

Rainfall Extraordinary Extreme Events (EEEs) Frequency and Magnitude Assessment: The EEE Occurred on 14th–15th October 2015 in Benevento Area (Southern Italy)

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Abstract. The identification of suitable statistical models of rainfall maxima at regional scale is a key element for the definition of reliable flood and landslide risk mitigation plans and for the design and security evaluation of high hazard strategic engineering structures. The ability to develop such models is highly dependent on a rain gauge monitoring network able to observe the extreme events that occurred in a region for several decades. In Italy, the density of the monitoring network and the time series lengths are often inadequate to capture some of the rainfall extreme events (referred to as extraordinary extreme events - EEEs), characterized by very low frequencies and spatial extent scales much smaller than those of rainfall ordinary maxima. In recent years, new operational statistical approaches were proposed to properly retrieve the EEEs frequency from the available database. However, the meteorological patterns of the EEEs are still poorly known, due to the limited number of documented cases studies available. The post-event rainfall analysis of observed EEEs and the evaluation of the efficiency of the monitoring network in detecting their magnitude and spatial properties may certainly help to improve the interpretation of the phenomena and their probabilistic modeling. In this study, new insights about the characteristics of EEEs are retrieved by analyzing data collected by different automatic rain gauge networks operating in Campania region (Southern Italy) from year 2001 to 2020. In this time frame, the extreme rainfall event occurred on 14th–15th October 2015 in Benevento area is the only daily EEE observed. The analyses show the capability of different monitoring networks to observe the phenomenon and the impact of different statistical regional models of rainfall maxima in assessing its frequency.

Keywords: Extraordinary Extreme Event (EEE) · Extreme rainfall · Rain gauge network density

1 Introduction

The ability to develop suitable statistical models of rainfall maxima at regional scale is highly dependent on a rain gauge monitoring network that has been effectively able

© Springer Nature Switzerland AG 2021
O. Gervasi et al. (Eds.): ICCSA 2021, LNCS 12956, pp. 264–278, 2021.
https://doi.org/10.1007/978-3-030-87010-2_18

to capture the main spatial features of the extreme events that occurred in a region for several decades [1, 2].

Rossi et al. [3] introduced the Two-Component Extreme Value (TCEV) distribution for modeling rainfall maxima, since they observed the existence of two independent meteorological processes generating rainfall extremes in Italy. The TCEV distribution describes the frequency distribution of maxima as a mixture of two independent populations of random variables, represented respectively by an ordinary component, more frequent and less severe in intensity, and an outlying component, which produces the higher, although rare, values. The use of TCEV in the regional frequency analysis for the statistical assessment of hydrological extremes has become very popular in Italy after it was implemented in the national reference procedure for flood hazard assessment [4].

Later, Pelosi et al. [5] showed that the density of the monitoring network and the length of the observed rainfall time series are often inadequate to capture some extraordinary extreme rainfall events (EEEs), characterized by very low frequencies and spatial extent scales much smaller than those of ordinary maxima. Stemming from a data-driven analysis, the occurrence of EEEs at daily scale was identified by a lower threshold of 250 mm day^{-1}. Then, it was proved that regional statistical analyses, even those that implement mixture models like TCEV, tend to underestimate EEEs probability of occurrence due to the limitations of the observational dataset that not consistently reflects the spatial occurrence of the extreme rainfall patterns in a region. This circumstance can deteriorate the reliability of flood and landslide risk mitigation plans as well as the design and security evaluation of high hazard strategic engineering structures, such as dam spillways. Therefore, a new operational statistical approach was proposed to properly retrieve the EEEs frequency from the available database and thus to avoid dramatic underestimations of the rainfall depth at very high return periods.

However, the meteorological patterns of the EEEs are still poorly known, due to the limited number of documented cases studies available. The post-event rainfall analysis of observed EEEs and the evaluation of the efficiency of the monitoring network in detecting their magnitude and spatial properties may certainly help to improve the interpretation of the phenomena and their probabilistic modeling at regional scale.

A recent study proposed the use of reanalysis data for classifying and analyzing heavy rainfall precipitation patterns and their synoptic evolution [6]. Nevertheless, this approach may not give interesting information on the rainfall patterns when the spatial extent scales of the rainfall events are smaller than the spatial resolution of the numerical grids of the reanalysis models that may varies from about 31 km, for the case of the most efficient European global reanalysis model, such as ERA5 [6] to about 9 km for its downscaled land application, i.e. ERA5-Land, whose performances have been already verified in Southern Italy for other hydrological applications [7].

In this study, new insights about the characteristics of EEEs are retrieved by analyzing data collected by automatic rain gauge networks that have been operating in Campania region (Southern Italy) from year 2001 to 2020. In this time frame, the extreme rainfall event occurred on 14th–15th October 2015 in Benevento area is the only daily EEE observed in the region. In Sect. 2, the study area and the available rainfall data are presented. In Sect. 3, the identified EEE is described. The ability of the rain gauge network to detect such type of events is discussed, along with an analysis of the network

efficiency, by comparing the spatial density of the rain gauge and the spatial extent scale of these extreme rainfall pattern.

2 Study Area and Data

2.1 Topographic and Meteorological Description of the Study Area

The study area is part of the Campania region, located in Southern Italy (Fig. 1). The extension of the whole region is of about 14000 km^2 placed between the Tyrrhenian Sea and the Apennines. The complex topography of the region strongly influences the weather [8] and the rainfall patterns that widely vary along the region with relevant local effects due to the presence of orography [9, 10] and the proximity of the sea.

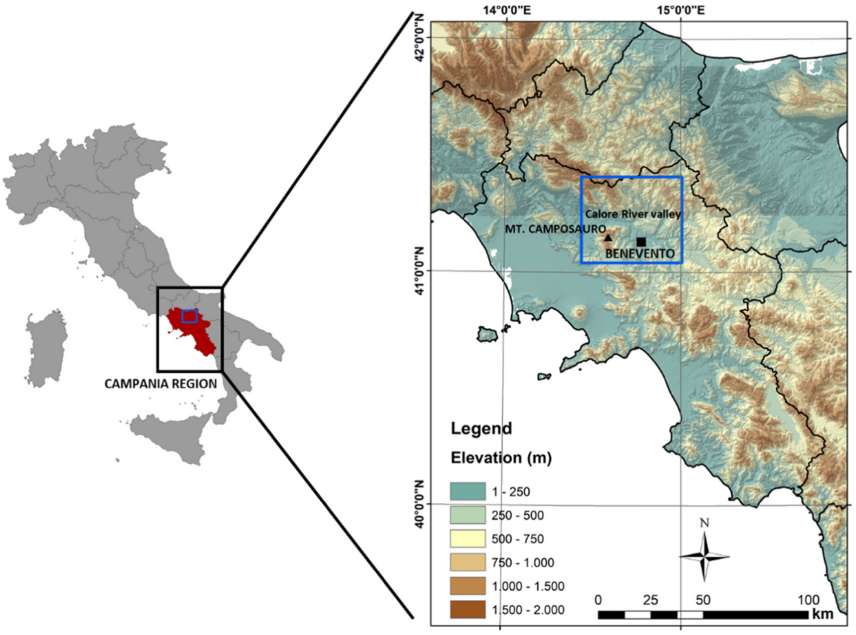

Fig. 1. Elevation map of the Campania region (Southern Italy) and overview of the study area (Benevento area – in the blue square). (Color figure online)

At regional scale, rainfall extremes are caused by atmospheric processes of very different characteristics and length scales. It is possible to identify three main mechanisms that generate maxima [5, 11]: (i) frontal systems, associated to baroclinic extratropical cyclones with a spatial domain greater than 10^4 km^2 and lifetimes greater than 12 h, (ii) convective systems with spatial domains less than 10^2 km^2 and lifetimes of several hours, (iii) "medicanes", from Mediterranean hurricanes, or TLC (tropical-like cyclones) that usually interest an area of 10^2–10^3 km^2 for several hours (~6–12 h, <24 h) with a combination of intense winds and heavy precipitation. The first two reported mechanisms

(i.e., convective and frontal) may also co-exist and one may trigger and influence the other in a complex way [12]. The latter represents a very rare [13] but strongly intense cause of extreme rainfall.

The focus area has an extent of about 2000 km^2 in the upper-eastern part of Campania region (see blue rectangle in Fig. 1), near the city of Benevento. The main river of the area is the Calore River flowing at the foot of the northern slope of Mt. Camposauro (1390 m a. s. l) that is the main relief of the area.

2.2 Rain Gauge Monitoring Networks and Available Rainfall Data

In Italy, the rain gauge monitoring network was controlled by the National Hydrographical Service (SIMN) for water management and scientific purposes until the late 1990s. The SIMN was also responsible for publishing hydrological annals, containing all the hydrological and rainfall observations in a year and some brief considerations, elaborations, and summaries.

However, after the end of the last century, the management of the ground-based network and rainfall data was progressively assigned to different regional agencies. In Campania, the maintenance and the development of the monitoring network was assigned to the Hydro-Meteorological Service of the regional Civil Protection Department, which also guarantees activities of supervision, alert and mitigation against flood and landslide risks generated by hydrometeorological events. In the transition from the management of the SIMN to the regional Civil Protection Department, the historical network (Fig. 2 – green squares) was partly abandoned and partly re-designed for the new functions, that are primarily directed towards civil protection purposes.

Currently, in Campania there are about 200 rain gauges operated by the regional Civil Protection Department (hereinafter, referred as CP network), with a mean coverage of one station per 70 km^2. However, the density of the network is quite uneven over the region: in the study area, we found 14 rain gauge stations in about 2000 km^2 that means the half of the expected number of stations. Moreover, these stations are distributed with a clear asymmetry that leaves the central portion of the area completely uncovered. Figure 2 shows the rain gauge stations in the study area with red triangles and a progressive code, with the prefix CP. Figure 2 also shows the rain gauges stations formerly managed by SIMN that have been either dismissed or re-placed.

In addition, there is an auxiliary network managed by the same regional Civil Protection Department but not still operationally used for the civil protection activities since its rain gauges have been installed at the beginning of 2015. These rain gauges are shown in Fig. 2 with blue circles and a progressive code with the prefix V. This auxiliary network has been designed to fill the well-known lack of rainfall data in mountainous sites [14, 15]: from Table 1 that reports some specifications of the rain gauge stations, it is possible to verify that all these rain gauges are indeed installed at an elevation above 350 m a. s. l.

Finally, beside these networks managed by the regional Civil Protection Department, there is another rain gauge network installed at the end of the 1990s and managed by the Regional Agrometeorological Service for the specific tasks of water management and support to agricultural, forestry and land policies and activities in the region [16, 17]. This network is made of 37 rain gauges distributed all over the region (on average:

one station per 380 km^2) but with a very uneven and irregular spatial distribution that reflects the peculiar purposes for which it has been designed.

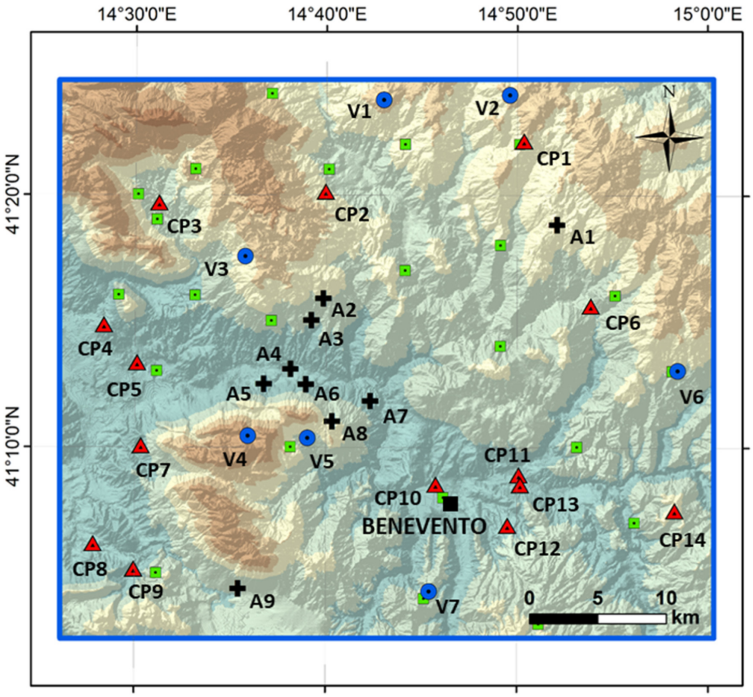

Fig. 2. Monitoring rain gauge networks managed by (i) the regional Civil Protection Department - in operation (CP – red triangles) and (ii) the Agrometeorological regional service (A – black crosses). The blue circles (V) represent an auxiliary network managed by the regional Civil Protection Department, not operationally used for civil protection. The green squares (with no assigned codes) are the rain gauges managed by the SIMN - in operation until the late 1990s. For the legend of the digital elevation model, please refer to Fig. 1. (Color figure online)

Figure 2 shows the nine rain gauge stations in the study area belonging to the agrometeorological network with black crosses and a progressive code starting with the letter A. These agrometeorological stations were installed to serve an area (i.e., the study area) where about the 50% of the regional wine is produced (i.e., Solopaca, S. Agata dei Goti, Torrecuso, Mt. Taburno) so that the number of stations in the study area is more than twice as expected and most of them (i.e., A2-A8) are in an area of 150 km^2 inside the zone of interest.

Table 1 provides a complete list of the rain gauge stations along with their spatial coordinates and elevation: in summary, in the study area, there are 14 stations managed by the regional Civil Protection Department, plus seven auxiliary stations and nine stations of the agrometeorological network.

Table 1. List of the rain gauge stations in the study area

Code	Name	Latitude (° N)	Longitude (° E)	Elevation (m)
CP1	Colle Sannita	41° 22′ 10.40′	14° 50′ 21.67″	777
CP2	Morcone	41° 20′ 9.90″	14° 39′ 57.63″	630
CP3	Cusano Mutri	41° 19′ 42.20″	14° 31′ 13.90″	364
CP4	S. Salvatore Telesino METEO	41° 14′ 51.49″	14° 28′ 22.09″	167
CP5	Sorgenti Grassano	41° 13′ 21.79″	14° 30′ 5.90″	52
CP6	Pago Veiano	41° 15′ 37.99″	14° 53′ 51.38″	259
CP7	Melizzano	41° 10′ 4.88″	14° 30′ 18.90″	190
CP8	S. Agata dei Goti Isclero	41° 6′ 11.08″	14° 27′ 50.29″	65
CP9	S. Agata dei Goti	41° 5′ 11.17″	14° 29′ 57.70″	153
CP10	Benevento	41° 8′ 33.78″	14° 45′ 44.65″	119
CP11	Paduli	41° 8′ 56.18″	14° 50′ 5.27″	130
CP12	Benevento METEO	41° 6′ 56.78″	14° 49′ 30.06″	236
CP13	Ponte Valentino	41° 8′ 32.58″	14° 50′ 9.67″	139
CP14	Rocchetta	41° 7′ 31.18″	14° 58′ 14.69″	670
V1	S. Croce del Sannio	41° 23′ 48.29″	14° 43′ 0.40″	827
V2	Castelpagano	41° 23′ 59.78″	14° 49′ 37.56″	819
V3	Cerreto Sannita	41° 17′ 35.37″	14° 35′ 45.39″	648
V4	Vitulano (Camposauro)	41° 10′ 28.33″	14° 35′ 55.44″	1124
V5	Vitulano	41° 10′ 23.75″	14° 39′ 2.12′	419
V6	Buonalbergo	41° 13′ 3.57″	14° 58′ 24.70″	432
V7	S. Leucio del Sannio	41° 4′ 19.90″	14° 45′ 24.14″	356
A1	S. Marco dei Cavoti	41° 18′ 50.88″	14° 52′ 5.92″	725
A2	Casalduni	41° 15′ 55.20″	14° 39′ 51.60″	482
A3	S. Lupo	41° 15′ 3.93″	14° 39′ 14.00″	346
A4	S. Lorenzo Maggiore	41° 13′ 7.60″	14° 38′ 8.40″	174
A5	Vitulano	41° 12′ 32.00″	14° 36′ 44.40″	96
A6	Paupisi	41° 12′ 31.50″	14° 38′ 56.80″	183
A7	Torrecuso	41° 11′ 51.70″	14° 42′ 19.00″	172
A8	Torrecuso	41° 11′ 3.50″	14° 40′ 19.00″	507
A9	Airola	41° 04’ ′ 25.73″	14° 35′ 26.02″	270

3 Rainfall Event Occurred on 14th–15th October 2015

This section describes the properties of the extraordinary extreme rainfall event (EEE) occurred on 14th–15th October 2015 in Benevento area. The descriptions are made for

evaluating the monitoring network efficiency in the detection of EEEs. An assessment of this efficiency is conducted considering the CP network.

In particular, the focus is on the efficiency of the current CP network that is operationally used for civil protection and represents the reference network for the hydrological extreme analyses in the region since it replaced the SIMN network. For the scope, Fig. 3 and Fig. 4 show the evolution of the rainfall spatial patterns obtained by using the inverse distance weighting (IDW) method for interpolating all the available rain gauge observations in the study area. However, only the CP network is displayed on the maps, to evidence how a coarse network may not detect the occurrence of an EEE. Moreover, Fig. 5 shows the 24 h accumulated rainfall computed by considering all the observations available from all the monitoring networks (on the left) in comparison with the 24 h accumulated rainfall measured only at the CP network (on the right). Further comments on this are provided in the following Section and in the Discussion and Conclusions Section.

3.1 Meteorological Description of the Event

On 14th October 2015, at about 8 pm, a mesoscale convective rainfall began to hit the study area in the southwestern-northeastern direction and, at 10:30 pm, reached an intensity up to 20 mm in 30 min at CP9 station (Fig. 3a) and up to 24 mm in 30 min at V4 station. In the subsequent hours (Fig. 3b-c-d), the center of the more intense rainfall proceeded slightly moving toward east and clearly increasing its intensity along the northeastern direction, then reaching 32 mm in 30 min at CP9 station, more than 40 mm in 30 min at A9 and V4 stations, and about 56 mm in 30 min at A6 station.

On 15th October at 12:30 am (Fig. 3e), the intensity reached 80 mm in 30 min at V4 station. This intensity is the highest that has ever been observed in Campania. At the same time, the intensities in the southwestern tail of the storm were already decreased, with a residual storm cell (that waned in the next 2 h as the main cell) observed at CP8 station with an intensity up to 34 mm in the same interval. Another cell developed around CP6 station where about 30 mm in 30 min were registered. Then, at 1 am, about 75 mm were measured in 30 min at A6 station while the other stations belonging to the agrometeorological network located in the center of the storm (i.e., A2, A3, A4, A5) observed intensities greater than 50 mm in 30 min. At the same time, the CP network observed the maximum intensity at CP6 station with a value of more than 30 mm in 30 min while at the other rain gauges no more than 15 mm in 30 min were measured, besides the active isolated storm cell at CP8 station.

On 15th October at 1:30 am (Fig. 4a), the rainfall intensity recorded by A6 station was above 60 mm in 30 min, while stations A2, A3, A4, A5, A7 and A8 recorded around 30 mm in 30 min. Rainfall in 30 min was around 50 mm at V4 station and above 30 mm at V5 station. At 2 am, A6 station recorded 45 mm in 30 min while the other stations in the center of the storm (i.e., A2, A3, A4, A5) observed values around 30 mm. Another cell with enhanced intensity developed at the northeastern tail of the storm, as registered by CP1 station, with about 30 mm in 30 min. The cell was detected by CP6 station with the same intensity.

In the time between 2:30 and 3:00 (Fig. 4c-d), the center of the storm moved in the southeastern direction with residual intensities around 30 mm in 30 min registered by the CP network (i.e., CP6, CP11, CP13) and by V6 station.

After 3 am, the rainfall persisted for more than ten hours with ordinary intensities.

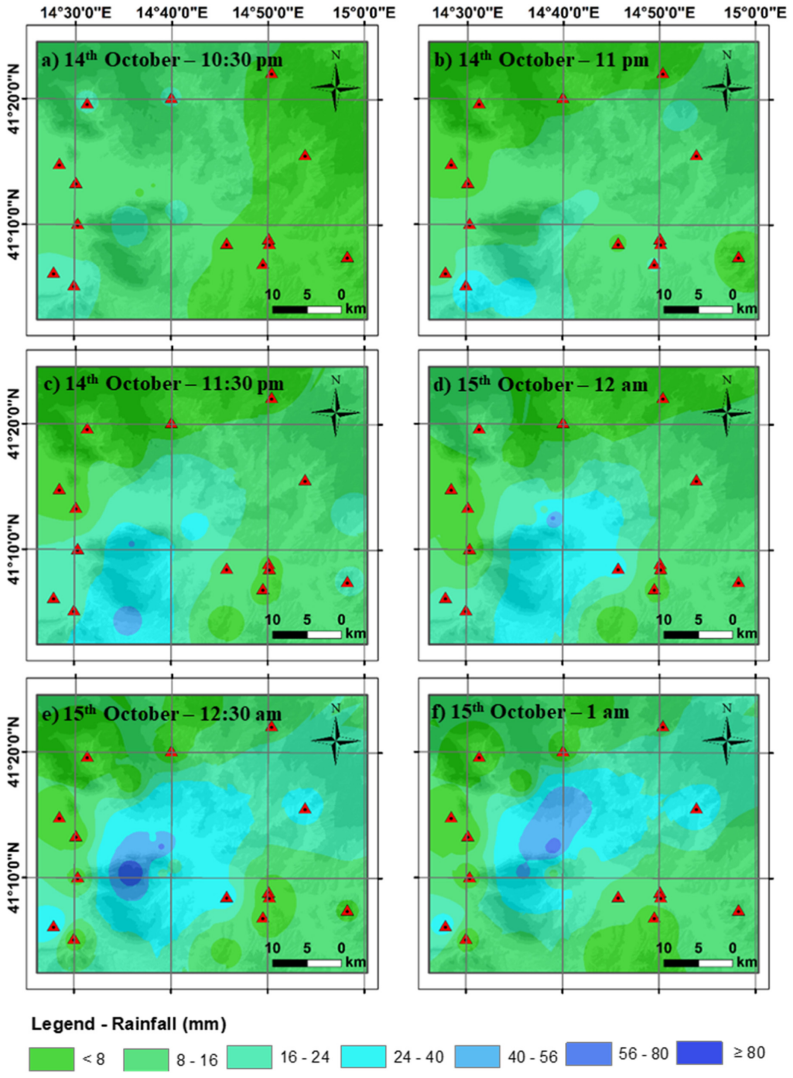

Fig. 3. Maps of the evolution of the event with rainfall aggregated into 30-min intervals. The red triangles are the rain gauges belonging to the CP network. (Color figure online)

The lifetime of the entire event was about 24 h. The 24 h accumulated rainfall values do not show a significative relation with elevation but a clear development along the southwestern-northeastern direction. Table 2 shows the 24 h accumulated rainfall values

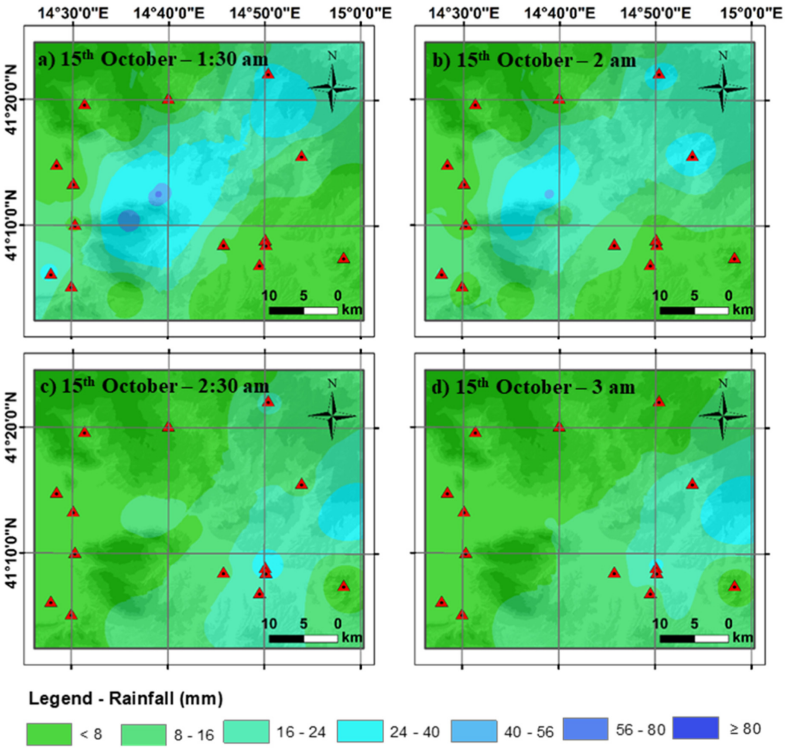

Fig. 4. Maps of the evolution of the event with rainfall aggregated into 30-min intervals. The red triangles are the rain gauges belonging to the CP network. (Color figure online)

at the stations that measured values close to and greater than 200 mm. Only two rain gauges of the CP network measured values close to 200 mm, but never greater than this value. Values even greater than 250 mm i.e., the lower threshold characterizing EEEs, were recorded at other sites. The two largest 24-h rainfall depths were 363.1 mm at V4 station and 415.4 mm at A6 station: the two stations were located along the same line oriented according the southwestern-northeastern direction. The two stations also recorded the highest rainfall depths ever observed in the region in 30 min: respectively, 80 mm and 75 mm.

Figure 5 compares the 24 h accumulated rainfall map retrieved by interpolating all rainfall data available (Fig. 5a) with the analogous map obtained by interpolating only at the CP rainfall data (Fig. 5b). The reconstruction of the rainfall patterns strongly depends on the observations available, and it is clear how a monitoring network, such as the CP network, too coarse with respect to the spatial properties of the rainfall pattern, is not able to assess the actual magnitude of the event and is not able to detect the occurrence of EEEs. These limitations can have severe impact of the reliability of long-term probabilistic predictions of extreme rainfall at regional scale [5].

Figure 5 also shows the characteristic lengths of the occurred phenomena compared with the size of the CP monitoring network. In particular, the EEE (24 h accumulated

Table 2. 24 h accumulated rainfall for values close to and greater than 200 mm.

Code	Name	Elevation (m)	24-h rainfall (mm)
CP6	Pago Veiano	259	201.0
CP8	S. Agata dei Goti Isclero	65	197.6
V4	Vitulano (Camposauro)	1124	363.1
V5	Vitulano	419	229.5
V6	Buonalbergo	432	199.8
A2	Casalduni	482	247.0
A3	S. Lupo	346	238.6
A4	S. Lorenzo Maggiore	174	267.6
A5	Vitulano	96	270.4
A6	**Paupisi**	**183**	**415.4**
A7	Torrecuso	172	229.6
A8	Torrecuso	507	222.0
A9	Airola	270	194.8

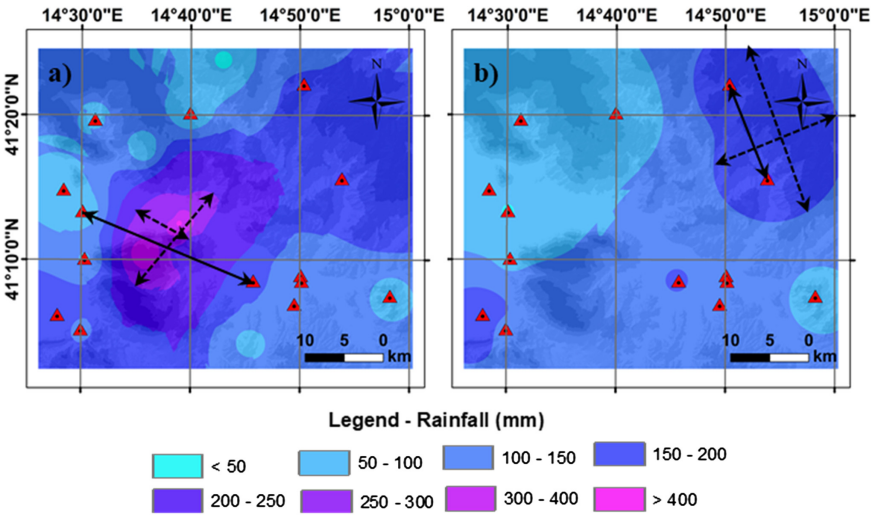

Fig. 5. Maps of the 24 h accumulated rainfall computed by IDW interpolation of **a)** all the stations and **b)** only the stations belonging to the CP network (red triangles). (Color figure online)

rainfall > 250 mm) was identifiable by an extent of about 9 km per 15 km (see the dashed arrows in Fig. 5a) that was not detected by a network made of rain gauge stations with a spacing of about 25 km in that specific zone (see the solid arrow in Fig. 5a). The

CP network detected just marginal fraction of the rainfall pattern, characterized by 24 h accumulated values larger than150 mm but smaller than 200 mm. This sub-event was located on the upper right corner of the study area and it was identifiable by an extent of about 17 km per more than 22 km (see the dashed arrows in Fig. 5b).

3.2 Statistical Description of the Event

Let consider the random variable, X, indicating the annual rainfall maxima in 24-h. According to the VAPI (VAlutazione delle PIene) project that provides the national reference procedure for flood hazard assessment in Italy [4], X can be modeled by the TCEV distribution, and its parameters can be regionally estimated through a three-level hierarchical procedure [18]. Then, the regional model is a simple model of homogeneous regions where parameters can be assumed constant at each level: at the first level, it deals with the estimation of the shape parameters of the distribution (i.e., skewness θ* and kurtosis λ*); at the second level, the scale parameter λ_1 is computed and, finally, at the third level, regression models for the mean (μ) estimation are provided, since the mean is strongly dependent from the elevation (z).

At first and second levels, the whole Campania region can be considered homogeneous, with the shape and scale parameters that assume unique values everywhere. Table 3 provides the values of θ*, λ* and λ_1 for the region, also valid for the study area. At the third level, the VAPI project considers six homogeneous sub-regions where the mean of the distribution, i.e., mean of the annual rainfall maxima in 24-h, can be computed by the following regression model with elevation, z (assuming d = 24 h):

$$\mu = \frac{\mu(I_0)d}{(1 + d/d_c)^{C-Dz}} \tag{1}$$

Table 3 also reports the parameters of Eq. 1 for the homogeneous sub-region A3, where the study area is located.

Table 3. Parameters for the regional analysis of rainfall extremes in the study area

θ^*	λ^*	λ_1	α	$\mu(I_0)$ (mm/h)	d_c (mm)	C	D (m)
2.136	0.224	41	4.688	117	0.0976	0.736	$8.730 \cdot 10^{-5}$

Equation 2 shows the TCEV cumulative distribution function (CDF, probability of not exceedance), whose parameters are specified in Eq. 3 as function of θ*, λ*, λ_1 and μ.

$$F_X(x) = exp\left[-\lambda_1 exp(-x/\theta_1) - \lambda_2 exp(-x/\theta_2)\right], x \geq 0 \tag{2}$$

$$\theta_1 = \frac{\mu}{\alpha}; \theta_2 = \theta^*\theta_1; \lambda_2 = \lambda^*\lambda_1^{1/\theta^*} \tag{3}$$

However, Pelosi et al. [5] proposed a new probabilistic model for annual rainfall maxima in 24-h, in regions where the presence of EEEs enhances the hazard. In these

regions, the at-site parameter estimation and the regional hierarchical approach have been replaced operationally by the definition of a support area around the monitoring stations, whose characteristic dimension has been estimated to be 20 km. This support area was employed to define the probability that an EEE (i.e., rainfall depths greater than 250 mm) occurs in any point belonging to that area. This probability is certainly more representative for the frequency assessment of EEEs than the probability estimated regionally in a point by using TCEV.

The cumulative distribution function of rainfall annual maxima in 24-h, above the threshold (x_0) of 250 mm, according to the new formulation becomes:

$$G_X(x) = 1 - p_E exp[(x - x_0)/\beta], x \geq 250 \quad (4)$$

where β is equal to 68 mm as reference national value while p_E varies regionally and it is equal to 0.1 in the study area [5].

Table 4 shows the probability of exceedance expressed through the definition of return period (Eq. 5), of the two highest 24 h accumulated rainfall depths registered at V4 and A6stations during the 14th–15th October 2015 event. Those values represent annual rainfall maxima in 24-h for each station in year 2015.

$$T = \frac{1}{P[X > x]} \quad (5)$$

Table 4 compares the return periods of the observed maxima obtained by using the TCEV model with the return periods obtained using the model proposed by Pelosi et al. [5]. It is clear how the TCEV tends to dramatically underestimate the probability of exceedance (i.e., to overestimate return periods) of the event in all the station where EEEs are observed.

Table 4. Return periods associated to the occurred EEE

Code	Name	24-h rainfall (mm)	μ (mm)	T (years) TCEV	T (years) Pelosi et al. [5]
V4	Vitulano (Camposauro)	363.1	83.6	10809	52
A6	Paupisi	415.4	53.2	21906106	112

4 Discussion and Conclusions

The availability of long time series of hydrological data has been always considered a critical aspect for providing reliable estimates of the frequency distribution of extremes, such as rainfall maxima and floods [19]. This aspect is even more relevant in studies aiming at assessing signals of climate change effects in hydrological processes [20].

Mapping the frequency distribution of rainfall maxima in a region is often essential for predicting flood extremes, since flow data are very poor and not representative of

the catchment response at all spatial scales of interest. It is also important to predict hydrological hazards generated at hillslope or small catchments scales, such as shallow landslides and debris flows [21, 22].

However, when dealing with regional analysis of rainfall extremes, the spatial density of the rainfall network can be as much important as the length of the time series. Indeed, the spatial scale of the monitoring systems should be comparable with the spatial scale of the rainstorm cells generating the related hydrological hazards. The spatial scales of a monitoring systems can be described by the well-known scale triplet [1]: i) the spacing between the measurements; ii) the support i.e., the spatial dimensions of the measurements; iii) the extent i.e., the dimension of the region covered by the monitoring system. In the case of rainfall network, the support corresponds to dimension of the rain gauge bucket and thus can be considered punctual, while the spacing is the average distance between adjacent rain gauges. If the rainstorm cells generating the extremes are smaller than the rain gauge spacing, the number of missed events in a region can be important over a long period of time. This issue was theoretically proved by Pelosi et al. [5] when looking at extraordinary extreme events (EEEs) in Mediterranean Regions, which probability of occurrence can be dramatically underestimated when the frequency distribution are retrieved by means of regional analysis that are based on time series of rain gauge networks with a spacing much larger than 20 km, which is the characteristic dimension of rainstorm cells producing relevant hydrological hazards, such as flood and shallow landslides.

This paper provides a clear example about how the occurrence of a EEEs and their actual magnitude can be completely missed if observed with a rain gauge network with a common spatial spacing. The examined event produced intense sheet and channelized flow along slopes as well as debris transport, causing severe losses at the toe of a massif located in the central portion of the Calore river valley, in Benevento province of Southern Italy [23]. The rainfall data detected by the automatic rain gauge network operated for early warning of hydrological hazards could not justify the physical evidence of an intense flow and debris transport along slopes, especially if compared with what was observed in adjacent similar slopes, which were apparently subjected to the same amount of rainfall. The actual magnitude of the event and its EEE features could be retrieved by only integrating data of other rain gauges operating in the surroundings.

This study also evidences how the frequency of the event could be completely mislead if it is computed with frequency distributions retrieved with the traditional regional analyses, which do not account for the mismatch between the spacing of the rain gauges and the spatial scales of the EEEs.

Pelosi et al. [5] proposed a theoretical framework for overcoming the scale mismatch for EEEs, characterized by return periods larger than 50 years and causing dramatic effects from the hillslope to the small catchment scale (i.e., of the order of 1–500 km^2). The return period estimated for the examined event would be of thousands of years according to the reference regional frequency analysis, while of the order of 50–100 years according to Pelosi et al. [5] probabilistic model.

This study also outlines the importance of having rain gauge networks designed with optimal criteria [24] and, even better, auxiliary distributed monitoring systems, such as meteorological radars, which eliminate the issue of the mismatch in the spatial

spacing of the point rainfall observation, with a spatial support scale (i.e., the radar image resolutions) smaller than the spatial dimensions of the rainstorm cells of interest. However, dense rain gauge networks are still fundamental for an effective assessment of the rainfall maps from radar reflectivity maps [25].

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