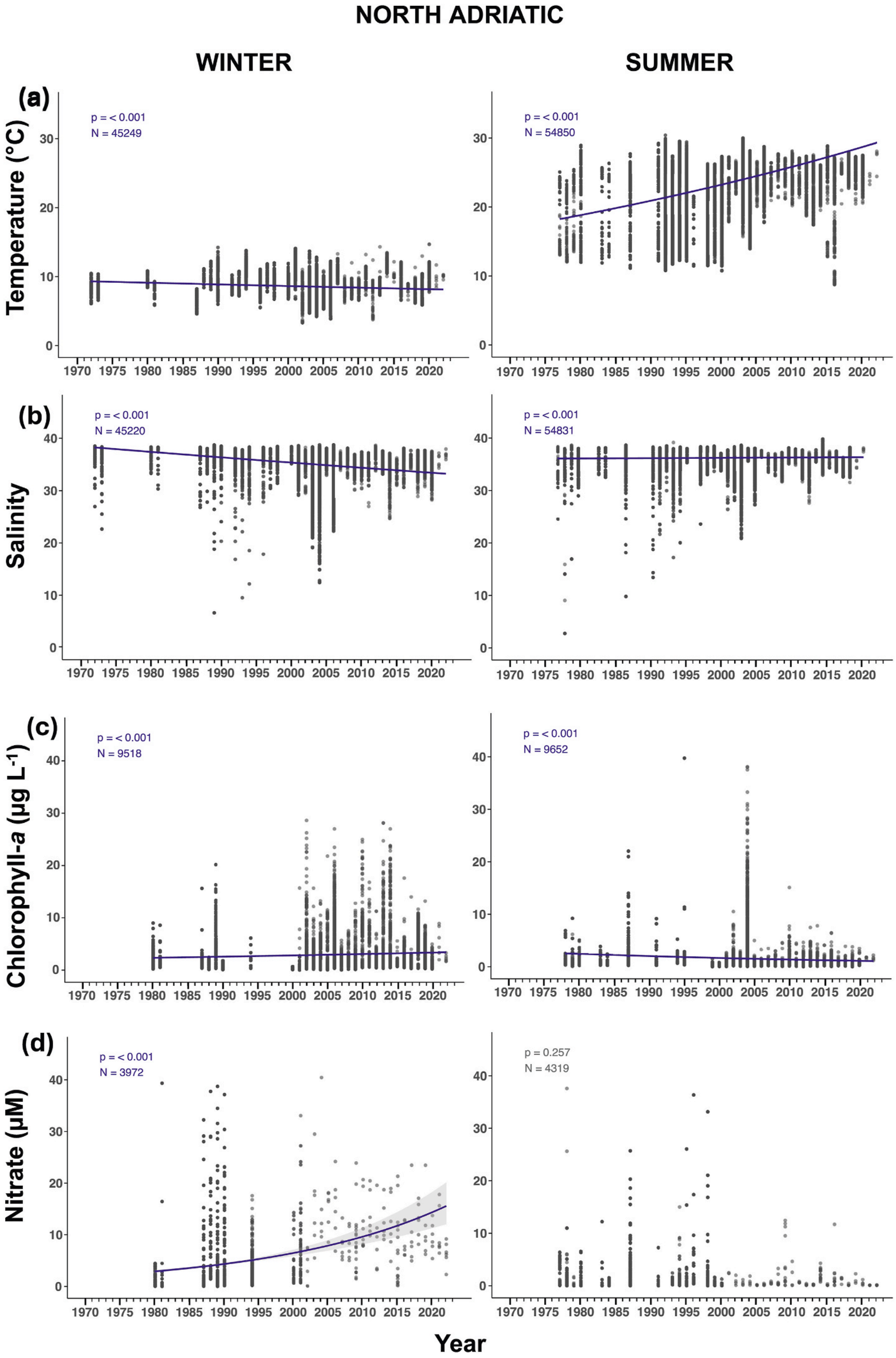

Fig. 4. North Adriatic seasonal bottom trends of (a) temperature (°C), (b) salinity, (c) chlorophyll-*a* (μg L^{-1}), and (d) nitrate (μM) from 1971 to 2023. The blue line represents the long-term trend with the 95 % confidence limits (grey range). When the slope was not significant (p-value >0.05), the long-trend line was not reported. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

dominant role in shaping salinity variability across the Adriatic basin (Grilli et al., 2020). The slight increase in summer salinity observed in the shallow North Adriatic may be linked to enhanced evaporation under warmer summer conditions (Grilli et al., 2020). In shallow coastal areas, increased evaporation can raise surface salinity, which may subsequently influence bottom waters through vertical mixing during periods of weak stratification. Conversely, the seasonal decrease in salinity observed during winter in the North Adriatic and in summer in the Central-South Adriatic likely reflects the combined effects of basin-scale circulation variability, air-sea fluxes, and mixing processes, rather than direct riverine forcing. Long-term changes in river discharge may nonetheless indirectly affect salinity patterns by modifying shelf water properties and dense water formation processes in the northern Adriatic. A persistent reduction in freshwater input has been associated with increased shelf salinity (Vodopivec et al., 2022), which may alter the characteristics and volume of dense water formed during winter. The subsequent spreading of this newly formed dense water toward the Central–South Adriatic could contribute to changes in deep-water salinity, although the relative importance of this mechanism remains uncertain and likely varies over time (Grilli et al., 2020). Moreover, the Central-South Adriatic dataset primarily covers the period from the 1990s onward, limiting the ability to fully capture earlier long-term

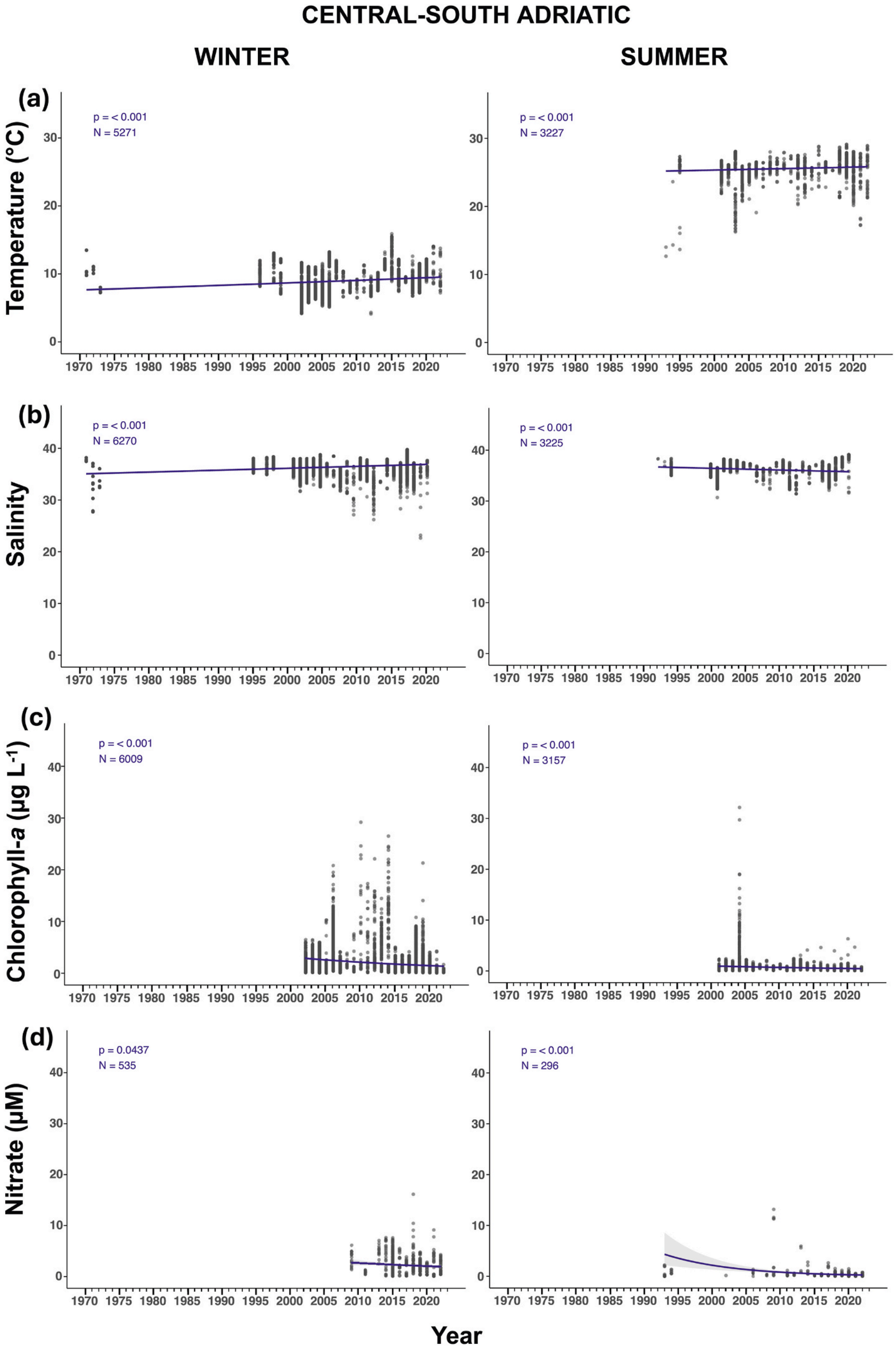

Fig. 5. Central-South Adriatic seasonal bottom trends of (a) temperature (°C), (b) salinity, (c) chlorophyll-*a* (μg L^{-1}), and (d) nitrate (μM) from 1971 to 2023. The blue line represents the long-term trend with the 95 % confidence limits (grey range). When the slope was not significant (p-value >0.05), the long-trend line was not reported. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

salinity trends. These results should therefore be interpreted with caution.

The long-term decrease in chlorophyll-*a* in the Central-South Adriatic, together with the summer decrease in the North Adriatic is consistent with the documented oligotrophication of the Adriatic Sea (Degobbis et al., 2000). This widespread reduction in primary production has been primarily linked to a significant decrease in phosphorus (P) loads from Italian rivers, rather than a decrease in nutrient inputs overall. Indeed, especially in the North Adriatic Sea, phosphorous is the limiting nutrient for primary production (Neri et al., 2022; Acquavita et al., 2024). Total phosphorous inputs have decreased from 15.6 to 8.1 × 103 t P yr^{-1} since 1978 (Sani et al., 2024; Degobbis et al., 2000), following regulatory measures introduced in the late 1980s that limited the use of phosphate in detergents (Bressan, 1986). These measures have led to a long-term shift of the Adriatic ecosystem from eutrophic conditions toward reduced primary productivity and increasing phosphorus limitation, often described as oligotrophication of the basin (Cozzi and Giani, 2011). Despite this overall trend, a slight increase during winter in chlorophyll-*a* concentration was observed in the North Adriatic. This positive trend, which aligns with the seasonal surface patterns reported by Grilli et al. (2020), appears to be consistent with the increase in nitrate concentrations observed in the same region during winter. While phosphorous loads have been significantly reduced, nitrogen inputs from the Po River have not followed the same trajectory resulting in a pronounced increase in the N:P ratio (Marini and Grilli, 2023; Campanelli et al., 2004). This imbalance likely reflects enhanced anthropogenic nitrogen inputs in the Po River drainage basin, delivered during high-discharge events (Cozzi et al., 2020), combined with increased atmospheric nitrogen deposition, a phenomenon observed worldwide (Kim et al., 1979). In contrast, the general decreasing trend in nitrate concentrations observed in both seasons in the Central-South Adriatic could be linked to a decline in runoff from several minor Italian rivers, including the Foglia (Marche, PU), Aterno-Pescara (Abruzzo, PE), Sangro (Abruzzo, CH), and Ofanto (Puglia, BT) (Ricci et al., 2024; Tariq et al., 2025; Darvini and Memmola, 2020). Available studies indicate a long-term decrease in river discharge along the central and southern Adriatic coast, driven mainly by decreasing precipitation and increased evapotranspiration associated with regional warming (Billi and Fazzini, 2017). However, the limited temporal and spatial coverage of chlorophyll-*a* and nitrate observations in this sub-basin introduces uncertainty, and these results should be interpreted with caution.

5. Conclusions

This study provides new insight into the long-term evolution of the Western Adriatic Sea by focusing on its coastal bottom waters, a critical less-studied compartment. Analysis of a 53-year dataset (1971–2023) reveals distinct physical and biogeochemical trends in the North and Central-South sub-basins, driven by the combined effects of hydrological variability and climate change. The analysis of the Po River discharge confirms a significant long-term reduction over the last 53 years, especially during summer, reflecting an ongoing drying trend of the main freshwater source to the basin. This decline has profound implications for coastal hydrography and nutrient dynamics, influencing salinity gradients and ecosystem functioning. Observed long-term changes in oceanographic and biogeochemical properties exhibit pronounced seasonal and regional contrasts. In the North Adriatic, bottom waters show a dual thermal signal: a pronounced summer warming ($+1.05$ % yr^{-1}) and a slight but significant cooling trend in winter (-0.27 % yr^{-1}). Salinity trends further emphasizethis this seasonal complexity, with decreasing values in winter and a slight increase during summer. In contrast, the Central-South Adriatic display a more consistent warming signal, characterized by significant winter warming ($+0.43$ % yr^{-1}), and weaker but still positive summer trends ($+0.08$ % yr^{-1}) accompanied by an opposite seasonal salinity behavior, with increases in winter and decrease in summer. These contrasting patterns indicate that bottom water variability in the Adriatic Sea is strongly modulated by basin-scale processes and seasonal atmospheric forcing, rather than by river discharge alone.

The widespread long-term decrease in chlorophyll-*a* concentrations, particularly evident in the Central-South Adriatic and during summer in the North Adriatic, is consistent with the documented phosphorus-driven oligotrophication of the Adriatic Sea. This shift is largely attributed to the substantial reduction in phosphorus inputs from Italian rivers following regulatory measures introduced in the late 1980s. However, the observed increase in nitrate concentrations in the North Adriatic during winter, coupled with the persistence of high nitrogen loads from the Po River, have increased the N:P ratio, raising concerns over nutrient imbalance and potential changes in plankton communities. In the Central-South Adriatic, the general decrease in nitrate concentration may reflect reduced runoff from several minor Italian rivers, although the limited availability of long-term data introduces uncertainty. Overall, our findings confirm that the Adriatic Sea is a highly dynamic system undergoing significant, multi-level changes. The combined effects of reduced freshwater input, climate-driven warming, and altered nutrient stoichiometry poses increasing challenges to ecosystem productivity and ecological stability. By focusing on long-term changes in the bottom-water environment, this study provides a foundation for future research linking these physical and biogeochemical shifts to benthic processes and community dynamics.

A major limitation of this study is the availability of homogeneous long-term datasets, especially for the Central-South Adriatic sub-basin, where chlorophyll-*a* and nitrates observations are affected by notable spatial and temporal gaps. This lack of uniformity complicated the identification of robust long-term trends in some areas and therefore results for this area should be interpreted with caution. Our findings highlight the need for continued monitoring and integrated management strategies that consider the complex interactions among hydrological, climatic, and anthropogenic factors. Therefore, future monitoring programs should prioritize uniform spatial and temporal coverage of the coastal zone and the entire Adriatic water column from north to south, with particular emphasis on winter and summer conditions, in order to improve the detection and interpretation of long-term environmental changes.

6. Limitations

Over the 53-year timeframe, the dataset exhibits several sources of heterogeneity related to differences in sampling strategies, data structure, and spatial coverage.

First, sampling frequency varied substantially among parameters. CTD-derived variables (e.g., temperature and salinity) were generally collected at high vertical and temporal resolution, while biogeochemical parameters such as nutrients and chlorophyll-*a* were sampled less frequently and often irregularly.

Second, dataset formatting differed among data providers. Observations obtained from the Regional Environmental Protection Agencies followed heterogeneous organizational formats, requiring extensive manual harmonization. In addition, unit conversions for nutrients and chlorophyll-*a* concentrations were necessary to ensure consistency across dataset.

Third, spatial coverage was uneven across the Adriatic Sea. The northern and central sectors were more intensively monitored, resulting in higher density of cruises and observations compared to the southern Adriatic. Data coverage was also less comprehensive in coastal environments, where the challenging conditions make sustained, high-frequency sampling difficult. This resulted in relative gaps in near-shore observations compared to offshore records.

As a consequence of these heterogeneities, the dataset required extensive harmonization, including unit conversions, metadata reconciliation, and rigorous quality control to ensure temporal consistency and data reliability. Despite these limitations, the compiled dataset provides broad spatial coverage of the Western Adriatic Sea and represents a valuable resource for investigating long-term variability and trends in coastal bottom-water properties.

CRediT authorship contribution statement

Teresa Sani: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Alessandra Campanelli:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Mauro Marini:** Writing – review & editing, Validation, Supervision, Conceptualization. **Stefano Goffredo:** Writing – review & editing, Supervision, Conceptualization. **Federica Grilli:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Conceptualization.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge the regional environmental protection agencies of the four Italian Adriatic regions for their essential role in providing the long-term observational data that made this study possible. Specifically, we thank ARPAE Emilia-Romagna (Agenzia Regionale per la Prevenzione, L'ambiente e L'energia dell’Emilia-Romagna), ARPAM Marche (Agenzia Regionale per la Protezione Ambientale), ARTA Abruzzo (Agenzia Regionale per la Tutela dell’Ambiente) and ARPA Puglia (Agenzia Regionale per la Prevenzione e la Protezione dell'Ambiente) for their commitment to environmental monitoring and for facilitating access to their valuable hydrochemical datasets.

This study represents partial fulfilment of the requirements for the doctoral thesis of Teresa Sani, within the international Program “Innovative Technologies and Sustainable Use of Mediterranean Sea Fishery and Biological Resources” (FishMed-PhD; www.FishMed-PhD.org) at the University of Bologna, Italy.

Data availability

Data will be made available on request.

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Glossary

DWF: Dense Water Formation
DW: Dense Water
NAddW: North Adriatic dense Water
SAP: Southern Adriatic Pit