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Review

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Review

Evolution of Freshwater Runoff in the Western Adriatic Sea over the Last Century

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Abstract: The evaluation of the hydrography and biogeochemistry of the Adriatic Sea over the last century was summarized in this review to point out any changes in river runoff and provide an overview of the cause and effect of these trends on marine ecosystems. Although several rivers flow into the Adriatic, the most affected area is the northern Adriatic, where the Po River loads into the basin half of the total freshwater input, carrying river runoff and causing algal blooms and hypoxia phenomena. These fresh waters of the northern Adriatic flow predominantly along the entire western side, reaching the southernmost part of the basin up to the Mediterranean Sea. Here, and in the whole basin, variations in river runoff and nutrient concentration have been observed through the years. Starting from 1960 until the end of the century, an increase in nutrient discharge and phytoplankton activity was reported, with negative repercussions on local fisheries, species richness, and recreational activities within the basin. However, a recent decrease in river inflow has been observed along the coastal belt, which can trigger negative consequences for the food web of the marine ecosystem. These trends, more broadly, corroborate the vulnerability of the Adriatic Sea and stress the importance of implementing strategies for the defense of the relevant ecosystems within its confines.

Keywords: Adriatic Sea; river runoff; nutrient concentration; eutrophication; plankton

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1. Introduction

The Adriatic Sea (Figure 1) is a continental basin of the Mediterranean Sea, located between the Italian peninsula (western coast) and the coasts of Slovenia, Croatia, Bosnia-Herzegovina, Montenegro and Albania (eastern coast) [1]. Around the world, coastal marine areas represent approximately 4% of the Earth's total land surface, yet they host about half of the world's human population and provide a key contribution to global economic profit and ecosystem services. The Adriatic basin presents these characteristics as well [2–5]. The entire western coast of the Adriatic Sea is part of Italian territory which, with 8 out of the total 20 regions overlooking this basin, marks a total length of coastal line of 1472.66 km. The morphology of the Adriatic coast, characterized by low and sandy beaches and a flat hinterland, have contributed over time to the construction of infrastructure and residential settlements, making the Italian eastern coast the most densely urbanized one in the entire Mediterranean basin. Between the 1950s and 2001, the population in coastal municipalities increased by almost 720,000 inhabitants, reaching 3,372,138 citizens in 2001. Economic interests, especially in the northern Adriatic, are tied to fishing, trade, intensive use of farming and, since the beginning of the 20th century in the northern and since the 1960s in the southern region, to tourist seaside development [6].

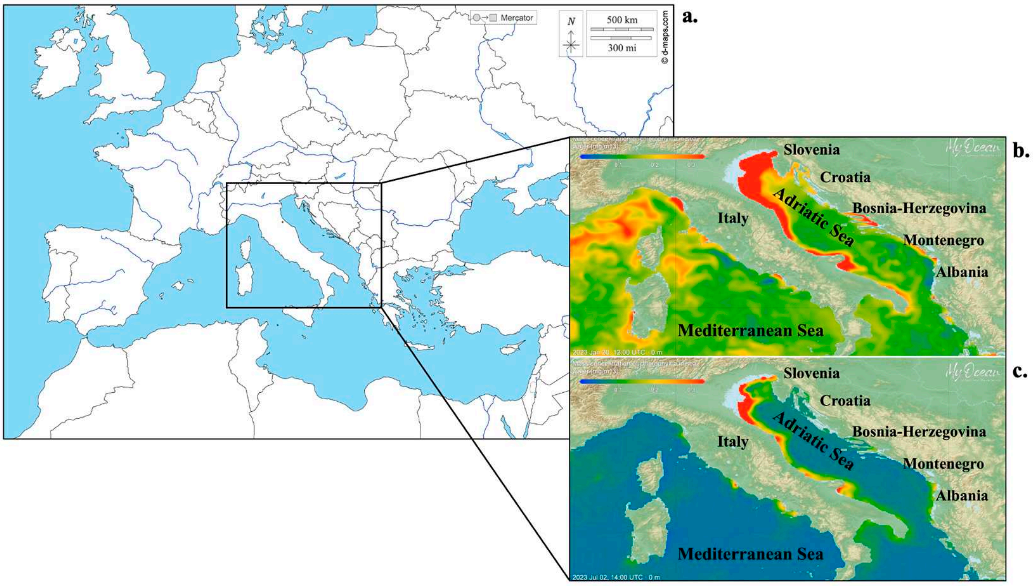

Figure 1. Location of the Adriatic Sea within the Mediterranean Sea. The map was downloaded from d-maps.com http://www.d-maps.com (accessed on 3 January 2024) (**a**). Map of the Chlorophyll a concentration (mg.m^{-3}) in the Adriatic Sea surface during the (**b**) winter (20 January 2023), and (**c**) summer (2 July 2023). Image provided by My Ocean, Copernicus Marine Service (accessed on 2 July 2023).

The Adriatic Sea extends for 800 km, oriented in the northwestern–southeastern direction. The basin has been divided into northern, central, and southern sub-basins [7,8], based on the bathymetry. The central Adriatic is deeper, reaching a maximum depth of 270 m (Jabuka Pit) and is divided from the southern Adriatic by the Palagruža Sill (170 m). In the southern basin, the maximum depth is 1250 m [9]. The central-southern Adriatic is characterized by lower primary productivity in comparison with the northern sub-basin, receiving lower continental influx of nutrients and presenting benthonic-pelagic interactions of lesser importance when compared to the northern area [10–13]. Conversely, the northern Adriatic is characterized by shallow waters (average depth ~35 m), a weak bathymetric gradient from northwest to southeast, and a significant influx of fluvial waters, mainly from Italian rivers [9,14,15]. The Po River, in particular, has an annual average flow rate of 1500 $m^3 s^{-1}$, representing approximately half of the total freshwater input into the Adriatic Sea. The Adriatic collects, in total, one-third of the freshwater flowing into the Mediterranean Sea [16–19]. Due to the predominant cyclonic circulation of the Adriatic Sea, the Po River and other alpine rivers located in the northernmost part of the basin discharge nutrients into its waters along the western side. These rivers are responsible for significant eutrophication processes that have been periodically observed along the Italian coasts [20–24], at least since the 1960s, causing hypoxia phenomena and dinoflagellate blooms [25,26]. Since the 1950s, the ever-increasing use of fertilizers, prompted by intensive farming along the Po River basin, has had a significant impact on the inflow of nitrogen (N) and phosphorus (P) into the Northern Adriatic Sea [27,28]. The release of these nutrients in the sea creates the perfect storm for the eutrophication process, where an excessive growth of phytoplankton and macroalgae creates a biomass cover that prevents sunlight and oxygen from penetrating the water column, potentially depleting oxygen levels and ceasing primary production within the ecosystem [23,29].

In the last decades, the Adriatic Sea, especially the Northern Adriatic Sea (NAS), has been the subject of several studies regarding algal or phytoplankton bloom [30–34] eutrophication [35–37] and discharge as well as enrichment of nutrients from Italian rivers [17,38–41].

However, there is still a knowledge gap regarding the variability of river runoff throughout the Adriatic Sea and the consequent changes, both in physical parameters and nutrient concentrations, over the last 150 years.

We performed a review of the evolution of river runoff in the Adriatic Sea in the literature. Hence, we used the Scopus database to conduct the query. Here, we report the specifics of our query: 'Search Within' > Keywords: "Adriatic Sea" AND "nutrient"; 'Publication Dates' > Range: From 1990 to 2022. This query resulted in 232 items. Among these, 83 were selected based on the relevance of the title and the abstract. Other articles were then added starting from the bibliography of these 83. Hence, the bibliography resulted in 134 scientific papers, published from 1873 to 2023, characterizing changes in oceanographic parameters and in nutrient discharge in seawater, highlighting their impact on this marine ecosystem.

2. River Runoff and Oceanographic Evolution of the Adriatic Sea

The Adriatic Sea is a continental sea and is therefore strongly influenced by its own geomorphological and meteorological conditions. These conditions trigger physical and chemical changes over the years. Freshwater inflow from rivers, as well as water exchange with the Ionian Sea and the influence of Levantine Intermediate Water (LIW), significantly impact the oceanographic properties of the Adriatic Sea. The Adriatic and Ionian Seas are connected through the Strait of Otranto, allowing for water exchange and influencing the oceanographic properties of both seas. LIW, originating in the eastern Mediterranean, plays a role in the water masses present in the Adriatic, contributing to the overall complexity of its hydrological characteristics [42,43]. The relatively shallow depth of the sea and the local river inflows contribute to variations in the hydrological characteristics of the water column. The coastal waters, with reduced salinity caused by river inflow, can impact the circulation of the basin in two ways. Firstly, they can act directly as a mechanism forcing circulation through buoyancy-related processes. Secondly, they can have an indirect impact by modifying the stratification conditions crucial for controlling specific features of the Adriatic, such as the exchange of water masses through the Otranto Strait and the generation of deep water along the northern continental margin [44]. Thanks to the influence of the freshwater inflow, mainly from the Po River, the northern Adriatic acts as a heat sink and a buoyancy factor. River runoff mainly depends on precipitation melting of glaciers, impacting water circulation through buoyancy input and affecting the ecosystem by introducing significant amounts of organic matter, nutrients, salts, and sediments [11,45]. The discharges into the Adriatic Sea are primarily attributed to the Dinaric Alps and the Julian Alps, with rivers such as the River Isonzo contributing to the inflow into the eastern part of the basin [19,46,47]. Rivers flowing into the northern Adriatic can be categorized by location, distinguishing between those located above and below the Po delta. Among the main rivers in the northern group are the Isonzo, Tagliamento, Livenza, Piave, Brenta, and Adige. The southern group consists of rivers of lesser importance, with lower flow rates, including the Po di Volano, Reno, Destra Reno, Lamone, Savio, Rubicone, Marecchia, Conca, Foglia, Metauro, Esino, Musone, Chienti, Tenna Tronto, Vomano, Pescara, Sango, Trigno, Biferno, and Fortone [38] (Figure 2). These Adriatic rivers showed an annual cycle characterized by two high-discharge periods, in late autumn and spring, alternating with two low-discharge periods, in winter and summer [48]. Unlike the Northern Adriatic Sea, in the south-western part of the basin, particularly the Gulf of Manfredonia, river discharges are relatively low. Here, among minor rivers that dry up during the summer, the Ofanto is the main river flowing into the basin, with an average flow of 13.9 m^3s^{-1} [49,50]. The Eastern Central Southern Adriatic Sea (ECSAS), in addition to the flow from the Neretva River, represents one important source of freshwater in this part of the basin, with cold waters with an average discharge of 300 m^3s^{-1} [51–54]. ECSAS receives waters from the Buna/Bojana River, which is the Southeastern Adriatic's most important river, with a discharge of about 700 m^3s^{-1}, second only to the Po River. The Southern Adriatic Sea is influenced by the freshwater inflow of several other Albanian rivers, among which are the

Drini, Mati, Ishimi, Erzeni, Shkumbini, Semani, and Vjosa Rivers, discharging a total of about 1250 m^3s^{-1} into the basin [43,55] (Figure 2).

Figure 2. Map of the Adriatic coast showing the locations of the main rivers and streams that flow into the Adriatic Sea. The map was downloaded from the d-maps.com website http://www.d-maps.com (accessed on 3 January 2024) with subsequent modifications applied.

The most affected areas by river runoff in the Adriatic Sea during all seasons are the northern and western regions, where a strong lateral temperature and nutrient gradient is experienced in spring and autumn [19,41]. Indeed, the annual hydrological regime observed for the Po River shows a low flow during winter (January and February) and an even lower flow in August, a period of maximum flow in May–June due to glaciers thawing, and another high flow period in October–November due to the intensive rainfall [38]. This trend is observed also for the Adige River, where two yearly periods of low water flow (winter and summer) and two of high flow (spring and autumn) occur. Although these two rivers are mainly responsible for the runoff flow in the Adriatic Sea, the Po River is the major source of freshwater in the northern Adriatic [40], with a mean flow rate of 1470 m^3s^{-1}, which is higher than that of the Adige River (220 m^3s^{-1}; [38]).

An analysis of long-term changes in river runoff pointed out three distinct periods in the historical series of the Po River, with a variable runoff from 1917 to 1941, followed by an increasing load from 1942 to 1975, and subsequently a decrease from 1976 to 2008, mainly due to the drought that characterized the most recent years. Overall, in the period from 1917 to 2008, the runoff of the Po ranged from 20.54 to 82.49 km^3yr^{-1}, with an average value of 47.17 km^3yr^{-1} [40]. This decreasing trend continued until October 2023 (Figure 3), as also reported in Marini and Grilli, 2023 [23]. However, regarding the Adige, Brenta, Piave, Isonzo, and the rivers along the Slovenian Coast, including Rizâna and Dragonja, throughout the whole period, a substantial decline in runoff was observed [40].

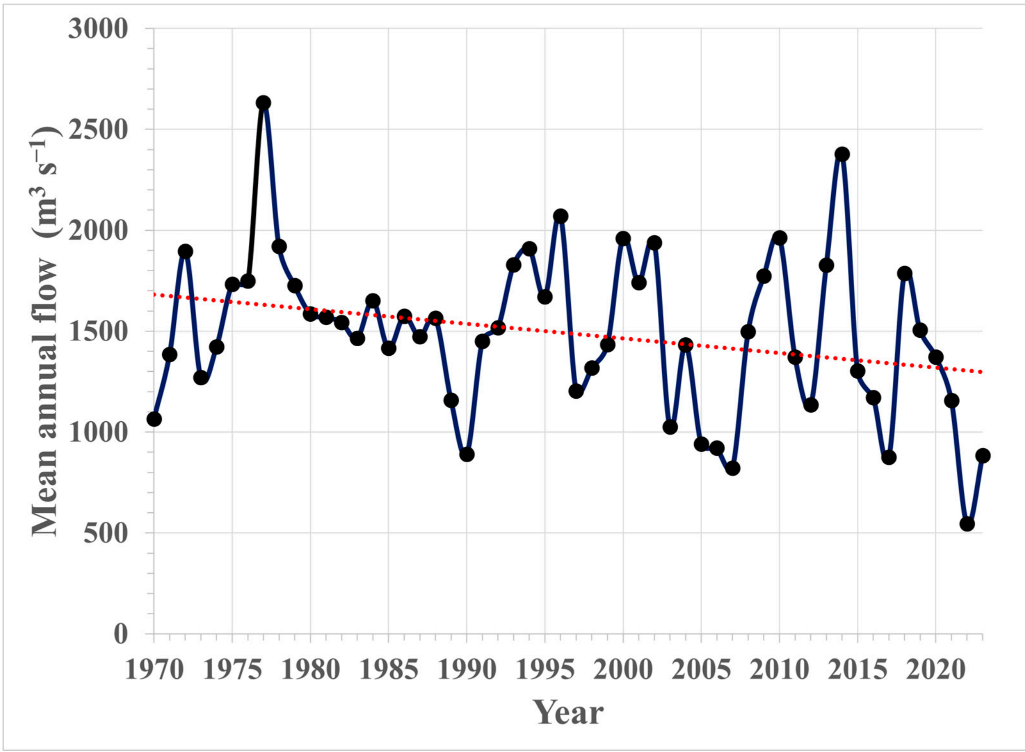

Figure 3. Long-term trends in daily discharge of the Po River (m^3s^{-1}) from January 1970 to October 2023, with a significant linear regression. Data sourced from the Pontelagoscuro station and provided by the Hydro-Meteorological Service of the Regional Agency for Environmental Protection of Emilia-Romagna Region (ARPAE-ER). Modified from Marini and Grilli., 2023, *Applied Sciences* [23].

The main winds affecting the Adriatic Sea are the bora winds, dry and cold winds blowing offshore from the east, and scirocco winds, humid and warm winds blowing from the southeast [56]. In particular, during autumn and winter, bora winds are responsible for the formation of very dense deep waters, known as Northern Adriatic Deep Water (NADW), characterized by low temperatures (less than 10 °C), and relatively low salinity (~38.3 psu) [57,58]. These waters flow southwards across the Palagruža Sill, near the bottom of the Italian shelf [59]. The major portion of these waters flow southwards until reaching the southern part of the shelf, which due to the presence of a canyon, becomes deeper [60,61]. Here, mixing processes occur with the inflowing warmer and saltier Modified Levantine Intermediate Water (MLIW) from the Mediterranean, resulting in the formation of the Adriatic Bottom Water (ABW). The ABW then outflows into the Ionian Sea at the bottom of the Otranto Strait.

3. Importance of River Runoff for the Food Web and Influence on Plankton

The rising frequency of short-term phenomena due to climate change, especially the increase in intense rainfall events and the resulting terrigenous loads entering coastal waters from rivers, has been the focus of several studies conducted around the world [22,59,62–67]. Eutrophication is the process resulting from the decomposition of large quantities of dead algal biomass following an algal bloom event, leading to the formation of hypoxic or anoxic sea areas [68]. Since the 1800s, the Po River in the northern Adriatic has carried a very high nutrient load (N range: 1–300 µM; P range: 0.01–4 µM [41]) leading to occurrences of algal, diatom, and dinoflagellate blooms [69–73]. However, it was only in the mid-1970s that eutrophication episodes developed a chronic yearly pattern, varying only in intensity [29,38,74]. Since the 1970s, eutrophication, in conjunction with adverse meteorological and hydrographic conditions, has led to the presence of oxygen-depleted bottom waters in the coastal areas, leading to lethal effects such as the impoverishment or mass mortality of benthic fauna [74], hence confirming the hypothesis that riverine influence is exacerbating hypoxia/anoxia [75]. It is well known that the frequency of eutrophic events increased exponentially in coastal areas of the Adriatic Sea until the 1990s, particularly due to the intensive release of inorganic nutrients from anthropic agricultural practices [76], continental emissions, and river runoff, resulting in a significant increase in nutrient concentration. Data available for the Po River, which can be considered a significant proxy of the total runoff in the north Adriatic, indicate that the transport of total nitrogen has increased about two times since the 1980s, reaching the highest estimate of 173×10^3 t N yr^{-1} in the years 1996–2000 due to a constant increase of anthropogenic activities. At the same time, the transport of total phosphorous has decreased from 15.6 to 8.1×10^3 t P yr^{-1} since 1978 thanks to Italian regulations that in 1986 required the reduction of phosphate in detergents [28,29,40]. Regarding the transport of nutrients of the Adige River, at the end of the 1980s, they reached values of 12.7×10^3 t N yr^{-1} for total nitrogen and 1.2×10^3 t P yr^{-1} for total phosphorous. However, due to the high correlation between runoff and nutrient transport, these changes could be related to pronounced oscillations rather than a progressive trend [40]. The mean Po River flow rate in the last two decades was significantly lower than in the years 1972–1999, producing a significant decreasing trend for P and Chlorophyll *a* concentration in North Adriatic Sea, but not for N [77]. The influence of river runoff on the Western Adriatic's plankton communities is notable [77,78]. Seasonal variations in river discharge, characterized by increased flows in spring and autumn and reduced flows in winter and summer, directly influence the composition and abundance of plankton species [14]. Moreover, the increase in nutrient discharge can interfere with the natural annual nutrient cycles, leading to an increase in primary producers' activity. This has significant ecological implications for both pelagic and benthic organisms, including an increase in phytoplankton activity [79]. Indeed, macroalgal blooms resulting from eutrophication processes can lead, in addition to hypoxia events and the production of toxic hydrogen sulfide, to negative effects on the abundance and diversity of benthic fauna living in coastal waters [80].

Although beneficial for an increase in fishery availability [81–83], higher primary production rates have been observed to result in phytoplankton blooms, with negative repercussions on local fisheries and recreational activities [84–89]. Phytoplankton blooms, often induced by increased nutrient input, provide a growing environment for specific zooplankton species [90]. This, in turn, influences the distribution and abundance of higher trophic levels, including fish and other marine organisms. Changes in plankton composition and abundance, in relation also to coastal oceanographic conditions, not only affect the survival and growth of fish larvae but also have repercussions on the distribution and availability of commercially valuable species, as well as on the diffusion of benthic species more tolerant to hypoxia and high nutrient concentrations [91,92]. Nowadays, the rise in sea temperatures is causing a reduction in primary production and, subsequently, a decrease in zooplankton populations [77,93,94]. Warmer waters, combined with more frequent extreme weather events, have the potential to intensify the competition among pelagic predators for food resources. As a result, we may see more significant fluctuations in the stocks of species, with dramatic impacts on the overall ecosystem [95–98].

The long-term alterations in nutrient concentrations within the northern Adriatic region are intricately linked to climatic fluctuations and, in particular, to the decrease in rainfall during the winter in northern Italy, and the Alps region [40,99]. Intensity of precipitation and increased frequency of rainfall events have the potential to influence several key factors. These can modify the hydrological cycles, such as the flow rate of the Po River (Figure 2), which is a significant source of freshwater input into the northern Adriatic Sea [41,48]. Variations in the Po River's flowrate can impact the quantity and composition of nutrients entering the sea, consequently affecting the overall nutrient balance in the ecosystem (Figure 1) [23,45,77,100,101]. The geostrophic circulation of the northern Adriatic comprises multiple gyres that can last for extended periods within the region [102–104]. Gyres have the capacity to transport freshened, nutrient-rich waters, originating from the region near the Po River delta, across extensive portions of the northern Adriatic, and potentially as far as the opposing eastern coast, including the Istrian Peninsula [45,105,106].

Furthermore, climatic fluctuations can also have a profound impact on the water dynamics within the Adriatic Sea. This includes alterations in the vertical mixing of the water column, which can be heavier under conditions of low stratification and lighter when the water column is highly stratified, including temperature and salinity [107–109]. These alterations in vertical mixing can have cascading effects on the distribution of nutrients throughout the water column [18,101,110], thus influencing the availability of these essential elements to marine organisms. Alterations in the water exchange rate between the northern and central Adriatic [10,105] can impact the overall nutrient content and ecological conditions in these areas, as the rate can determine the extent to which they are connected and influence the exchange of organisms and materials. A recent study comparing physical and chemical data of the 2002–2007 and 2007–2016 periods showed that the latter decade was characterized by an increase in phytoplankton abundance, as well as biomass and inorganic nutrient concentrations [14,111]. This indicates a reversal trend compared to the tendency of oligotrophication observed in the previous period, due to a combination of factors that includes nutrient load mitigation strategies, different use of the land of the watersheds, and reduced runoff due to prolonged drought periods [10,93,100]. Moreover, a marked change occurred in the community structure and seasonality of phytoplankton [14,100].

Nutrient distribution and concentration in the Adriatic Sea are strongly affected by the physical characteristics of the basin. The Western Adriatic basin is characterized by a decrease in surface nutrient concentration, from north to south and from inshore to offshore, due to different freshwater inputs; this is particularly significant in the northern Adriatic [112]. Here, a dominant cyclonic circulation determines a southward nutrient flow along the western coast [13,14,41,100,101,105,113–115]. The Adriatic circulation is also strongly influenced by winds, due to the seasonality difference in wind regimes [116], and meteorological conditions, among which hydrological balance as well as densification related to river inflows and perturbations, with the resulting cooling and mixing, affect the thermohaline structure [8]. Among the winds affecting the Adriatic biogeochemical characteristics and its marine ecosystems are the bora winds. Previous studies showed that bora events, which occur more frequently in winter [9], could generate a relevant increase of nutrient loads exported from the northern Adriatic through the accentuation of the Western Adriatic Current (WAC), which, forced by the Po River runoff, enfolds the Western Adriatic coast, flowing south-eastward to finally leave the Adriatic basin via the Otranto Strait [117], and therefore playing a relevant role in the nutrient balance of the basin [118–120]. Due to the WAC, during bora events, sediments with nutrients and other waterborne materials are resuspended and driven southward along the Italian coast [16,22,45,115].

4. Future Directions

The Adriatic Sea is a segment of the Mediterranean Sea enclosed by the mountain chains of the Alps, the Apennines, and the Balkans. It is rich in resources such as subsoil, supports fishing and tourism industries, and is marked by intense maritime transport and cultural exchanges among the people along its shores. The western side, encompassing the entire Italian state, is densely populated and heavily influenced by human activities [6]. The current trend of ocean warming, coupled with an increase in the frequency of extreme events, may intensify water stratification. This, combined with reduced water exchange, could extend the turnover time of Adriatic waters. Under these conditions, the Adriatic Sea ecosystem's susceptibility to eutrophication and acidification processes could increase, despite the ongoing trend of lower eutrophication [77]. Additionally, increased rates of primary production due to the rising temperatures in shallow water have been noted to give rise to phytoplankton blooms, causing adverse impacts on local fisheries and recreational activities [89]. Nevertheless, alterations in the structure of the fish community have taken place, potentially reducing the efficiency and resilience of the ecosystem [77]. In recent decades, climate change, with a specific emphasis on the increase in sea temperature and salinity, has manifested itself not only in the Mediterranean Sea but also in the Adriatic Sea. This environmental shift has triggered the proliferation and spread of alien species of marine organisms [121]. Mariculture and shipping represent potent mechanisms for introducing native warm-water species into the northwestern Mediterranean and the Adriatic Sea [122–132]. The majority of the introduced species are adapted to warm temperatures, exhibiting thermophilic characteristics and forming self-sustaining populations, like the ornate wrasse *Thalassoma pavo* (Linnaeus, 1758) and the parrotfish *Sparisoma cretense* (Linnaeus, 1758) [133]. These species impact the survival of native species and engage in resource competition, such as the predation of small pelagics by tunas [134] and the voracious feeding behavior of the blue crab, *Callinectes sapidus* (Rathbun, 1896), on benthic organisms [125]. The Adriatic Sea, a hotspot of biodiversity and economic activities, faces significant challenges due to climate change and the introduction of invasive species. Proactive measures, informed by scientific research and community engagement, are essential to preserve the ecological integrity and economic sustainability of this vital marine environment. Observing the evolution of coastal oceanographic conditions on the western side of the Adriatic, we believe they can be of particular interest in shaping the prospects for research development. An interdisciplinary approach, integrating marine biology, oceanography, and socio-economic factors, will provide a comprehensive understanding of ongoing changes. Research in this direction will provide valuable insights that can prove beneficial for a diverse array of stakeholders engaged in economic activities throughout the Adriatic region.

5. Conclusions

The analysis of the freshwater runoff evolution in the Western Adriatic Sea over the past century has provided valuable insights into the dynamic interactions between climatic factors and hydrological processes. A comprehensive examination of historical data and present-day observations has facilitated a nuanced comprehension of the diverse factors influencing freshwater discharge into the Adriatic. Changes in precipitation patterns, snowmelt dynamics, and land-use practices have contributed to fluctuations in freshwater runoff. Notably, climate change emerges as a significant driver, with observable impacts on the timing and intensity of runoff events. Eutrophication, driven by increased nutrient concentrations since the 1970s, adversely affects marine life and ecosystems, favoring hypoxic areas and causing benthic fauna to suffer. Hydrodynamic variations within seasons influence river flow and impact plankton communities, with altered nutrient cycles impacting primary production. Increasing sea temperatures pose further challenges, resulting in reduced primary production and subsequently decreasing zooplankton populations. Indeed, the long-term changes in nutrient concentration could lead to wider diffusion of benthic species tolerant to hypoxia and high nutrient concentrations. The findings of this review highlight the importance of considering long-term trends in freshwater runoff to comprehend the broader environmental implications. Shifts in runoff patterns have direct consequences on coastal ecosystems, influencing nutrient dynamics and overall water quality. These changes, in turn, have significant implications for the ecological balance of the Adriatic Sea and its marine biodiversity.

Observed changes in the Western Adriatic Sea show that different patterns have occurred over time in the offshore and coastal waters. Indeed, in coastal waters, a decrease in the river runoff corresponds to a decrease in the concentration of nitrogen and phosphorous, while at basin level, they continue to represent an important food source for the trophic chain.

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