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River water and nutrient discharges in the Northern Adriatic Sea: Current importance and long term changes

Stefano Cozzi [a,*], Michele Giani [b,1]

[a] CNR-ISMAR, Istituto di Scienze Marine, Trieste. Viale Romolo Gessi 2, 34123 Trieste, Italy
[b] OGS-Istituto Nazionale di Oceanografia e di Geofisica Sperimentale. Via A. Piccard 54, 34151 Trieste, Italy

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ABSTRACT

Runoff and nutrient transport by rivers were analysed in the Northern Adriatic continental shelf, in order to evaluate their interannual and multidecal variability, as well as their current contribution to determine freshwater and nutrient budgets in this marine region. During the years 2004–2007, the runoff in the basin (34.1–64.6 $km^3\ yr^{-1}$) was highly imbalanced, being 84% of freshwater discharged along the western coast, because of the contributions of Po, Adige and Brenta rivers. In the northern and eastern sections of the coast, freshwater discharge by rivers was less important (10 and 6%, respectively), but not negligible in determining the oceanographic properties at sub-regional scales. The oscillations of the transport of biogenic elements ($124–262 \times 10^3$ t N yr^{-1} for TN, $72–136 \times 10^3$ t N yr^{-1} for DIN, $4.5–11.1 \times 10^3$t P yr^{-1} for TP, $2.2–3.5 \times 10^3$ t P yr^{-1} for PO_4 and $104–196 \times 10^3$ t Si yr^{-1} for SiO_2) were strictly dependant to the differences in the annual runoff. A strong excess of N load in comparison to P load characterised all rivers, both in inorganic nutrient (DIN/PO4=37–418) and total (TN/TP=48–208) pools, particularly in the northern and eastern areas of the basin.

The annual runoff showed significant oscillations for Po on multidecadal time scale, whereas a general decrease (−33%) was observed for the other N Adriatic rivers as the recent discharges were compared to those before the 1980s. During the dry years 2005–2007, a strong reduction of river water flows and nutrient loads was experienced by the N Adriatic ecosystem with respect to years characterised by medium-high regimes. An increased frequency of similar drought periods, due to ongoing climate changes or to a larger human usage of continental waters, would be easily able to significantly change the biogeochemistry of this basin.

1. Introduction

The Northern Adriatic continental shelf region (hereafter N Adriatic) is a shallow and semi-enclosed marine area subjected to a sub-tropical climate cycle and to a large runoff, which make the dynamics of its ecosystem the most strongly depending by air–land–sea interactions in the whole Mediterranean (Malone et al., 1999). The Po River is the major source of freshwater and nutrients for this area, as it carries 47 $km^3\ yr^{-1}$ of water, 6×10^6 t yr^{-1} of solid transport, 255×10^3 t C yr^{-1} of TOC and 155×10^3 t N yr^{-1} of TN (Pettine et al., 1998). Since damming of the Nile in 1970, Po together with Rhone account for about one-third of the total runoff in the Mediterranean (Ludwig et al., 2009).

Several basic oceanographic features of the N Adriatic are determined by river loads. The baroclinic circulation is dominated, in particular during winter, by the North Adriatic Current that originates from horizontal density gradients off the Po delta and concurs to the formation of the larger West Adriatic Current, flowing southwards along the Italian Coast. The combination of high runoff and weak circulation, determined by low wind forcing, often generates extended coastal fronts that spread towards the Istria Coast (Artegiani et al., 1997; Kourafalou, 2001).

The distribution of land borne nutrients follows the structure of the haline fronts, showing a complex patchiness characterised by horizontal and vertical gradients, eddies and meanders (Cozzi et al., 2002). Their supply sustains the large productivity of the coastal zones triggering intense phytoplankton blooms, especially in late winter and autumn (Zoppini et al., 1995; Cantoni et al., 2003). Adriatic rivers also discharge high quantities of dissolved organic matter, which can become available for marine bacteria in particular after photochemical transformations (Puddu et al., 1998) and of particulate matter, which affects sedimentation

* Corresponding author. Tel.: +39 040305312x526; fax: +39 040308941.
E-mail addresses: stefano.cozzi@ts.ismar.cnr.it (S. Cozzi), mgiani@inogs.it (M. Giani).
[1] Tel.: +39 0402249713; fax: +39 0402249770.

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rates in the western portions of the shelf (Frignani et al., 2005). Loads of river nutrients have caused increasing problems of eutrophication in the coastal zones of N Adriatic at least since 1960s, causing recurrent dinoflagellate blooms and hypoxia in the deeper waters (Justić et al., 1987; Sellner and Fonda Umani, 1999). The concern about their negative impact on fishery and tourism has promoted a more strictly control of the anthropogenic inputs (Chiaudani et al., 1980; Palmeri et al., 2005; Artioli et al., 2008). Dynamics and extension of the Po plume also have effects on the evolution of mucilage phenomenon, as they generate alternate hyper-oligotrophic conditions that affect plankton metabolism and strong density gradients that favour mucilaginous aggregation (Cozzi et al., 2004; Giani et al., 2005).

The N Adriatic is a region where ongoing climate changes are expected to have significant consequences on the marine environment (Alcamo et al., 2007). However, long term trends in this ecosystem are still difficult to separate from interannual and decadal oscillations. In the Gulf of Trieste, a phase of frequent positive anomalies of sea-level superimposed to its overall rise was detected since 1989 (Raicich, 2003). An increase of seawater temperature was reported in the Gulf of Trieste, mainly during summer, for the period 1991–2003 (Malačič et al., 2006), as well as in the NW Adriatic in 1988–1999 with respect to 1911–1987 (Russo et al., 2002). The reduction of the concentrations of some nutrients and chlorophyll *a* was also observed during the last decades (Solidoro et al., 2009; Mozetič et al., 2010). Important components of the pelagic compartment seems to respond to these environmental changes as well. An increase in the abundance of small sized copepods, due to possible limited supply of food or reduced phytoplankton size, and their irregular oscillations of biomass was observed in the Gulf of Trieste since 1990 (Kamburska and Fonda Umani, 2006). The northward spreading of the thermophilic ichthyofauna was reported along the eastern coast of the Adriatic since the 1980s (Dulčić et al., 2004).

Despite the essential role of rivers in modulating the biogeochemistry of N Adriatic, few information is still available on their freshwater and nutrient loads. A number of studies were published since the 1970s, mostly for the Po and Adige rivers, as a result of the efforts addressed to the mitigation of eutrophication problems in the NW coastal zone. However, specific analyses of their interannual variability, estimates for several minor rivers and information on the characteristics of the runoff at local scales are largely incomplete, to date. The aim of this study is to present the first detailed analysis of the runoff and nutrient loads by N Adriatic rivers, in order to point out their current impact on this marine ecosystem. Long term trends and possible future evolution of river flows, due to the effects of anthropogenic water usage and climate changes, are also discussed in the perspective of their potential consequences for the N Adriatic ecosystem.

2. Methods

2.1. Study area

The Po River, with a mean flow rate of 1496 $m^3 s^{-1}$ in the period 1917–2008, is the major source of freshwater in the N Adriatic (Fig. 1). It collects the runoff of a large drainage basin (71057 km^2) that has a resident population of 16×10^6 inhabitants. The other Italian rivers have much smaller drainage basins (2221–12100 km^2) and populations ($0.17–1.5 \times 10^6$ inhabitants) compared to those of Po (Basin Authorities of Italian Rivers, URL: http://www.adbpo.it/, http://www.bacino-adige.it/, http://www.adbve.it/). The major contribution by Slovenian rivers to the runoff in the N Adriatic originates in the Julian Alps and flows through Isonzo, whereas Mirna constitutes the most important tributary located along the Croatian coast of Istria Peninsula (Knežević, 2003; Comici and Bussani, 2007; Frantar, 2007).

The annual cycle of Adriatic rivers is characterised by two high-discharge periods, in late autumn and spring, alternated to two low-discharge periods, in winter and summer. High discharge periods are respectively due to intense precipitation and snowmelt in the mountainous portions (altitude < 4600 m) of their drainage basins (Zanchettin et al., 2008). Winter precipitation in

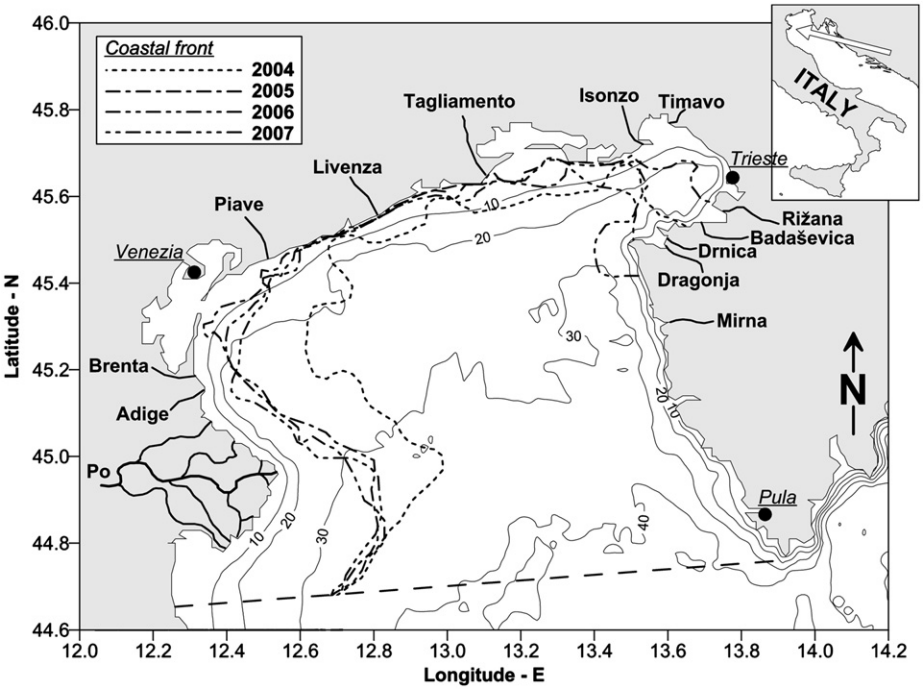

Fig. 1. Location of N Adriatic rivers. Dashed line indicates the southernmost limit of the marine region that is compared to the runoff. Annual averaged extension of the coastal fronts from 2004 to 2007 is also shown.