DERIVATION OF RAINFALL THRESHOLDS FOR PLUVIAL FLOOD RISK WARNING IN URBANISED AREAS

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KEY POINTS

- *Development of an operational tool for pluvial flooding warning in an urban area based on off-line rainfall thresholds derived by coupling a rainfall–runoff modelling and a hydraulic routing*
- *Inundation criteria has been considered instead of the usual flooding flow in order to assess threshold rainfall in urban areas*
- *The proposed methodology includes the diversity of rainfall threshold in urbanized areas*

1 INTRODUCTION

In the recent past throughout the Mediterranean area, many extreme events such as floods, debris flows and landslides occurred. Mediterranean ephemeral streams have specific features compared to other river systems; their basins are small and highly torrential and may generate flash-floods (*Camarasa-Belmonte & Soriano-Garcia*, 2012). Moreover, the rapid transformation processes of urban areas induced the increase of catchment imperviousness and the derived increase of surface runoff generated during rainfall events. However, flooding events in urban areas occur quite frequently as a consequence of rain events of lower intensity than the design one, even in case of correct network dimensioning.

The use of a reliable flood forecasting model in urban areas can play an important role in managing land and water resources. The purpose of this work is the development of a Decision Support System (DSS) for flash flood warning in an urban area. Usually, flood warning systems are based on on-line hydrological and/or hydraulic models in order to provide forecasts of water stages or discharges at critical river sections (*Martina et al.*, 2006; *Diakakis*, 2012; *Wu et al.*, 2015). This procedure is inappropriate for flash flood warning in urban areas or in catchments with a small area. According to the approach proposed by [Amadio et al., 2003; *Wu et al.*, 2015], in this study the rainfall threshold has been estimated in an urban area by coupling results of hydro-dynamic model in terms of water stage and flooding area. Particularly, dependency of the antecedent soil moisture conditions has been neglected because urban areas are characterized by imperious surfaces.

2 METHODOLOGY

This study proposes a methodology to point out in urban areas rainfall thresholds used in flash flood warning which should be influenced by the uncertainties in the rainfall characteristics, including rainfall duration, depth and storm pattern. Particularly, the methodology here developed has a modular structure consisting of different modules: synthetic hyetographs definition to gain the hydrological input to the hydraulic model; transformation of flood discharge to inundated area through a two-dimensional hydraulic model the FLURB-2D model (*Aronica & Lanza*, 2005) and, finally, quantification of threshold rainfall associated with specific inundation criteria.

2.1 Synthetic hyetographs derivation

Rainfall depth and duration can be directly calculated from observations recorded at the raingauges in the catchment. In order to define the temporal patterns of rainfall for each event, we used here the idea of mass curves (*Huff*, 1967; *Garcia-Guzman & Aranda-Oliver*, 1993; *Wu et al.*, 2006; *Candela et al.*, 2014). The variability of precipitation within a rainy period is represented by a dimensionless hyetograph $H(d)$:

$$H(d) = \frac{1}{I \cdot D} \int_{0}^{t} h(t)\, dt \tag{1}$$

that identifies the fraction of rainfall accumulated over the time interval [0, d]; t ($0 \leq t \leq D$) is a fraction of the total duration D of the considered event and d = t/D ($0 \leq d \leq 1$) is the correspondent dimensionless duration, h(t) is the rainfall depth at time t ($0 \leq h \leq V$), V= I•D is the total storm volume and D the storm duration for the event.

2.2 Flood propagation

FLURB-2D is a two-dimensional inertial model based on the Saint Venant equations originally developed for simulating the overland flow propagation on alluvial plains with uneven topography and applied to urban areas (*Aronica et al.*, 1998; *Aronica & Lanza*, 2005). Only the convective terms are neglected in order to eliminate the related numerical instabilities and to maintain the efficiency of the hyperbolic scheme in dealing with flow fields with small water depths:

$$\frac{\partial H}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0; \quad \frac{\partial p}{\partial t} + gh\frac{\partial H}{\partial x} + ghJ_x = 0\,; \quad \frac{\partial q}{\partial t} + gh\frac{\partial H}{\partial y} + ghJ_y = 0 \tag{2}$$

where $H(t,x,y)$ is the water surface elevation, $p(t,x,y)$ and $q(t,x,y)$ are the x and y components of the unit discharge (per unit width), h is the water depth, J_x and J_y are the hydraulic resistances in the x and y directions.

2.3 Threshold rainfall definition

A flood warning status can be easily recognised in a fluvial cross-section based on the estimated water stage by the rating curve or the hydraulic routing with the calculated runoff. However, in a urban basin, flood inundation is mostly due to the overland flow attributed to the overtopping runoff or heavy rain, and is defined as “critical inundation” according to various inundation criteria, including the critical water depth and critical flooding area. In this study thresholds rainfall are defined using the approach proposed by *Wu et al,* (2015); particularly, the flood inundation is defined when maximum water level and corresponding flooding area exceed critical values to find out the corresponding rainfall amount for the rainfall duration.

Starting from estimated water stages and flooding area from inundation simulation, carried out by the FLURB-2D hydrodynamic model, rainfall thresholds can be obtained according a specific inundation criterion, including, together, a critical water depth and a critical flooding area. In detail, for each rainstorm event, the first time step when the maximum of simulated water stages and the corresponding flooding area exceed specific inundation criteria. This time step, t^*, is named "time-to-inundation" and it differs for each rainfall event. Then, the corresponding rainfall threshold $R_i^{t^*}$, for the i-event and for a duration t, can be calculated starting from R_t, the rain at the time step t^*, using:

$$R_i^{t^*} = \sum_{t=0}^{t=t^*} R_t \tag{3}$$

3 CASE STUDY

The drainage basin (25 km^2), as study area, is Mondello catchment (Palermo) located in Sicily, Italy (fig. 1a). During the past century, this semi-rural zone has been progressively transformed into a tourist area, coupled with strong urban expansion; this fast urbanization has not been coupled with adequate drainage systems aimed to collect stormwater. As consequence, during rainfall events, the runoff volumes mainly propagate along the roads. Due to capacity of the drainage system being highly related to change in rainfall (*Zhou et al.*, 2012; *Freni & Oliveri*, 2005), the rainfall threshold plays an important role in the flash flood warning in this area. A portion of the semi-rural catchments surrounding the urbanised area does not contribute to the runoff generation due to the catchment topography. A covered drainage channel (the so-called Ferro di Cavallo (Horseshoe) (red line in figure 1a) delimits the area considered in this study. The channel was transformed into an underground sewer at the beginning of the twentieth century collecting both stormwater and wastewater from the urban area.

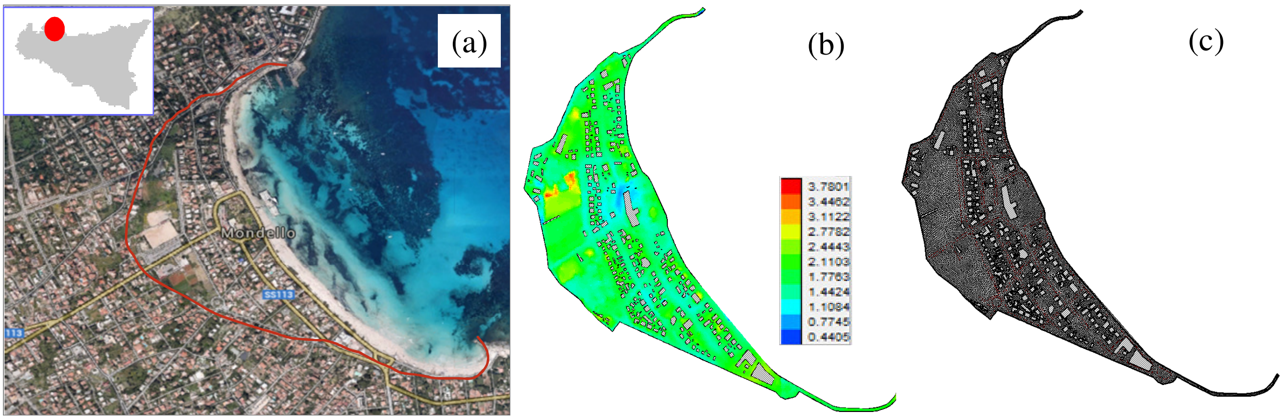

Figure 1. (a) Mondello catchment and study area (red line); (b) DEM (2x2) (elev. in meters above sea level); (c) finite elements mesh of the study area.

4 RESULTS AND CONCLUSIONS

Independent rainfall events were derived starting from rainfall data recorded at the raingauge Uditore, located in Palermo city, around 10 km from the study area and managed by a Regional Agency (SIAS) from 2000. Starting from rainfall data recorded from August 2001 to September 2014 on 10 minutes basis, 1051 significant rainfall events have been extracted. Particularly, two events were considered independent if they were separated by a dry period of at least 3 h. Information regarding rainfall events are summarized in Table 1. Rainfall events selected show a large range of volume (from 1 mm to 184.4 mm) associated with the maximum intensity on 10-min basis (from 1.2 mm/h to 148.8 mm/h), respectively. In addition, the durations of these events range from 30 to 2630 minutes.

	Average max intensity (mm/h)	10-min max intensity (mm/h)	Event rainfall volume (mm)	Event rainfall duration (min)
Max	45.60	148.8	184.4	2640.0
Min	0.19	1.2	1.0	40.0
Mean	2.03	10.35	9.18	347.93
Standard deviation	2.74	13.20	12.47	326.63

Table 1. Information and statistics of the rainfall data for 1051 events registered from August 2001 to September 2014

For the hydraulic simulations, 200 synthetic hyetographs have been generated using the Shuffle method constrained to the 10% and 90% percentiles of the historical events (fig. 2a). 200 hydraulic simulations have been carried out by using as input to the 2-D model the 200 synthetic hyetographs derived above. A single value of Manning coefficient was fixed at 0.02 s/m$^{1/3}$ for the entire domain, chosen to account for the blockage effects due to the presence of debris, wood, stones, etc. [*Aronica & Lanza*, 2005; *Aronica et al.*, 2014). Hence, the rainfall threshold is determined based on the water stage and flooding area reaching their critical values. According to Section 2.2, a finite elements mesh of the study area is required. The derivation of the mesh was based upon the morphology of the study area in order to cover the whole surface drainage network. Buildings and other obstacles are considered as islands in the mesh. The total meshed area is about 0.31 km^2, discretized as 22932 triangular elements. The geometric features (x,y,z coordinates) of 13208 nodes have been derived from a Digital Elevation Map (DEM) with 2m resolution obtained from an IDW interpolation operated on the digital vector map (1:1000) containing information at variable resolution (contour lines plus a number of measured local elevations mainly located along the streets). In figs. 1a and 1b DEM and the finite elements mesh for the study area are reported.

Eventually, using the FLURB-2D model with 200 generated rainfall hyetographs, 200 simulations of flooding cases in the Mondello catchment are obtained. Figure 2b shows an example of the flooding simulation. In accordance with *Wu et al.* (2015) designed inundation criterion include, together, a critical water depth of 0.3 m and a critical flooding area of 5% of the total area. According to section 2.3, for each rainstorm event, the time to inundation has been evaluated and the rainfall threshold for various durations with simulated hyetographs has been calculated using equation (3) under the inundation criteria. Figure 2c shows accumulated volume of rain versus corresponding times to inundation and rainfall threshold for the study area. Antecedent soil moisture conditions have been neglected because in urban areas soils can be considered impervious.

In this study, an advanced methodology is proposed to include the diversity of rainfall threshold for urban flooding. Issuing warning information to the public when rainfall exceeds given threshold is a simple and widely used method for flood prevention; moreover, inundation criteria has been considered instead of the usual flooding flow.

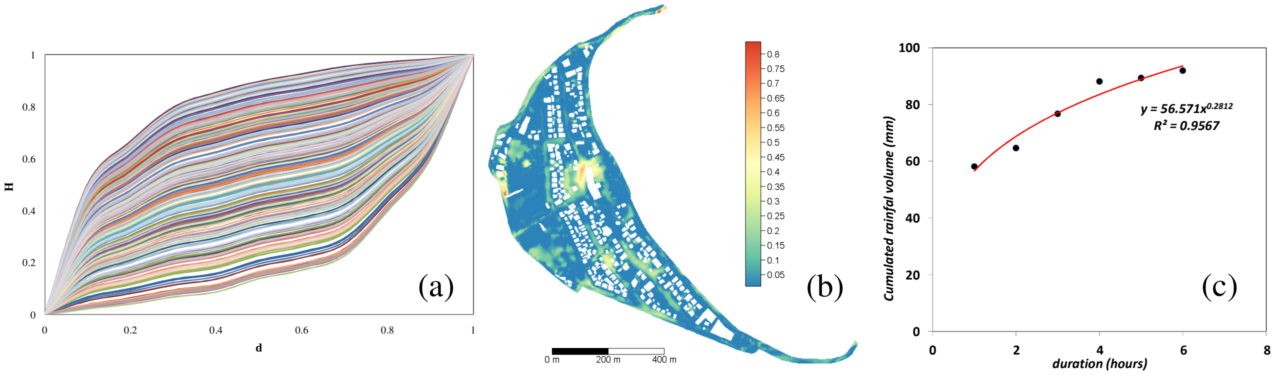

Figure 2. (a) Dimensionless synthetic hyetographs used for the simulations; (b) Example of single hydraulic simulations for given synthetic hyetographs and fixed rainfall duration and volume; (c) Rainfall threshold for given inundation criteria.

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