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Changes in the physical characteristics of the water column at the mouth of a torrent during an extreme rainfall event

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SUMMARY

The city of Genoa (Italy) was hit by a severe flash flood on the 4th November, 2011. The effects of this event on the water column at the mouth of the Polcevera Torrent, the main water course flowing into the Port of Genoa, are presented in this paper. The hydrological characteristics were measured with two conductivity–temperature–depth probes equipped with a turbidimeter, one fixed on the port breakwater and one used at mobile stations around the mouth of the torrent. The dynamics were measured with a horizontal acoustic Doppler current profiler (H-ADCP) fixed on the breakwater. Data collected before, during and after the flash flood were analysed to quantify the changes due to the event. The weather conditions during the event showed extremely heavy rain associated with strong weather instability, the convergence of a low-level southerly flow and the persistence of a squall line over a restricted area. The temperature, salinity, turbidity and dissolved oxygen measurements taken during the event showed the strong influence of the weather conditions and the fresh water input of the torrent itself on the water column at its mouth, an influence that dissipated during the following days. Instead, the dynamics measured at the mouth of the torrent were affected more by the strong south-easterly wind and the sea than the flow of fresh water.

1. Introduction

Historically, flash floods are one of the most dangerous and destructive natural hazards in the world (Llasat et al., 2014). In the Mediterranean area (Llasat-Botija et al., 2007), flash floods have a relatively high frequency and can affect a large number of people (Fiori et al., 2014). As stated above, in the Mediterranean region these events are particularly frequent and show a high concentration along the coast, due to its peculiar orographic and climatic characteristics and the consequent formation of torrents, which lead to irregular temporal and spatial rainfall patterns (Liste et al., 2014; Llasat-Botija et al., 2007). During these events the quantity of rain measured by local weather stations in one hour can be of the same order of magnitude as the quantity of rain measured monthly or yearly in the same place.

The already high frequency of flash floods in the Mediterranean region is expected to increase in the short and medium term because of global warming (Dourte et al., 2015; Li et al., 2015). In fact, simultaneous regional climate models forecast a decrease in the yearly precipitation and an increase in the maximum daily precipitation in the Mediterranean region in the near future (Ruiz-Bellet et al., 2015). In the north-western Mediterranean region these events, are not only becoming more frequent but are also evolving more rapidly, appearing in a few days or, even, hours, and are typically caused by the extreme meteorological conditions (fast and intense storm events; Fiori et al., 2014; Fouilland et al., 2012; Zanon et al., 2010) that often hit this region.

The meteorological characteristics of the Ligurian Sea (north-western Mediterranean Sea) and the Port of Genoa have been highlighted since the 1970s (Englebreston, 1989; Reiter, 1971); in fact, Genoa is located on the northern side of one of the most active areas of cyclogenesis in Europe, which produces frequent periods of unstable weather (Lionello et al., 2012; Schär et al., 2003). Furthermore the city and the port are ringed to the north by rugged mountains with wide gaps between them that serve as barriers and guides, channelling and controlling the movements of air masses (Faccini et al., 2015). These morphological characteristics of the region, combined with very moist and unstable convergent winds, can facilitate the formation of extreme rainfalls. These events mainly occur mostly in the months of October and

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November (Brandolini et al., 2012; Buzzi et al., 2014), as was the case on the 10th October 2014, when another disastrous flash flood hit the City of Genoa.

Much research has been carried out over the years on the different processes related to rainfalls, such as rainfall evolution (Zanon et al., 2010), land erosion, sediments and suspended matter input (Francke et al., 2014; He et al., 2012; Malmon et al., 2004; Wei et al., 2010), contaminant mobilisation (Roussiez et al., 2013), chemical and bio-geochemical processes (Moraetis et al., 2010; Winston and Criss, 2002), effects on ecosystems (Fouilland et al., 2012; Li et al., 2015; Reichwaldt and Ghadouani, 2012), but little is known of the effects on the water column and the water masses at the mouth of a watercourse and along the nearby coast during these events, due to the rapidity of their evolution and their episodic and unpredictable nature.

On the 4th November, 2011, a catastrophic flash flood event took place in Genoa causing considerable damage to the city area and causing the two city torrents (the Bisagno and Polcevera) to carry a considerable amount of freshwater, contaminants and material of every kind to the sea. Buzzi et al. (2014), Fiori et al. (2014), Hally et al. (2015) and Silvestro et al. (2012) have described this event from the meteorological and modelling point of view, while Brandolini et al. (2012) and Faccini et al. (2015) have presented the circumstances that can lead to an increased geo-hydrological risk in the city of Genoa and the mitigation strategies that could be adopted by local administrators for civil protection purposes during such an event as examples of land/urban management.

Bearing in mind that flash floods can affect the marine ecosystem (e.g. Arhonditsis et al., 2002), in the present work we only report the effect of the flash flood of the 4th November, 2011 on the physical characteristics of the water column at the mouth of the Polcevera Torrent, using data from different local weather and measurement stations during November, 2011.

2. Study area

The Port of Genoa (Fig. 1) is situated at the apex of the Ligurian Sea in the north-western Mediterranean Sea and extends along the coast almost uninterrupted for 20 km, protected for most of its length by a seawall. The western port entrance is 185-m wide at its narrowest point and exposed to south-easterly seas.

The western port sector includes the mouth of the Polcevera Torrent (Fig. 1), a torrential watercourse that has a catchment surface area of 140 km^2, characterised nowadays by the presence along its banks of abandoned industrial areas, factories, railway and motorway networks, quarries, and the suburbs of the city of Genoa. Its mean annual flow rate is 4.8 $m^3\,s^{-1}$ with the minimum in August (1.5 $m^3\,s^{-1}$) and the maximum during the autumn and winter (6.94 $m^3\,s^{-1}$ in December). The maximum flow rate is 1377 $m^3\,s^{-1}$ with a return period of 50 years and 1763 $m^3\,s^{-1}$ with a return period of 200 years. The monthly mean cumulative rainfall in the entire catchment area ranges from a minimum of 53.6 mm in July to a maximum of 221.5 mm in October (Fig. 2), the month in which the main flash floods usually occur (http://cartogis.provincia.genova.it/pdb/bilancio_idrico/bilancio_idrico/documenti/RelazionePolcevera.pdf).

The principal winds affecting the City of Genoa come from two directions: the NNE (which is the most frequent) and the SE, with a mean velocity of 3.1 $m\,s^{-1}$ for both the two directions (Castino et al., 2003). The annual water temperature in the port varies from 12–14 °C in February to 14–26 °C in July, in accordance with the atmospheric temperature trend. The salinity has a bimodal pattern with a maximum in summer and winter (37–38 PSU) and a minimum in early spring and autumn (36–37 PSU), in relation to the seasonal rainfall distribution. The temperature fields are influenced by exchanges with the sea (slightly higher values in the areas near the port entrances), while the salinity values are more related to strong rainfall events that magnify the freshwater discharge (Ruggieri et al., 2011). The tide is generally less than 30 cm inside the port.

3. Materials and methods

Although the flash flood of the 4th November 2011 affected the entire city of Genoa and involved both the Bisagno and the Polcevera torrents (in the eastern and western sectors of the city, respectively), dynamics and hydrology data were only available for the mouth of the Polcevera Torrent, due to the presence of instruments installed on the breakwater to monitor port dredging operations underway there.

The data on the dynamics were collected every 15 min using a horizontal Teledyne RDI 300-kHz acoustic Doppler current profiler (H-ADCP) positioned at a 7 m-depth along the breakwater at the western port entrance (Fig. 1). The size and the maximum number of bins of the H-ADCP were set at 4 m and 40 m, respectively, to cover 160 m of the port entrance.

The wind direction and intensity were obtained hourly from the weather station of the Weather Service of the Ligurian Environmental Protection Agency (ARPAL), while the cumulative data of the rainfall and stream flow rate were obtained from the Genoa Pontedecimo weather station positioned 75 m above sea level on the Polcevera Torrent, 7 km from its mouth (http://www.cartografiarl.regione.liguria.it/SiraQualMeteo/script/PubAccessoDatiMeteo.asp).

The hydrological data was collected every 15 min using a con ductivity–temperature–depth (CTD) multiparametric probe equipped with a turbidimeter (0–200 Formazine Turbidity Units, FTU) and a dissolved oxygen sensor (%) positioned near the ADCPs to continuously investigate the characteristics of the water flow, and, once a week, a second CTD with a turbidimeter (0–200 FTU) used at four stations around the mouth of the torrent (Fig. 1) to investigate the state of the entire water column in the area. We collected the CTD data and analysed the temperature (values in °C) and salinity (measured using the practical Salinity Scale), the dissolved oxygen (%) and the turbidity (Tu, values in FTU). The probes were factory-adjusted before use.

In order to objectively evaluate a possible correlation between the time series of data collected during the month of November, 2011, an analytical analysis method based on cross-correlation was applied to both meteorological (i.e., precipitation) and hydrological (i.e., hydrometric level, water temperature, turbidity, etc.) data. Cross-correlation makes it possible to evaluate both the degree of similarity between the time series and the eventual shift in time between them. In this work the Normalized Cross-Correlation Function (N-CCF) was considered, defined as:

$$C'_{12} = \frac{C_{12}(\tau)}{\sqrt{C_{11}(0)C_{22}(0)}} \tag{1}$$

where

$$C_{12}(\tau) = \int_{-\infty}^{+\infty} a_1(t)a_2(t+\tau)dt \tag{2}$$

The time series of the quantity of rain, hydrometric level, dissolved oxygen, salinity, temperature and turbidity were pre-processed by considering a common sampling (15 min), eliminating the offset and selecting a common time window of the 2nd–15th November, 2011. We assiduously checked the