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

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Abstract. In the last years, some regions of the Mediterranean area have witnessed a progressive increase in extreme events, such as urban and flash floods, as a response to the increasingly frequent and severe extreme rainfall events, which are often exacerbated by the ever-growing urbanization. In such a context, the urban drainage systems may not be sufficient to convey the rainwater, thus increasing the risk deriving from the occurrence of such events.

This study focuses on a particularly intense urban flood that occurred in Palermo (Italy) on July 15, 2020; it represents a typical pluvial flood due to extreme rainfalls on a complex urban area that many cities have experienced in recent years, especially in the Mediterranean region. 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 for modelling pluvial floods in complex urban areas under extreme rainfall conditions. Although the approaches and the related policies cannot be identical for all cities, the modelling 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

During the last decades, floods and flash floods have reached unprecedented levels in several parts of the globe (Andersson-Sköld and Nyberg, 2016;Gariano and Guzzetti, 2016;Hoeppe, 2016;IPCC, 2019;Jia et al., 2019;Messeri et al., 2015) including the Mediterranean region, where Sicily (Italy) has been one of the most affected areas in between 2008 and 2018 (Trigila and Iadanza, 2018).

Sicily is the largest island of the Mediterranean Sea and is characterized by a very complex morphology. The combination of its geographic position, morphology, and climate can lead to the generation of severe rainfall events, especially in between the end of the summer and the fall. In that period, indeed, the warmer air masses that move over the hot water of the Mediterranean Sea increase their atmospheric moisture-holding capacity (Drobinski et al., 2018;Pumo et al., 2019;Pumo and Noto, 2021) and, interacting with the steep orography on the coasts, can generate local convection processes that cause very heavy rainfalls (Dayan et al., 2015;Sheffield and Wood, 2008;Tramblay and Somot, 2018). In the last years, these rainfall events have become increasingly frequent and severe over the Mediterranean area (Arnone et al., 2013;Cipolla et al., 2020;IPCC, 2019), especially at the sub-hourly scale (Treppiedi et al., 2021), with a rainfall-runoff response often exacerbated by the ever-growing urbanization (Arnone et al., 2018;Easterling et al., 2000;Pumo et al., 2017).

Consequentially, in recent times, some intense rainfall events have caused urban floods and flash floods in many cities of the island, with consequent economic damages and, sometimes, human lives losses. For instance, on October 1, 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, a 160 mm rain event with a duration of 3 hours occurred in the city of Licata causing several damages and forcing the mayor of the city to adopt extreme measures of civil protection (e.g., people confined at home, closure of schools and all the economic activities, etc.). On August 8, 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, some heavy rainfall events in the east and south parts of the region, between the cities of Trapani, Palermo, and Agrigento, caused thirteen fatalities and more than 230 displaced people. In the town 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. Figure S1 in the supplementary material shows some of the impacts that these floods had on the territory that they affected.

All these flooding events occurred between the end of the summer and the fall and 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 scarcely able to infiltrate the water. Most of these floods can be classified as pluvial floods. Although this type of floods usually occur gradually with levels of water that rarely exceeds one meter (Palla et al., 2018;Stone et al., 2013;Sušnik et al., 2015) and does not cause an immediate threat to life, they may cause significant economic damage in some cases.

Modelling such a type of floods is never easy, especially when these affect very complex urban areas. Bulti and Abebe (2020) provided a review of the main flood modelling methods adopted for the study of pluvial floods highlighting the benefits and drawbacks of each approach. Some approaches, such as the rapid flood spreading (Lhomme et al., 2008;Wallingford, 2006), are easy to apply but return only the final state of inundation. Other approaches, such as the 1D, are recommended for studies that do not require high precision in describing the surface runoff routing, while still others, such as the 2D approach, seem to be more suitable for applications in urban areas where there is no stormwater drainage or the influence of stormwater drainage is considered insignificant on the flood phenomenon under study. Coupled models (i.e., 1D-2D) can provide accurate information but being computationally expensive both in terms of run-time and data requirements. In all cases, however, reliable modelling of the phenomenon always requires many kinds of information and level of accuracy, which are not always available or easy to obtain.

In this perspective, one of the main issues to deal with is the lack of observed data to be used as a reference for the calibration and validation of models (See, 2019). Indeed, differently than the case of fluvial floods in gauged systems, where the monitoring of the rivers makes available measures (i.e., water level, discharge, etc.) in different points of the domain, in urban areas there are no gauged sites that provide water level observations. Nowadays, one of the possibilities to overcome such a problem is represented by remote sensing data, which can provide the opportunity to overview flooded areas quickly and precisely (Di Baldassarre et al., 2009;Bates, 2012;Grimaldi et al., 2016). However, remote sensing data may not be always adequate to describe the evolution and the effects of a pluvial flood either because they are often not timely available for the satellite orbit revisit time (Annis and Nardi, 2019), especially when floods have rapid temporal evolution and limited flood area extent (Notti et al., 2018), or because the substantial areas of urban ground surface may not be visible due to the shadow caused by buildings (Lu et al., 2010;Mason et al., 2021;Mason et al., 2014;Notti et al., 2018). In addition to remote sensing data, data gathered by citizens (i.e., crowdsourced data) are becoming increasingly important, even because of the spreading of smartphones and social media users (Hilbert, 2016). The growing availability of crowdsourced data, especially in urban areas, such as pictures and videos acquired by mobile devices (e.g., smartphones, tablets, digital cameras, etc.) and content sharing on social media platforms (e.g., YouTube, 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 of hydraulic models. Many studies have used crowdsourced data to investigate flood events in the last years (Annis and Nardi, 2019;Mazzoleni et al., 2015;Mazzoleni et al., 2018;Smith et al., 2017;Yu et al., 2016).

Although the highlighted difficulties, a correct pluvial flood model in a complex urban area is extremely important for a correct residual risk management by means of opportune civil protection plans and the continuous updating of the flood emergency plans. Moreover, pluvial flood modelling can be useful to demonstrate how in some cases a drainage system may not be efficient, thus increasing the hydraulic risk deriving from the occurrence of such events. Many of these systems, indeed, have been designed without regard to the impacts of urbanization and climate change on natural systems and, for this reason, are no longer suitable to drain the rain coming from some extreme events that are likely to become more frequent and heavier. All these aspects make it necessary for new paradigms in urban drainage design to develop new strategies for flood risk management based on the acceptance of a new concept in which flooding can be tolerated and viewed as a driver for societal development (La Loggia et al., 2020).

In this perspective, this study addresses questions regarding the way to deal with the flood risk in urban settlements where the economic, social, and cultural conditions do not allow either to build new drainage systems or to renew the existing ones. To do this, the study focuses on a particularly intense urban flood that occurred within the Uditore - Passo di Rigano district in Palermo on July 15, 2020, which represents a typical extreme rainfall pluvial flood over a complex urban area that many cities, especially in the Mediterranean region, have experienced in recent years. On that occasion, a precipitation lasted about two hours, with a cumulative rainfall of 134 mm and an intensity peak of 168 mm/h in five minutes, caused the flooding of the ring road of Palermo and its underpasses with several damage to cars and inconveniences to people. In that case, as well as 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 last decades, especially in the areas most affected by the event.

We capitalize on this event to create a modelling framework that can be assumed as a "paradigm" for those cases in which: i) complex hydrologic domains are linked to complex systems of natural channels integrated within an urban settlement; ii) the domain is forced with extreme precipitation; iii) there is a lack of observed data but a plenty of crowdsourced data that can be used qualitatively to verify the reliability of results returned by the modelling chain.

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, and the data used to validate the hydraulic model. The results and some insights about future management strategies are shown and discussed in Section 4. Section 5, finally, provides 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 the 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 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 is about 22 °C, with peaks higher than 35 °C during the summer.

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 conveyance 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 channel cross sections (Oliveri, 1996).

As it is possible to observe in Figure 3, there are four different main drainage areas that feed the above-mentioned channels 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 (i.e., culverts) 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 effects of rainfall-runoff response of more severe precipitation events. Moreover, the tramline, which is bordered by sidewalks and walls, acts as a channel that conveys the stormwater and causes a faster propagation of the flood wave towards the underpass Da Vinci.

The hydraulic hazard and risk maps for the study area are reported in the Hydrogeological Setting Plan (*Piano stralcio per l'Assetto Idrogeologico* - PAI) for Sicily, which is a regional plan that maps the hydraulic and geomorphological hazard and risk for the Sicilian territory. The PAI shows the presence of a hydraulic hazard only for two little areas in the upper and central parts of the domain of study, which were scarcely affected by the flood here studied. In this case, the hazard map of the study, which dates to the early 2000s, was made by using a very simplistic approach just based on the position of the morphological depressions and without modelling any flooding dynamics in the study area.

2.1 Overview of the most significant past flooding events

Over the past 15 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 that occurred between 2009 and 2019. As it is possible to notice from these examples, all the events occurred between the end of summer and the mid-fall as a consequence of convective rainfall events, 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 collectors 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 associated with the flooding events reported in Figure 4. All the events are relative to the 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 October 6, 2013) and about 4 hours (e.g., event of November 3, 2018), with an instantaneous (i.e., 10-min) intensity peak between 62.4 mm/h (e.g., event of September 21, 2009 and November 3, 2018) and 116.4 mm/h (e.g., event of October 6, 2013). All the events are characterized by a total rainfall higher than 40 mm, with a maximum of about 60 mm during the event of November 3, 2018 and 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 effects of rainfall-runoff response.

2.2 The precipitation event of July 15, 2020

The severe storm that affected the city of Palermo on July 15, 2020 was the heavier rainfall event recorded in the Palermo area during the last 90 years. It was due to a self-healing supercell that stationed in 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 rapid cooling of the humid air coming from the sea. Moreover, the presence of hills and mountains close to the sea favoured the downdraft of cold and dry air down to the sea, where the presence of warmer and humid air created the conditions for a new updraft that fed continuously the supercell. Figure S2 in the supplementary material 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) 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 6 shows the geopotential heights of the 500mb pressure surface (coloured map in Figure 6) and the MSLP (mean sea level pressure – solid lines in Figure 6) for the July 15, 2020 as forecasted by the 12Z GFS (Global Forecast System). From the analysis of Figure 6, 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 favoured the ascent, up to Sicily, of a subtropical jet stream. These conditions of instability were further exacerbated by the positive values of potential vorticity, extending from the lower Mediterranean/Sardinia Channel up to western Sicily, which injected further cold and dry air from the stratosphere.

The presence of a strong subtropical jet stream (around the 300hPa), cold and dry air (above the 600hPa), and very warm and humid air in lower layers are confirmed by the data recorded at the Radiosonde Data Station Trapani-Birgi (see Figure S3 in the supplementary material).

The storm caused a very high intense precipitation, especially over 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 7a). 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 July 6, 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 July 15, 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 July 15, 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 200 years, thus highlighting the exceptionality of the rainfall event occurred on that day in Palermo.

Similar rainfall depths were recorded also by the rain gauges nearby. Figures 7b, 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 7a), Zootecnico (Figure 7b), and UIR (Figure 7c) show similar shapes of hyetographs, 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 7d) and OTT (Figure 7e), 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 damages to cars and inconveniences to people. In the underpass Da Vinci, as measured by the Fire

Department, 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. 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 hydrological and hydraulic models that were used for simulating the event that affected the district Uditore – Passo di Rigano. Both the models have been developed at the Department of Engineering of the University of Palermo. A brief description of data used to verify the reliability of hydraulic model results is given as well.

3.1 Hydrological Modelling: the TOPDM

The *TOPography-based Probability Distributed Model* - TOPDM (Liuzzo et al., 2015;Noto, 2014) is a lumped conceptual model that allows the simulation, at the basin scale, of all the hydrological processes of interest for the sort of flooding here studied. The model belongs to the family of the *Probability Distributed Models* - PDMs (Moore, 1985), which represent 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 scales (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 comes from a saturation excess mechanism, the Hortonian runoff, 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 (i.e., baseflow) of the basin. The fast response (i.e., surface runoff) of the system is routed to the basin outlet by means of a routing module based on the concept of the Distributed Unit Hydrograph (Noto and la Loggia, 2007).

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:

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

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:

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

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:

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

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

The model returns in output, in addition to the hydrograph at the outlet of the basin, different hydrological state variables, such as the mean level of soil moisture within the watershed, the percentage of saturated area, the groundwater storage, and the potential and actual evapotranspiration.

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

3.2 Hydraulic Modelling: the WEC-FLOOD

The WEC-FLOOD (Filianoti et al., 2020;Sinagra et al., 2020) is a two-dimensional (2D) hydraulic model that solves the Saint Venant equations to study the flood propagation within a 2D domain. The model is suitable for the study in urban areas, where the high complexity in the modelling of the surface runoff prompts for the adoption of 2D models for a better simulation of the flooded areas (Abderrezzak et al., 2009;Dottori and Todini, 2013;Lamb et al., 2009;Mignot et al., 2006). 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:

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

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. To make the model work properly, it is necessary to define the initial and boundary conditions for the domain (Eq. 4). 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):

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

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

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 8), 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 8), or by the storm hydrograph, if the cell is a boundary cell.

3.3 Crowdsourced data

One of the main difficulties to evaluate the reliability of hydraulic simulations in urban areas is the absence of measured water depth values to be used for the validation of results. To overcome this problem, many studies have used crowdsourced data to analyse flood events (Annis and Nardi, 2019;Mazzoleni et al., 2015;Mazzoleni et al., 2018;Smith et al., 2017;Yu et al., 2016).

Considering the high density of population that characterizes the city of Palermo in the proximity of the viale Regione Siciliana and that it is a very busy road, especially during the summer period, the flood occurred on July 15, 2020 was photographed and filmed by many social network users.

Many data (e.g., videos and pictures) from YouTube and online local magazines (e.g., PalermoToday, Giornale di Sicilia, Live Sicilia, La Voce dell'Isola, etc.) were used to verify the reliability of hydraulic modelling results, above all in correspondence of viale Regione Siciliana and the underpasses Da Vinci and Michelangelo, which were the most affected areas of the investigated domain. The georeferencing of the images was possible by matching the crowdsourced data with information gathered from Google Street View.

4 Results and Discussion

This section presents the results of the numerical reconstruction of the flooding event that hit the city of Palermo on July 15, 2020 arising from the modelling framework proposed in this study. In particular, the hydraulic forcing to be propagated within the study area consists of the hydrographs simulated at the outlets of the four contributing catchments (yellow circles in Figure 3) with the TOPDM. The hydrographs were propagated within the study area with the WEC-FLOOD to simulate the flood map for the event under study.

4.1 Hydrological Modelling

The spatial distribution of the topographic index λ was derived from the 2 meters resolution Digital Elevation Model (DEM) data of the study area (Figure 3) with the Single-Flow Direction algorithm (SFD; O'Callaghan and Mark (1984)). The DEM is available at the SITR (*Sistema Informativo Territoriale Regionale della Sicilia* – Geographical Information System of Sicily). λ was used to derive the specific contributing area and the slope of each catchment with the W-M method (Wolock and McCabe Jr., 1995). 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) method to provide the spatial rainfall field over the study area; the distributed rainfall was then used to obtain the rainfall forcing, at the catchments scale, of the hydrological model.

The Passo di Rigano drainage system was supposed to be in perfect condition of maintenance, even though its actual state is not known because of its complexity. The information provided by the Municipality of Palermo was used to set the maximum discharge (i.e., channel capacity) for the Borsellino, Celona, Luparello, and Mortillaro channels equal to 40, 14, 25, and 11 m^3/s, respectively. These channel capacities were then subtracted from the simulated hydrographs and supposed to be conveyed downstream the study area by the culverts.

Figure 9 shows the flow hydrograph for each channel after the subtraction of its channel capacity. As it is possible to notice from Figure 9, 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 Modelling

4.2.1 The domain reconstruction

The digital reconstruction of the hydraulic computing domain was carried out using the 2 meters resolution DEM provided by the SITR. The complexity of the urban area required an improvement of the built-up environment, 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 10), 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 9) were assigned as inlet boundary conditions and then propagated within the domain of study with the hydraulic model. Moreover, a precipitation over the entire domain was obtained from the interpolated rainfall field. A zero-diffusion condition was assigned to the outlet boundary (blue line in Figure 10). Particular attention has been paid to the choice of the roughness coefficient to be used for the simulations; two different Manning coefficient values have been adopted for urbanized and natural areas (Chow, 1959), with values equal to 0.03 $s/m^{1/3}$ and 0.05 $s/m^{1/3}$, respectively.

4.2.2 2D urban flood simulation

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 11 shows the map of the flooded areas returned by the simulations 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 11, 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 12). It was precisely the underpass Da Vinci (box 1 in Figure 11 and Figure 12), along with the underpass Michelangelo (box 2 in Figure 11 and Figure 13), the most critical area on July 15, 2020.

Figures 12 and 13 show the results of simulations in WEC-FLOOD for the underpasses Da Vinci and Michelangelo, respectively. During the flood event, the two underpasses worked as two reservoirs where the water depth reached values higher than 4 m. 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 12) and Michelangelo (Figure 13). The simulation returned a water depth of about 3.2 and 5.0 m in points 1 and 2 of Figure12, 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 model returned a water depth of about 1.5 m in points 1 and 2 and about 2.3 m in point 3 of Figure 13, which are compatible with the water levels shown by the pictures.

In order to make a further evaluation of the goodness of the results in terms of flooded area extent, these have been qualitatively compared with images provided by the Copernicus Sentinel-2 project (Drusch et al., 2012) of the European Space Agency (ESA) for the July 16, 2020 at around 09:50 limited to the areas of the underpasses Da Vinci and Michelangelo. The Sentinel-2 images of the July 14, 2020 at around 10:00 (i.e., the day before the flooding event) and July 16, 2020 at around 10:00 (i.e., the day after the flooding event) are reported in the supplementary material (see Figures S4a and b, respectively). In particular, the Figure S4b 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 WEC-FLOOD numerical simulations.

4.3 Future directions in urban stormwater management

Effective assessment and 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, and a correct residual risk management. The increasing availability of accessible crowdsourced information, along with always more accurate hydrological and hydraulic models, suggests new approaches in urban flood modelling, highlighting the importance to develop frameworks capable to:

1. produce reliable reconstructions of occurred events and map particularly vulnerable areas;
2. use crowdsourcing data also considering that satellite data are not always adequate to obtain observations during (or after) such critical events (see, for instance, the Figure S4 in the supplementary material) and that are often not timely available because of the satellite orbit revisit time;
3. forecast in near real-time the potential effects of incoming rainfall and, consequently, select adequate mitigation strategies;
4. run multi-scenario simulations during the urban expansion planning phase to preliminarily evaluate the effects of both new urban expansions, including grey, green, and blue infrastructures, and possible alternative interventions on the urban drainage systems for the adaptation of cities to the future hydraulic risk.

In areas particularly susceptible to pluvial and flash floods, it is extremely important to enhance the capability for rainfall monitoring and early flood warning, in order to take appropriate civil protection actions (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) could be an important option to drive emergency actions and reduce the potential flood damages.

With this regard, after the urban flood event of July 15, 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 July 15, 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).

Nowadays, 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 for the assessment of future risk and aiming to find new paths towards risk adaptation of smart, sustainable, and flood resilient cities. In highly urbanized areas, where modifications to the existing urban drainage system are difficult, and under a climate change context, with more frequent heavy rainfall events, it is necessary to shift towards a new way to manage the hydraulic risk and adapt cities to it.

There is therefore the need for a new paradigm capable to propose solutions changeable according to the rainfall event that is causing the flooding event. In 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), in significantly reducing runoff volumes and peak discharges and increasing the times to peak of an urban flooding. In this regard, it would be possible to plan the use of sparsely distributed NBS and BMP, such as urban green areas, green roofs, pervious pavements, or rainfall harvesting systems, which could contribute to mitigating the effects of rainfall-runoff response of ordinary rainfall events, with a return period comparable to that used 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 urban drainage system.

For extraordinary rainfall events, such as the one that has originated the event of Palermo investigated here, the only solutions that could contribute to reducing damages and risks are probably those oriented to the concept of floodability (La Loggia et al., 2020), which is based on the concept that flooding can be tolerated by the society and has to be viewed as a driver for societal development. A floodable system is a well-informed aggregation of resistant, resilient, and floodable subsystems in which people are the key actors. In such a system, people are instructed and trained to prepare themselves and adapt their properties and activities to the possibility of flood events and then to "live with floods". A learning-by-doing process is adopted to make the population able to adapt its strategies to the evolution of events and then to face also unexpectedly severe events. Moreover, the involvement of other actors, such as public bodies, citizen organizations, professional associations, commercial and industrial corporations, and technical experts, support the integration of structural mitigation measures with individual and coordinated actions that results into a reduction of cities' vulnerability and an improvement of the society's adaptivity.

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 fulfill hydrological roles. Open spaces could thus become spaces for restoring the damage done by excessive urban development, both in terms of hydrology and architecture, thus making it possible to adapt cities to future risk.

5 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, and the hydrological and hydraulic modelling framework necessary to correctly simulate its effects on rainfall-induced runoff response. 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 the new normal in the Mediterranean area; this is leading to an increased 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 centres, with continuous losses of natural soil and substantial modifications to natural drainage systems, is profoundly altering the effects of rainfall-runoff response of heavy precipitation on urban areas, often with dramatic consequences. With this regard, the case study investigated here, due to the precipitation characteristics, effects of rainfall-runoff response, flooding dynamics, and degree of urbanization can be considered as representative of what many cities in the Mediterranean area could have to deal with in the near 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. The crowdsourced data, which represent a new frontier to improve the observation, understanding, and modelling of floods especially in an 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, have made possible to verify the reliability of hydraulic model by means of reports and hundreds of pictures and videos found on social media. With this regard, the modelling framework here developed can be assumed as a paradigm for modelling of extreme rainfall pluvial floods in complex urban areas.

The study of the event of July 15, 2020 has pointed out 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. 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 adapt and 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

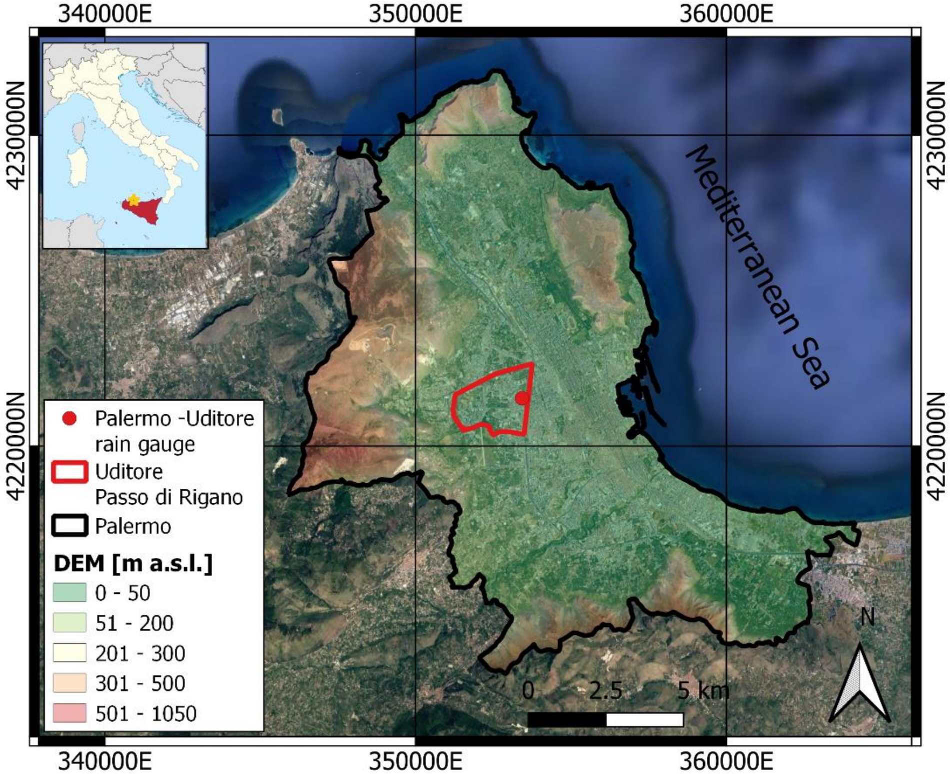

Figure 1. Aerial view of the city of Palermo (Sicily, Italy) overlaid to its Digital Elevation Model (DEM). Red line and red point indicate the Uditore - Passo di Rigano district and the Uditore rain gauge station of the SIAS rain gauges' network, respectively. The yellow star in the inset indicates the location of Palermo. Source aerial: © Google Maps Satellite basemap available within the QuickMapServices plugin of Quantum GIS.

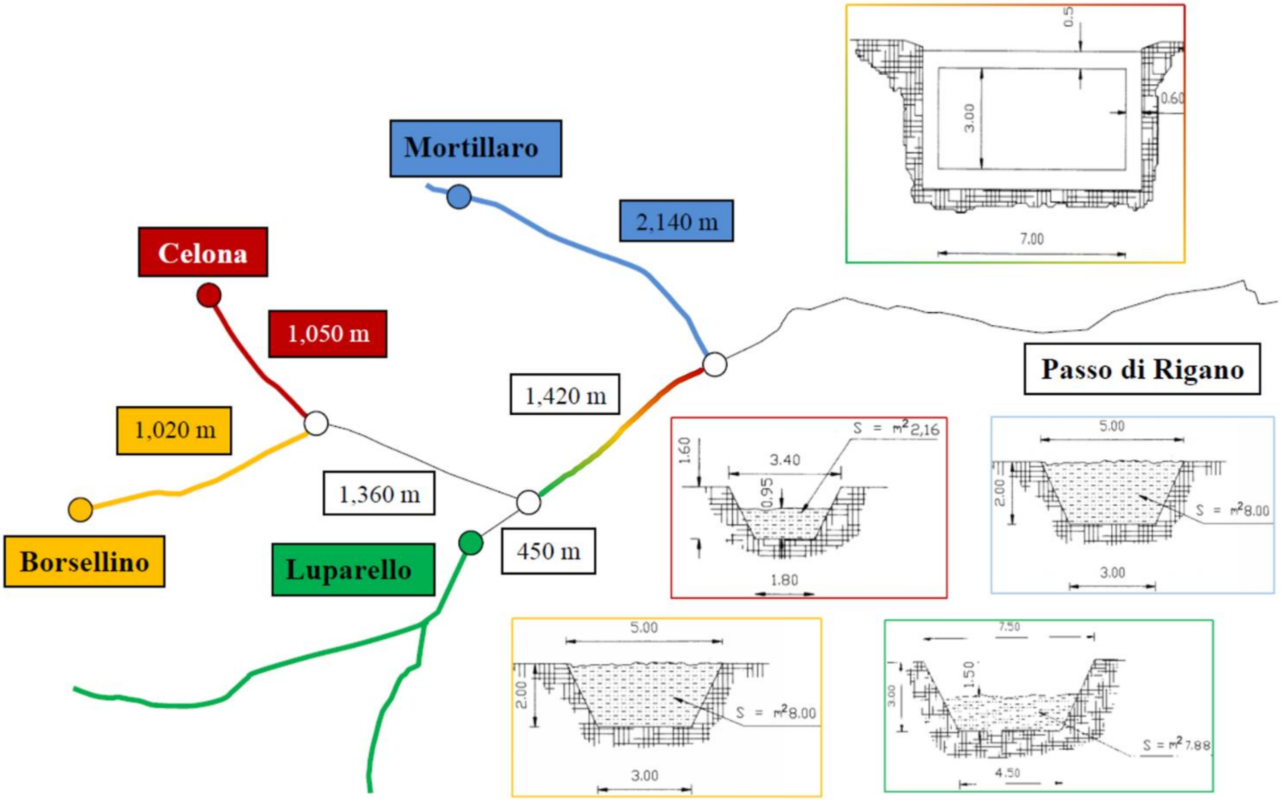

Figure 2. Passo di Rigano drainage system for the conveying and regulation of rainwater in the study area. Yellow color is associated with Borsellino, the red with Celona, the green with Luparello, and the blue with Mortillaro channels; the box within mixed colors (red, yellow, and green) refers to the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

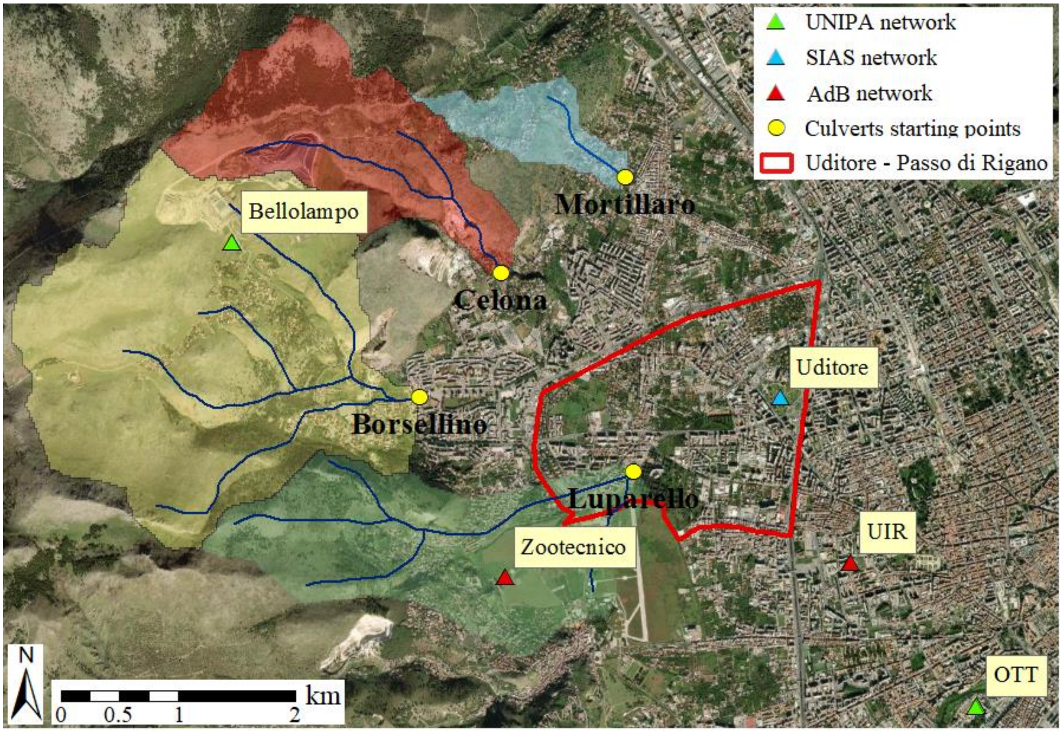

Figure 3. Main contributing catchments for the study area: Borsellino, Celona, Luparello, and Mortillaro. The yellow circles indicate the outlets of the contributing catchments and match with the start points of the culverts. The red, cyan, and green triangles indicate the rain gauges of the Basin Authority (AdB), SIAS, and University of Palermo (UNIPA) networks, respectively. The red line indicates the Uditore - Passo di Rigano district. Source aerial: © Google Maps Satellite basemap available within the QuickMapServices plugin of Quantum GIS.

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

Source picture 1: Rosalio (https://www.rosalio.it/2009/09/22/allagamenti-in-citta/).

Source picture 2: La Voce dell'Isola (https://www.lavocedellisola.it/2013/10/palermo-nubifragio-in-corso-aerei-dirottati-viale-lazio-chiuso/).

Source picture 3: PalermoToday (https://www.palermotoday.it/foto/cronaca/temporale-palermo-allagamenti-foto-5-ottobre-2014/via-leonardo-da-vinci-foto-antonio-rao.html).

Source picture 4: Giornale di Sicilia (https://palermo.gds.it/video/cronaca/2018/11/04/maltempo-a-palermo-strade-come-fiumi-e-auto-impantanate-il-video-di-viale-regione-allagata-8592631d-fcf3-4afe-a92c-db35376cd5ac/).

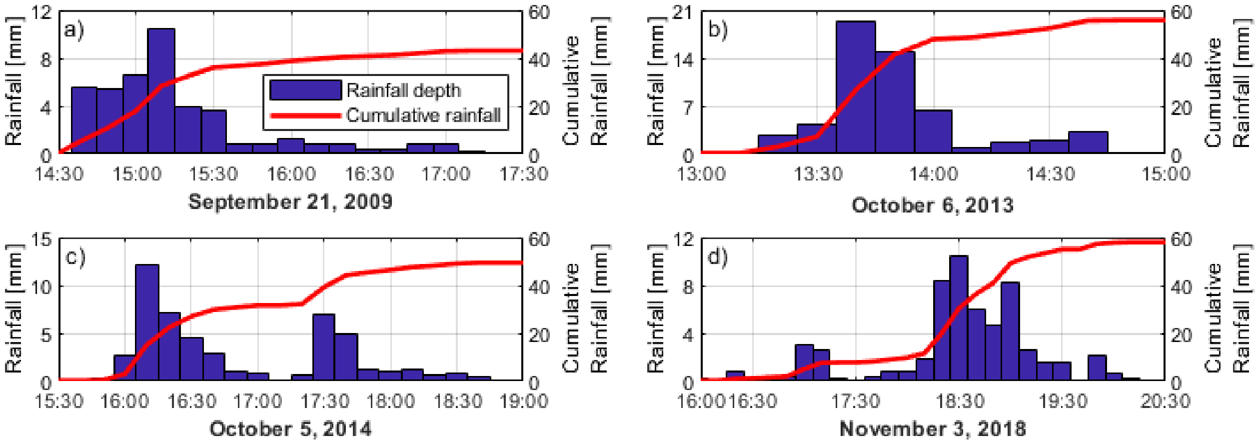

Figure 5. Rainfall collected at the rain gauge Uditore for the events occurred on a) September 21, 2009, b) October 6, 2013, c) October 5, 2014, and d) November 3, 2018.

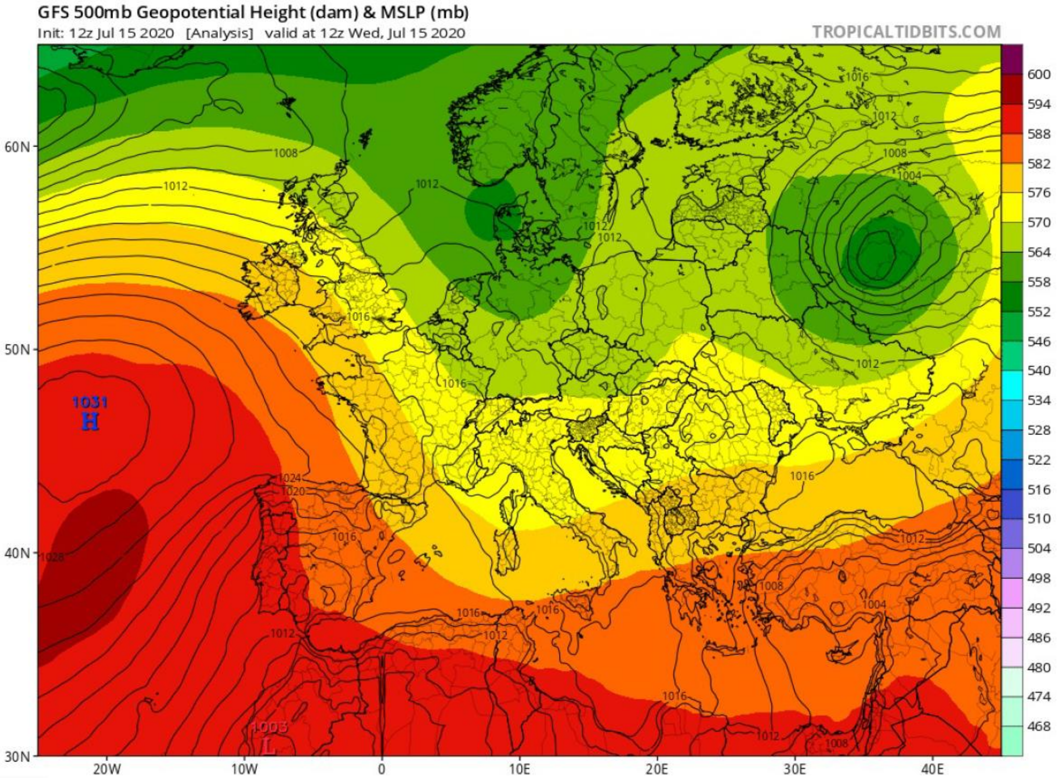

Figure 6. Geopotential heights at the 500mb level (12Z GFS) and mean sea level pressure (MSLP). Coloured scale bar indicates the geopotential height values in dam (i.e., decametre), while contour black lines indicate MSLP in mb (i.e., millibar). Source image: NCEP of the NOAA.

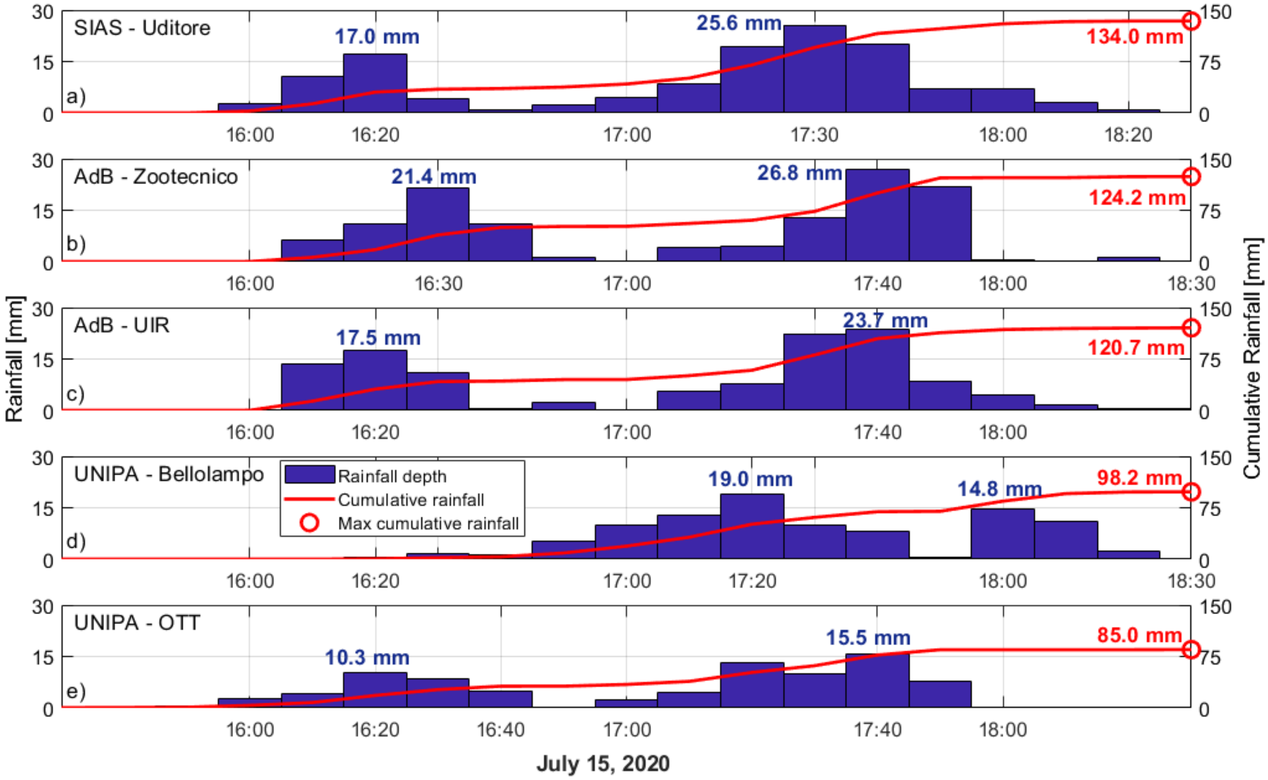

Figure 7. Rainfall collected at the rain gauges a) Uditore, b) Zootecnico, c) UIR, d) Bellolampo, and e) OTT on July 15, 2020 between 15:30 and 18:30.

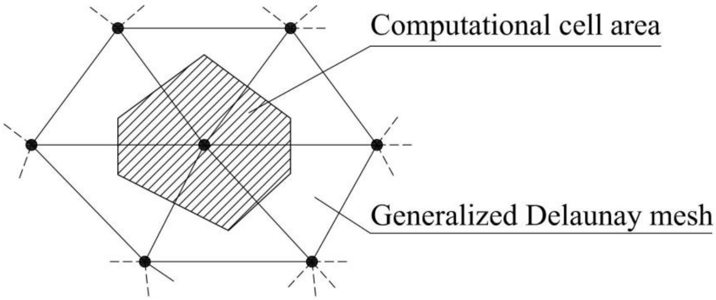

Figure 8. Computational mesh of WEC-FLOOD model. The vertices of each cell (black dots) are the computational centers of the cells (i.e., the point where the water surface is computed for the cell) and are obtained as the circumcenters of the generalized Delaunay triangulation.

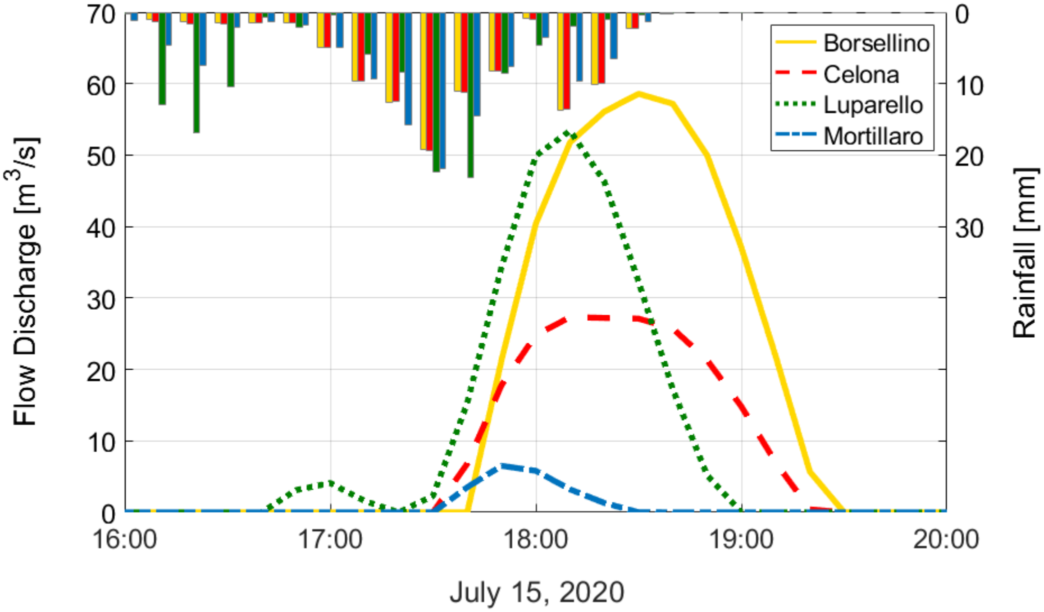

Figure 9. Rainfall Discharge obtained from the hydrological simulations in TOPDM. The bars in the upper part of the figure indicate the IDW interpolated precipitation over the four basins. 695

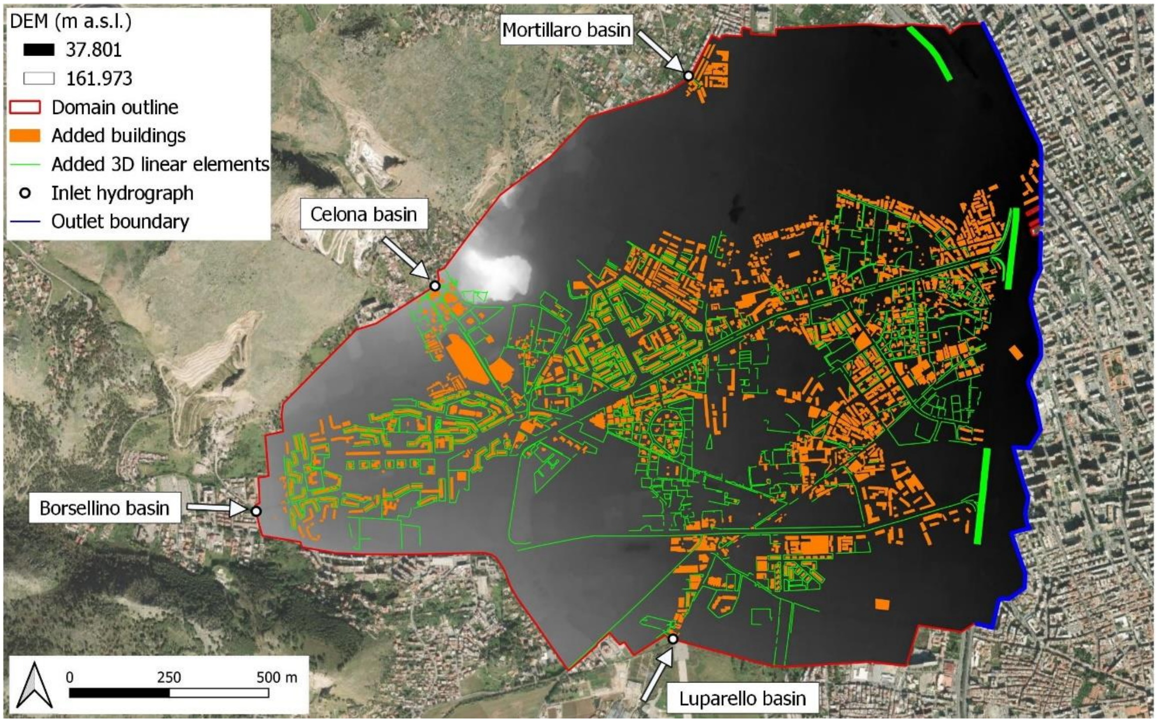

Figure 10. Domain reconstruction for the 2D hydraulic simulation in WEC-FLOOD. Source aerial: © Google Maps Satellite basemap available within the QuickMapServices plugin of Quantum GIS.

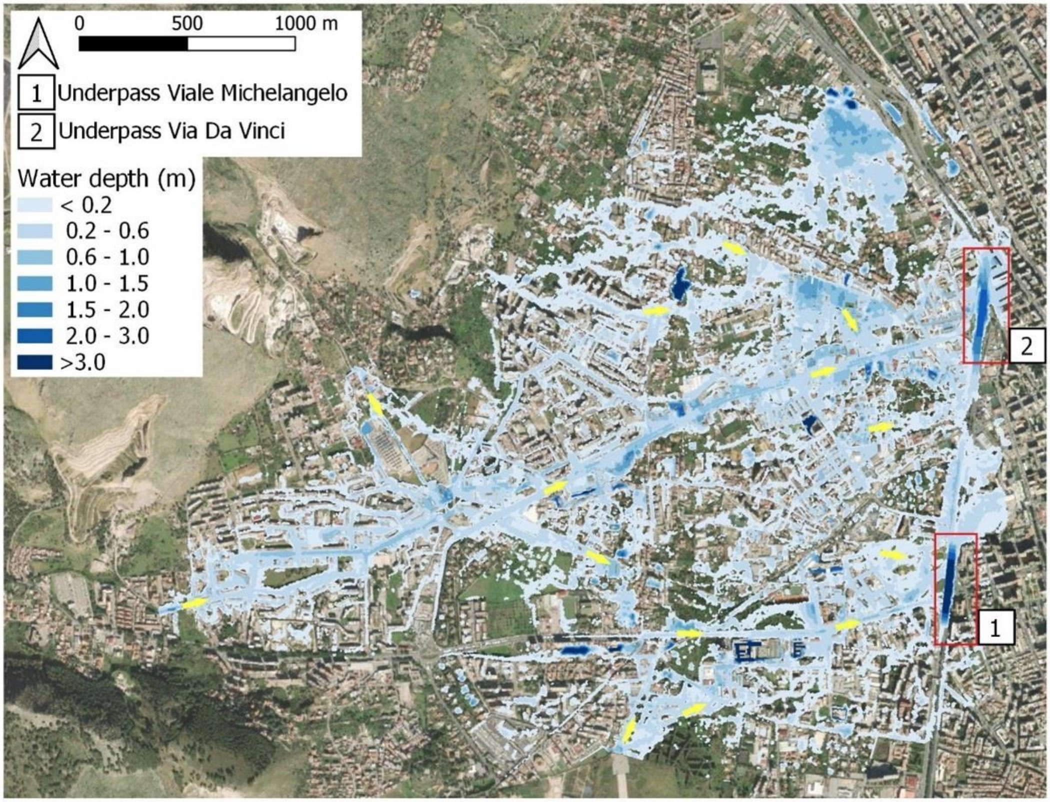

Figure 11. Map of the maximum flood depths reached on July 15, 2020 for the district Uditore - Passo di Rigano as simulated in WEC-FLOOD. The yellow arrows indicate the flow directions of the flood. Source aerial: © Google Maps Satellite basemap available within the QuickMapServices plugin of Quantum GIS.

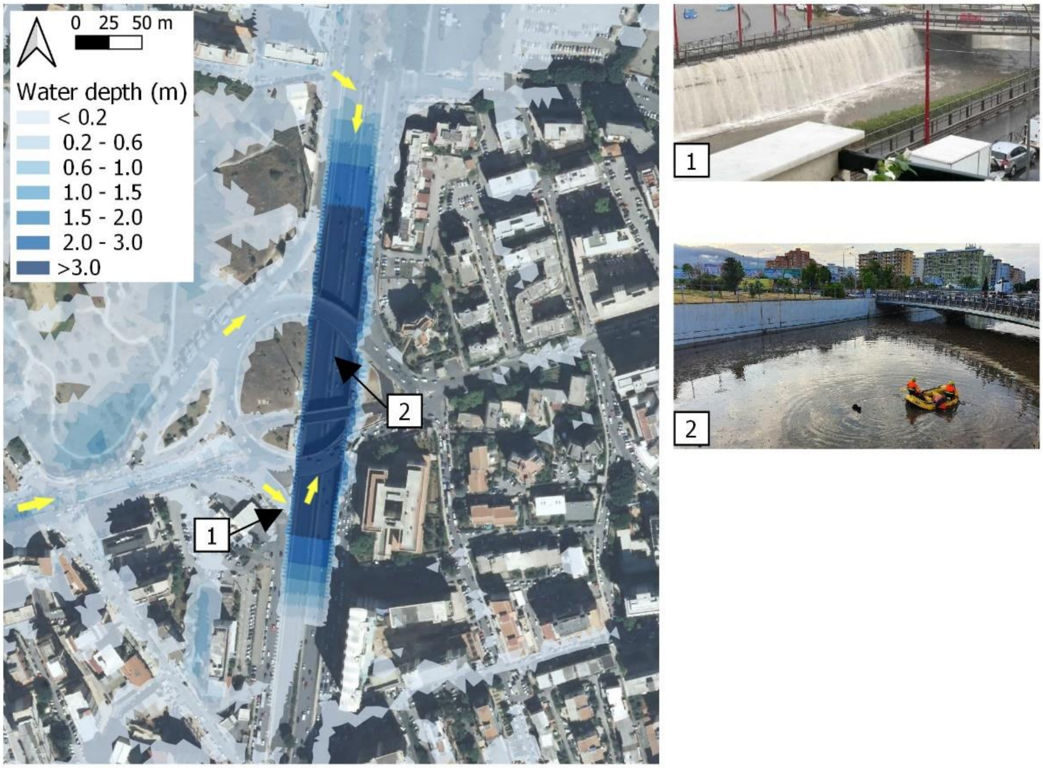

Figure 12. Maximum flood depths for the underpass Da Vinci as simulated in WEC-FLOOD. The yellow arrows indicate the flow directions of the flood. Source aerial: © Google Maps Satellite basemap available within the QuickMapServices plugin of Quantum GIS.

Source picture 1: PalermoToday (https://www.palermotoday.it/cronaca/nubifragio-palermo-15-luglio-2020.html).

Source picture 2: Monreale Press (https://www.monrealepress.it/2020/07/15/tragedia-in-viale-regione-morte-quattro-persone-nei-sottopassi/).

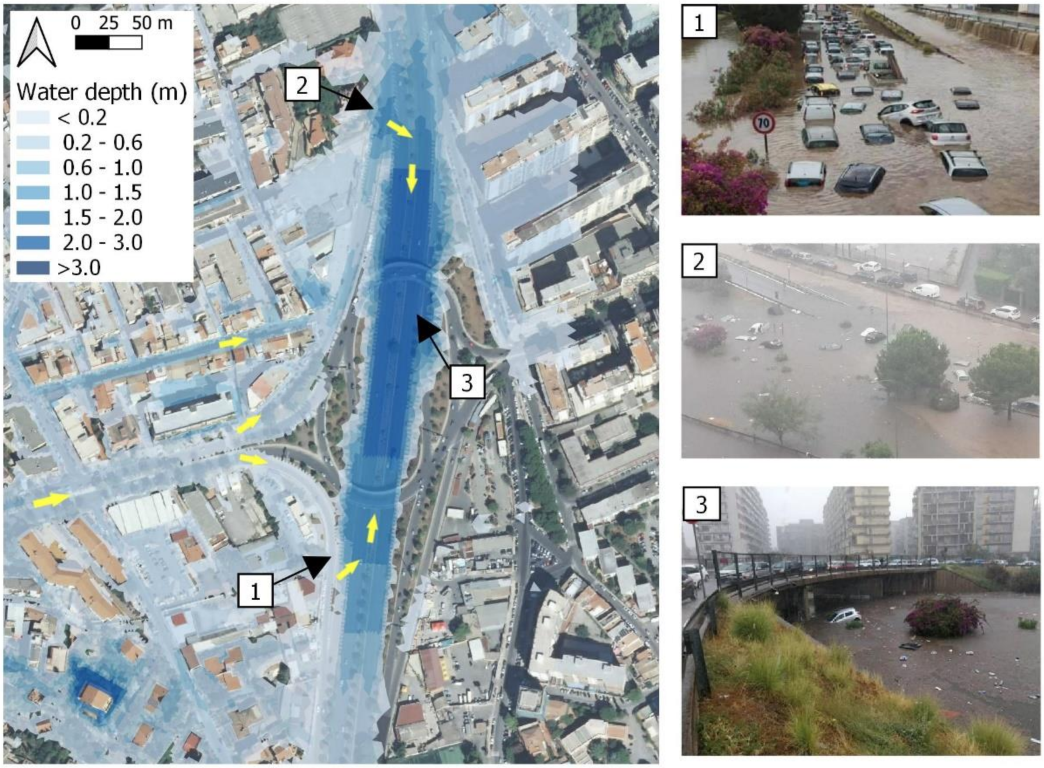

Figure 13. Maximum flood depths for the underpass Michelangelo as simulated in WEC-FLOOD. The yellow arrows indicate the flow directions of the flood. Source aerial: © Google Maps Satellite basemap available within the QuickMapServices plugin of Quantum GIS.

Source picture 1: PalermoToday (https://www.palermotoday.it/foto/cronaca/allagamento-palermo-15-luglio-2020-foto/#allagamento-festino-2020-viale-regione-4.html&gid=1&pid=1).

Source picture 2: La Repubblica Palermo (https://palermo.repubblica.it/cronaca/2020/07/15/news/palermo_-262015602/).

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