Multi-instrumental Analysis of the Extreme Meteorological Event Occurred in Matera (Italy) on November 2019

Virginia Coletta[1,3(✉)], Alessandra Mascitelli[2], Alessandra Bonazza[4], Alessandro Ciarravano[3], Stefano Federico[3], Fernanda Prestileo[3], Rosa Claudia Torcasio[3], and Stefano Dietrich[3]

[1] Geodesy and Geomatic Division, University of Rome "La Sapienza", Rome, Italy
virginia.coletta@uniroma1.it
[2] Department of Geosciences, University of Padova, Padova, Italy
alessandra.mascitelli@unipd.it
[3] CNR-ISAC, The Institute of Atmospheric Sciences and Climate, Rome, Italy
[4] CNR-ISAC, The Institute of Atmospheric Sciences and Climate, Bologna, Italy

Abstract. Most of the municipalities of the Italian territory are located in areas of high hydrogeological risk, i.e. exposed to flooding and landslides. Consequently, part of the existing cultural heritage on the national territory is located in areas subject to flood risk, which compromises the accessibility, preservation and integrity of cultural heritage. As an example, we consider a single flood event that occurred in southern Italy on November 11th and 12th, 2019, which mainly affected the city of Matera and its surroundings. This episode appears to be significant for the violence of the phenomenon that led to considerable quantities of water flowing inside the city, a UNESCO World Heritage Site, causing damage to buildings, including historical ones. The event has been analysed using both meteorology and geomatic technologies, to have an overview on spatial and temporal evolution of the phenomenon. Global Navigation Satellite System Zenith Total Delay (GNSS-ZTD) data obtained by receivers located around the city of Matera, were compared with measurements from ground-based devices (i.e. weather stations), Numerical Weather Prediction (NWP) models, and ERA5 reanalysis. To assess the extent of the flood and show the flooded areas, the images provided by the Sentinel-1 Synthetic Aperture Radar (SAR) were used, isolating and analyzing the images captured before and after the event. Finally, through a digital terrain model, developed using Agisoft Metashape software from satellite images, the morphology of Matera was recreated to evidence the areas of accumulation of water. Once all the information was obtained, the data correlated showed an overall view of the event.

Keywords: Photogrammetry · GNSS · Meteorology · Cultural heritage · Flooding

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1 Introduction

In recent years there are increasingly violent and frequent flood events that cause physical and economic damage to entire countries and cities. Cultural heritage is not unaffected by these hazards that compromise their integrity and appropriate conservation [6,9,14]. In recent years, several World Heritage Sites have been exposed to high-intensity flooding events that have caused the loss of inestimable assets or have simply led to their closure. Technological advances are bringing great support in the study of floods. The advent of satellites has allowed post-event study without coming into direct contact with the area by evaluating the first estimate of damage and possible emergency plans to save the population [1,2,11]. Increasingly accurate weather models permit short-term forecasts with high accuracy. These can be useful for the creation of evacuation and risk prevention strategies for the protection of people and the safety of cultural heritage [20,30]. In this study, the flood event that occurred in the town of Matera, Basilicata Region (Italy), on November 11th and 12th, 2019 is examined with the aim of assessing the importance of the meteorological event that affected the city. The historic centre of Matera is characterised by a rupestrian habitat, consisting of dwellings and places of worship dug into the soft calcareous stone and open to the free air with a built part, known throughout the world as the *"Sassi di Matera"* [10]. The *Sassi* were inscribed on the UNESCO World Heritage List in 1993 after a long process of urban and socio-cultural recovery [19]. In this investigation, interdisciplinary work was carried out including a combination of meteorological methodologies and geomatic technologies. In this sense, in order to analyse the event as comprehensively as possible, a multi-instrumental approach was performed. The meteorological aspect was studied using a dataset from different techniques (GNSS, NWP models, ERA5 and weather station) described more in depth in the following section. Assessing the expansion of a flood event through satellite imagery is possible with synthetic aperture radar (SAR) spectral satellites, that are not dependent on weather and time conditions [35]. In recent years, images provided by SAR satellites are used very frequently for the construction of flooding maps during or immediately after the flood event [3,13,27,36]. In this paper, we have used the images provided by the Sentinel-1 satellites. These satellites are part of the Sentinel family developed by the European Space Agency (ESA) to support the operational requirements of the Copernicus program. The Sentinel-1 mission is composed of two satellites that provide continuous images (day, night, and in all weather conditions) [38]. For the processing of these images was used the Google Earth Engine (GEE) platform, this platform provides a very rich data set and allows their elaboration in remote accelerating the process [12,16,26].

Two different digital elevation models (DEMs) have been considered to better evaluate the pathways and areas of water accumulation. The first one is a digital terrain model (DTM), the WWF HydroSHEDS with lower spatial resolution, present in the GEE dataset having quasi-global scale [40]. The second one is a digital surface model (DSM), with high spatial resolution, that is developed only for the historical centre of Matera [28].

2 Case Study: Matera the City of *Sassi*

The city of Matera (coordinates 40° 40' N 16° 36' E; altitude 401 m a.s.l.; area 392.09 km^2), located near the Ionian coast in the North-Eastern corner of the Basilicata Region (Italy), is considered one of the oldest cities in the world, a veritable open-air museum that has been continuously inhabited for 7000 years, bearing witness to the presence of man from the Palaeolithic to the present day [18,19,32–34]. In the terraced plateaus formed by limestone, the Murge of Lucania and Apulia, the gravines are a spectacular example of erosion valleys, geological features rich in carsic phenomena (underground water circulation, dolinas, gorges, caves), used for this purpose since the earliest times by humanity. While part of the town spreads out across the Murgia plateau, the famed *Sassi di Matera*, the old center of the town, comprises cave dwelling built on and dug into the side of the *Gravina Gorge* which drops vertiginously away beneath it (Fig. 1).



Fig. 1. View of the *Sassi di Matera*: the *Sasso Barisano* with the *Civita* and the Cathedral (photo by Fernanda Prestileo©, May 2018)

The *Sassi di Matera*, or cliffs and stones, are an architectural and urban ensemble of exceptional quality, a living system built in the geological material itself, the *Gravina Calcarenite* (a soft calcareous rock known locally as "tuff", which is of Upper Pliocene-Pleistocene age, easy to excavate while ensuring high stability) along the slopes of a deep and grandiose *Gravina Gorge* [32–34]. Over the centuries, the slopes of the *Gravina of Matera* were excavated by man, drilled and sculpted to create tunnels, cisterns and underground architectural environments. The excavated materials, cut into quadrangular "tufa" blocks, were used to build dry walls, terraces, roads and stairways in an architecture that responds perfectly to the climatic conditions, composing an original urban fabric. The city develops vertically on the two natural amphitheatres of *Sasso Caveoso* and *Sasso Barisano*, with the *Civita* in the centre. The dwellings carved into the rock face with deep underground chambers open up to the outside with terraces and hanging gardens. An extraordinary and prolonged example of symbiosis between the natural site and human intervention, like many others in the Mediterranean Basin and the Near East, the

Sassi find their originality in the ability to create architecture with few means and sustainable use of available resources. Also used in modern times as dwellings in which people and animals often lived together, in conditions of extreme degradation and poverty until after the Second World War, the *Sassi*, following a national law, were subjected to an operation of eviction for reasons of health and hygiene, which from the 1960s onwards saw the relocation of the population (about 15,000 people) in accommodation built in the new districts of the city. Thus the *Sassi* were marked in Italy as one of the "national shames" of the South. The *Sassi* so remained a mysterious and fascinating historic centre, uninhabited and abandoned until the 1970s, when a slow but important programme of urban recovery and restoration of the houses and prestigious places of worship, many of which are adorned with prestigious but much-deteriorated pictorial wall decorations from the early Middle Ages (there is evidence of Longobard, Byzantine and Benedictine art), was initiated by illuminated citizens and experienced Lucanian professionals [18,19]. This long and complex process of urban and socio-cultural recovery allowed the *Sassi di Matera* to be included in the UNESCO World Heritage List in 1993, even amidst the incredulity and scepticism of some of the local population. From that date onwards, Matera will no longer stop its process of urban recovery and socio-cultural enhancement, with important benefits in the economic sector, especially tourism, which sees the proliferation of accommodation facilities in the *Sassi*. The continuous restoration of the main monuments in and around the city, as well as the increased hotel accommodation, means that it is even more visited by tourists from all over the world. Another important recognition, further proof of this unstoppable process of redemption, was Italy's nomination of Matera as European Capital of Culture in 2019 thanks to its rich history and cultural diversity [18].

3 Data and Methods

3.1 Dataset Description

The first technique applied is GNSS (Global Navigation Satellite Systems), which defines all the constellations of artificial terrestrial satellites for positioning and navigation. In this section we will focus on the added value that this technology brings to the meteorological field [8,23,25,31], referring essentially to the tropospheric delay parameter, Zenith Total Delay (ZTD), and to the Precipitable Water Vapor (PWV) [7,21,24] content derived from it [4,17,22]. In this specific case study GNSS data, from November 8th to 15th, 2019 referred to 11 geodetic receivers located around Matera (Fig. 2) were processed.

To compute GNSS-ZTD values, starting from dual-frequency observational files (RINEX Version 3 format), a multi-constellation PPP processing [37] was applied by goGPS software [15,29], using precise products provided by Center for Orbit Determination in Europe (CODE) and applying ionosphere-free combination to estimate GNSS-ZTD values for each epoch, by daily processing sessions. The conversion from GNSS-ZTD to GNSS-PWV was carried out using data from the empirical model GPT (Global Pressure and Temperature) [5].

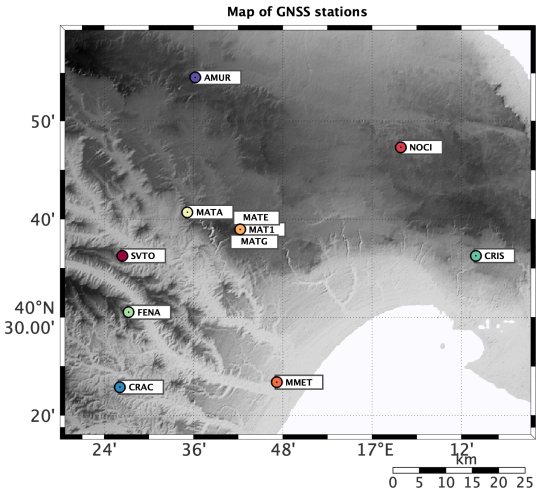


Fig. 2. GNSS receivers location around Matera (Table 1)

Table 1. Data features

Technique	Box latitude	Box longitude	Source
GNSS	$39N < \varphi < 41N$	$16E < \lambda < 18E$	Kindly provided by GReD srl
ERA5	$39N < \varphi < 43N$	$10E < \lambda < 20E$	https://cds.climate.copernicus.eu
Rain gauge	$\varphi = 40.64N$	$\lambda = 16.70$	Civil Protection Department

In order to compare our results with a renown dataset, ERA5 has been employed. ERA5 is the fifth generation of meteorological reanalyses issued by ECMWF. Reanalysis combines the background field, provided by the IFS (Integrated Forecasting System) model, with observations to give the best estimate of the atmospheric state. ERA5 dataset offers hourly estimates of a large number of atmospheric, land and oceanic climate variables. The data cover the whole Earth and resolve the atmosphere in the vertical using 137 levels from the surface up to a height of 80 km. The horizontal resolution of the model used in ERA5 is about 30 km. For this paper, we used the following parameter of ERA5 reanalyses: Total Column Water Vapour (TCWV) [kg m^2], which represents the total amount of water vapour in a column extending from the surface of the Earth to the top of the atmosphere (i.e. the area-averaged value for a grid box).

To assess the extent of flood areas, in this work, images captured by the Sentinel 1 satellites were used. The Sentinel-1 mission comprises a constellation of two satellites in polar orbit, operating day and night performing C-band synthetic aperture radar imaging, allowing them to acquire images regardless of weather and time conditions. Sentinel-1A and Sentinel-1B satellites share the same quasi-polar heliosynchronous orbit but are 180° out of phase; a cycle for one satellite lasts 12 days, considering both is 6 days. Sentinel-1 satellites are equipped with a C-band synthetic

aperture radar that supports dual-polarization operations including four different choices: HH, VV, HV, VH. The main acquisition modes are Interferometric Wide swath (IW) and Wave mode (WV), the first is the default mode for acquisition on the Earth's surface and meets almost all service requirements, the second is used in open sea [38]. To assess flooded areas the Interferometric Wide swath has been used as an acquisition mode, which has a spatial resolution of 5×20 m, with VH polarization, this is widely suggested for flood mapping, since it is more sensitive to changes on the Earth's surface. The images captured by the Sentinel 1 satellites were not downloaded but processed directly on the online platform Google Earth Engine (GEE) in which you can work on the images directly in the cloud. GEE has an extensive library and for processing, it is possible to use the programming languages Javascript and Python.

Two different digital elevation models (DEMs) have been considered to better evaluate the pathways and areas of water accumulation. The first one is a digital terrain model (DTM), the WWF HydroSHEDS with lower spatial resolution, present in the GEE dataset having quasi-global scale [40]. The second one is a digital surface model (DSM), with high spatial resolution, that is developed only for the historical centre of Matera [28].

3.2 Operative Workflow

The operational workflow adopted was summarized in Fig. 3.

Different techniques and methodologies were adopted to provide a comprehensive analysis of the flood event studied. Moreover, the techniques applied in this case study provided an overview of the event, integrating satellite and ground-based information and facilitating a survey of both the state of the atmosphere and the flood condition.

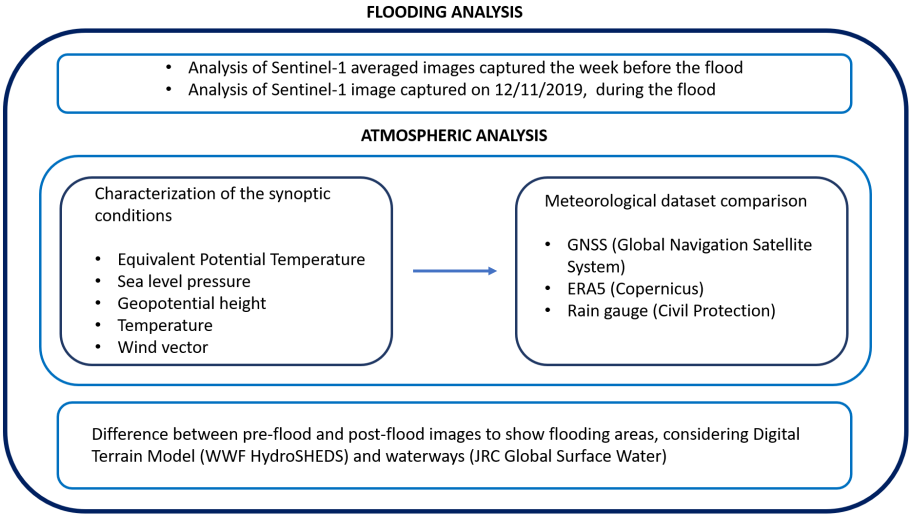


Fig. 3. Operative workflow

4 Results and Discussion

4.1 Synoptic Conditions of the Matera Case Study

To characterize the synoptic conditions of the Matera case study we used the ECMWF operational analyses at 00 UTC on 12th November 2019 (Fig. 4). The surface map shows a low pressure (994 hPa) over the southern Tyrrhenian Sea, between the Italian mainland, Sardinia and Sicily. With this baric situation, winds are advected from the Ionian Sea towards Calabria and Basilicata Regions, bringing warm and unstable air masses over southern Italy. This is shown by the equivalent potential temperature, which is larger than 330 K over the Ionian Sea. Also, surface winds (10 m above the surface) in this sector are sustained, being larger than 20 m/s.

At 500 hPa (Fig. 4.b) it is apparent a deep wave trough, extending from polar latitude towards the Central Mediterranean Sea. The trough developed a cut-off downwind of the Atlas Mountains, which is over Tunisia at the time of Fig. 4.b. The cut-off determines a diffluent flow over southern Italy, which favours the sustainment of convection. An important ingredient of the Matera case is the atmospheric river of large water vapour values advected from the tropical latitudes over the Central Mediterranean Sea, especially towards Calabria and Basilicata. The storm circulation conveyed considerable amounts of water vapour over southern Italy determining favourable humidity conditions to trigger and sustain the convection at all tropospheric levels.

So, the meteorological analysis of the Matera case shows that the event occurred in a favourable synoptic environment characterized by a cyclone evolving into the Mediterranean Sea, reinforced by the interaction between the atmo-

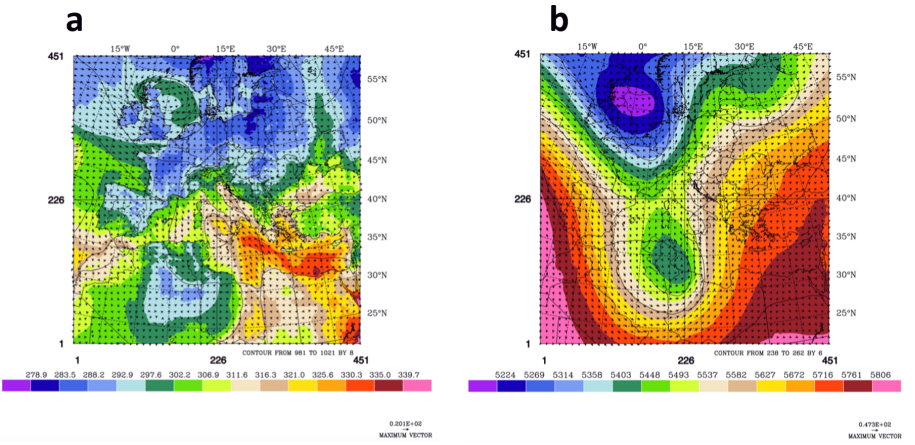


Fig. 4. a) Equivalent potential temperature (filled contours, [K]), sea level pressure (black contours, [hPa]), wind vector [m/s] at 19 m above the surface; **b)** Geopotential height (filled contours, [m]), temperature (black contours [K]), wind vector [m/s] at 500 hPa

spheric flow and the Atlas Mountains. The circulation close to the surface advected warm and unstable air masses over Italy forcing the development of convection. In addition, the circulation at mid and high tropospheric levels conveyed a water vapour plume from tropical latitudes towards the Mediterranean.

4.2 Meteorological Dataset Comparison

In order to characterise the phenomenon identified as a case study, the trends of the GNSS-ZTD parameter were examined with specific attention to an area including the city of Matera (Fig. 2). The whole dataset is internally consistent, indicating that the convective event affected the entire area covered by the receiver network; Fig. 5, indeed, shows the maximum peak of the week during the day of November 12th, followed by a sudden decrease of the parameter.

At this point, moving to a more local level, a single receiver (closest to the event) was analysed. In this case, the analysis of the observations of the meteorological variables was carried out mainly by direct comparison on a weekly dataset of the GNSS-PWV pattern, referred to the GNSS receiver located in Matera (MATE), with the data recorded by a nearby rain gauge. Results, given in Fig. 6, show excellent consistency between the two sets of data, also highlighting how the extreme event under study is immediately identifiable as a function of both the amount of GNSS-PWV and the precipitate rate.

A further step was made in order to compare the observed data with the ERA5 one. In this case, as previously mentioned, a map containing at each pixel the corresponding ERA5-TCWV (Total Column Water Vapour) value, at the time of the event (7.00 UTC), was plotted. From Fig. 7.a it is clear the agreement between the two sets of data that, at the Matera coordinates, show an ERA5-TCWV of comparable amount with the observed GNSS-PWV.

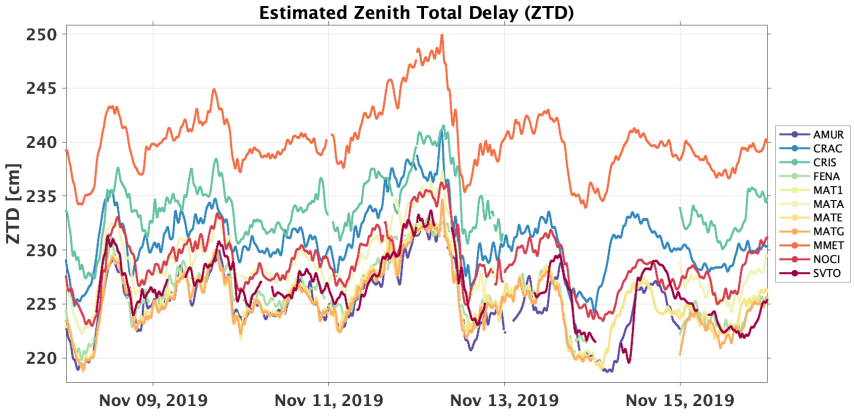


Fig. 5. GNSS-ZTD from November 8th to 15th, 2019 referred to 11 geodetic receivers located around Matera

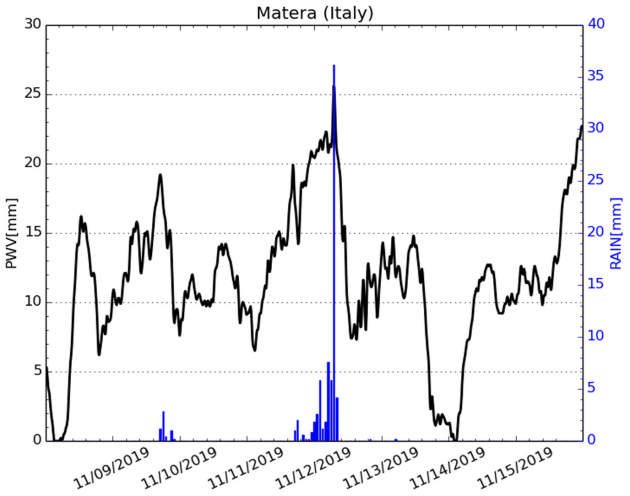


Fig. 6. Weekly comparison between GNSS-PWV at MATE receiver and rain data from a close weather station

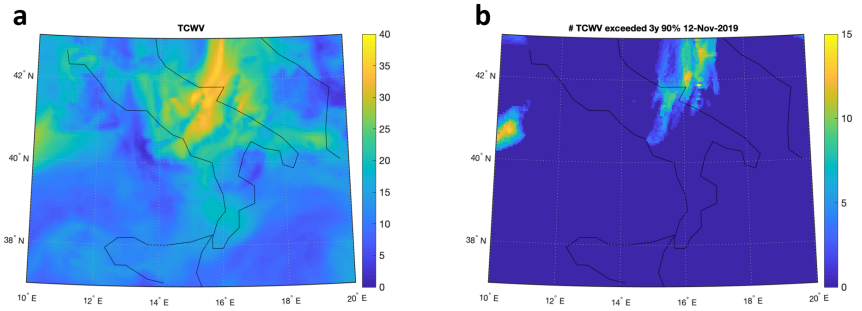


Fig. 7. a) Amount of ERA5 Total Column Water Vapor (TCWV) at the time identified by peak of GNSS-PWV and of rain gauge: 7.00 UTC of November 12th, 2019; **b)** How often on November 12th, 2019 the ERA5 Total Column Water Vapor exceeded the 90th percentiles computed on three years (2018–2020)

Finally, at the end of this analysis, the number of times on 12th November that the 90 percentile calculated over the three-year period 2018–2020 was exceeded was plotted for each pixel. As can be seen from Fig. 7.b, the event that took place in southern Italy is not an ordinary case study and is therefore certainly interesting from the point of view of analysing extreme weather events.

4.3 Flooding Areas

In order to assess the extent of flooded areas as a first step the Sentinel 1 images were imported to GEE and the area of interest was cropped. As mentioned earlier the IW mode with VH bias was considered. An approach was chosen that shows

the change between two images collected on different days, before and after the flooding event that occurred on 11th November 2019. In this case, the satellite flew over the area of interest on 6th November (Fig. 8.a) and 12th November (Fig. 8.b).

Different pre-processing steps would need to be performed before using the images: noise removal, radiometric calibration and terrain correction; but on GEE the available images are already pre-processed. We have operated only on the smoothing filter to reduce the speckle effect associated with radar images. In order to evaluate the change that occurred between the two temporal instants in which the images were acquired, the colour difference between two corresponding pixels, i.e. including the same portion of terrain, was considered. High values (bright pixels) indicate a high change, low values (dark pixels) indicate a minimal change. Several additional datasets were used to eliminate possible interpretation errors. The JRC Global Surface Water dataset is used to mask all areas covered by water for more than 10 months per year. The dataset has a resolution of 30 m and was last updated in 2018. To remove areas with a slope greater than 5%, a digital elevation model (WWF HydroSHEDS) was chosen, based on SRTM data, and has a spatial resolution of 3 arc-seconds, available on GEE. The analysis has shown, in accordance with meteorological data, that the southern area of the Basilicata Region has been severely affected by this event. Focusing on the city of Matera we can see that the flood has mainly affected the area north-east of the city, where "The Murgia National Park" is located, added to the UNESCO World Heritage List in 1993, creating numerous flood areas, blue areas in the (Fig. 9). On the other hand, there are no particular accumulations of water in the historical part of the city the *Sassi*. In order to investigate this phenomenon, a DSM with a very high spatial resolution, equal to 0.5 m, was used, relative only to the historical centre of Matera [28]. The area is morphologically very complex, being composed of erosive inci-

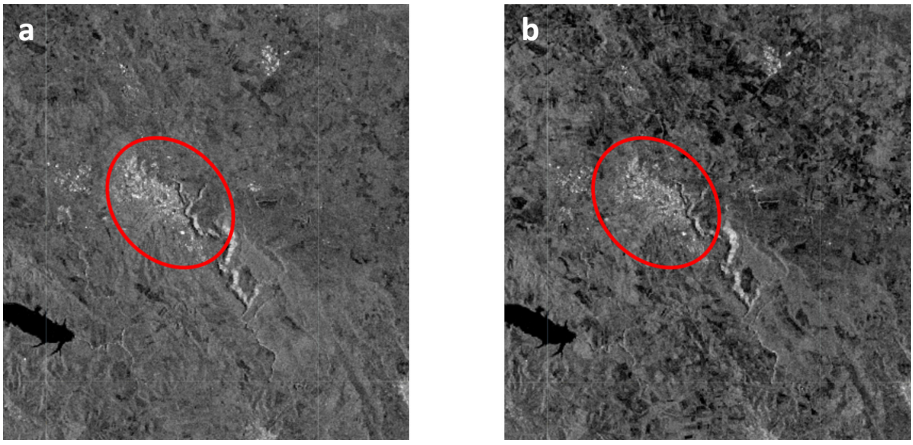


Fig. 8. a) Image captured by Sentinel 1 on 6th November 2019, Before Flooding, in IW/VH mode; **b)** Image captured by Sentinel 1 on 12th November 2019, After Flooding, in IW/VH mode

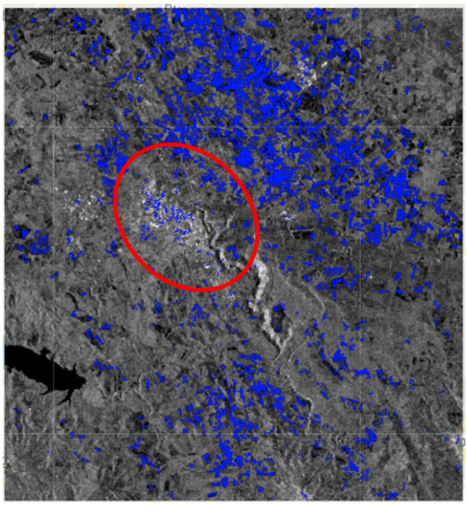


Fig. 9. Flooding Areas in blue, obtained from the color difference between the pixels of the images captured by Sentinel 1 before and after the flood event (Color figure online)

sions similar to canyons, typical carsic morphologies of the Murgia (Fig. 10). This particular morphology has contributed to generate a flow of water that has flowed inside the archaeological areas (Fig. 11), without creating areas of accumulation, exposing the heritage present to very strong and sudden stress and consequently to significant damage.



Fig. 10. View of the *Sassi* Area showing the particularity of morphology (photo by Fernanda Prestileo©, May 2018)



Fig. 11. View of a street of the *Sassi* Area flooded during the event examined. Image is taken from the newspaper *Quotidiano Nazionale* of the day 12/11/2019 [39]

5 Conclusion

The aim of this work was to analyze, using an interdisciplinary approach, the flood that affected the Region of Basilicata (Italy) in November 2019, especially the city of Matera. This event was significant both for its meteorological characteristics, which are not ordinary and for the uniqueness of the site involved. The flood event has been studied by combining geomatic technologies with meteorological methodologies in order to have a complete description of the event. From the meteorological point of view a multi-instrumental approach has been performed using datasets from different techniques (GNSS, NWP models, ERA5 and meteorological station). In this specific case study, GNSS data, from November 8th to 15th, 2019, referred to 11 geodetic receivers located around Matera were processed. The meteorological analysis shows that the event occurred in a favourable synoptic environment characterized by a cyclone evolving towards the Mediterranean Sea, reinforced by the interaction between the atmospheric flow and the Atlas Mountains. In order to characterize the phenomenon identified as a case study, the GNSS-ZTD parameter trends have been examined with specific attention to an area including the city of Matera. The entire dataset is internally consistent, showing the maximum peak of the week during the day of November 12th, followed by a sudden decrease of the parameter. Moving to a more local level, a direct comparison was made on a weekly dataset of the GNSS-PWV pattern, referred to the GNSS receiver located in Matera, with the data recorded by a rain gauge nearby, showing a very good consistency between the two datasets. Finally, the number of times the 90th percentile calculated over the three-year period 2018–2020 was exceeded on November 12th, was plotted

for each pixel, and it was found that the event had characteristics out of the ordinary. To assess the extent of the flood, images transmitted by the Sentinel-1 SAR satellites were used. By comparing the images from the days immediately before the flood with the images transmitted by the satellite the days immediately after the flood, it was possible to highlight the flooded areas. In total agreement with the meteorological data, it has been highlighted that the flooding has affected the southern area of the Basilicata Region. In particular, in the area of Matera the most flooded areas are located in the North-Eastern part of the city, where "The Murgia National Park" is located. Instead, in the historical part, characterized by morphologically very complex areas, the water has run in the *Sassi* damaging significantly cultural heritage unique in the world. In the future, more resolute digital terrain models will be used, to improve the analysis of satellite images. In addition, hydrogeological studies will be conducted, in order to project possible protections and increase the resilience of the city.

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