

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

Marco Capello<sup>a,\*</sup>  
capello@dipteris.unige.it

Laura Cutroneo<sup>a</sup>

Gabriele Ferretti<sup>a</sup>

Stefano Gallino<sup>b,1</sup>

Giuseppe Canepa<sup>c</sup>

<sup>a</sup>DISTAV, University of Genoa, 26 Corso Europa, Genoa I-16132, Italy

<sup>b</sup>Weather Service CFMI-PC of ARPAL, Ligurian Environmental Protection Agency, 2 Viale Brigate Partigiane, Genoa I-16129, Italy

<sup>c</sup>Port Authority of Genoa, Palazzo San Giorgio, 2 Via della Mercanzia, Genoa I-16123, Italy

\*Corresponding author. Tel.: +39 (0)1035338143; fax: +39 (0)10352169.

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Summary

The city of Genoa (Italy) was hit by a severe flash flood on the 4<sup>th</sup> 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.

**Keywords:** Flash flood; Hydrology; Dynamics; Water column

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

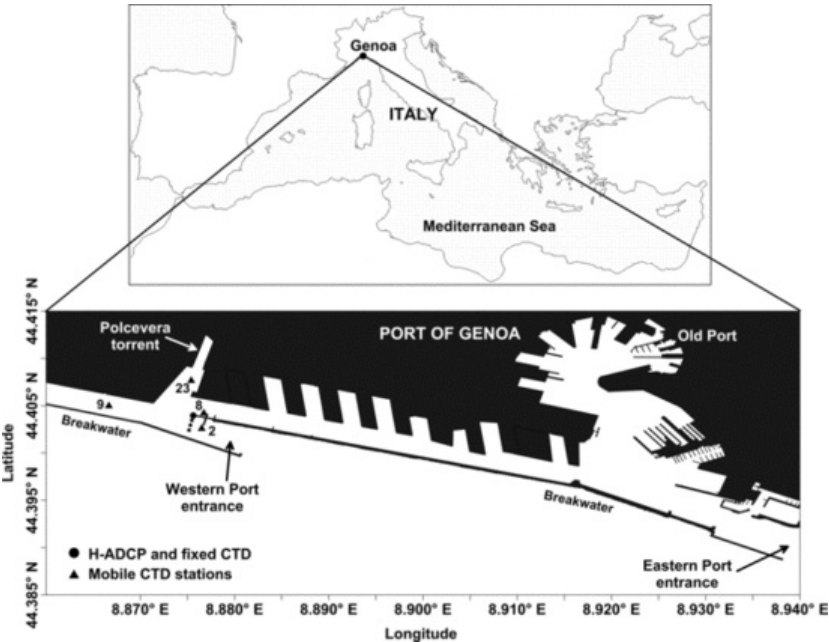
Much research has been carried out over the years on the different processes related to rainfalls, such as rainfall evolution (Zanon et al., 2010), land erosion, sediments and suspended matter input (Francke et al., 2014; He et al., 2012; Malmon et al., 2004; Wei et al., 2010), contaminant mobilisation (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 4<sup>th</sup> 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 4<sup>th</sup> 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.

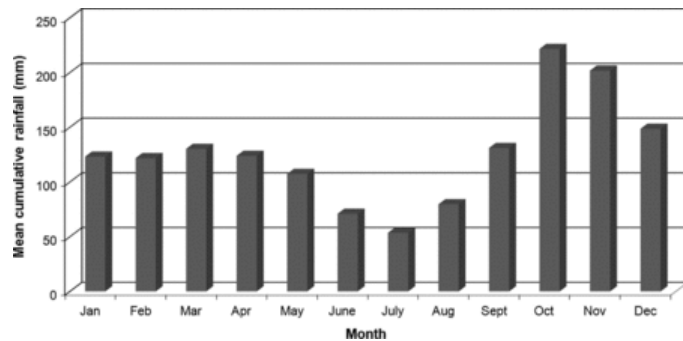
## 2 Study area

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.



**Fig. 1** Map of the Port of Genoa (Northern Italy) and the study area (western port area). Position of the sampling stations (black triangles) and the H-ADCP and fixed CTD (black circle). The dotted line starting from the fixed instruments shows the theoretical H-ADCP measurement line.

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<sup>2</sup>, 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<sup>3</sup> s<sup>-1</sup> with the minimum in August (1.5 m<sup>3</sup> s<sup>-1</sup>) and the maximum during the autumn and winter (6.94 m<sup>3</sup> s<sup>-1</sup> in December). The maximum flow rate is 1,377 m<sup>3</sup> s<sup>-1</sup> with a return period of 50 years and 1,763 m<sup>3</sup> s<sup>-1</sup> 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](http://cartogis.provincia.genova.it/pdb/bilancio_idrico/bilancio_idrico/documenti/RelazionePolcevera.pdf)).



**Fig. 2** The mean monthly cumulative rainfall (mm) in the entire catchment area of the Polcevera Torrent.

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<sup>-1</sup> 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.cartografiar.ligione.liguria.it/SiraQualMeteo/script/PubAccessoDatiMeteo.asp>).

The hydrological data was collected every 15 min using a conductivity–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:

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

where

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

(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 2<sup>nd</sup>–15<sup>th</sup> November, 2011. We assiduously checked the cross-correlation function between the amount of precipitation and the hydrograph and between the hydrograph and hydrological parameters provided by the CTD measurements. In particular, we calculated the cross-correlation functions considering the hydrometric level, the inverse of the temperature, the inverse of the dissolved oxygen, the turbidity and the inverse of the salinity.

## 4 Results and discussion

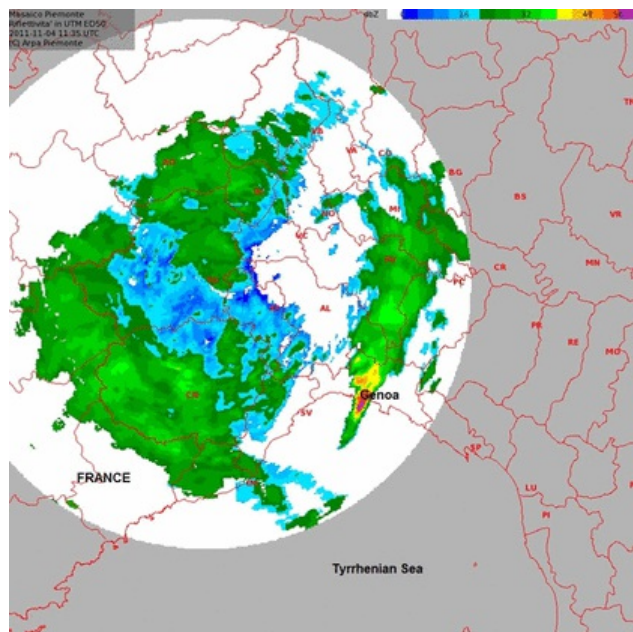
### 4.1 Meteorological overview of the extreme rainfall event of the 4<sup>th</sup> November, 2011

An enormous, subtropical, low-pressure front, coming from the Atlantic, passed over western Europe from the 3<sup>rd</sup> to the 9<sup>th</sup> November, 2011, causing very heavy rain, firstly in southern France and, then in the northern Tyrrhenian Sea. In the days before the event most of Europe had enjoyed stable weather with mild sea and air temperatures, despite the season.

The movement of the low-pressure system was blocked by the development of a robust anticyclonic front (max 1025 hPa at ground level) over Eastern Europe. In fact, the anticyclone, pushed by a progressive trough (1031 hPa), expanded towards the north, creating a vast eastern barrier. This situation caused a series of intense storms, strong winds and high seas, particularly in southern France, the Tyrrhenian Sea and north-western Italy.

The storm hit Genoa in three phases:

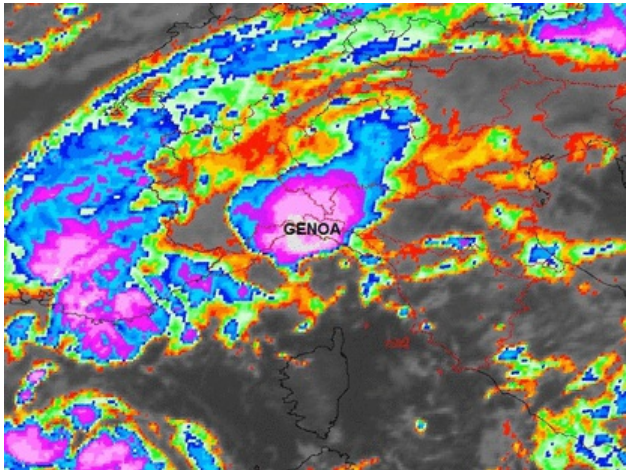
- Phase I: a convective, stormy prefrontal phase. The cold front moved through France to Liguria, producing low, unstable, humid, south-easterly wind currents that converged on the coast and caused prefrontal stormy phenomena of moderate intensity in Genoa on the night of the 3<sup>rd</sup> November. The self-regenerating storm system (Fig. 3) remained above the city, causing a maximum rainfall of 180 mm 1 h<sup>-1</sup> and, cumulatively, 400 mm 12 h<sup>-1</sup>, causing the flooding of various urban torrents. The storm exhausted itself in the early afternoon of the 4<sup>th</sup> November. The 5<sup>th</sup> November was characterised by notable instability. This phase concluded on the morning of the 6<sup>th</sup> November.



**Fig. 3** Phase I: Reflectivity map referring to 11.35 UTC of the 4<sup>th</sup> November, 2011, showing the hydrometeors with very high echo (yellow–red) linked to the presence of the storm over Genoa, as revealed by radar (Environmental Protection Agency of Piedmont – ARPAP – modified). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Phase II: pause in the rain. This phase (the 6<sup>th</sup> November) ended with the arrival of a second front that hit Liguria from the south.

- Phase III: anafront phase with stormy and advective precipitation. This stage was characterised by the passage of an anafront (a frontal boundary in which the main shield of clouds and precipitation is located behind the actual frontal boundary) through Liguria, generating new marine convective systems in central Liguria during the night of the 7<sup>th</sup>–8<sup>th</sup> November and a storm with heavy rains (max 40 mm 1 h<sup>-1</sup>) and very rough south-westerly seas that remained over Genoa (Fig. 4). This phase ended on the morning of the 9<sup>th</sup> November.

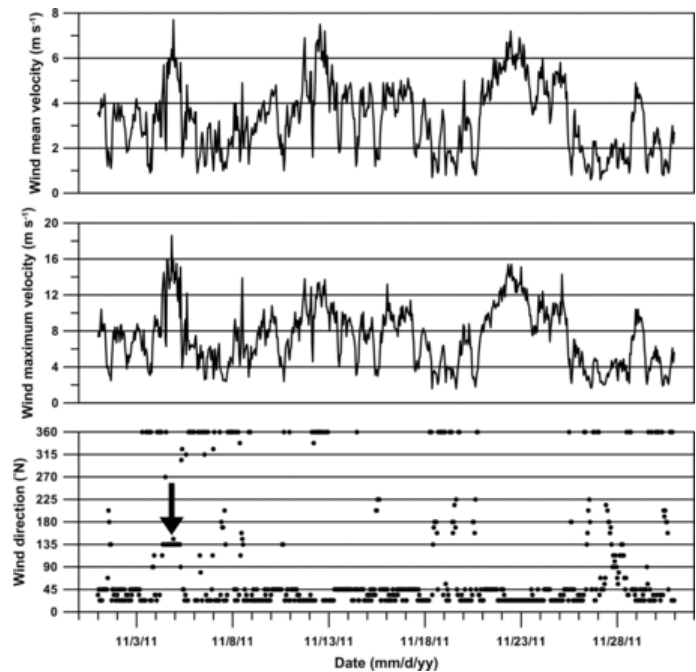


**Fig. 4** Phase III. Meteosat Second Generation (MSG) IR 10.8  $\mu\text{m}$  image referring to 03.00 UTC of the 8<sup>th</sup> November, 2011. The storm (violet–white) is visible over Genoa and central Liguria. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

## 4.2 Hydrological and physical observations

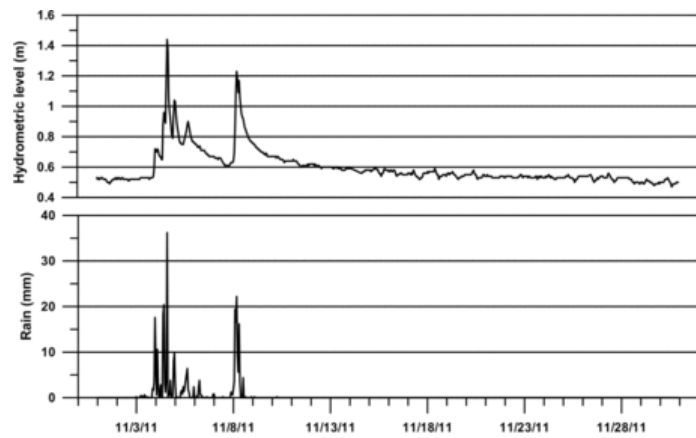
The accelerometer wave buoy of La Spezia (Eastern Ligurian Sea) recorded two sea storms during November 2011 (ARPAL, 2012): the first, from the SE, happened between the 4<sup>th</sup> and the 5<sup>th</sup> November and was characterised by a significant wave height of 2.7 m and a maximum height of 4.0 m; the second (the 8<sup>th</sup> November) from the S-SW had a significant wave height of 2.0 m and a maximum height of 3.8 m.

During the storm, the wind reached a maximum velocity of 18 m s<sup>-1</sup> with a mean value of 4.6 m s<sup>-1</sup> on the 4<sup>th</sup> November (Fig. 5). The wind direction was principally from SE on the 4<sup>th</sup> and the 5<sup>th</sup> November; while for the rest of the month, the wind direction was mainly from the N-NE.



**Fig. 5** Mean (above) and maximum (in the centre;  $\text{m s}^{-1}$ ) wind velocity and wind direction (below;  $^{\circ}$  N) measured by the weather station of the Weather Service of ARPAL (Ligurian Environmental Protection Agency) during November 2011. The arrow shows the prevailing south-easterly wind direction on the 4<sup>th</sup> and 5<sup>th</sup> November.

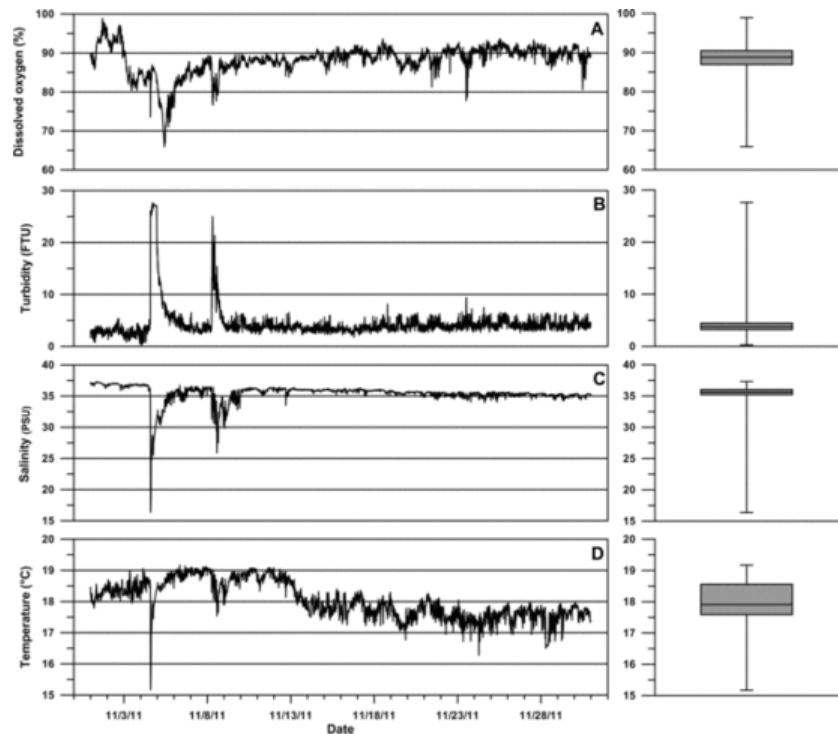
On the 4<sup>th</sup> November, the weather station on the Polcevera Torrent collected 132 mm of cumulative precipitation with a peak precipitation amount of  $36 \text{ mm h}^{-1}$  at 2:00 p.m. (Fig. 6, below). On the 8<sup>th</sup> November, the station measured 103 mm of cumulative precipitation with a peak precipitation amount of  $22 \text{ mm h}^{-1}$  at 4:00 a.m. (Fig. 6, below). The hydrometric level showed two corresponding peaks of 1.4 m at 3:00 p.m. on the 4<sup>th</sup> November and 1.2 m at 5:00 a.m. on the 8<sup>th</sup> November (Fig. 6, above).



**Fig. 6** Hydrometric level (m; above) and quantity of rain (mm; below) measured by the Genoa Pontedecimo weather station, situated on the Polcevera Torrent, during November 2011.

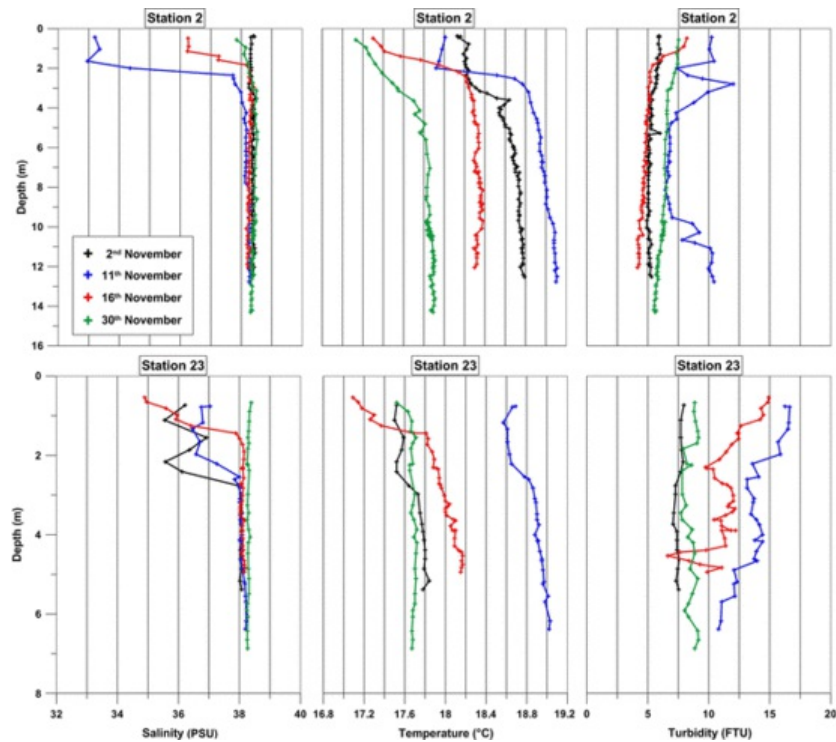
To study the effect of the flood event on the hydrological characteristics of the water column we, initially, took the CTD data from the fixed station on the breakwater, then the CTD data from the mobile stations, and, lastly, the dynamics data from the H-ADCP.

The fixed CTD measured relatively homogeneous values (Fig. 7, box-plots) in accordance with the seasonal trend during November 2011 (Ruggieri et al., 2011), with two relatively strong variations in the water characteristics induced by the two fresh-water inputs of the 4<sup>th</sup> and the 8<sup>th</sup> November. In fact, on the 4<sup>th</sup> November the temperature, salinity and dissolved oxygen (Fig. 7, line-plots) showed marked decreases that reached their minimum values for the period around 2:00 p.m. (15.17 °C, 16.37 PSU and 73.6%, respectively), while the turbidity showed a marked increase that reached 27.6 FTU (maximum value) and persisted for 10 h (from 2:00 p.m. to midnight). The second variation occurred between the 8<sup>th</sup> and 9<sup>th</sup> November, but was relatively weaker than the first; in fact, the temperature reached a minimum of 17.54 °C, the salinity 27.49 PSU and the dissolved oxygen 77.7%, while the turbidity reached a maximum of 25.02 FTU. In this second phase, the minimum temperature, salinity and dissolved oxygen values also persisted for only a few minutes, while the maximum turbidity values persisted longer (4 h).



**Fig. 7** Variations in dissolved oxygen (A; %), turbidity (B; FTU), salinity (C; PSU) and temperature (D; °C) measured by the fixed CTD on the breakwater and the corresponding box-plots of data variability.

The weekly CTD measurements showed a similar trend to the principal parameters in the water column at all the stations around the mouth of the torrent in the port. In particular on the 2<sup>nd</sup> November, 2011 (two days before the event) stations 2, 8 and 9 (Fig. 1) showed that the salinity, temperature and turbidity in the water column were relatively homogeneous (Fig. 8, above; we have reported the vertical profile of station 2 for conciseness only) but that, starting from the 11<sup>th</sup> November (3 days after the second phase of the event), there was a 2-m surface layer with a minimum salinity value, a maximum turbidity value and lower temperature. The minimum values after the event (salinity 33.17 PSU, temperature 17.92 °C and turbidity 12.0 FTU) were recorded at station 2 located at the entrance to the port (open sea) between two breakwaters (Fig. 1). The second minimum salinity value (35.29 PSU) was measured in the 4-m surface layer at station 9 on the 11<sup>th</sup> November, indicating the westward flow of the fresh water inside the breakwater (Fig. 1). During the following days the salinity and turbidity values returned to those normally found before the event, while the temperature showed a gradual decrease, in accordance with the general seasonal trend.

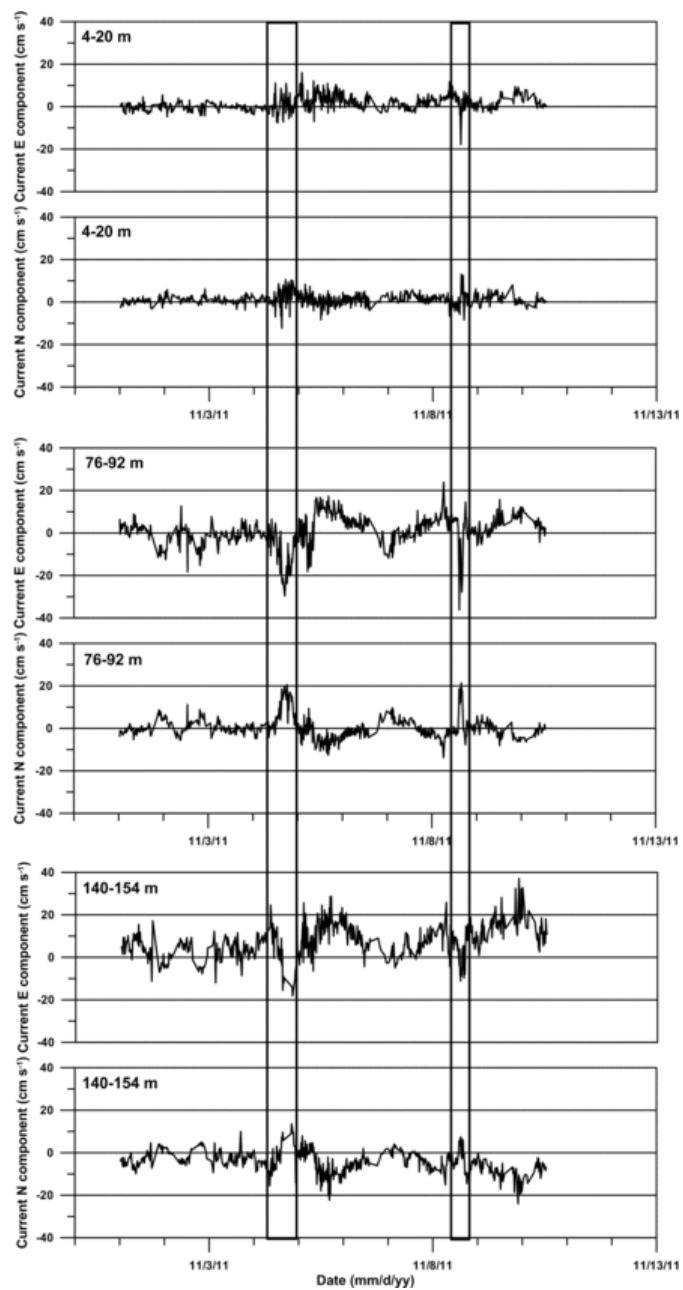


**Fig. 8** Vertical profiles of the salinity (left; PSU), temperature (middle; °C) and turbidity (right; FTU) at stations 2 (above) and 23 (below) measured with a CTD on the 2<sup>nd</sup> (black), the 11<sup>th</sup> (blue), the 16<sup>th</sup> (red) and the 30<sup>th</sup> (green) November, 2011. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The water column at station 23 (Fig. 8, below), located inside the mouth of the torrent (Fig. 1), was more directly affected by the water from the torrent, having a surface layer with low salinity during the entire month (also before the event), except on the 30<sup>th</sup> November, and a temperature that did not clearly follow the decreasing seasonal trend.

After the event (the 11<sup>th</sup> November), the temperature was higher than before at all the stations with the exception of a colder surface layer at station 2. At station 23, there was an increase of more than 1 °C in the entire water column. Warmer water was also found by Fouilland et al. (2012) in the waters of Thau Lagoon (France) after a flash flood, with an increase of more than 2 °C six days after the event.

Fig. 9 shows the mean current components measured by the H-ADCP at three points at the port entrance: 4–20 m from the instrument, 72–96 m from the instrument and 140–154 m from the instrument (maximum range but not total coverage of the entrance). It is possible to see the effect of the meteorological event on the dynamics at the port entrance from the early afternoon of the 4<sup>th</sup> to the early hours of the 5<sup>th</sup> November (in the box in Fig. 9). During this time, the current intensity generally increased. The prevalent current direction 4–20 m from the instrument was to the NE, flowing out of the port. In the rest of the channel it was to the NW, flowing into the port. This situation was forced by the strong south-easterly wind and related sea that controlled the event, despite the greater flow of water from the torrent. The particular direction of the current, south-easterly waves and the breakwater impeded the free flow of the torrent waters from the port and forced them westwards to the area of station 9. This forced flow direction is in accordance with Xia et al. (2010) and Liste et al. (2014), whom both found that local wind forcing was one of the primary factors determining plume behaviour and orientation at the small and medium scale.

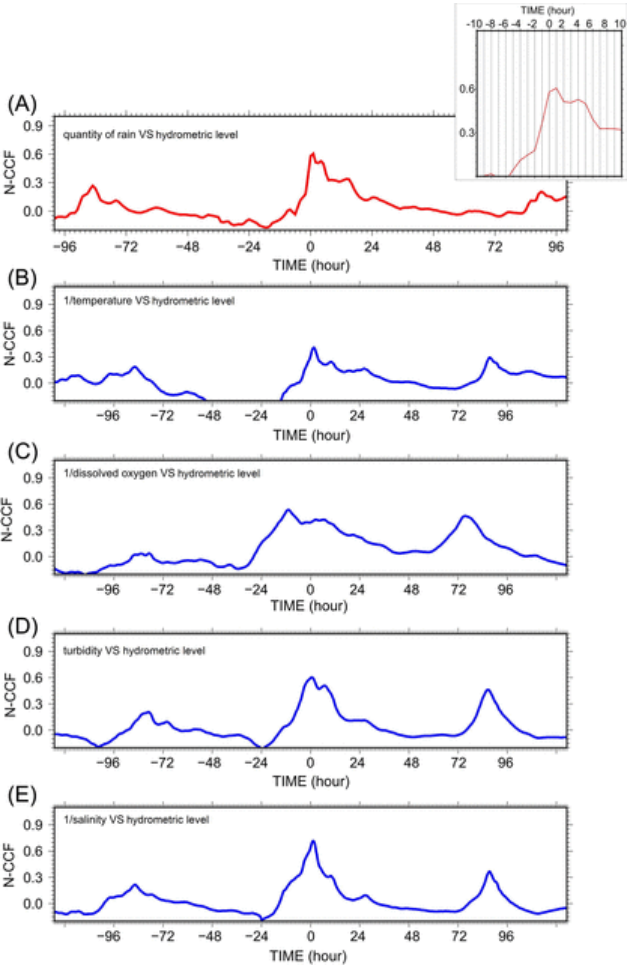


**Fig. 9** Mean Easterly (E) and Northerly (N) components of the currents measured by the H-ADCP at three different distances from the instrument: 4–20 m (above), 76–92 m (middle) and 140–154 m (below). The black boxes show the changes in the dynamics due to the two phases of the events of the 4<sup>th</sup> and 8<sup>th</sup> November.

The complex situation created at the mouth of the torrent and a particularly high tide (0.4 m), due to the minimum barometric pressure (1008 hPa measured at sea level), increased the effects of the flooding.

On the 8<sup>th</sup> November there was a second change in the current direction, less intense and briefer, due to the lesser intensity of the second phase of the event and with south-westerly seas that influenced the dynamics inside the port much less than the south-easterly ones.

The time series shown in Figs. 6 and 7 were then analysed by computing the cross-correlation function in order to objectively evaluate the possible correlation between these time series collected during the event. Fig. 10 shows the cross-correlation functions obtained considering the precipitation (Fig. 10A), the inverse of the water temperature (Fig. 10B), the inverse of the dissolved oxygen (Fig. 10C), the turbidity (Fig. 10D), and the inverse of the salinity (Fig. 10E) correlated with the hydrometric level. The results obtained allowed us to draw several conclusions.



**Fig. 10** Normalized Cross-Correlation Function (N-CCF) obtained by considering different pairs of time series of data measured during November, 2011. Cross-correlation functions between (A) precipitation and the hydrometric level; (B) inverse of the water temperature and the hydrometric level; (C) inverse of the dissolved oxygen and the hydrometric level; (D) turbidity and the hydrometric level; (E) inverse of the salinity and the hydrometric level. In the top right box there is a magnification corresponding to the function of the cross-correlation obtained by analyzing the values of precipitation and the hydrometric level, from which it is possible to observe the existing time shift.

The time series of precipitation and the variation in the hydrometric level exhibit a similarity greater than 60% and a time shift equal to approximately 1 h (the hydrograph results delayed by about 1 h compared to the hyetograph). The reader should keep in mind that the assessment of the delay between the two time series is strongly dependent on the data sampling step of 1 h, which does not allow a more accurate evaluation of this parameter (Fig. 10A).

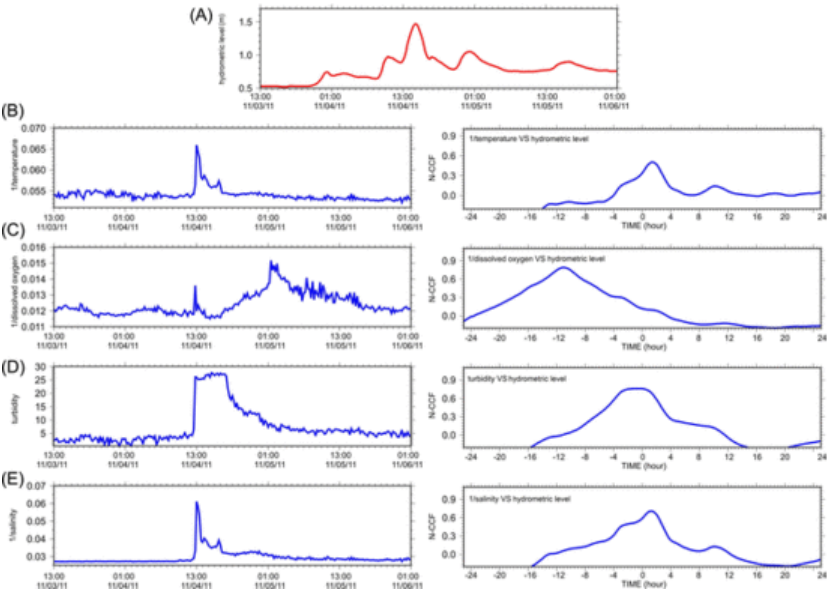
The signals relating to the hydrometric level and the hydrological parameters of the sea water appear to be related in a different way. In particular, the measurements of salinity, dissolved oxygen and temperature show a degree of similarity with respect

to the hydrometric level data equal to 71%, 53% and 41%, respectively, following a relationship of inverse proportionality. The similarity between the turbidity data and hydrometric level is equal to 60%.

The relatively low level of similarity between the water temperature and the hydrometric level can be due to the particular characteristics of this physical parameter, which is strongly influenced by the heat exchange between the atmosphere and water masses. In fact, during November, 2011, the temperature trend was characterised by a general decrease forced by the seasonal trend as shown in Fig. 7, independent of the torrent water input. Conversely, salinity is more affected by the fresh water input and consequently shows a higher degree of similarity with the hydrometric level.

In order to better evaluate the possible temporal shift between the hydrometric level and the physical–chemical parameters of the sea water, a specific analysis was performed considering only the time interval of the main precipitation event of 4<sup>th</sup> November, corresponding to the period between 1:00 p.m. of the 3<sup>rd</sup> and 1:00 a.m. of the 6<sup>th</sup> November, 2011.

The graphs in Fig. 11 represent the signals analysed and the corresponding cross-correlation functions. The similarity between the various hydrological parameters increases slightly, showing a degree of similarity between hydrometric level and salinity, dissolved oxygen, temperature and turbidity of 71%, 79%, 50% and 76%, respectively (Fig. 11). The correlation between the turbidity and hydrometric level values shows a broad bell-shaped maximum (79%; Fig. 11D) principally due to the relatively long interval during which the turbidity maximum (26–27 FTU) was maintained (9 h).



**Fig. 11** Time series (on the left) and corresponding normalized cross-correlation functions (on the right) obtained by considering the period between 01:00 p.m. of the 3<sup>rd</sup> and 01:00 a.m. of the 6<sup>th</sup> November, 2011. [A] hydrograph; [B] inverse of temperature; [C] inverse of dissolved oxygen; [D] turbidity; [E] inverse of salinity.

The maximum hydrometric level shows different temporal shifts from the maxima of the other hydrological parameters; in fact, the strong change in salinity, turbidity and temperature is in step with or slightly in advance (about 1'30") of the peak of the hydrometric level (Fig. 11A, B and D), while the significant decrease in dissolved oxygen (the increase of 1/dissolved oxygen, Fig. 11C) was approximately 11 h behind the peak of the hydrometric level.

The strong change in salinity, turbidity and temperature may be generically correlated to the rising limb of the hydrograph (i.e. concentration curve) rather than the peak of the hydrometric level. Moreover, interpreting the time shift between the hydrometric level and the hydrological parameters, the 7 km-distance between the weather station where the flow rate was measured and the CTD station must also be considered, and consequently, also the input of fresh water and precipitation from the area downstream from the weather station.

Conversely, the significant delay in the dissolved oxygen with respect to the hydrometric level and the low levels of dissolved oxygen measured after the event (Fig. 7) could be due to different physical and ecological processes that took place in the water column immediately after the event.

In the early hours of the 5th November (starting from 1:00 a.m.), the water temperature and salinity increased rapidly after the minimum reached during the maximum of the hydrometric level (Fig. 7), and at the same time, the hydrometric level decreased gradually (Fig. 6) while the wind and current velocity decreased rapidly (Figs. 5 and 9, respectively). This evolution could have produced a state that favoured a decrease in the dissolved oxygen within hours. Furthermore, after the maximum hydrometric level was

reached the establishment of ecological processes that involved primary production could have played an important role in the consumption of the dissolved oxygen. In fact, Fouilland et al. (2012) found that osmotic shock experienced by river phytoplanktonic communities transported into saline waters may explain the reduction in primary and oxygen production as much as the strong increase in turbidity and its related strong reduction in light penetration of the water column due to the great quantity of suspended material discharged by the flash flood. Moreover, the great quantity of organic matter discharged during the event could have initiated intense degradation processes with a consequent greater oxygen consumption.

## 5 Conclusions

In this paper, we have analysed the water masses at the mouth of the Polcevera Torrent during the flash flood event that took place in Genoa (Italy) on the 4<sup>th</sup> November, 2011, from the physical point of view, to highlight the effect of this event on the water column.

The physical characteristics of the water column were strongly affected by the flash flood, and the cross-correlation confirmed this, showing that the time variations in the physical parameters of the surface water measured at the torrent mouth were related to the data on the hydrometric level with an inverse proportionality for salinity, temperature and dissolved oxygen, and a direct proportionality for turbidity. Moreover, temperature, salinity and turbidity showed variations that were contemporary with the maximum input of fresh water and disappeared during the days after the event, returning to the pre-event condition by the end of the month. The dissolved oxygen also showed changes directly affected by the flash flood, but its behaviour was complicated by physical and ecological processes established after the event.

Lastly, the dynamics of the area were, on the contrary, affected more by the heavy seas and the wind from the SE than the fresh water flow that was forced to the western sector of the port, inside the breakwater.

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#### Highlights

- The city of Genoa (Italy) was hit by a severe flash flood on 4th November, 2011.
- The effect of the flash flood on the water column was studied at the stream mouth.
- The cross-correlation was applied to the hydrological and oceanographic data.

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