A paradigm of extreme rainfall pluvial floods in complex urban areas: the flood event of 15 July 2020 in Palermo (Italy).

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Abstract. In the last years, some regions of the Mediterranean area are witnessing a progressive increase in extreme events, such as urban and flash floods, as a response to the increasingly frequent and severe extreme rainfall events and their ground effects, which are often exacerbated by ever-growing urbanization. In such a context, the traditional defense of urban areas, which are usually based on urban drainage systems designed without regard to the impacts of urbanization and climate change on natural systems, may not be sufficient to deal with the risk deriving from the occurrence of such events.

This study focuses on a very recent and particularly intense urban flood that occurred in Palermo on 15 July 2020 that represents a perfect example of extreme rainfall pluvial floods in a complex urban area that many cities, especially in the Mediterranean region, have been experiencing in recent years. A conceptual hydrological model and a 2D hydraulic model, particularly suitable for simulations in a very complex urban context, have been used to simulate the event. Results have been qualitatively validated by means of crowdsourced information and satellite images.

The experience of Palermo, which has highlighted the urgent need for a shift in the way of managing stormwater in urban settlements, can be assumed as a paradigm of management of extreme rainfall pluvial floods in complex urban areas. Although the approaches and the related policies cannot be identical for all cities, the modeling framework here used to assess the impacts of the event under study and some conclusive remarks could be easily transferred to other and different urban contexts.

1 Introduction

Natural hazards, such as floods and flash floods, have gone up to unprecedented levels in several parts of the globe during the last decades (Andersson-Sköld and Nyberg 2016; Gariano and Guzzetti 2016; Hoeppe 2016; IPCC 2019; Jia et al. 2019; Messeri et al. 2015). With reference to urban floods, this increase has been often attributed to a combined effect of increasing urbanization and intensification of rainfall extremes due to climate change (Arnone et al. 2018; Easterling et al. 2000; Held and Soden 2006; IPCC 2019; Pumo et al. 2017; Pumo et al. 2019).

Many studies (e.g., Jones et al. 2010; Lenderink and Van Meijgaard 2008; Westra et al. 2014) have demonstrated how atmospheric temperature strongly influences extreme rainfall intensity, due to the increased atmospheric moisture-holding capacity of warmer air that implies more water availability for rainfall process under warmer temperatures. This strong linkage between temperature and precipitation extremes has been observed also in the Mediterranean region (Drobinski et al. 2018; Pumo et al. 2019; Pumo and Noto 2021), which is referenced as a primary hotspot of climate change (Giorgi 2006), and is the cause of more and more frequent and severe extreme precipitation events over the last decades (Sheffield and Wood 2008; Tramblay and Somot 2018). One of the main consequences of such changes is an increasing in frequency and magnitude of urban and flash floods in the Mediterranean region and especially all over Italy (Faccini et al. 2018), where about fifty events have caused fatalities in the last twenty years. In particular, Sicily is among the most affected areas of the Italian peninsula with 69 victims in between 2008 and 2018 (Trigila and Iadanza 2018). On the one hand, the combination of geographic position, climate, and morphology of the island causes rainfalls originating from the interaction between steep orography on the coasts and winds carrying humid air masses from the Mediterranean Sea, especially between the end of the summer and the fall. On the other hand, the ground effects of the more and more severe and frequent extreme precipitation (Arnone et al. 2013; Cipolla et al. 2020; IPCC 2019; Treppiedi et al. 2021) are further exacerbated, in many areas of the region, by the ever-growing urbanization.

The increasing severity of flooding events is demonstrated by the analysis of extreme events that have occurred in Sicily over the last five years, some of which are described in the following. On 1 October 2015, about 75 mm of rainfall with an intensity peak of about 65 mm/h, flooded the city of Catania, prompting the intervention of the Civil Protection Department to drain the streets with sump pumps. In November 2016, 160 mm of rainfall fell in 3 hours flooded the city of Licata, causing several damages and forcing the Mayor of the city to adopt extreme measures of civil protection (people confined at home and closure of schools and all the economic activities). On 8 August 2018, in only 20 minutes, a precipitation of about 75 mm/h intensity endangered the city of Palermo, transforming the urban streets in rivers and flooding most of the old city and several other districts of the city. Between 1 and 3 November 2018, a series of some heavy rainfalls in the east and south parts of the region, between the cities of Trapani, Palermo, and Agrigento caused thirteen fatalities and more than two hundred and thirty displaced people. In the city of Casteldaccia, eighteen kilometres far from the city of Palermo, a flash flood trapped and killed nine people within their house. The rainfall peak over the three days reached an intensity of about 190 mm/h in five minutes with a total rainfall depth of 180 mm in three days, which is approximatively equal to about one third of the mean annual precipitation of some of the affected areas. ~~As it is possible to notice from the few aforementioned examples,~~ all of these flooding events happened between the end of the summer and the fall, when air masses moving over the hot water of the Mediterranean Sea become warmer and humid thus generating local convection processes, often causing very heavy rainfalls (Dayan et al. 2015), usually referred to as convective precipitation.

Most of the urban floods belong to the category of ~~the so called~~ pluvial (or surface water) floods, which can be addressed to a combined effect between convective precipitation, that saturates very quickly the urban drainage system, and the runoff due to the rain falling on elevated terrain, e.g., hillsides, that are unable to absorb the water. Pluvial floods, usually, occur gradually and the level of water rarely exceed one meter (Palla et al. 2018; Stone et al. 2013; Sušnik et al. 2015). Although a pluvial flood does not cause immediate threat to life, depending on the flooded area, it may cause significant economic damage. In some cases, such as the city of Palermo (Sicily, Italy), urban floods can be due to a combination of pluvial floods and flash floods coming from the small hilly/mountain basins around the city. In such conditions, the potential damage to buildings and the risk for the safety of human beings become a very important issue to deal with (Rappazzo and Aronica 2016).

Traditionally, the defense of urban settlements from natural events is mainly based on urban drainage, which applies a defensive approach based on the concept of "design against nature" and "resistance paradigm", that usually does not consider the impacts of urbanization and climate change on natural systems. Moreover, in many cases, the old urban drainage systems are no longer suitable to drain the rain coming from some extreme events that are likely to become always more frequent and heaviest. All these aspects make it necessary a new paradigm in urban drainage design to develop new strategies for flood risk management based on the new concepts of "design with nature" and "resilience paradigm". In this context, it is possible to define the flood resilience of a city as its capacity to move along development trajectories after the occurrence of flood events: in this sense, an improvement of "resilience paradigm" is given by the "floodability" concept. It may be considered a consequential condition that emerges from the developmental process shaped by the ability of a city to prevent, recognize, adapt to, and learn from the changes, instabilities, disturbances, and calamities that may damage things that people care about (La Loggia et al. 2020). Floodability, as mentioned above, can be viewed as a new path towards sustainable urban growth in which flooding can be tolerated and viewed as a driver for societal development.

This study focuses on a very recent and particularly intense urban flood occurred in Palermo on 15 July 2020, describing the event and exploring its causes, especially in terms of rainfall forcing and urbanization. The event has been reconstructed using in cascade a hydrological and a 2D hydraulic model, particularly suitable for simulations in very complex urban contexts; the results have been validated through a qualitative comparison with crowdsourced information and some satellite post-event images. Precipitation causing the flood event lasted about two hours with a cumulative rainfall of 134 mm and an intensity peak of 168 mm/h in five minutes, causing the flooding of the ring road of Palermo and its underpasses with several damage to cars and inconveniences to people. Beyond the extraordinary characteristics of the precipitation, a significant impact on the flooding dynamic is surely attributable to the substantial alterations in the land use and land cover occurred over past years, especially in the areas most affected by the event.

Even though the city of Palermo has suffered many flooding events in the past, the event occurred on 15 July 2020 is particularly significant, since it represents a perfect example of extreme rainfall pluvial floods in complex urban areas that many cities, especially in the Mediterranean region, have been experiencing in recent years and that, most probably, will have to face even more frequently in the near future due to the combined effects of an intensification in extreme rainfalls and an always more rapid urban growth. Therefore, the main aim of the work is to capitalize on this experience to highlight the urgent need for a shift in the way of managing flood risk assessment in urban settlements, introducing the idea of an independent paradigm, the floodability, which is an evolution of resilience or a facilitating strategy that introduces and achieves environmental sustainability in cases where the economic, social, and cultural conditions do not allow for a green revolution. Although the approaches and the related policies strictly depend on a local level, thus requiring a site-specific approach that cannot be identical for all cities, the modeling framework here reported to assess the impacts of the event under study could be easily transferred to other and different urban contexts.

The paper is organized as follows. Section 2 introduces the case study (i.e., the flooding event) and the analysis of the rainfall event that caused it. Section 3 describes the hydrological and hydraulic models used to model the forcing coming from the contributing basins around the study area and the propagation of the hydrographs within it, respectively. The results and some insights about future management strategies are shown and discussed in Sections 4 and 5, respectively. Section 6, finally, shows the main conclusions of the study.

2 Case study: The district Uditore - Passo di Rigano in Palermo

Palermo is the capital of Sicily (Italy), which is the largest island of the Mediterranean Sea (Figure 1). The city lies on a valley of about 100 km^2, called *Conca d'Oro*, in between the Mediterranean Sea and the mountains that reach a maximum elevation of about 1,000 m a.s.l. (Figure 1). The original hydrographic configuration of the city has been completely changed over the years. Two rivers that originally crossed through the city, the Kemonia and the Papireto, today are forced underground, while there is only a river, the Oreto, that still runs on surface. The city is characterized by some ephemeral streams, called *Valloni*, that convey rainwater from the mountains and the hills around the city to the inner city, causing sometimes damage and several inconveniences to people.

The city has a Mediterranean climate with hot and dry summers and cool and wet winters. The mean annual precipitation (MAP) is about 800 mm with precipitation mostly concentrated in fall and winter, whilst the summer season (i.e., June, July, and August) is usually almost rainless. The mean annual temperature (MAT) is about 22 °C, with peaks higher than 35 °C during the summer. In the last years, the city has been experiencing some intense rainfall events, usually concentrated in between the end of the summer and the beginning of the fall, that frequently cause urban floods with consequent economic damage and inconvenience to people.

The study area (i.e., the Uditore - Passo di Rigano district - red line in Figure 1) is located at the foot of Mount Cuccio (1,050 m a.s.l.) and Mount Gibilforni (about 520 m a.s.l.) and is crossed by two of the most important streets of the city, i.e., via Leonardo Da Vinci and viale Michelangelo, the ring road of Palermo, also known as viale Regione Siciliana, and its underpasses under the two streets above mentioned (hereafter named underpass Da Vinci and underpass Michelangelo, respectively). The district includes a rather articulated water drainage system for the conveying and regulation of rainwater (Figure 2). It is made of the artificial channel Passo di Rigano, its left tributaries Mortillaro, Celona and Borsellino, which flow into a unique stream further downstream, and its right tributary Luparello, which is the extension of the channel Passo di Rigano upstream of the confluence between the Celona and the Borsellino channels. This drainage system, which is almost completely underground and embedded within the urban structure, flows toward the industrial harbour of Palermo. In Figure 2, within the coloured boxes, are reported the hydraulic sections of channels (Oliveri 1996).

As it is possible to observe in Figure 3, there are four different main drainage areas (i.e., small catchments) that feed the channels above mentioned and mainly contribute to the total runoff formation within the study area. The outlets of the four contributing catchments (yellow circles in Figure 3) match with the start points of the covered parts of channels Mortillaro, Celona, Borsellino, and Luparello. Apart from the rain gauge Uditore, located within the Uditore – Passo di Rigano district (cyan triangle in Figure 3), other rain gauges very close to the study area are the rain gauges Zootecnico and UIR (red triangles in Figure 3), which are part of the rain gauge network of the *Autorità di Bacino della Regione Sicilia* (Basin Authority of Sicilian Region), hereinafter AdB, and the gauges Bellolampo and OTT (green triangles in Figure 3), which are part of the rain gauge network of the Department of Engineering of the University of Palermo, hereinafter UNIPA.

In the last fifteen years, the area has undergone a significant change in its urban environment due to the construction of a new mall in the north-west part of the district, immediately downstream of the Celona basin outlet in Figure 3, and a new tramline that crosses the entire district along the WSW-ENE axis. Both the interventions have increased the impervious areas within the district thus exacerbating the ground effects of more severe precipitation events. Moreover, the tramline, which is bordered by sidewalks and walls, acts as a channel that conveys the stormwater thus causing a faster propagation of the flood wave towards the underpass Da Vinci.

2.1 Overview of the most significant past flooding events

Over the past fifteen years, the district Uditore – Passo di Rigano has been affected by at least one flooding event per year. Figure 4 shows a collection of pictures of some of the most important events occurred between 2009 and 2019. As it is possible to notice from the examples reported in Figure 4, all the events occurred between the end of summer (e.g., September) and the mid-fall (e.g., the first days of November). This confirms that most of the flooding events affecting the city of Palermo are likely due to convective precipitation, which are typical of that period (Cipolla et al. 2020). Figure 4 also shows that the most affected area of the district is usually the ring road of Palermo along with its underpasses, since they act as a collector of the water conveyed by the “via Leonardo Da Vinci”, “viale Michelangelo”, and the tramline. The water that flows on the streets and the tramline generates fast flooding events that may cause considerable difficulties to drivers who often have no time to leave the ring road.

Figure 5 shows the hyetographs of the rainfall events ~~that caused the above-mentioned flooding events~~. All the events are relative to rainfall collected at the rain gauge Uditore (red circle in Figure 1). The duration of the events ranges between about 1.5 hours (e.g., event of 6 October 2013) and about 4 hours (e.g., event of 3 November 2018), with an instantaneous (i.e., 10-min) intensity peak between 62.4 mm/h (e.g., event of 21 September 2009 and 3 November 2018) and 116.4 mm/h (e.g., event of 6 October 2013). In all the cases, the total rainfall cumulated over the event is higher than 40 mm, with a maximum of about 60 mm during the event of 3 November 2018. ~~Despite all the events reported in Figure 5 have caused considerable flooding events within the district Uditore – Passo di Rigano~~ (see Figure 4), they can be statistically classified as ordinary events with a return period ranging between 5 and about 20 years. The fact that even an ordinary rainfall event can generate a considerable flooding of the district is probably due to its high urbanization, which has completely unset the natural rain drainage network in that area, thus exacerbating the ground effects of rainfall events.

2.2 The precipitation event of 15 July 2020

The severe storm that affected the city of Palermo on 15 July 2020 was certainly the heavier rainfall event recorded in the Palermo area during the last 90 years. It was due to a self-healing supercell that stationed on the same area for different hours, dumping a large amount of rainwater on it in a very short time. At the origin of the event, which assumed a marked oblique axis, there was a convergence line between the air coming from WNW and the sea breeze coming from NNE. At high altitude, this convergence line joined to a considerable increasing in divergence due to a strong instability area (region of positive vorticity advection) for the passage of a trough on the Mediterranean Sea. This generated an intense updraft that favoured the cooling of the humid air coming from the sea in a time window of the day favourable to the development of a thermal conductive thunderstorm activity. The developing of the phenomenon was favoured by the closeness of Palermo to the sea, which acted as a large reservoir of wet and humid air, and the presence of hills and mountains close to the sea, which favoured the downdraft of cold and dry air down to the sea, where it encountered warmer and humid winds blowing from the sea itself, thus creating the conditions for a new updraft that fed continuously the supercell. Figure 6 shows the self-healing thunderstorm cell observed around the 17:00 on the city of Palermo from the visible channel of Meteosat-11 project satellites and provided by the *EUropean organisation for the exploitation of METeorological SATellites* (EUMETSAT) of the UK Met Office.

The phenomenon was not easy to forecast; the Global Forecast System (GFS) model of National Centers for Environmental Prediction (NCEP) of the National Oceanic and Atmospheric Administration (NOAA) had forecasted between the 15:00 and the 20:00 a cumulated rainfall in the range of 5-20 mm for some areas of the city of Palermo. However, from the observation of the synoptic pattern associated with the event, it was possible to deduce a risk of locally intense thunderstorm phenomena. Figure 7 shows the geopotential heights of the 500mb pressure surface (coloured map in Figure 7) and the MSLP (mean sea level pressure – solid lines in Figure 7) for the 15 July 2020 as forecasted by the 12Z GFS (Global Forecast System). From the analysis of Figure 7, it is possible to observe a trough progressing southward, from the Denmark to the Mediterranean Basin, with a strong positive vorticity advection quickly moving toward Sicily. The activity between the descendent trough from Denmark and the anticyclone from the North Africa has favoured the ascent, up to Sicily, of a subtropical jet stream. These conditions of instability have been further exacerbated by the positive values of potential vorticity, extending from the lower Mediterranean/Sardinia Channel up to western Sicily, which have injected further cold and dry air from the stratosphere.

The strong sub-tropical jet stream (about 300hPa) mentioned above, which indicates the presence of cold and dry air (600hPa) and very warm and humid air in lower layers (Precipitable Water > 39 mm) are confirmed by the data recorded at the Radiosonde Data Station Trapani-Birgi (see Figure S1 in the supplementary material).

The storm caused a very high intense precipitation, especially on the district Uditore – Passo di Rigano (red line in Figures 1 and 3) and the hilly/mountain area around it, which started around 16:00 and lasted about two hours. In that occasion, the rain gauge Uditore (red circle in Figure 1) of the regional agency SIAS (*Servizio Informativo Agrometeorologico Siciliano* - Agro-meteorological Information Service of Sicily) reported a maximum hourly intensity of the event equal to 87.8 mm/h, with an instantaneous intensity peak of 168 mm/h in five minutes at around 17:35 and a cumulative rainfall of 134 mm (Figure 8a). Even without a robust statistical analysis made on historical data, considering that this is the highest value ever recorded from the station since its installation (i.e., 2002) and represents the wettest day in July for the city of Palermo since 1797, much higher than the previous record (i.e., 39.2 mm on 6 July 1935), it is clear how the storm under analysis was not an ordinary rainfall event. Comparing the rainfall recorded for different accumulation periods with the annual maxima precipitation (AMP) for the same accumulation periods and recorded from 2002 through 2020 at the Uditore rain gauge, it is possible to notice how the precipitation on 15 July 2020 is much higher than the corresponding annual maximum values (e.g., 25.6 mm vs 19.4 mm at 10 min, 87.8 mm vs 48.2 mm at 1 hour, and 134 mm vs 55.8 mm at 3 hours). Also looking at the rainfall collected at the nearby rain gauges UIR and Zootecnico, which are characterized by a 48-year and a 40-year time series, the precipitation of 15 July 2020 shows much higher values of depth at the durations of 1 hour (i.e., 67 mm for the UIR station and 51.8 mm for the Zootecnico station) and 3 hours (i.e., 85.4 for the UIR station and 99 mm for the Zootecnico station); the return period for both the 1- and 3- hour rainfalls, which has been estimated through the rainfall growth curves derived by (Forestieri et al. 2018), resulted much higher than 100 years, thus highlighting the exceptionality of the rainfall event occurred on that day in Palermo.

Also the rain gauges nearby collected rainfall data with similar characteristics of those collected at the rain gauge Uditore. Figures 8b, c, d, and e show the hyetographs for the rain gauges Zootecnico, UIR, Bellolampo, and OTT (see Figure 3), respectively. As it is possible to notice, the rain gauges Uditore (Figure 8a), Zootecnico (Figure 8b), and UIR (Figure 8c) show similar shapes of hyetographs (e.g., rainfall duration and depth), with two peaks ranging between 17 mm and about 21 mm around 16:20 and about 24 mm and about 27 mm around 17:30, respectively, and a total rainfall depth between about 121 and 134 mm over the total duration of the rainfall event. The rain gauges Bellolampo (Figure 8d) and OTT (Figure 8e), despite still having a two-peak shape and a similar duration to the previous ones, instead, show different values of peaks and lower total rainfall depths than the previous rain gauges. Moreover, the hyetograph related to the rain gauge Bellolampo (Figure 7d) is shifted forward in time, suggesting that the supercell moved from the sea towards the mountains showing its exceptional nature especially over the district Uditore – Passo di Rigano.

The result of such a precipitation on a very high urbanized area was the flooding of the ring road of Palermo and its underpasses with several damage to cars and inconveniences to people. In the underpass Da Vinci, the water level reached a depth of about 5 m, with an estimated water volume of 28,000 m^3 entrapping many drivers within their cars thus causing the prompt intervention of the Fire Department. Moreover, the precipitation caused some flash floods from the small hilly and mountain catchments around the Uditore – Passo di Rigano district that carried out mud and debris from the slopes of hills and mountains to the city. Although an exact quantitative estimation of the damages is still under evaluation, the Regional

Government of Sicily has already allocated a first extraordinary contribution for damages of 900,000 euros; the amount includes 350,000 euros for damages to warehouses, shops, and production activities, 250,000 euros for vehicles, 150,000 euros for damage to furnishings, 100,000 euros for damages to homes, and 50,000 euros for physical damage to people.

3 Material and Methods

This section presents the hydrological and hydraulic models that will be used for the determination (i.e., hydrographs) of the hydraulic forcing for the district Uditore – Passo di Rigano and its propagation within the study area, respectively. Both the models have been developed at the Department of Engineering of the University of Palermo.

3.1 Hydrological Modeling: the TOPDM

The *TOPography-based Probability Distributed Model* - TOPDM (Liuzzo et al. 2015; Noto 2014) is a lumped conceptual model that allows the simulation of the main hydrological processes at the basin scale. It is based on the *Probability Distributed Models* - PDMs (Moore 1985) and, as part of these models, represents the basin as a series of storages of capacity c variable within it. In particular, the TOPDM uses the spatial distribution of the topographic index to derive the probability distribution of capacity of the considered storages. The model is capable to work at different temporal scale (i.e., from sub-hourly to daily); this makes the TOPDM suitable to simulate runoff and analyse hydrological processes at the catchment scale using a daily time-step, or to simulate the flood forcing within the small Mediterranean basins using an hourly or sub-hourly time-step (Forestieri et al. 2016).

TOPDM conceptualizes the basin as two different bucket types: the soil moisture system, which is represented by a series of storages with capacity c, and the groundwater bucket, which interacts with the sub-surface system (i.e., soil moisture storage) and receives water volumes from it exclusively. Each storage in the soil moisture system can take water from rainfall and lose it by evaporation and/or vertical drainage, until one of the following conditions occurs: the storage fills and generates direct runoff, q', or empties and ceases to lose water by evaporation and vertical drainage. The complex process of evapotranspiration from the buckets is here indicated in its totality by the water lost. The storage capacity, c, is modelled as a random variable with a probability density function, $p(c)$. Therefore, that portion of basin characterized by a capacity ranging between c and $c+dc$ can be described as $p(c)dc$.

According to the type of saturation mechanism in the soil column, the direct runoff from the soil moisture system (i.e., fast response) can be of two types: Hortonian or Dunnian. While the Dunnian runoff is due to a saturation from below, due to the saturation excess, the Hortonian mechanism, instead, occurs in the storages not yet saturated, because of infiltration excess. Vertical drainage to groundwater, conceptualized by the model as a storage with unlimited capacity, is also simulated. This storage does not exchange water with the sub-surface system and generates the slow response of the basin. The fast response of the system is routed to the basin outlet by means of a routing module based on the concept of the Distributed Unit Hydrograph.

Estimation of the spatial distribution of the capacity is based on the catchment morphology through the topographic index, which is, as the capacity, an indicator of the catchment capability to produce runoff. The topographic index, λ, is expressed as:

$$\lambda = ln\left(\frac{\alpha}{tan\beta}\right), \quad (1)$$

where α is the cumulative area drained through a unit length of contour line and β is the local surface slope. The probability distribution of the storage capacity is derived by assuming a linear relationship between topographic index λ and storage capacity c:

$$c = c_{min} + \frac{\lambda_{max}-\lambda}{\lambda_{max}-\lambda_{min}}(c_{max} - c_{min}), \quad (2)$$

where c_{min} is here set equal to 0 and c_{max} is a model parameter. Eq. (2) allows to relate a high topographic-index value to all those elements located along the network and characterized by a higher probability of saturation and a low topographic-index value to those elements located on the hillslope. Once defined the spatial distribution of c, the next step is to fit on it a probability distribution. Here, a gamma distribution has been used:

$$p(c) = \left(\frac{c-\varepsilon}{\theta}\right)^{k-1} \frac{e^{-[(c-\varepsilon)/\theta]}}{\theta\Gamma(k)}, \quad (3)$$

where the parameters θ, ε, and k derive from the mean, standard deviation, and skewness of the sample, respectively.

For a complete description of the TOPDM, interested readers are referred to (Noto 2014).

3.2 Hydraulic Modeling: the WEC-FLOOD

Urban areas are characterized by a high complexity in the modeling of the runoff surface, that prompts the adoption of 2D models for a better reconstruction of the flooded areas (Abderrezzak et al. 2009; Dottori and Todini 2013; Lamb et al. 2009; Mignot et al. 2006). In this study a 2D diffusive model of the Saint Venant equations, named WEC-FLOOD (Filianoti et al. 2020; Sinagra et al. 2020), has been applied. The use of the diffusive form, instead of the fully dynamic one, is mainly motivated by the smaller sensitivity of the computed water depth with respect to the topographic error (Aricò et al. 2011). The hydraulic 2D model (Aricò et al. 2016; Aricò et al. 2011) in the diffusive form can be written as:

$$\frac{\partial H}{\partial t} - \frac{\partial}{\partial x}\left(\frac{h^{5/3}\cos\alpha^{2/3}}{n\sqrt{|\nabla H|}}\frac{\partial H}{\partial x}\right) - \frac{\partial}{\partial y}\left(\frac{h^{5/3}\cos\alpha^{2/3}}{n\sqrt{|\nabla H|}}\frac{\partial H}{\partial y}\right) = Q, \quad (4)$$

where t is the time, H is the piezometric head, h is the water depth, α is the bottom slope, n is the Manning roughness coefficient, Q is the source term and x and y are the Cartesian directions. Initial and boundary conditions must be specified to make problem (Eq. 4) well posed. Boundary conditions may be of Dirichlet (prescribed piezometric head or water depth) or Neumann (prescribed flux) type.

The solution of problem (Eq. 4) in the H unknown is attained by means of a time-splitting approach, named MAST (MArching in Space and Time) (Aricò et al. 2011), solving for each time-step consecutively a convective prediction system (Eq. 5) and a diffusive correction system (Eq. 6):

$$\frac{\partial H}{\partial t}-\frac{\partial}{\partial x}\left(\frac{h^{5/3}\cos\alpha^{2/3}}{n\sqrt{|\nabla H^k|}}\frac{\partial H^k}{\partial x}\right)-\frac{\partial}{\partial y}\left(\frac{h^{5/3}\cos\alpha^{2/3}}{n\sqrt{|\nabla H^k|}}\frac{\partial H^k}{\partial y}\right)=Q \quad (5)$$

$$\frac{\partial \eta}{\partial t}-\frac{\partial}{\partial x}\left(\frac{\left(h^{km}\right)^{5/3}\cos\alpha^{2/3}}{n\sqrt{|\nabla H^k|}}\frac{\partial(\eta-\vartheta)}{\partial x}\right)-\frac{\partial}{\partial y}\left(\frac{\left(h^{km}\right)^{5/3}\cos\alpha^{2/3}}{n\sqrt{|\nabla H^k|}}\frac{\partial(\eta-\vartheta)}{\partial y}\right)=0 \quad (6)$$

where $\eta = H - H^{k+1/2}$, $\vartheta = H^k - H^{k+1/2}$ and h^{km} is a water depth value in the computational cell (Figure 9), obtained by local mass balance. It is worth observing that the formulation of Eq. (5) differs from the original one (Eq. 4) in the time level of spatial gradients of H, which in the prediction step are kept constant in time and equal to the values computed at the end of the previous time step. The reader is referred to the original papers for more details.

The spatial discretization of the 2D domain is performed with an unstructured triangular mesh, satisfying the Generalized Delaunay conditions (Aricò et al. 2011). The source term Q in Eq. (4) is given either by the net rainfall intensity, which is integrated over all the cell area (Figure 9Figure), or by the storm hydrograph, if the cell is a boundary cell.

4 Results

This section presents the results of the numerical reconstruction of the flooding event that hit the city of Palermo on 15 July 2020 arising from the modeling framework proposed in this study. In particular, the hydraulic forcing to be propagated within the study area was simulated with the TOPDM (Liuzzo et al. 2015; Noto 2014) and consists of the hydrographs simulated at the outlets of the four contributing catchments (yellow circles) shown in Figure 3. The hydrographs so simulated were propagated within the study area by means of the WEC-FLOOD (Filianoti et al. 2020; Sinagra et al. 2020) to obtain the flood map for the case study.

4.1 Hydrological Simulation

Starting from the 2 meters resolution digital elevation model (DEM) data, available from the SITR (*Sistema Informativo Territoriale Regionale della Sicilia* – Geographical Information System of Sicily) for the entire study area (Figure 3), the spatial distribution of the topographic index λ was derived using the single-flow direction algorithm (SFD; O'Callaghan and

Mark (1984)) to derive the specific contributing area of each catchment, together with the W-M method (Wolock and McCabe Jr. 1995) to derive the slope. The grid cells with a null value of slope, which would make the λ calculation impossible, were replaced by very small values of slope. By the calculations, the areas characterized by the highest values of topographic index are located along the drainage network. The relative frequency of topographic index has been used to derive the spatial distribution of the storage capacity, c, using Eq. (2), while a three-parameters Gamma distribution has been fitted to the distribution of c through Eq. (3).

Rainfall data collected at the rain gauges Uditore, Zootecnico, UIR, Bellolampo, and OTT (see Figure 3) were interpolated with the inverse distance weighted (IDW) interpolation to provide the rainfall field to be used as climatic forcing, at the catchments scale, for the hydrological simulations.

In order to consider the discharge capacity of channels Borsellino, Celona, Luparello, and Mortillaro, the simulated hydrographs were reduced of a value equal to their discharge capacity, using the information provided by the Municipality of Palermo. The channels were supposed to be in perfect condition of maintenance, even though their actual state is not known because of the complexity of the system, and the maximum discharge (i.e., channel capacity) for the Borsellino, Celona, Luparello, and Mortillaro channels was set equal to 40, 14, 25, and 11 m^3/s, respectively. The subtracted volumes were supposed to be delivered downstream the study area by the underground channels.

Figure 10 shows the flow hydrograph for each channel after the subtraction of its channel capacity. As it is possible to notice from Figure 10, as compared to the Borsellino, Celona, and Luparello hydrographs, the contribution of the Mortillaro basin is very small (i.e., hydrograph peak about 6 m^3/s) since its channel capacity can intercept almost the entire hydrograph.

4.2 Hydraulic Modeling

4.2.1 The domain reconstruction

The digital reconstruction of the hydraulic computing domain was carried out using the 2 m resolution DEM provided by the SITR. The complexity of the urban area required an improvement of the built-up area, manually inserting the plano-altimetric trend of the elements that may affect flow direction, such as traffic islands, tramline, buildings, and underpass roads (green and orange elements in Figure 11), not reproduced by the DEM model. The study area has a surface of 9.2 km^2 and is very irregular due to its high anthropization.

According to the outline and the constrained elements inside the domain, a computational mesh of 771,018 elements and 412,919 nodes was generated. The resulting mean length of the triangle sides is between 3 m and 8 m. A null water depth was assumed as initial condition. The discharge hydrographs of the basins named Borsellino, Celona, Luparello, and Mortillaro simulated with the TOPDM (Figure 10) were used to force the hydraulic model and then assigned as inlet boundary conditions. Moreover, a constant value of precipitation over the entire domain was obtained from the interpolated rainfall field previously obtained. A zero-diffusion condition was assigned to the outlet boundary (blue line in Figure 11).

Particular attention has been paid to the choice of the roughness coefficient; different Manning coefficient values have been adopted for urbanized and natural areas (Chow 1959), with values ranging between 0.03 s/m$^{1/3}$ and 0.05 s/m$^{1/3}$, respectively.

4.2.2 2D urban flood simulation

One of the main difficulties to evaluate the goodness of hydraulic simulations, especially when these regard urban floods, is the absence of measured values of water depth to be used for the validation of results. Nowadays, however, the growing availability of crowdsourced data, especially in urban areas, such as pictures and videos acquired by common mobile devices (e.g., smartphones, tablets, digital cameras, etc.) and shared in social media (e.g., You Tube, Facebook, Instagram, etc.), offers the possibility to gather precious information about the temporal and spatial evolution of flooding events to be used for the calibration and validation of hydraulic models. Moreover, remote sensing data can provide the opportunity to overview flooded areas quickly and precisely overcoming the limitation of surveying the ground right after the occurrence of an extreme hydrological event.

In this study, the numerical results from the hydraulic model in some of the most affected areas during the flood under analysis were compared with specific reports, crowdsourced data, and satellite images to assess the goodness of the simulations.

Figure 12 shows the map of the maximum flood depths for the flooded areas obtained by means of the simulation in WEC-FLOOD. The results show a good agreement with what happened on that day based on the Fire Department reports, images, videos, and interviews collected from the web and the people on that day and the following. As it is possible to notice from Figure 12, most of the district Uditore – Passo di Rigano (see red polygon in Figures 1 and 3) was flooded. The most affected areas were the streets within the district and the tramline, which turned into a river that finished its race with a waterfall in the underpass Da Vinci (picture 1 of Figure 13). It was precisely the underpass Da Vinci (box 1 in Figure 12 and Figure 13), along with the underpass Michelangelo (box 2 in Figure 12 and Figure 14), the most critical area on 15 July 2020. In that occasion, as it is possible to notice in Figures 13 and 14, the two underpasses worked as two big reservoirs where the water depth reached values higher than 4 m.

With regard to the numerical simulation results, Figures 13 and 14 show the results of simulation in WEC-FLOOD for the underpasses Da Vinci and Michelangelo, respectively, as well. Also in this case, it is possible to notice a good qualitative match with the historical pictures taken from the people in the underpasses Da Vinci (Figure 13) and Michelangelo (Figure 14). The model simulation provided a value of about 3.2 and 5.0 m of water depth in points 1 and 2 of Figure11, respectively, which are totally compatible with values reported by the Fire Department (i.e., between 4.5 and 5.0 m in the deeper point of the underpass Da Vinci). With reference to the underpass Michelangelo, instead, the WEC-FLOOD returned a maximum water depth of about 1.5 m in points 1 and 2 and about 2.3 m in point 3 of Figure 14 thus demonstrating, ~~once again,~~ the reliability of results.

In order to make a further evaluation of the goodness of the results in terms of flooded area extent, these has been qualitatively compared with that provided by Copernicus Sentinel-2 satellite image (Drusch et al. 2012) of the European Space Agency (ESA) for the 16 July 2020 at around 09:50 limited to the areas of the underpasses Da Vinci and Michelangelo. The Sentinel-2 images of the 14 July 2020 at around 10:00 (i.e., the day before the flooding event) and 16 July 2020 at around 10:00 (i.e., the day after the flooding event) are reported in the supplementary material (see Figures S2a and b, respectively). In particular, the Figure S2b reveals the traces left by the mud the day after the flooding event in the two underpasses, which are compatible with the extension of the flooded area returned by the numerical simulations in WEC-FLOOD.

5 Discussion

An effective management of the hydraulic risk in an urban context should be the result of a well-balanced and dynamic development of all the essential components of a protection system that include accurate activities of forecast and assessment of the risk, the adoption of adequate prevention and protection measures, a correct residual risk management with the definition of opportune civil protection plans, and the elaboration and continuous updating of the flood emergency plans.

In areas particularly susceptible to pluvial and flash floods it is extremely important to enhance the capability for rainfall monitoring and early flood warning, for example by forecasting well in advance the causes (i.e., the storm event) or monitoring in real time some precursive factors, in order to take appropriate civil protection actions to minimize the impacts (e.g., closure of roads and underpasses, warnings to the population, etc.). However, as it has been shown in this study, sometimes the rainfall event causing an urban flood can be extremely difficult to forecast due to its very fast emergence and intrinsic morphometric characteristics of the area. In such a case, the real-time monitoring of the flood event (e.g., real-time observation of water levels and precipitation in some strategic points or locations), if on the one hand cannot prevent damage to property, on the other could be an important option to drive emergency actions and reduce the potential flood damage to people closing, as an example, the underpasses during the flood event.

With this regard, after the urban flood event of 15 July 2020, the Municipality of Palermo and the Integrated Water Service company AMAP SPA have planned the realization of a real-time monitoring network, including seven water level sensors and cameras installed at different strategic and particularly vulnerable sites over the city; two of these sensors have already been installed in the underpasses Da Vinci and Michelangelo and are connected to traffic lights, opportunely installed over the ring road of Palermo, to inhibit the vehicular transit when a prefixed threshold water level in the underpasses is exceeded. Such a measure could have probably significantly reduced the damage for vehicles during the flood of 15 July 2020 and, more in general, could reduce considerably the risk for mortality, considering that more than half of the fatalities attributed to flash floods (i.e., 56.1%) in the 50-year period 1965-2014 in Italy are car-related (Salvati et al. 2018).

For the case studied here, the intensive and sometimes uncontrolled urbanization has probably exacerbated the ground effects of the rainfall event thus playing a dominant role in driving the flooding dynamic for the flood event, as demonstrated also by the fact that the district Uditore - Passo di Rigano is frequently flooded also during non-extraordinary storms. A significant impact in altering the rainwater drainage over this area could be addressed to the construction in recent years of a new mall and commercial areas in the north-west part of the district and a new tramline that crosses the entire district along the WSW-ENE axis; both these building works have considerably increased the impervious areas within the district and, together with previous interventions, such as forcing original surface flow channels into underground stretches, have completely unset the natural rain drainage network in that area.

Nowadays, the increasing availability of accessible crowdsourced information along with always more accurate hydrological and hydraulic models suggests new approaches in the urban flood modeling, highlighting the importance to develop frameworks capable to:

1. produce reliable reconstructions of occurred events, which are essential to identify possible critical aspects of the existing drainage system and map particularly vulnerable areas;
2. forecast in near real time the potential effects of incoming rainfall and, consequently, select adequate mitigation strategies;
3. run multi-scenario simulations during the urban expansion planning phase to preliminarily evaluate the effects of both new urban expansions, including gray, green, and blue infrastructures, and possible alternative interventions on the urban drainage systems.

With regard to the last aspect, it is important to point out the need to pay greater attention to the development/modification of urban areas, where the alterations induced on the soil properties must be accompanied by an integrated planning system aiming to find new paths towards smart, sustainable, and flood resilient cities.

In light of the urban flood that affected Palermo on 15 July 2020, it is clear that a paradigm shift in the management and design of urban water systems is urgently needed in order to reduce the vulnerability and increase the capacity of cities to cope the combined effects of climate and land use changes. With this regard, several studies (Ahiablame et al. 2013; Liu et al. 2014; Zahmatkesh et al. 2015) have demonstrated the effectiveness of Best Management Practices (BMP) and solutions inspired and supported by nature, i.e., the so-called Natural Based Solutions (NBS), on urban flooding. Some of the NBS, such as urban green areas, green roofs and pervious pavements, and BMP, such as rainfall harvesting systems, bio-retention, and rain gardens, could relevantly contribute to the flood risk reduction in urban areas, significantly reducing runoff volumes and peak discharges and increasing the times to peak. An effective selection and location of these types of sustainable and cost-efficient interventions could create a network of green infrastructures for a smarter and more natural flood management in urban areas, which is able to also provide a series of co-benefits that span from the heat stress mitigation to the creation of recreational areas, from increasing climate resilience of the cities to the biodiversity conservation (Raymond et al. 2017).

With regard to the city of Palermo, already in the past, considering the recurrent flooding of the district Uditore – Passo di Rigano even for ordinary rainfall events, the Municipality of Palermo has tried to find a solution to the problem. For many years, most attention was focused on the option to build a new flood diversion channel for intercepting and draining the water contribution from the Luparello basin and conveying it to the already existing Boccadifalco channel, which is connected to the Oreto river. The *Plan of the Drainage System* for the city of Palermo planned to extend the channel to the basins Borsellino and Celona as well. However, this ambitious project has now been abandoned due to several difficulties related to the high level of urbanization and the morphology of the area, which would require to force underground a large part of the channel with unsustainable costs. More in general, the difficulties related to the permeation of new infrastructures into already highly urbanized areas, nowadays, represents the main limitation to the development of traditional stormwater engineering solutions in many cities, especially for old cities.

It is therefore clear that in highly urbanized areas, where it is no longer possible neither to make changes to the existing urban drainage system nor to build a new one, and in a climate change context, which makes the existing urban drainage system no more suitable for conveying the stormwater of heavy rainfall events, it is necessary to shift towards a new way to manage the hydraulic risk.

There is the need of a new paradigm capable to propose solutions changeable according to the rainfall event that is causing the flooding event. In this respect, for instance, it would be possible to plan the use of NBS and BMP sparsely distributed, which could contribute for mitigating the ground effects of ordinary rainfall events, with a return period comparable to that considered to design the drainage system, while solutions such as the urban flood retention basins may be suitable to reduce the effects of more severe rainfall, with return period slightly higher than that characteristic of the drainage system.

Probably, for extraordinary rainfall events, such as the one that has originated the event of Palermo investigated here, the only solution that could contribute to reduce damages and risks are those oriented to the concept of floodability.

Such a new paradigm probably requires a change in the aesthetic convention by which the only purpose of parks and playgrounds is recreation. Indeed, instead of assigning recreation as the exclusive use of parks, these could be designed to serve as temporary storage areas to fulfil hydrological roles. Open spaces could thus become spaces for restoring the damage done by an excessive urban development, both in terms of hydrology and architectural. With regard to Palermo, for instance, two areas of several hectares within the district Uditore – Passo di Rigano, namely the *Parco Villa Turrisi* and the *Parco Uditore*, respectively, which are right upstream the underpass Da Vinci and currently used as a recreational city park, could be probably suitable for such a type of project.

6 Conclusions

This study reproduces the dynamics and impacts of a recent urban flood that affected the city of Palermo (Sicily, Italy), mainly focusing on the analysis of the precipitation event that caused it, which can be classified as an extraordinary event. According to the last report released by IPCC (2019), climate change and global warming are significantly changing the frequency of this type of events, which are becoming less and less rare especially in the Mediterranean area, thus leading to an increasing occurrence of short duration rainfall extremes that have caused landslides and floods in the last decades (Yin et al. 2018). Moreover, the rapid and progressive urbanization, especially for the larger cities with important historical centers, with continuous losses of natural soil and substantial modifications to natural drainage systems, is profoundly altering the ground effects of heavy precipitation on urban areas, often with dramatic consequences. With this regard, the case study investigated here, due to the precipitation characteristics, ground effects, flooding dynamics, and degree of urbanization can be considered as an effective paradigm of what many cities in the Mediterranean area could have to deal with in the next future.

The flooding event has been simulated using in cascade a hydrological and a 2D hydraulic model and the results validated through a qualitative comparison with crowdsourced information and some satellite post-event images. The hydraulic model has shown relevant performances in reproducing the flooding under analysis, as demonstrated by the qualitative comparison with reports, pictures and satellite images acquired during and after the event. In this respect, the crowdsourced data, which represents a new frontier to improve the observation, understanding, and modeling of floods especially in urban area, where the enormous and increasing diffusion of mobile devices (e.g., smartphones, tablets, etc.) makes it possible to acquire real time and no cost monitoring of both rain and flood events, has made possible to calibrate and validate the hydraulic model by means of reports and hundreds of pictures and videos found on the social media.

The study of the event of 15 July 2020 has shown that the city of Palermo, with its long track of history – as many cities in the world - cannot plan the design of new larger sewer pipes that pass under the city or the construction of flood diversion channels that drain the water coming from the upstream contributing basins. There is, therefore, the need to implement some new ideas such as the one of floodability (i.e., flood control is not the only way to achieve flood safety). Floodable cities are able to avoid physical damage and socioeconomic disruption during a flood. Due to this feature, floodable cities are more than resilient because their systems do not aim to return to their pre-existing equilibria quickly and efficiently, but to find new equilibria in which flooding is an event “to live with”. As a matter of fact, change cannot be solely technical or infrastructural; considered that services, functions, land use and infrastructure will change and may be different in the steady state (i.e., when the flood is not happening) than they are in the event state (i.e., during flooding), change must involve an entire society.

Thus, water and urban planning integration can be considered as the keys needed to develop useful strategies that are able to make cities resilient and floodable. Floodability does not introduce new mitigation measures; rather, it provides a new perspective through which it is possible to combine existing measures in a framework that incorporates societal, economic, environmental, and technical aspects, as demonstrated for the city of Palermo.

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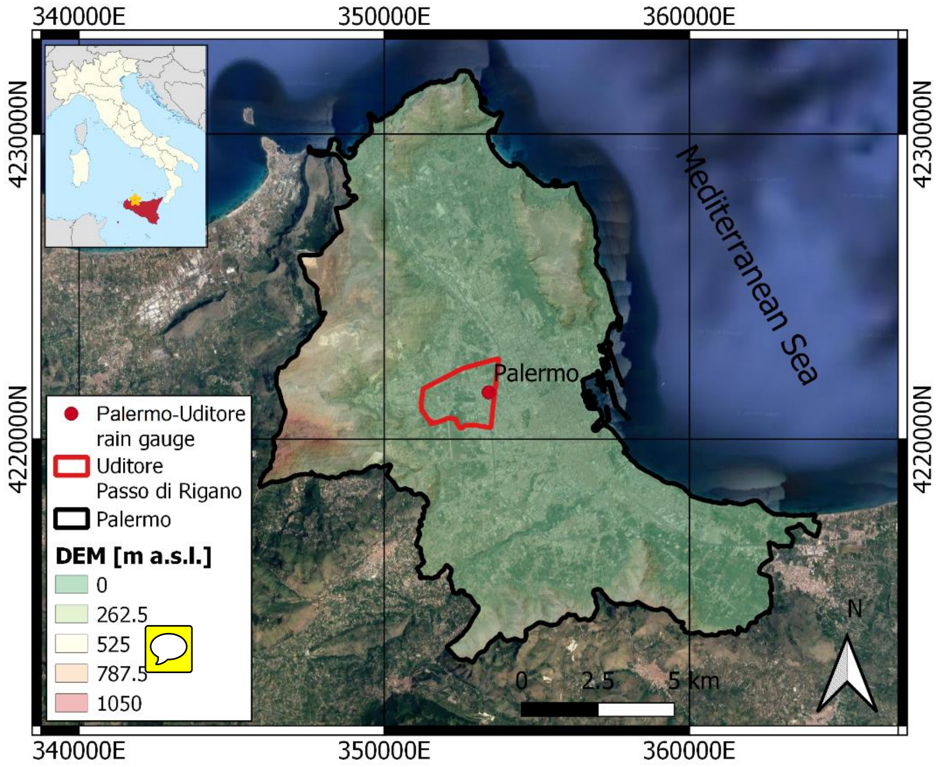
Figures



625 **Figure 1. Digital Elevation Model of Palermo (Sicily, Italy) with location of the Uditore - Passo di Rigano district (red line) and the Uditore rain gauge station (red point) of the SIAS rain gauges' network. The yellow star in the inset indicates the location of Palermo.**

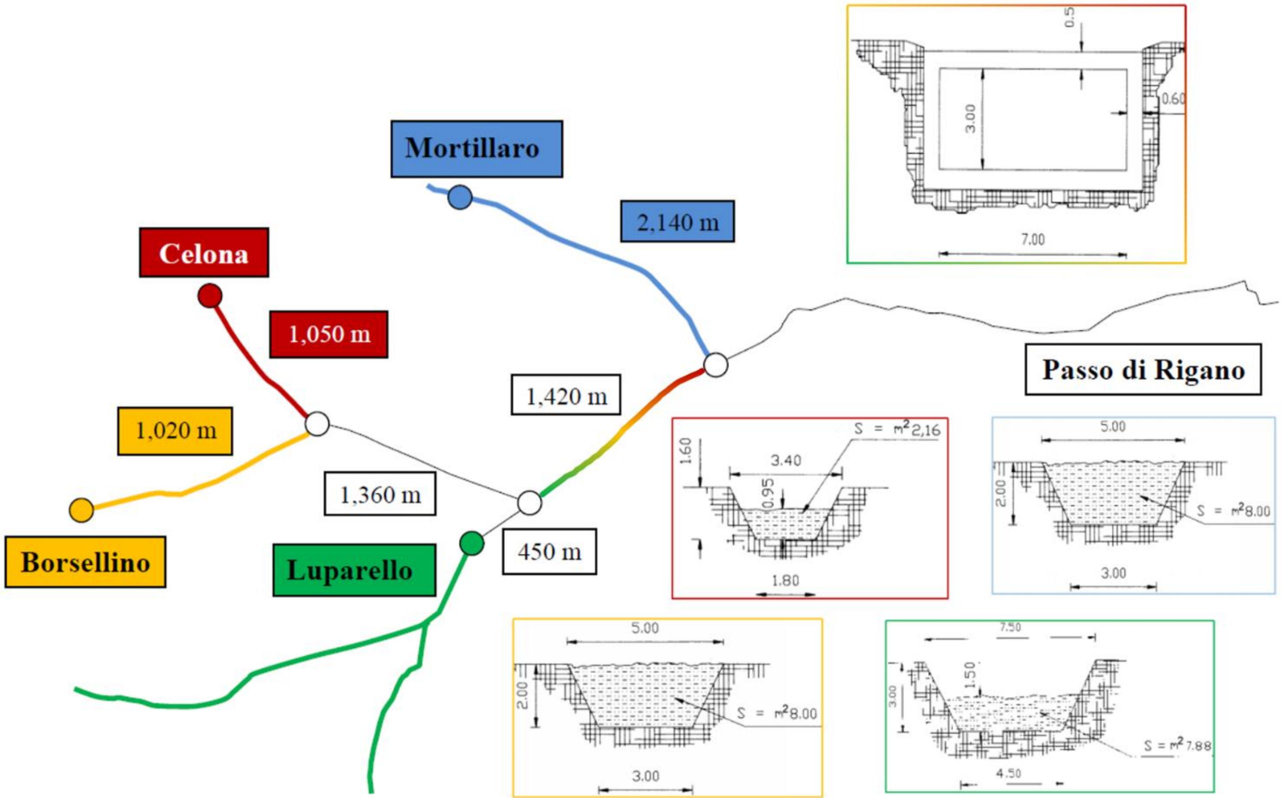


Figure 2. Passo di Rigano drainage system for the conveying and regulation of rainwater in the study area. Yellow color is associated with Borsellino, the red with Celona, the green with Luparello, and the blue with Mortillaro channels; the box within mixed colors (red, yellow, and green) refers to the section of the Luparello channel downstream the confluence with the Borsellino and Celona channels.

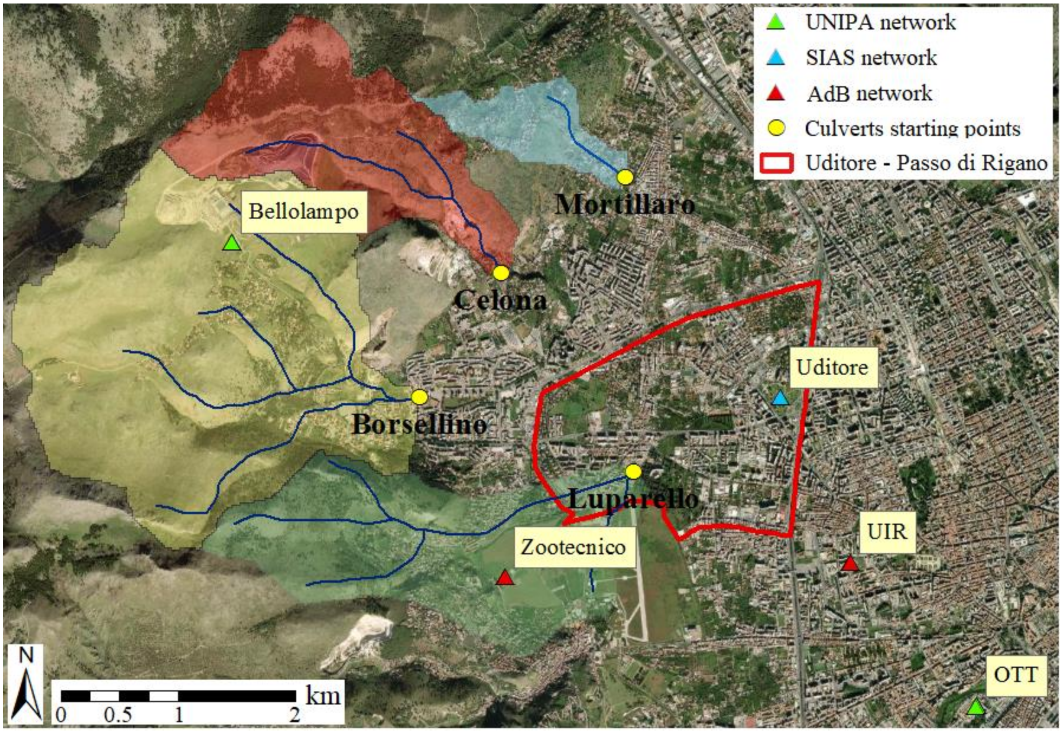


Figure 3. Main contributing areas for the study area: catchments of Borsellino, Celona, Luparello, and Mortillaro. The yellow circles indicate the outlets of the contributing catchments and match with the start points of the covered parts of channels. The red, cyan, and green triangles indicate the rain gauges of the Basin Authority (AdB), SIAS, and University of Palermo (UNIPA) networks, respectively. The red line indicates the Uditore - Passo di Rigano district.

Figure 4. Flooding events that affected the district Uditore – Passo di Rigano on a) 21 September 2009, b) 6 October 2013, c) 5 October 2014, and d) 3 November 2018. Source: web.

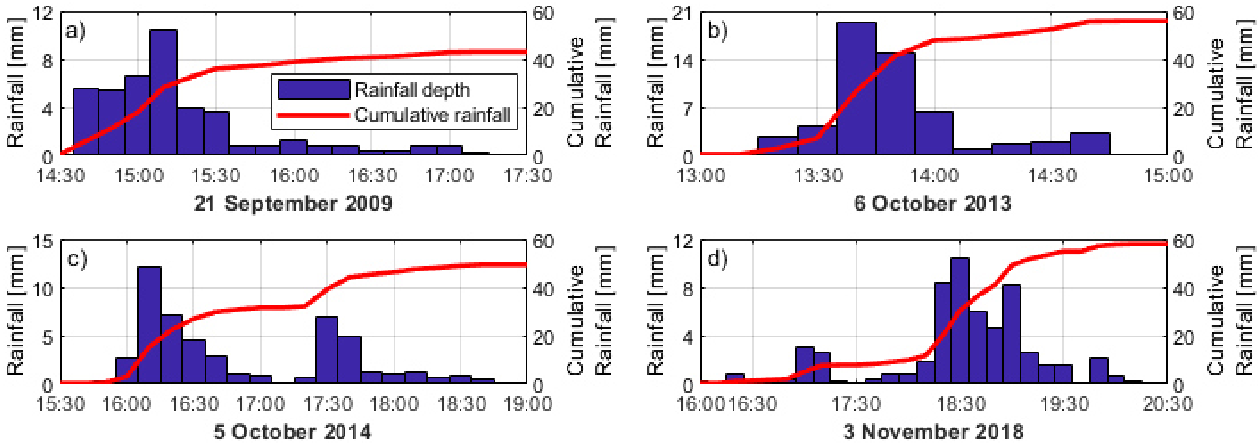


Figure 5. Rainfall collected at the rain gauge Uditore for the events occurred on a) 21 September 2009, b) 6 October 2013, c) 5 October 2014, and d) 3 November 2018.

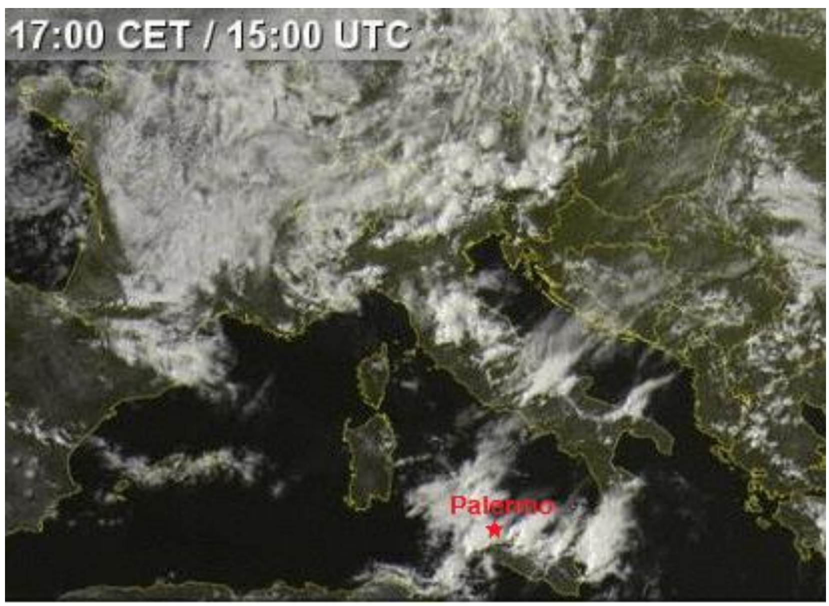


Figure 6. Thunderstorm cell observed from the Meteosat-11 project satellites (image in the visible channel) on 15 July 2020 at 17:00. Image provided by the EUMETSAT of the UK Met Office (https://en.sat24.com/en/it/visual).

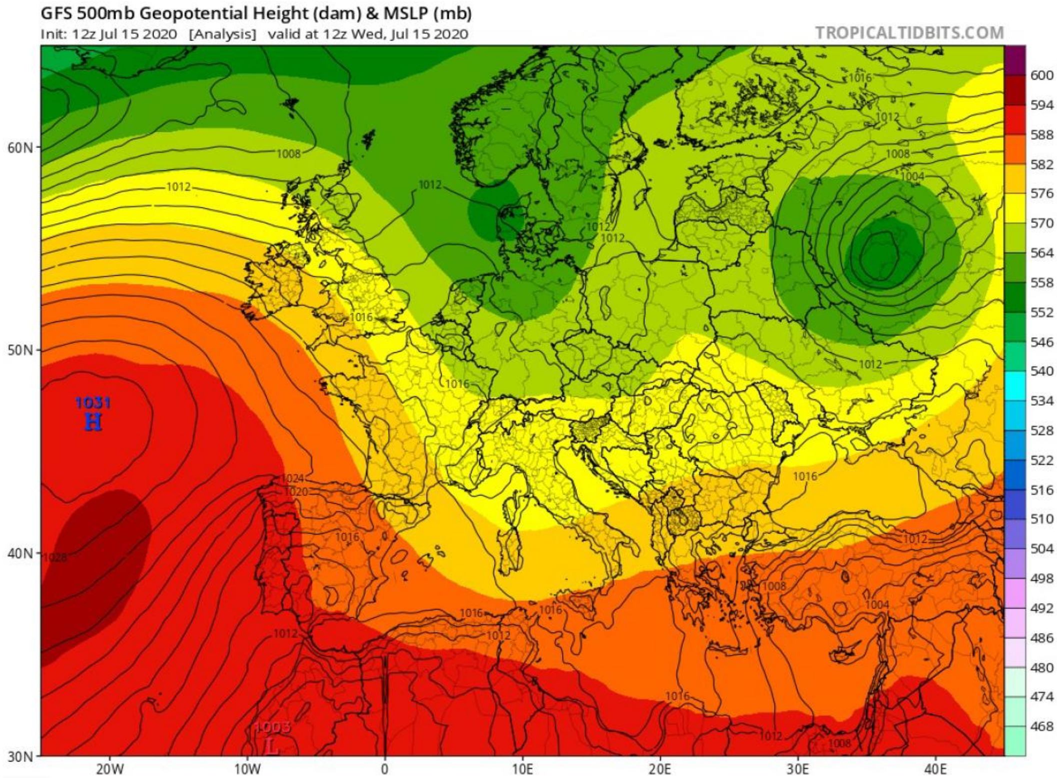


Figure 7. Geopotential heights at the 500mb level (12Z GFS) and mean sea level pressure (MSLP). Coloured scale bar indicates the geopotential height values in dam (i.e., decametre), while contour black lines indicate MSLP in mb (i.e., millibar). Image provided by the NCEP of the NOAA.

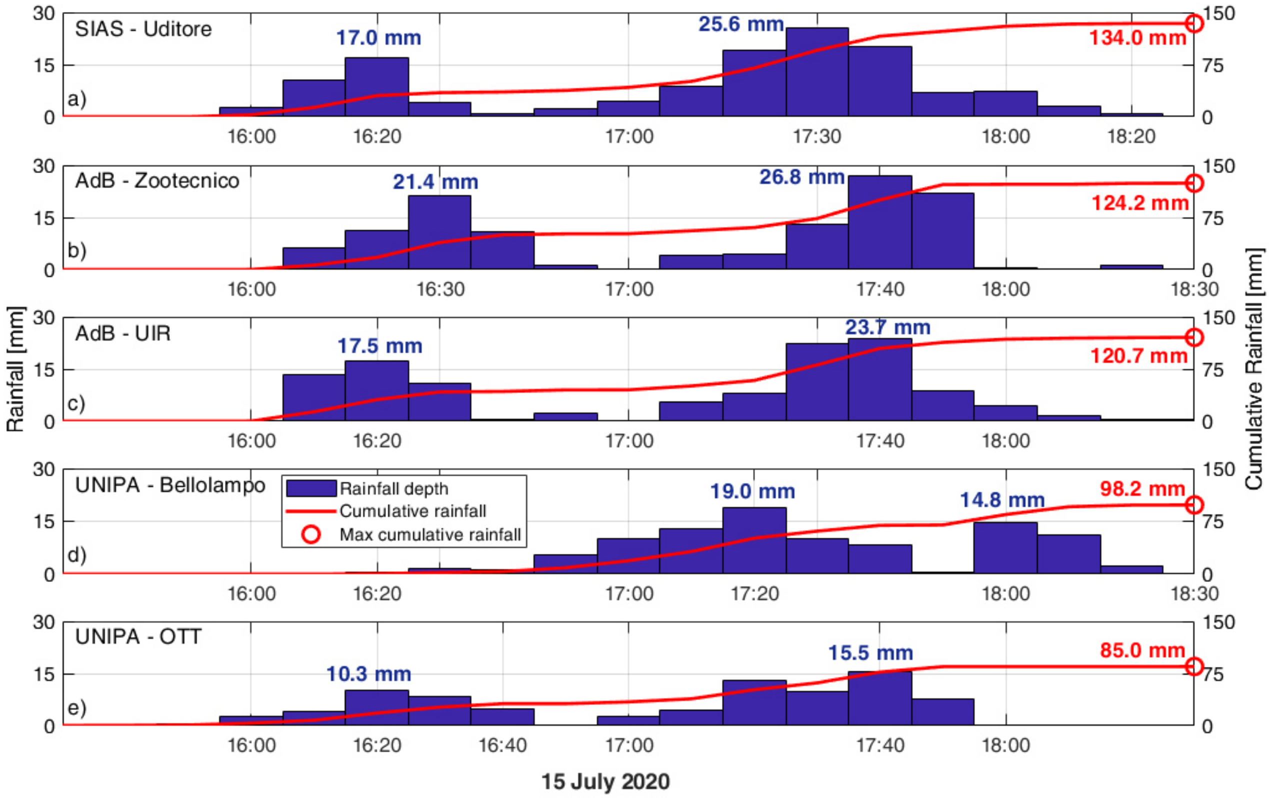


Figure 8. Rainfall collected at the rain gauges a) Uditore, b) Zootecnico, c) UIR, d) Bellolampo, and e) OTT on 15 July 2020 between 15:30 and 18:30.

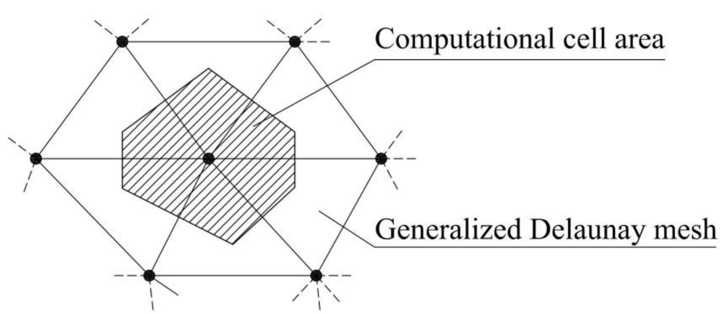


Figure 9. Computational mesh.

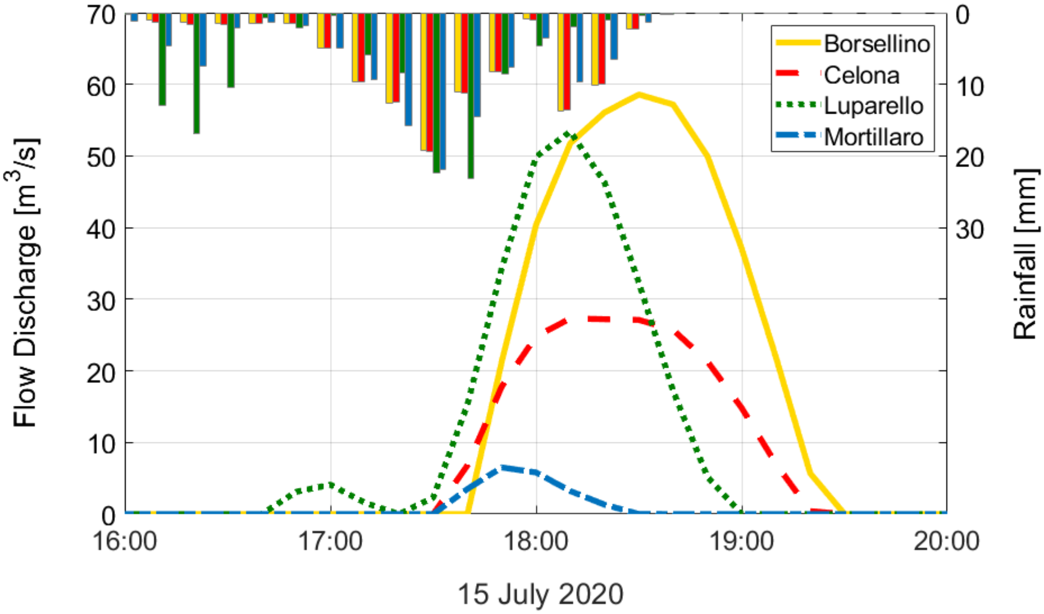


Figure 10. Rainfall Discharge obtained from the hydrological simulations in TOPDM. The bars in the upper part of the figure indicate the IDW interpolated precipitation over the four basins.

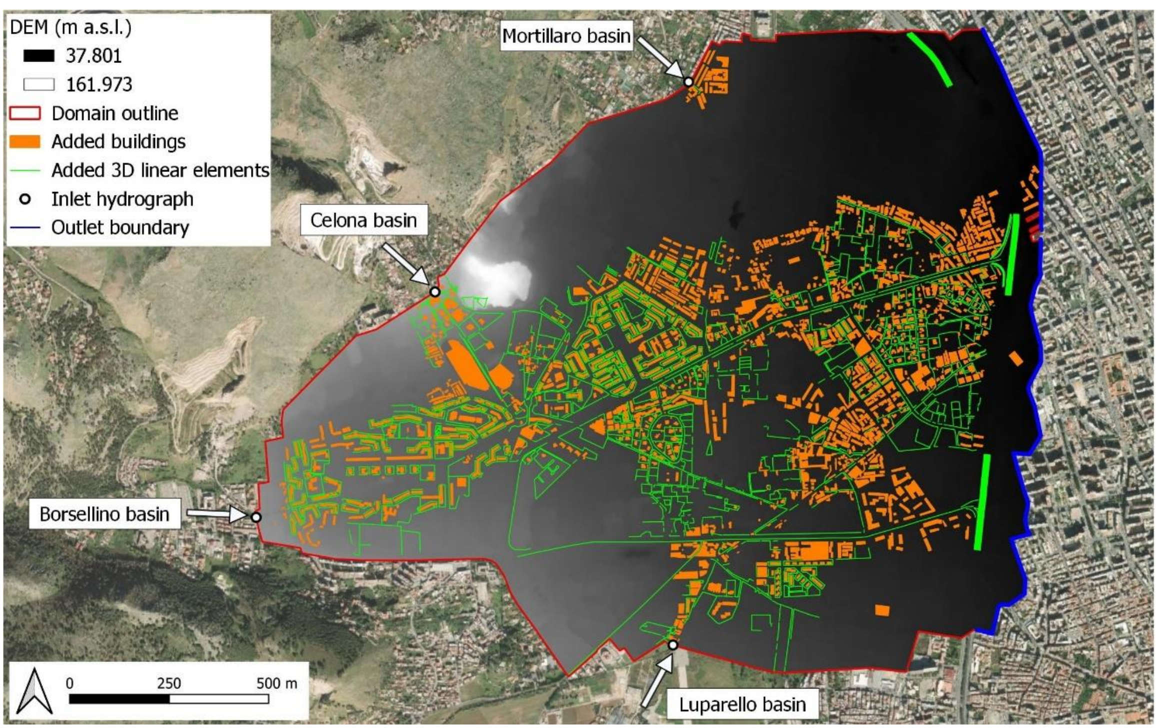


Figure 11. Domain reconstruction for the 2D hydraulic simulation in WEC-FLOOD.

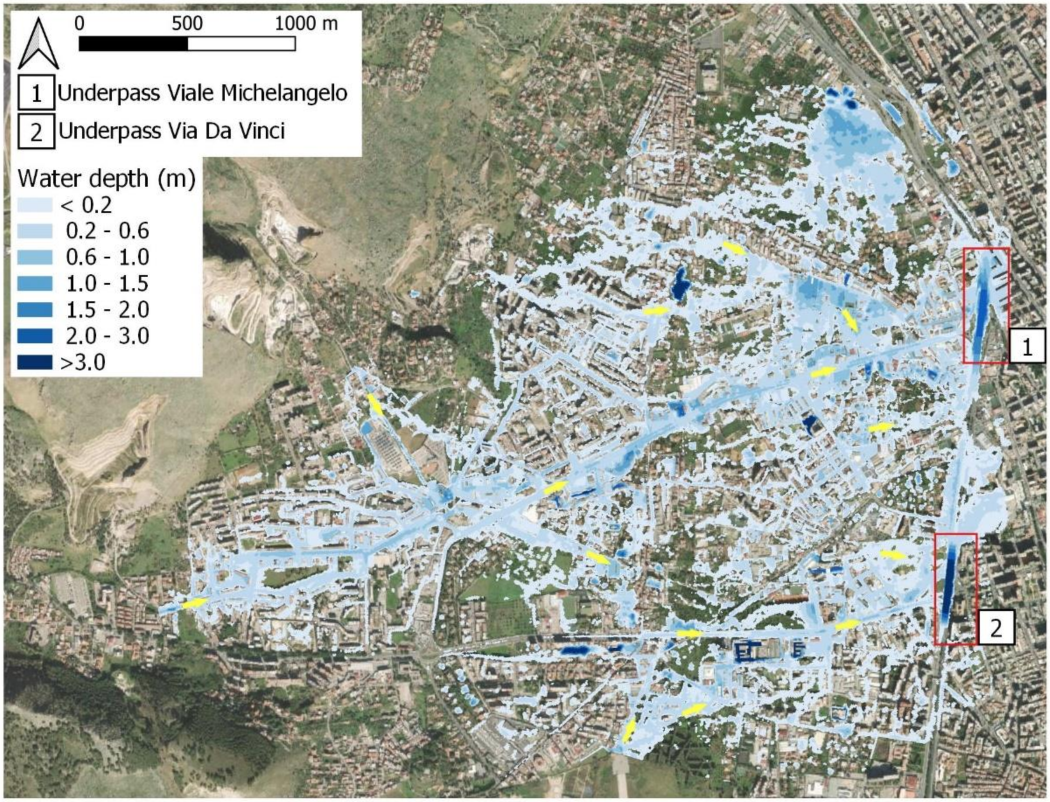


Figure 12. Map of the maximum flood depths reached on 15 July 2020 for the district Uditore - Passo di Rigano as simulated in WEC-FLOOD. The yellow arrows indicate the flow directions of the flood.

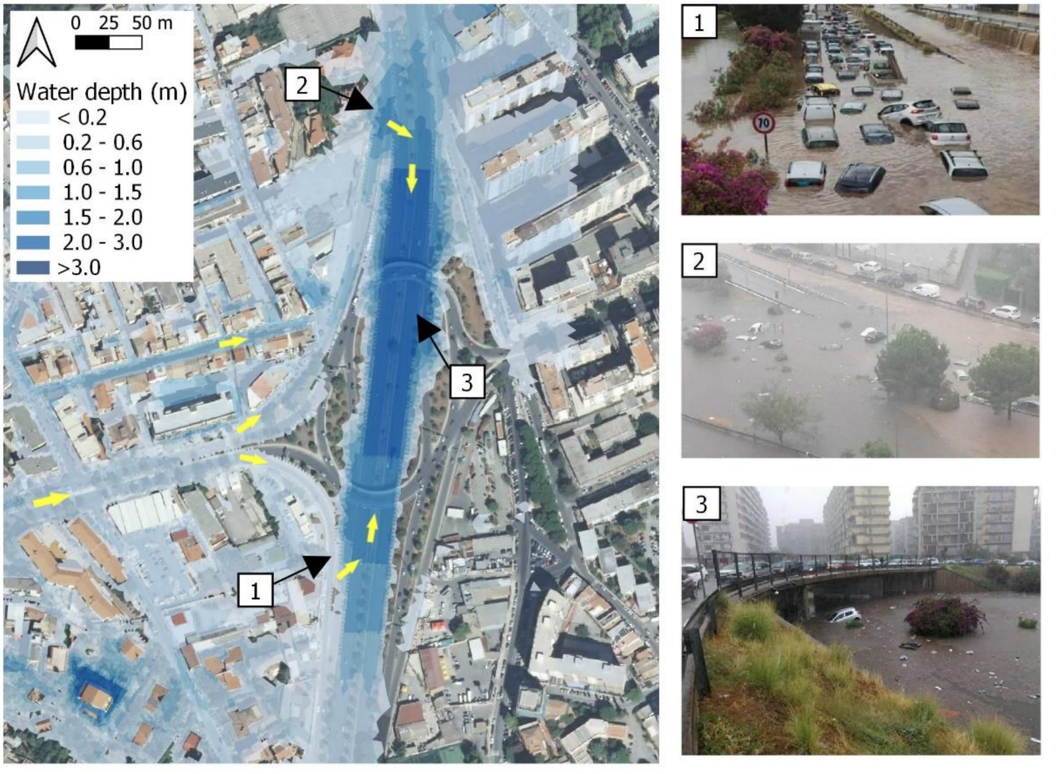


Figure 13. Maximum flood depths for the underpass Da Vinci as simulated in WEC-FLOOD. The yellow arrows indicate the flow directions of the flood.

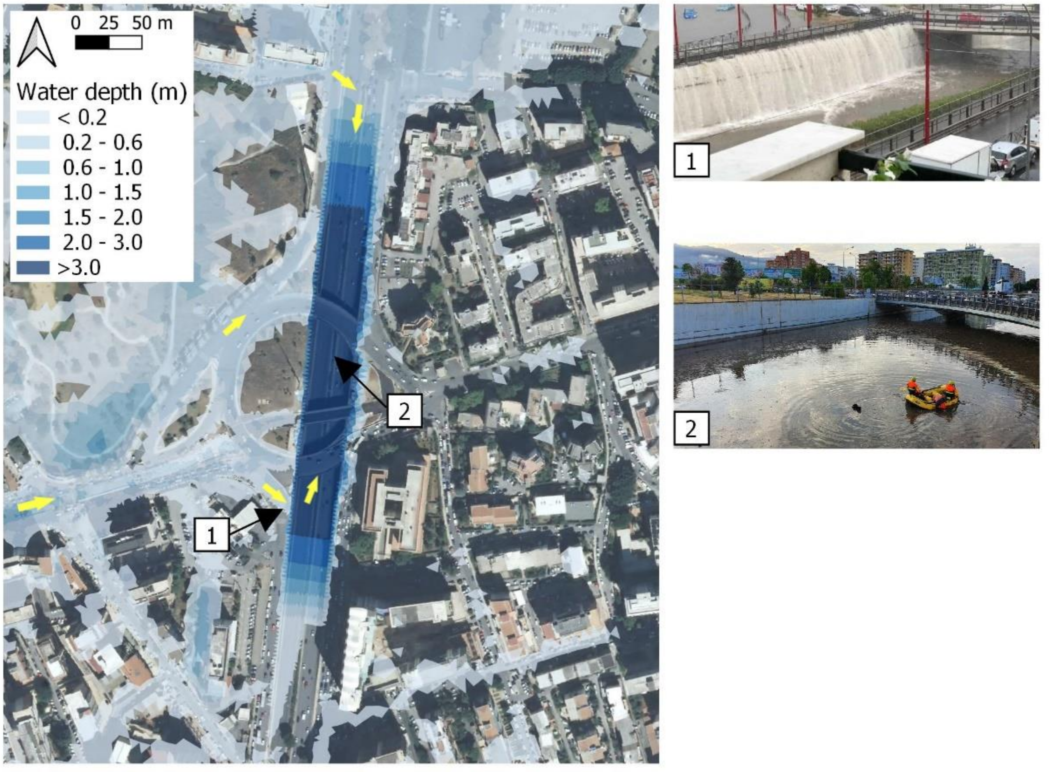


Figure 14. Maximum flood depths for the underpass Michelangelo as simulated in WEC-FLOOD. The yellow arrows indicate the flow directions of the flood.