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Flood-driven transport of sediment, particulate organic matter, and nutrients from the Po River watershed to the Mediterranean Sea

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ABSTRACT

The Po River (Northern Italy) discharge represents a considerable input of the land-derived material entering the Mediterranean Sea. Most of its particulate and dissolved constituents are supplied to the sea in response to short-lived climate events. Although these floods exert first-order control on the transport of organic and inorganic elements, both composition and magnitude of the river material are poorly constrained during high discharge periods. In order to fill this knowledge gap, in this study we carried out an event response sampling in the Po River in November 2011. Beginning in early November, intense rainfall occurred in the Po watershed that resulted in a flood of ~6000 $m^3 s^{-1}$ (2.5 year return period). Water samples were collected from the river before and during the flood. Dissolved nitrate, nitrite, ammonia, and silicate were measured and the particulate material was analyzed for total suspended sediment, elemental composition, $\delta^{13}C$, $\delta^{15}N$, grain-size, and ^{137}Cs activity.

Our results showed a temporal decoupling between solid and water discharge implying that predicted sediment loads simply derived from sediment rating curves could potentially give rise to large errors, especially when calculations are used to understand the sediment export in response short-lived events. The suspended organic material during high flow was dominated by soil organic matter while high $\delta^{15}N$ indicated the influence of an additional ^{15}N-enriched source (e.g., manure, sewage, and algal biomass) during low discharge. Because the concentrations of nitrite and ammonia were positively correlated with the content of particulate material in suspension, we inferred that nitrite and ammonia concentrations were driven by either bacteria activity (ammonification–nitrification) or ionic exchange whose rates were proportional to concentration of the suspended material. In addition, due to the dilution with nitrate-poor rainfall, the concentration of nitrate decreased with increasing water discharge. High concentrations of nitrate were instead attributable to the influx of nitrate-rich water from groundwater that is chronically contaminated and constitutes most of the baseflow during low flow. Our results indicate that the event-dominated transport in the Po drainage basin is particularly important for the organic matter supply as flood events account for at least one-third of the particulate annual export (organic carbon and nitrogen). Finally, this study has demonstrated the utility of event-response sampling for understanding the importance of event-dominated transport in rivers.

1. Introduction

The export of land-derived constituents from drainage basins exerts first-order control on the cycling of organic and inorganic elements in river-dominated coastal margins (McKee et al., 2004). In recent years several hydrological studies highlighted that the river export can significantly vary in magnitude and frequency as a result of episodic discharge (Hatten et al., 2012; Hilton et al., 2008; Raymond and Saiers, 2010). However, although the stochastic supply from rivers can represent a significant fraction of the total annual export to the ocean, the chemical composition and flux of different land-derived constituents are still poorly constrained during these high-flow periods mainly because there are evident logistical issues with sampling short-lived events that require quick-responses and high-resolution sampling.

Human-induced changes have significantly altered both the composition and magnitude of allocthonous material entering the coastal regions (Syvitski et al., 2009). For example, the Mediterranean drainage basins have a long history of human

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settlement and impacts (Liquete et al., 2004; Hooke, 2006). Nevertheless, some of the European rivers maintained their dynamic nature characterized by episodic discharge (Salles et al., 2008; Roussiez et al., 2011). Even though this distinctive feature is currently well known and further confirmed by event-strata in marine deposits (Palinkas et al., 2005; Bourrin et al., 2008; Tesi et al., 2011), only a few studies have addressed the composition and magnitude of the material supplied during short-lived events from the Mediterranean watershed. In order to fill this knowledge gap, an event-response sampling was carried out in the Po watershed (Italy) in November 2011 when the Po River experienced a flood having a return period of ~2.5 years (peak discharge ~5858 $m^3\ s^{-1}$). Although this event was relatively small in comparison to the most extreme events observed since discharge measurements started (highest flow ever recorded ~9780 $m^3\ s^{-1}$), a flood of this kind with an intermediate frequency has the highest potential for exporting constituents to the ocean (Wheatcroft et al., 2010). Specifically, based on the conceptual model of *effective discharge* (i.e. the discharge that cumulatively transports the majority of material in a river), high-frequency events transport too little material to be effective, while low-frequency events do not occur frequently enough to be effective (Wolman and Miller, 1960). Therefore, the Po River November 2011 flood, which has an intermediate frequency, represents an extraordinary opportunity to investigate the export of land-derived material in response to event-dominated mobilization (Wheatcroft et al., 2010).

Daily samples were collected throughout the November 2011 flood ~90 km from the river mouth. The particulate fraction was analyzed to measure the total suspended sediment, ^{137}Cs activity, grain-size, elemental composition of organic carbon, inorganic carbon and nitrogen, as well as stable isotopes of carbon and nitrogen ($\delta^{13}C$, and $\delta^{15}N$) while nutrients ($N–NO_3$, $N–NO_2$, $N–NH_3$, and $Si–SiO_4$) were measured in the dissolved fraction. Our overarching goal was to characterize the composition of both bulk particulate and dissolved fractions transported in response to precipitation in a watershed that has suffered from a lack of high-resolution data. Focus herein is placed on the temporal variability of all aforementioned parameters during the flood event. In addition, this event-response study allowed us to assess (i) the magnitude and (ii) the transit time of each constituent during short-lived events as well as (iii) the relevance of event-controlled transport relative to the annual budget of dissolved and particulate elements.

2. Background

2.1. The Po River and watershed

With an average population density of 260 habitant/km^2, the Po watershed (75,000 km^2) is one of the most urbanized and agriculturally developed areas in Europe while the river is one of the most important point sources within the Mediterranean watershed. Over a third of the drainage basin is mountainous whereas the rest is composed of a wide, low-gradient alluvial plain (Fig. 1a). Its basin represents the confluence of Alpine (maximal relief ~4500 m) and Apennine (maximal relief ~2000 m) streams. The river typically experiences two seasonal floods driven by rainfall in the autumn and snowmelt later in the spring which generally overlaps with the rainy season (Palinkas et al., 2005; Tesi et al., 2008). The river annually supplies ~13 Tera (10^{12}) g of sediment (Syvitski and Kettner, 2007) and ~40–50 km^3 (Cozzi and Giani, 2011) of freshwater representing over 25% of total freshwater entering the Mediterranean Sea via rivers (Ludwig et al., 2009). A third of the annual flow is regulated by reservoir management for hydropower and irrigation purposes (Syvitski and Kettner, 2007). Despite this, the river still experiences short-lived event in response to precipitations (Palinaks and Nittrouer, 2007; Syvitski and Kettner, 2007; Tesi et al., 2008). In particular in recent decades it was observed an increased in peak-flow during flood events likely as a result of massive leeve works along the river network completed in the 1960s rather than consequences of climate change (Zanchettin et al., 2008). Without the chance of flooding within the watershed, the flow during short-lived events is constrained between leeves resulting in higher peak-flows.

The Alpine and Apennine belts resulted from the subduction of Tethyan oceanic crust followed by the continent–continent collision between African and European plates that began since the middle Cretaceous. The Alpine belt contains marine sediment and continental crust scraped off from both margins, as well as ophiolites. The majority of the geologic units in the Apennine are made up of marine sedimentary rocks that were deposited over the southern margin of the Tethys Sea. At present, the Apennine watershed is characterized by high sediment yield because of the nature of the easily erodible material that experiences frequent landslides (Fig. 1b) (Trigila et al., 2010). As a result, the sediment yield along the Apennine belt is about one order of magnitude higher compared to the Alpine belt. On average, the Alpine and Apennine watersheds combined yield ~200 tons of sediment/$km^2\ y^{-1}$ (Cattaneo et al., 2003).

2.2. The November 2011 flood

Since discharge measurements began in 1918 at Pontelagoscuro gauging station (Fig. 1b) there have been only two floods exceeding 9000 $m^3\ s^{-1}$ (1926 and 2000) (Fig. 1s; Supplementary material). The mean and mode discharge recorded daily at this station are ~1500 m^3/s and ~1000 m^3/s, respectively (Fig. 1s). Beginning in early November 2011, intense rainfall occurred in the southwestern portion of the Po River drainage basin (Fig. 2s; Supplementary material). In this part of the watershed, local distributaries experienced overflowing banks (e.g., Tanaro and Orba Rivers, Figs. 1b and 2) because of the high precipitation. The resultant flood wave took several days to reach Pontelagoscuro station from the western watershed but only a few days to reach the central-eastern Apennine belt (Figs. 1b and 2). In contrast, the water export from the northern regions was relatively low (e.g., Adda River, Figs. 1b and 2). The highest discharge was 5858 m^3/s recorded on the 11th of November corresponding to a flood return period of ~2.5 years (Fig. 1s).

3. Methods

3.1. Sampling

The event-driven transport of particulate and dissolved constituents was monitored between the 4th and the 21st of November 2011 at Pontelagoscuro gauging station located ~90 km from the coast (Fig. 1b). Surface water samples were collected across the river axis in three locations along the Pontelagoscuro bridge (i.e., left, middle, and right). These three locations formed an ideal riverbank-normal transect. The essential elements of the collector device were a 1 l HDPE bottle (large neck to promote rapid filling), a rope, and a weight at the end of the rope to allow instantaneous sinking of the bottle. The reproducibility of this method was tested before the experiment (Tesi et al., unpublished data) and the standard error for replicate measurements of the suspended material was <4%. For ^{137}Cs analyses, large volumes (25 l) of water samples were collected using a bucket from the middle of the bridge.