

Review

The Role of Nitrogen and Phosphorus in Eutrophication of the Northern Adriatic Sea: History and Future Scenarios

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Abstract: In the last two decades of the 21st century, a gradual decrease in nitrogen and phosphorus has been observed along the coastal area of the Northern Adriatic Sea. This depletion is attributed to reduced river flows. Studies conducted over the past four decades have indicated that the N/P ratio in the open sea is unlikely to undergo significant change. In fact, it tends to increase due to the unique characteristics of the Northern Adriatic Sea, which experiences slow water turnover and is influenced by strong winds. Additionally, the Northern Adriatic Sea receives a substantial amount of freshwater from rivers, accounting for about one-third of the total freshwater flow into the Mediterranean. These rivers carry nutrient loads that contribute to the high productivity and abundance of fish in this sea, making it one of the most productive areas in the Mediterranean. It has been observed that the cessation of anthropogenic phosphorus input, which has been regulated since the late 1980s with legislation limiting its use in detergents, has significantly affected the trophic chain. The aim of this review is to provide an overview of the eutrophication trend in the Northern Adriatic Sea, highlighting the importance long-term data series.

Keywords: Northern Adriatic Sea; eutrophication; nitrogen; phosphorus; freshwater; plankton; fishing resource; long term research



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1. Peculiarity of the Northern Adriatic Sea

The Northern Adriatic Sea is particularly vulnerable to nutrient pollution due to its unique characteristics, including shallow depths, limited water exchange, and the influence of river discharges. The Northern Adriatic Sea (Figure 1), covering an area of 19,000 km² with an average depth of 35 m, receives freshwater input from numerous rivers and streams, including the Po River (1500 m³ s⁻¹, [1]), which contributes more than 50% of the external nutrient input [2–4]. The Adriatic's salinity is lower than that of the Mediterranean because the Adriatic collects one-third of the freshwater flowing into the Mediterranean Sea [5].

The Po watershed is very large (75,000 km², [1]) and includes highly developed Italian regions with a resident population of 16 million people [6,7]. This area is intensively cultivated with heavy use of natural and artificial fertilizers [8]. Being one of the most densely populated and agriculturally productive areas in Europe [9], the Po Valley significantly influences the nitrogen (N) and phosphorus (P) input to the Northern Adriatic Sea, affecting the productivity and trophic dynamics of the whole Mediterranean basin [10–13]. When these N and P inputs enter the sea, they fuel the growth of phytoplankton and macroalgae. However, when present in excessive amounts, they can lead to eutrophication. This process in the Adriatic Sea is significantly influenced by seasonal circulation patterns [14–16]. In winter, the anticlockwise superficial and deeper circulation along the western coasts (Figure 2) brings in nutrient-rich waters from the Po River [5,17–19] and other rivers originating in the Apennines [20–23]. These colder and less saline waters flow close to the Italian coast throughout the water column.



Figure 1. Map of the Mediterranean Sea with details of the Northern Adriatic and the hydrographic basin of the Po Valley (bottom left corner: Lat. 43.324050 N, Lon. 6.547654 E; top right corner: Lat. 46.537197 N, Lon. 16.027382 E; Source: Google Maps).

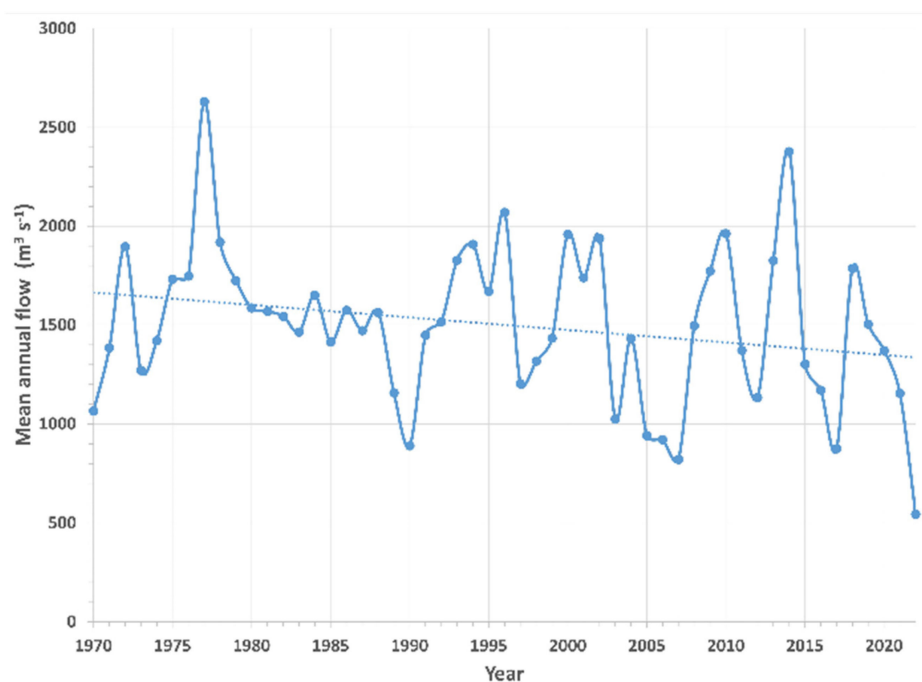


Figure 2. Trends of the daily Po River discharge ($\text{m}^3 \text{s}^{-1}$) from 1970 to 2022, with the significant long-term linear regression. Data from the Pontelagoscuro station available through the Regional Open Data Portal <https://simc.arpae.it/dext3r/> (accessed on 1 July 2023), provided by the Agenzia Regionale per la Protezione dell’Ambiente of the Emilia Romagna Region (ARPAE-ER).

In contrast, during the summer season, the hydrodynamic conditions change, resulting in weaker currents and a series of clockwise and anticlockwise gyres, as well as strong water column stratification, with colder waters from the previous winter near the bottom [12,24–29]. As a result, nutrient concentrations in the surface waters increase, creating favorable conditions for the growth of phytoplankton and macroalgae. Following the cyclonic circulation, the waters of the Mediterranean Sea flow into the Adriatic Sea from the eastern side of the Strait of Otranto while on the western side, they flow from the Adriatic to the Mediterranean Sea [30–34].

We used long-term data from the Northern Adriatic Sea, in conjunction with a comprehensive literature review, to illustrate the impact of anthropic factors during this post-industrial century on the future state of the continental shelf. Moreover, our investigation aims to assess the responses of aquatic ecosystems to the persistent impacts of climate change.

2. Influence of Climate Change in the Northern Mediterranean Area

Several authors have demonstrated the Mediterranean's particular sensitivity to the North Atlantic Oscillation (NAO). However, the influence of the NAO on the Mediterranean exhibits heterogeneity and distinct trends in two regions: the Northern Mediterranean (southern Europe) and Central/Northern Europe. These regions demonstrate contrasting patterns to the NAO trend [35–39]. An analysis of rainfall data collected in the Mediterranean spanning two centuries, namely the XIX and XX centuries, was conducted, and the trends over the Italian territory starting from the 1970s were analyzed. The findings revealed a negative trend in rainfall, particularly pronounced during the winter season. This decrease in rainfall was more prominent in northern Italy compared to the southern regions. Moreover, the study documented an increase in the occurrence of more intense rainfall events during the analyzed period [36,38].

In recent decades, the fluvial loads of rivers in the Mediterranean Sea have undergone significant changes, particularly in the last two to three decades (see the Po River discharge in Figure 3). These changes have had more pronounced and evident effects in the Mediterranean Sea due to two main factors: firstly, the constrained availability of water resources in the Mediterranean region, and secondly, the increased anthropic pressure, especially in coastal areas and the Po Valley. The construction and utilization of river dams have evolved rapidly since the 1950s [40], substantially altering the natural outflow of Mediterranean rivers. The widespread use of these dams for irrigation and various other purposes has led to profound modifications in the fluvial dynamics of the region's rivers. The second crucial factor contributing to these changes is the ongoing climatic shifts in the Mediterranean region. These changes have been extensively documented through the monitoring programs that have recorded variations since the latter part of the 20th century. Additionally, modeling processes have forecasted an increase in drought occurrences, primarily attributed to the rise in temperatures [41–45]. As we progress through this century, we can anticipate significant effects, including substantial reductions in river water discharges [6]. These climatic changes are expected to further compound the challenges posed to the fluvial loads of Mediterranean rivers and have far-reaching implications for the region's hydrological systems.

Grilli et al. [46] confirmed that during the first two decades of the 21st century, the river flows of the Po River have exhibited a continuous decrease, along with variable trends in flood events. Specifically, the average daily flow of the Po River was observed to be 12% lower in the period from 2006 to 2015 compared to the earlier period from 1971 to 2005. Notably, the annual mean flow of the Po River experienced significant changes due to the occurrence of persistent drought periods. Moreover, the frequency of flow rates higher than $3000 \text{ m}^3 \text{ s}^{-1}$ declined between 2006 and 2015 (the latter period considered in the analysis), and such higher flow events were more concentrated in certain months, namely February, April, November, and December. In contrast, previous decades experienced a greater number of these events that were spread over a larger period throughout the year.

Different authors have reported significant changes in various aspects of marine ecosystems [47,48]. These changes include alterations in the composition of plankton communities, shifts in the distribution of macrobenthos, the introduction and spreading of non-indigenous species, changes in the total biomass of target demersal fishes, and fluctuations in the catches of small pelagic fish [49–57].

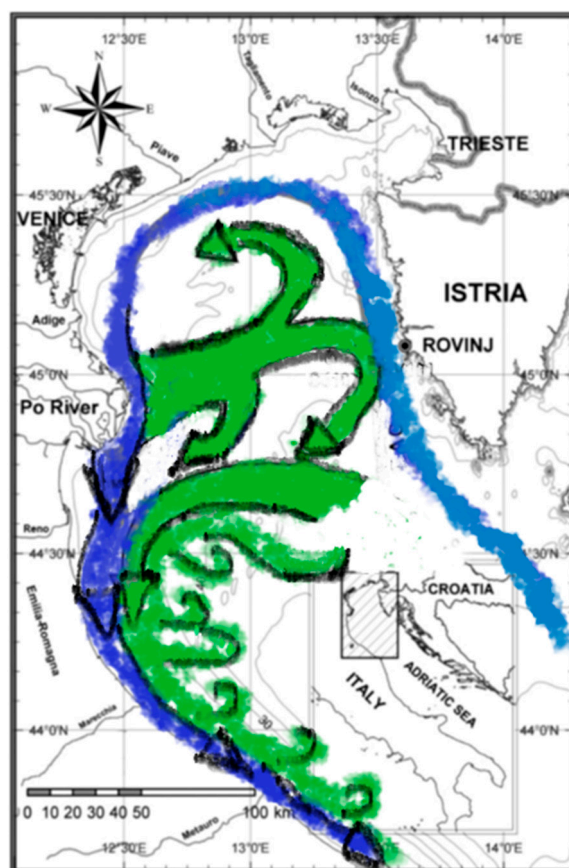


Figure 3. Simplified description of the seasonal surface circulation in the Northern Adriatic Sea, image adapted from [15] in agreement with [57,58]; blue (WAC, Western Adriatic current) and light blue (EAC, Eastern Adriatic current) for winter conditions; green for summer conditions, with eddies along the western coast.

3. Nitrogen and Phosphorus Conditioning in the Sea

The period of significant social changes, robust post-World War II industrial development, and the subsequent globalization of trade from the 1950s to the 1990s led to a substantial increase in the consumption of N and P for various purposes. Notably, N was extensively used as a fertilizer in agriculture, and its subsequent mineralization in surface and ground water, rather than industrial discharges into the atmosphere and urban wastewater, resulted in a substantial input of N watercourses eventually reaching the sea [8]. This pattern was also observed in the Northern Adriatic basin. As for P, its primary uses were prevalent in domestic environments and industry [8]. N and P are two elements that exhibit different behaviors once emitted into terrestrial and aquatic environments. The fate of P in the soil is primarily determined by chemical processes, such as adsorption/desorption and dissolution/precipitation. In contrast, the fate of N is primarily governed by biological processes including mineralization, nitrification, and denitrification [59].

Indeed, the extensive use of P and N during the latter half of the 20th century, along with the effects of climate change, has had significant implications for the Northern Adriatic Sea. The impact of climate change has become particularly evident in this region, starting from the end of the 20th century [36,60]. Notably, these changes are characterized by intense precipitation events, especially in spring and autumn, which significantly influence river outflows, leading to the transport of freshwater and suspended sediment into the sea [18,61,62]. As a consequence, these freshwater and sediment inputs carry pollutants, including N and P [19,23,63,64]. The combination of nutrient inputs from anthropogenic sources and climate-induced changes in hydrological patterns has contributed to alterations in nutrient concentrations and dynamics within the Northern Adriatic Sea.

In Italy, the total use of P in domestic detergents was prevented through Ministerial Decree n. 413 of 13 September 1988, which took effect from January 1989. Previously, from 1985 to 1988, there were other gradual measures implemented to reduce the use of P. Subsequently, in 2012, Europe adopted restrictive measures through Regulation 259/2012/EC, setting limitations for P of 0.5 g/dose in domestic laundry detergents and 0.3 g/dose in domestic dishwasher detergents. These regulatory measures have significantly contributed to the reduction of P inflow in surface watercourses up to the sea. As a result of this reduction, observable effects were recorded in the coastal strip with particular evidence in the Western North Adriatic Sea.

The predictions made by Caggiati & Ferrari [9] anticipated a decrease in P levels by the year 2020. Subsequent observations from the late 1990s to the 2000s showed a leveling off of P inputs into the sea, followed by a downward trend in the first two decades of the 21st century. However, the same trend was not observed for N. Despite the study by Caggiati & Ferrari [9] and subsequent works (e.g., [46]), N levels did not exhibit evident decreases, except in the strictly coastal strip around 3 km from the coast, where observations by Ricci et al. [23] demonstrated lower river flows and consequently reduced N and P loads. Over the years, the annual runoff of the Po River has exhibited significant fluctuations on a multi decadal time scale, with an overall decrease (−33% [65]) observed in all rivers of the Northern Adriatic when comparing recent discharges to those before the 1980s. Notably, during the dry years 2005–2007 (the last period of data analysis considered), the Northern Adriatic ecosystem experienced a considerable reduction in river water flows and nutrient loads compared to previous years characterized by medium-high regimes, as confirmed by Cozzi & Giani [65].

The decreasing temporal trend of N and P levels observed in the Adriatic Sea is consistent with trends seen in other European seas that are characterized by shallow waters (continental shelf) and are strongly influenced by freshwater inputs. For example, similar trends have been observed in the coastal zone of Baltic Sea as well [66].

The excess accumulation of N and P has significantly accelerated the expansion of eutrophication in these seas. In the Northern Adriatic Sea, the eutrophication phenomenon has been perceived as a pollutant due to the excessive proliferation of algae, which have degraded water quality, benthic habitats, and community structures [67–69].

In particular, offshore of the Po Delta and along the western coast, the process of oxygen consumption (hypoxia/anoxia) was accentuated during the summer when waters are warm and calm, and stratification of the water column occurs. This leads to widespread and persistent oxygen deficiencies in bottom waters, resulting in the suffering of benthic communities [3,70–73]. Another important phenomenon that occurred concomitant with eutrophication was the excessive proliferation of mucilage, which was documented especially in the late 1980s and in the early 2000s [3,7,25,74–79].

4. Final Considerations, and Future Directions

The Northern Adriatic Sea has experienced significant changes in eutrophication pressure over the past decades. From the 1970s to the mid-1980s, eutrophication increased, but it reversed course in the 2000s. This shift can be attributed to the combination of factors. Firstly, there was a reduction in anthropogenic impact, mainly due to a substantial decrease in phosphorus loads. Additionally, climatic changes played a role, leading to a decline in atmospheric precipitation and, subsequently, a decrease in runoff into the Northern Adriatic Sea. During the period 2000–2009, there was a significant decrease in the Po River outflow, which caused altered circulation patterns. As a consequence, there was a more frequent inflow of high salinity and oligotrophic water from the central Adriatic, resulting in a change in salinity and nutrient budget of the entire Northern Adriatic [15,33]. A four-decadal data set was analyzed to gain a better perspective of the driving pressures of phytoplankton in the Northern Adriatic. It was found that spring is the more critical season for the overproduction of organic matter [16,80,81]. Consequently, during the period 2000–2009, the intensity of phytoplankton blooms diminished, as evidenced by the

decrease in chlorophyll *a* concentration [82]. Kužat et al. [83] analyzed spatio-temporal distribution data extracted from a long-term phytoplankton in situ monitoring data set conducted by monthly to quarterly sampling between the years 1978 and 2020 offshore in the Northern Adriatic Sea. The analysis revealed hydrodynamic regime shifts in the system which had altered the phytoplankton abundance, community composition, and seasonal cycle. Notably, appearance and frequency alterations of some prominent taxa (e.g., *Pseudo-nitzschia delicatissima* group and *Pseudo-nitzschia seriata* group) were detected.

Casabianca et al. [84] described the changes in phytoplankton time series along the western coast of the Northern Adriatic Sea, showing a regular annual period in the composition structure of the coastal strip. The research indicates that the phytoplankton composition is influenced by various environmental factors, including physical variables and nutrient availability. The persistence of species in phytoplankton communities over the long term is normally affected by factors such as nutrient loads, climate change, and human pressures, while still maintaining a stable structure. In the Northern Adriatic Sea, this may impact the succession of functional groups of species and overall productivity of the ecosystem. However, due to stochastic environmental and climate changes, as well as enhanced environmental pressures, the time series have lost their regularity, causing changes in the succession and species composition of phytoplankton communities. Neri et al. [85] conducted a comparison between one coastal strip station and one offshore station along a transect along the western coast. The Western Adriatic Current (WAC, [14,20,86]), combined with river inflows, exerts a direct impact on coastal stations, resulting in heightened variability, as illustrated in the comparison with an offshore station. This disparity is particularly evident during winter and autumn, whereas similarity increases during the summer months when river waters spread outwards into the open sea. Owing to its oligotrophic nature, the offshore phytoplankton community demonstrated a greater level of biodiversity in contrast to observations along the coastline, where more prominent algal blooms tend to take place.

Over the past four decades, a gradual depletion of N and P has been observed along the coastal strip of the Northern Adriatic [23,87], compared to the previous period (1969–1992) [80]. This trend is expected to continue in the coming decades [19,79], due to lower flows from rivers with minor anthropic impact, resulting in reduced N and P loads. The study conducted by Ivančić et al. [88] on alkaline phosphatase activity during the decade 2004–2013 emphasized the significance of anthropogenic P and the effects of its continuous depletion along the coast. This reduction is attributed to lower river inputs and a delayed mixing of the water column in autumn, which is caused by the rise in sea temperatures. However, according to [46], the N/P ratio in the open sea of the Northern Adriatic Sea is not likely to undergo substantial changes. This is attributed to the unique circulation patterns of the Northern Adriatic Sea, characterized by slow turnover, and influenced by specific factors such as the Bora [72,89–93] and the Scirocco [94,95]. Additionally, the presence of freshwater promotes the reproduction of plankton and supports the entire trophic chain up to nekton, making the Northern Adriatic one of the most abundant fishing grounds in the Mediterranean.

One example of coastal phytoplankton adaption is showed in [96], which demonstrates how the *Ostreopsis* cf. *ovata* becomes highly competitive in P-limited water. Indeed, *Ostreopsis* has the ability to filter and store allochthonous organics, preventing the loss of autochthonous organics, and to rapidly process them. This process could explain why *Ostreopsis* is able to thrive in low-P environments as noted recently in the Northern Adriatic, particularly on the Conero Riviera [20,97]. Xing et al. [98] have also verified that other species of microalgae could take advantage of organic matter, for example during strong storm events involving wastewater flow along the coastal strip as described in [99] and [100]. Kužat et al. [83] also highlight how even micro phytoplankton communities respond with morphological and physiological adaptations to the reduction in P.

Moreover, changes in the zooplankton community have also been observed because zooplankton act as a link between primary producers of organic matter and the higher-order consumers, and they provide grazing control on phytoplankton blooms [54,101]. Mozetič et al. [102] show that while in a regime of reduced resources and biomass, plankton community control can occur seasonally, either through climatic or anthropogenic forcing.

The decline in ground fish, large predators, and small pelagics during 1980–1990 has also been attributed to both overfishing and the reduction in eutrophication [49,103,104]. In fact, the excessive abundance of fish in this sea attributed to the strong eutrophication has led to excessive fishing. As a result, the biological resource has now been reduced, and this will likely lead to a leveling of the resource equivalent to other seas. However, the North Adriatic Sea will remain particularly abundant in fish [103].

Table 1 presents the datasets available in the literature and analysed in this study.

Table 1. Datasets in the Northern Adriatic Sea.

Dataset	Time Period (Years)	References
River load	1970–2022	https://simc.arpae.it/dext3r/ (accessed on 1 July 2023) [5,45,64]
Nitrogen and phosphorus in the sea	1972–2019	[2–4,23,70]
Meteorological data	1850–2003	[36,38,39]
Plankton	1978–2020	[13,15,83–85]
Oceanographic data	1911–2019	[14,23,28,46,73,79,87,94]

5. Conclusions

It is of paramount importance for future studies to continue investigating the consequences of climate change and human impacts on the marine food chain, particularly in the Western Northern Adriatic coastal strip which serves as the main nursery area for many species of fish (e.g., *Solea solea*, *Mullus barbatus*, *Pagellus erythrinus*, *Squilla mantis*, *Engraulis encrasicolus*, and *Eledone moschata* [105–108]).

The recent basin evolution with a significant positive trend in nitrate concentrations in offshore seawater in almost all seasons during the decade 2006–2015 occurred despite a decreasing trend in N concentration in the Po River water. The rise in N/P ratios in river water and the excess of N in the marine environment, which cannot be utilized by phytoplankton due to P limitation, can explain this phenomenon. The change in the hydrodynamic regime was one of the main factors that altered phytoplankton abundance, community composition, and seasonal cycles.

The changes in nutrient dynamics indicate that the productivity of the Northern Adriatic Sea has been largely affected in the last 40 years by the combination of river water discharges and human activities. Further changes can be expected in the future, particularly in the case of a further reductions in anthropogenic phosphorus loads. Furthermore, another UE directive (91/676/EEC) aims to regulate the use of N in agriculture, but specific measures have not yet been adopted by many EU countries, including Italy.

Studies in this direction will be indispensable in the management of fisheries and the development of aquaculture, which are important policy concerns, such as in the EU, where the development of aquaculture is currently supported at the expense of industrial sea fishing. Additionally, the findings from these studies can inform policy decisions and help in designing targeted measures to mitigate the impacts of eutrophication and other environmental stressors. Implementing effective nutrient management strategies, reducing anthropogenic inputs, and promoting sustainable fishing practices are key steps towards safeguarding the Adriatic Sea's ecological integrity and ensuring the continued availability of its marine resources for future generations.

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