Seismic signature of an extreme hydrometeorological event

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Abstract

Flash floods are a major treat for Mediterranean countries and their frequency is expected to increase in the next years due to the climatic change. Civil protection agencies are called to deal with increasing hydrological risk, but existing hydro-meteorological monitoring networks might be not enough for detecting, tracking, and characterizing rapidly evolving floods produced by severe convective storms. Here, we leverage seismic data from a national monitoring network to characterize the hydrometeorological event that hit central Italy and resulted in a devastating flash flood in September 2022. The spatio-temporal evolution of seismic noise highlights remarkable anomalies that culminate around 6 hours before major flooding. Our results show that seismic noise generated by different, combined processes (rainfall, wind and increasing discharge in the basin headwaters), provides precious information to support hydrological risk management. We foresee seismic approaches to complement well-established procedures to early detect the occurrence of flash floods at regional scale.

Introduction

Flash floods are triggered by high-intensity and short-duration rainfalls and represent a major hazard for small river basins[1,2]. Given the heavy rainfall in a short period of time and the following rapid concentration of the runoff, flash floods populate the upper tail of the flood frequency distribution in small- to medium-size catchments ($10^3 - 10^4$ km^2), posing at high-risk large communities and infrastructures. The flash floods risk is exacerbated by the increasing in frequency of extreme meteorological events. This increase is nowadays more and more imputed by the scientific community to the consequences of the climate changes; for instance, according to climate model projections, the annual damage caused by flooding in the United Kingdom is expected to increase by more than one fifth over the next century if the COP26 and Net Zero promises are not collectively met[3].

The Mediterranean region is particularly exposed to the consequences of the climate change, and despite the foreseen overall drying, extreme precipitation events are expected to increase[4]. Even the vulnerability to floods is expected to increase at regional scales given the population growth that is experiencing the Mediterranean basin.

Despite the damage potential of such phenomena, the capability to monitor them can be limited by the quantity and type of instruments normally adopted for monitoring. In fact, the existing hydrometric and raingauge monitoring networks are not everywhere dense as needed and generally prone to low recording frequency and lack of information beyond stage height[5]. Furthermore, there are still remote mountain areas where precipitation and hydrometric information are not available at all. This can be a relevant limitation for understanding the hydro-meteorological processes that control flash floods. In this concern, there is the urgence to make the monitoring system more efficient and reliable, even by the opportunistic integration of different sensors.

Italy is especially exposed to the hydrological risk. A consistent number of flood events occurred there in the recent years, such as the one occurred in Liguria on October 2021[6], or in the Island of Ischia on October 2009[7] and on November 2022, or the recent flood that hit the Marche region on September 2022[8], which is the target of this work. A detailed list of floods occurred in Italy and all over the word can be found at FloodList (https://floodlist.com/).

The flash flood that hit the Marche region (Central Italy) between the 15 and the 16 September 2022 (Fig. 1) cumulated a rainfall peak of 437 mm in less than 12 hours (Cantiano rain gauge) that corresponded to a return period exceeding 500 years[9]. The rainfall triggered 1687 landslides in an area of 550 km^2 affected by the peak rainfall intensity[10] and led to 12 fatalities and severe damages to transport, infrastructures and buildings, especially in the Misa basin (Fig. 1). Such exceptionally severe event occurred at the end of a climatic anomaly of prolonged drought and warm conditions over Europe and the Mediterranean region. In particular, on the 15 September 2022, a deep trough over Scandinavia, a secondary lower one over the Iberian Peninsula and a high pressure on North Africa produced convective systems on the Tyrrhenian side. The slow movement of such baric structures determined the stationarity of its western flow in which these convective structures were developing. As a consequence, they continued to affect the same area for several hours, resulting in very high accumulations. In the early afternoon of the 15 September 2022, storm cells developed on the Apennines side in the mountain part of Marche region, generating intense, localized, and stationary phenomena. In the final part of that day, the system progressively moved towards the coast, gradually weakening in its intensity. At the same time, another thunderstorm system developed in the southern part of the region persisting for a more limited period, with intense phenomena but with considerably lower accumulations. In order to highlight the strength of the 15 September 2022 hydro-meteorological event, which leads us to define it as an extreme event, we recall that the total rainfall accumulation of this event (437 mm) was more the half of the total accumulation value for the Marche region over an entire year (i.e., the mean annual precipitation over the 1981–2010 period is 803,6 mm, https://www.reterurale.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/16319).

Although Italy has an advanced multi-parametric monitoring system (i.e., raingauges, disdrometers, hydrometers), and the national civil protection agency has at its disposal even ground-based weather radars and satellite-borne active and passive sensors, the 15 September 2022 event highlights that dealing with extreme floods calls for a paradigm change monitoring. Hydrometric network, in particular, seems not fully adequate to monitor the evolution of flash floods, given: (i) the low temporal resolution of the measurement, (ii) the exposure to damage by water discharge, coarse sediment and large wood transport, (iii) the lack of information beyond stage height, and (iv) malfunctioning due to erosion/deposition processes[5,11–12]. For instance, most of the hydrometers in Italy sample water level once in 30 min, which seems insufficient to characterize rapidly evolving floods featuring short-duration pulses.

In this retrospective study, we leverage seismic data from a national monitoring network to characterize the hydrometeorological event that between the 15 and the 16 September 2022 hit the Marche region.

Different structural and environmental factors are responsible for the temporal and spatial variation of seismic noise[13]. Non-tectonic seismic sources such as landslides, debris flows, dam collapses, floods, and avalanches generate seismic signals that are considered as “exotic” sources of noise when the objective is to perform a classical seismological analysis. Building upon a pioneering experiment carried out in the early 90s[14], a growing number of studies dealing with the monitoring of river networks during monsoons[15], typhoons [16], and controlled floods[17] are nowadays relying on seismometers placed near torrents. Separating the contribution of various “exotic” seismic sources – including precipitation, bedload transport, and flow turbulence – would allow to characterize different processes with a single sensor at very high temporal resolution.

Fluvial seismology has already shown that important characteristics about river flow processes, such as bedload transport and turbulence, are encoded in ground vibrations[18]. Worth to mention, during the last twenty years, the Italian seismological community made great efforts in establishing dense seismic networks at national scale, standardizing formats for data transmission and archiving, and creating open data repositories for sharing real-time and archived data streams (e.g., the Observatories and Research Facilities for European Seismology European Integrated Data Archive, https://www.orfeus-eu.org/data/eida/). Such infrastructure and methodological developments open new scientific avenues, including the upscaling of fluvial seismology from single rivers to watersheds, which would be precious during large-scale flash floods.

In the following, we show as during the main precipitation event of the Marche hydrological crisis (i.e., between 12:00 and 20:00 UTC of the 15 September 2022) the seismic power registered by the seismic stations of the national seismic network (i.e., we used data from the network IV, INGV Seismological Data Centre, 2006), coherently increases and shows maxima in the frequency band 30–50 Hz. The spatio-temporal evolution of seismic noise recorded by stations distributed over central Italy highlights a remarkable temporal coincidence of seismic signals, which in turn also agrees with peak of rainfall from rainguages. Worth to note, our results highlight that anomalous high amplitudes on seismic signals culminate about 6 hours before the major flooding, with high spatial coherence of seismic amplitude at different stations during the rainfall crisis (i.e., at the 17:50 UTC of the 15 September 2022). Our results show higher seismic amplitudes in coincidence with the principal rivers of the area, where indeed most damaged villages are located and indicate eventually that the analysis of the seismic noise recorded by dense, regional seismic networks can provide powerful information on the spatio-temporal evolution of the flood that can efficiently complement hydrometric data.

Results

Cumulated rainfall time series of raingauges in the Marche and Umbria regions (Figs. 2a and S1) provide a clear picture of the temporal evolution of the meteorological event occurred between the 15 and 16

September 2022. In particular, a couple of raingauges (i.e., Cantiano and Fonte Avellana stations) that are in the upper part of the Metatauro river basin and are 6.9 km apart (light blue lines in Fig. 2a), recorded between 12.00 and 20.00 UTC of the 15 September 2022 a huge amount of precipitation, reaching a cumulative value of about 400 mm. This value is significantly larger than the cumulative precipitation measured during the crisis at any other station in the region.

The temporal evolution of four hydrometers located in the basin of the rivers involved in the event provides useful information, as well (Fig. 2b). According to these data, the stations at Pontedazzo, on the Metatauro river, and at the Bettolelle, on the Misa River, recorded over 6 m of flow height, but with a temporal shift of few hours and a different rate. The peak of the height flow at Pontedazzo - located in the upper part of the Misa River - is delayed of about 3 hours with respect to the height flow maximum at Bettolelle, in the lower part of Metatauro river. For comparison, we also report the height flow at Moie and S. Severino stations, located in the basins of the Esino and Potenza rivers, respectively. The flow heights at these stations indicate that the intensity of the hydro-meteorological event was reduced when moving southwards.

Following an increasing usage of the seismic noise (i.e., also referred to as 'ground vibration') as monitoring tool for a broad spectrum of gravitative processes ranging from bedload transport to debris flows[19], we calculated the spectra of the seismic signals recorded at 54 stations spread over the area hit by the hydro-meteorological event (see Methods and Fig. S2). After some tests, we verified that the clearest imprinting of the flood event on the seismic signals appears in the frequency band 30–50 Hz. In particular, the seismic signal acquired by station ATPC, located at the Metatauro river upstream, shows a remarkable temporal coincidence of its maxima with those of rainguages (Fig. 2c). To better observe the temporal relationship among the different signals, in Fig. 2a we highlighted the occurrence time of the seismic peaks at the seismic station ATPC. Similar indications are also provided by the SSFR station placed at the upstream of Esino River. Finally, it is worth to emphasize the characteristics of signals recorded by the station COR1, located at the Misa River downstream. The latter station, in fact, shows the largest power peaks in coincidence with the rainfall peak registered by the raingauges and before the flow height peaks registered by hydrometer station located in the lower part of the Misa basin (Fig. 2b). The latter behaviour can be due to the large distance between the COR1 station and the Misa River, (around 14 km) that can prevent the detection at this station of the seismic vibrations directly induced by the river flow.

Further complementary information can be obtained by the spectrogram of signals recorded at ATPC station (Fig. 3). The latter shows a first peak starting approximately at 8:00 a.m. and lasting almost 1 hour followed at 12:00 a.m. by a second peak with high signal power that lasts several hours. Both peaks cover a wide frequency range, with the largest values observed in the frequency band 30–50 Hz. Furthermore, also in this case, we compare the seismic signal with the temporal evolution of signals from raingauges located within 10 km from the seismic station. Interestingly, the temporal limits of the second peak at ATCP well match those of the hourly cumulated rainfall registered at s. Benedetto Vecchio and Monte Nerone raingauges. The seismic data well match the duration of the precipitation event (i.e., between 12:00 and 20:00 UTC of the 15 September 2022). These results suggest that the seismic stations captured the effects of the hydro-meteorological event and hence could be opportunistically used to complement the observations of other instruments and eventually to detect and monitor the evolution of adverse weather phenomena.

We extended the analysis of the seismic signals looking at their spatial coherence over the areal extension of the 15 September flood event along the duration of the crisis. We compared the temporal evolution of the median seismic amplitude for the 54 considered stations (Fig. 4a, Figs. S3-S56). When we look at the average of the median amplitudes over all the stations (Fig. 4a, where amplitudes are represented in logarithmic scale), we observe two main features: i) a one-day periodicity, and ii) a peak in coincidence with the start of the precipitation event (i.e., around the 12:00 am of the 15 September). While the one-day periodicity is a well-known kind of trend in seismic noise due to mainly anthropic sources[20], the effects of rainfall on seismic amplitude is remarkable. Interestingly, the averaged seismic signal over the whole set of stations shows a marked increase starting from 12:00 am that matches the time at which the measured rainfall and flow height starts to sharply increase (see Fig. 2a, b and animation in the Supplemental Material). In Fig. 4a, we marked four periods of time (vertical dashed lines). Three of them correspond to periods before and after the hydro-meteorological event (black), while the fourth one marks the strong rainfall phase. For each of these time marks, we represent the spatial coherency of seismic amplitudes (Figs. 4b-e, see Methods). Before the onset and after the end of the high-rainfall phase (subpanels b, c, and e), we can observe that the largest seismic amplitudes show high coherency close to the seacoast, likely as an effect of the sea waves hitting the coast and producing coherent seismic noise (i.e., at periods around 5 seconds the seismic noise is referred as microseismic noise). Noteworthy, differently from all the others, subpanel (4d), representing the spatial distribution of seismic amplitudes during the rainfall crisis (15/09 h. 5.50 pm), shows a large peak elongated in the south-west to north-east direction. The large seismic anomaly well relates with the distribution of hydrometers (red diamonds in Fig. 4d) and perfectly fits with the basin between the Metatauro and the Misa rivers (blue lines), where indeed most damaged villages are located (black stars).

Discussion

The rising trend in the occurrence of fatal flash floods recorded worldwide is probably the result of changes in environmental and global climatic settings[21]. Under this increasing risk for communities and infrastructures, additional research efforts are needed to better understand predisposing factors, to nowcast the occurrence of critical events, as well as to develop reliable rapid responses to mitigate the exposure of people to risk.

In this study, we have explored the possibility of detecting ground vibrations associated to large precipitation events by extracting and analyzing segments of continuous data of the stations of the Italian national seismic network downloaded from the ORFEUS-EIDA repository (https://www.orfeus-eu.org/data/eida/), where they are identified with the network code IV.

We have applied simple signal processing that already resulted successful for the detection and characterization of flash floods upland catchments[19]. The adoption of approaches using ground vibration data analyses as monitoring tools for debris flows is increasing worldwide[22–24]. Seismic records can be also used to retrieve rainfall, although to date only very few studies have investigated this possibility[25–26]. Furthermore, recently[5] it was shown that seismic approaches can also sense rapid flooding and provide information on flood magnitude, velocity and trajectory in near real-time. These approaches exploit single, or a few seismic sensors placed nearby the monitored rivers, and it is worth noting that upscaling the signal strategies from data recorded at short distances from small rivers confined in valleys to large scale events is challenging. This is indeed the case of the Marche flood crisis of the the 15 and 16 September 2022, which affected an area of 550 km^2. Nevertheless, the scientific community is increasingly engaged on this research field with the aim to opportunistically complement data from existing networks (e.g., raingauges, disdrometers, hydrometers), which might suffer of insufficient density, low sampling rate, saturation, and large latency, with other pieces of information.

To our knowledge, only a few attempts of detecting catastrophic flow events with regional seismic networks have been proposed so far. For instance, some authors[27] have shown that the devastating 7 February 2021 Rishi Ganga and Dhauli Ganga valleys flash flood of northern India was detectable at seismic stations located up to 100 km from the event.

In our study, we have shown that during the most intense part of the Marche precipitation event (i.e., from 12:00 to 20:00 UTC of the 15 September 2022) the seismic power in the frequency band 30–50 Hz significantly increases and presents remarkable temporal coincidence with rainguages peaks. Furthermore, by following the spatio-temporal evolution of signal amplitudes recorded by seismic stations in the region, we show that it is possible to track the evolution of the precipitation and flooding event. It is worth noting that the region with higher seismic amplitudes matches the area between the Metatauro and Misa rivers, which hosts very damaged villages, but notably the anomalous high amplitudes of seismic data anticipate of a few hours the major flooding.

Our results suggest that seismic noise during the precipitation event is related to different and combined sources (e.g., rainfall, wind and increasing discharge in the basin headwaters). If it were possible to discriminate in real-time and to characterize the contribution of the different processes to seismic noise, then we would be in the condition to integrate these pieces of information within well-established procedures to early detect the occurrence of flash floods at regional scale. With respect to such a goal, our study represents a first step of a long journey.

Following the pioneering study of 2012 by Tsai and colleagues[28], who provided an analytical model for seismic noise produced by impacting river sediments, a priority step to take is certainly the definition of novel analytical models that would combine both the contribution described by Tsai and colleagues and the effect of rainfall intensity on seismic noise. Being able to provide information about the intensity of precipitation from seismic data would allow to improve the accuracy of stream flow simulation and flood forecasting[29].

A further target is to extend the approach proposed by Dietze and colleagues[5] to large scale monitoring networks to obtain real-time estimation of flood volume, velocity, and trajectory. With respect to the latter goal, both the study of processes contributing to the generation of seismic noise, the definition of regional scale models describing the attenuation of seismic signals generated by floods with distance and the required network density for the detection and characterization of flood events in seismic noise would be relevant. In this regard, an important step would also be to collect and to organize datasets combining multiparametric signals related to large flood events occurred in recent years. The creation of catalogues of well recorded large-scale flood episodes would foster the cooperation among seismologists and hydrologists and would likely lead to improved approaches for the real time detection and characterization of future catastrophic floods.

Methods

Seismic data

We selected continuous data in the period 13.09.202–17.09.2022 from three-component seismic stations located in the latitude-longitude ranges 42.7-44.350 and 11.9–13.9, respectively. Recordings of 54 seismic stations from the Italian national seismic network[30] (network code IV) in this time interval have been downloaded from the ORFEUS-EIDA repository (https://www.orfeus-eu.org/data/eida/) and processed. Continuous signals have been frequency filtered in the bands 0.5-2 Hz and 30–50 Hz, labelled respectively as low-frequency (lf) and high-frequency (hf) bands. Envelopes on the signals in the two frequency bands have been computed and then downsampled at one sample per minute. The median of the detrended envelopes at each seismic station was then calculated in a time window of 15 minutes sliding 10 minutes at each step. Finally, amplitudes of the seismic envelopes have been spatially interpolated using the model[31] $\frac{x}{D} - \left(\frac{x}{D}\right)^3$, where x is the distance between sampled and interpolated point and D defines the interpolation range and was fixed to 1 degree.

Hydro-meteorological data

For the same period and area considered for seismic data, we downloaded data from 270 raingauge stations managed by Regione Marche and Regione Umbria. The data consists of time series of rainfall amount (in mm) collected in a given time interval, which can vary between 15 minutes and 60 minutes. All data have been cumulated over 60 minutes to obtain the hourly cumulated rainfall.

The hydrometer data used in the work are managed by Regione Marche and consists of the measurement of the water level (in m) at the station each 30 minutes.

Declarations

Author contributions

V.C. conceived the work and prepared the datasets. All authors jointly analyzed the data, interpreted the results and wrote the manuscript.

Competing interest

The authors declare no competing interests.

Additional information

Supplementary information includes 56 Figures.

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Correspondence and requests for material should be addressed to -

Data availability

Seismic data are available via the website: https://www.orfeus-eu.org/data/eida/

Hydro-meteorological data are available at http://app.protezionecivile.marche.it/sol/indexjs.sol?lang=it for the hydrometers and raingauges managed by Regione Marche and at https://www.regione.umbria.it/-/servizio-idrografico for the raingauges managed by Umbria Region. The data are freely available upon registration for Regione Marche and upon request for Regione Umbria.

Code availability

Data was processed using MATLAB R2019b (https://www.mathworks.com/products/matlab .html). For inquiries about the code please contact matteo.picozzi@unina.it or mauro.palo@unina.it.

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Figures

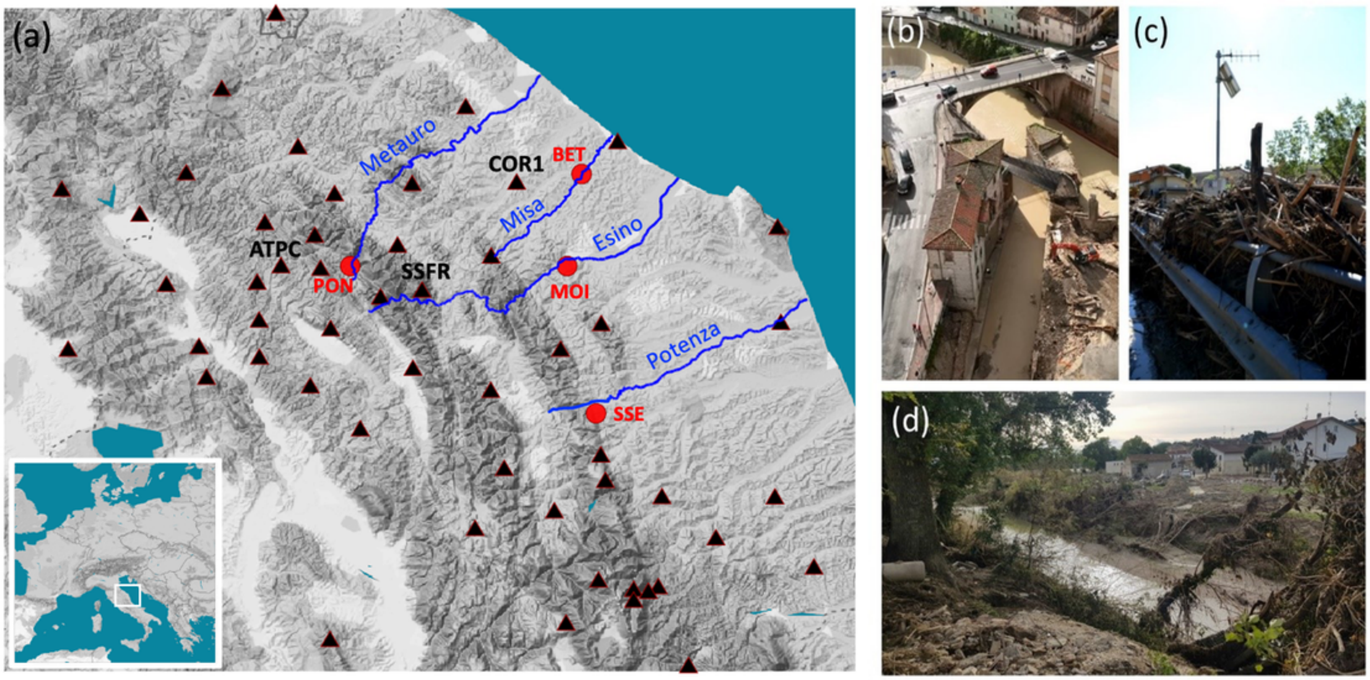

Figure 1

Area hit by the Marche hydrological crisis occurred between 12:00 and 20:00 UTC of the 15 September 2022. a) Distribution of seismic stations (black triangles). Please note, those discussed in the main text and shown in Figure 2 are highlighted by the IV seismic network code: COR1, ATPC, SSFR. A complete map of the seismic stations can be found in Fig. S2. Hydrometers discussed in the main text (red circles; Pontedazzo, PON, Bettolelle, BET, Moie, MOI, and S. Severino, SSE). From b) to d) examples of damages at villages between the Metauro and Misa rivers.

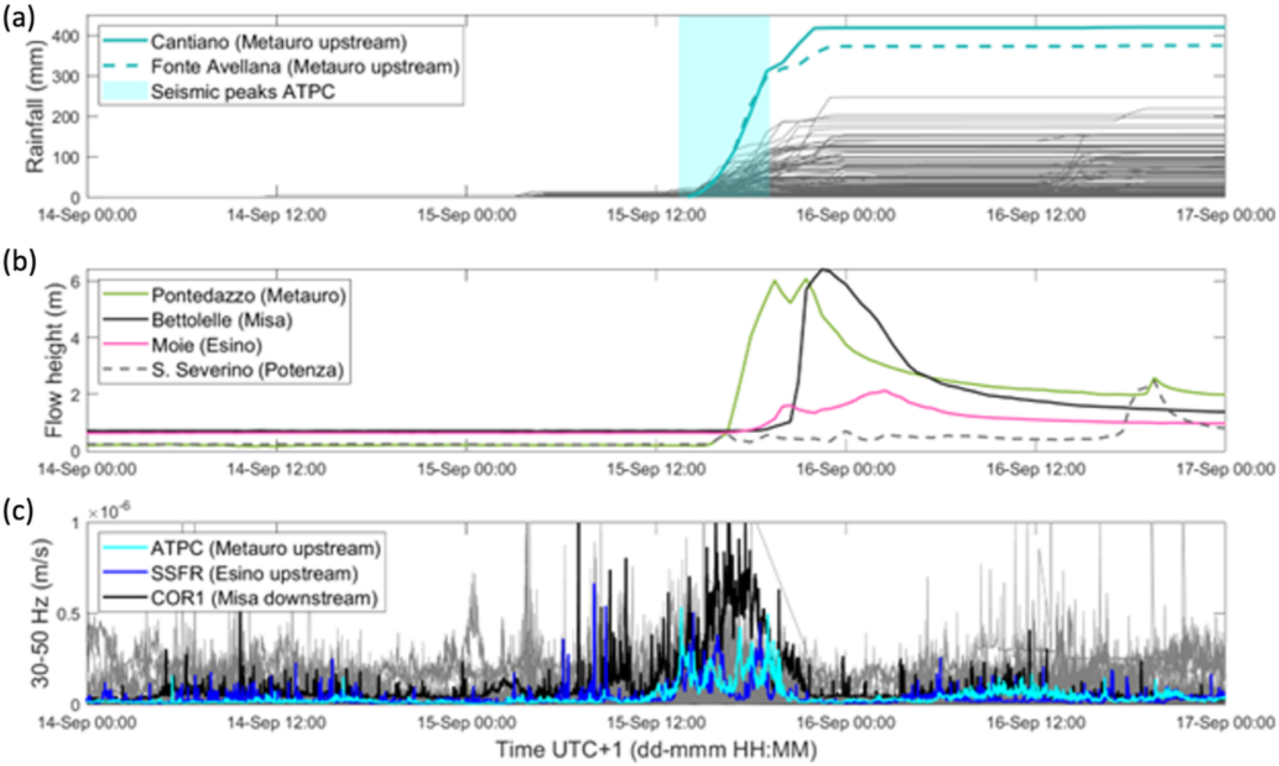

Figure 2

a) Time series of the cumulated rainfall (mm) between the 14 and the 17 September 2022 obtained from all raingauge stations considered in this study (gray lines). Please note that the distribution of rainguages is shown in Fig. S1. The light blue lines represent the cumulated rainfall registered at Cantiano and Fonte Avellana stations, which are 6.9 km apart and are located upstream of Metauro river. Finally, the light blue rectangle represents the time range when the station ATPC registered the largest seismic signals. (b) Time series of the flow heights (in meters) registered between the 14 and 17 September 2022 by four hydrometers located in the river basin involved in the event (whose location is shown in Fig. 1a). (c) Envelopes on the seismic signals for the stations shown in Fig. 1a (gray lines) and with the stations COR1, ATPC, SSFR highlighted.

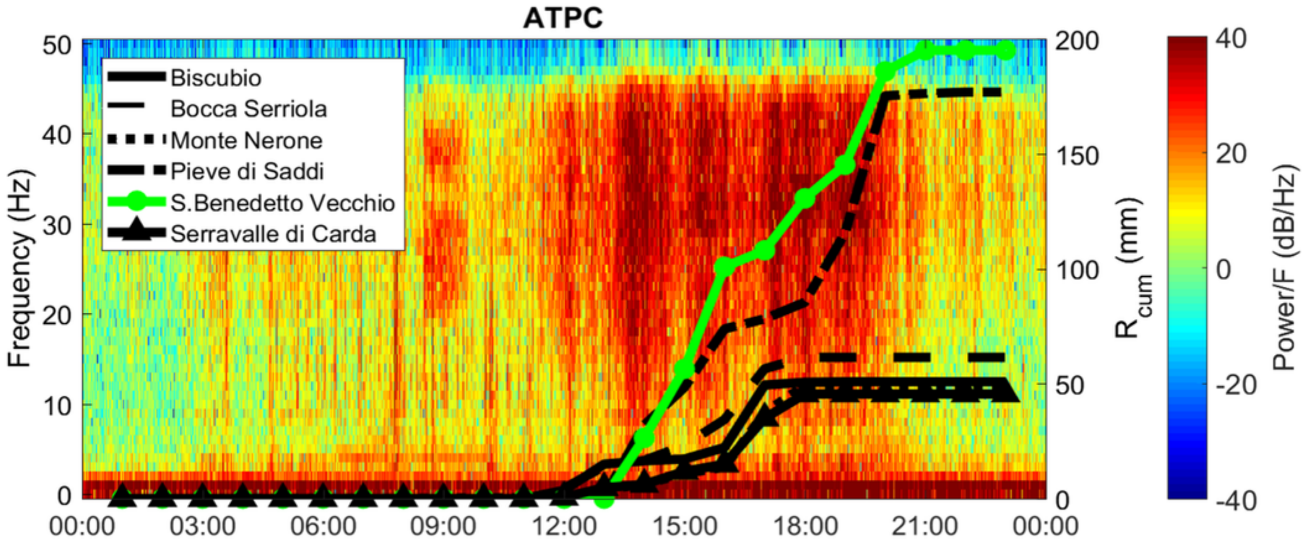

Figure 3

Spectrogram of the ATPC seismic station (Metauro upstream) during the 15 September 2022. Black lines represent the hourly cumulated rainfall measured by the raingauge stations within 10 km from ATPC (please note that the names of the raingauge stations are listed in the legend). The green line displays the hourly cumulated rainfall of the closest raingauge (i.e., 5.4 km away from ATPC).

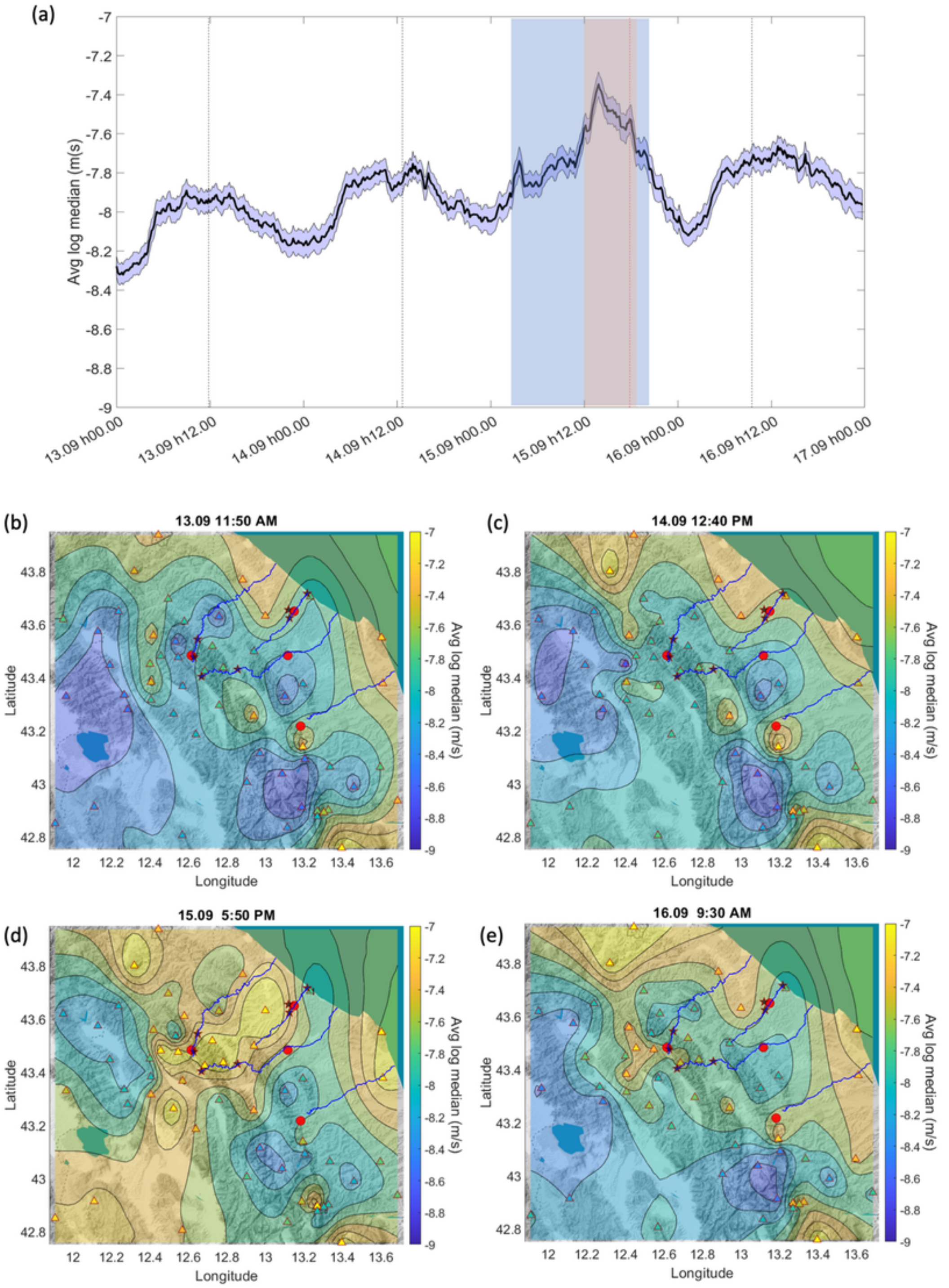

Figure 4

a) Time history of the median amplitude of the seismic signal averaged over the stations and corresponding standard deviation (log scale). The vertical dotted lines mark the time frames at which the spatial distribution of the seismic amplitude is displayed in the following subpanels. (b-e) Spatial distribution of the amplitude of the seismic signals (hf, z component) at four timeframes. Triangles mark the station positions and colors scale with the signal amplitude (in m/s - log scale). Isolines display the amplitude of the seismic signal interpolated over the whole target area (see methods for details). Red circles show the position of hydrometers, while black stars are located at the position of strongly damaged villages or towns. The four blue irregular lines show the rivers (from north to south) Metauro, Misa, Esino, Potenza.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- CovielloetalSuppMaterialv20.pdf