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ScienceDirect
Procedia Engineering 154 (2016) 818 – 825
Procedia Engineering
www.elsevier.com/locate/procedia

12th International Conference on Hydroinformatics, HIC 2016

Derivation of rainfall thresholds for flash flood warning in a Sicilian basin using a hydrological model

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Abstract

The damages caused by flash floods are among the most onerous in terms of loss of lives and damage to properties. Derivation of rainfall threshold is one of the approaches commonly used for the development of flash flood warning systems. Specifically, rainfall threshold is the rainfall amount that, for a given basin area and duration, is enough to cause flooding and, therefore, it indicates the maximal sustainable rainfall for a basin.

The aim of this paper is deriving flash flood-rainfall thresholds for a Sicilian basin (Italy) throughout a deterministic approach. The conceptual hydrological model TOPDM was used to estimate the amount of rainfall that, for given duration, hydrological initial conditions (i.e., initial soil moisture) and hyetograph type, causes the maximum flow at selected basin outlet. To reduce the uncertainty associated with the non-linearity of the rainfall-discharge process, different initial conditions in terms of soil moisture were considered. Additionally, the rainfall thresholds have been parameterized by taking into account three synthetic hyetographs types characterized by: (i) linearly increasing rainfall intensity, (ii) decreasing intensity and (iii) linearly increasing-decreasing intensity, which are able to describe the typical trends of rainfall events occurring in temperate climates. Results indicated that, for several events, the derived thresholds are able to identify events with peak discharge very similar to the discharge which characterizes the threshold, confirming the goodness of the methodology.

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doi:10.1016/j.proeng.2016.07.413

Keywords: rainfall thresholds; flash flood; Sicily; hydrological model.

1. Introduction

Flash floods represent a serious hazard in many areas of the world. Determining the rainfall responsible for flash floods is important, and may contribute to save lives. Operational real-time flash flood forecasting systems generally require a hydrological model to run in real time as well as a series of hydro-informatics tools to transform the flash flood forecast into relatively simple and clear messages to the decision makers involved in flash flood defense. One important aspect in the quantitative evaluation of the hazard associated with flash floods is the assessment of the characteristics of rainfall events (i.e., duration and intensity). The definition of critical rainfall intensity-duration thresholds can be a very useful tool to identify potentially critical areas, setting up early-warning systems or designing appropriate protection measures [1, 2]. Threshold runoff is the amount of rainfall accumulated during a given time period over a basin that is enough to cause flooding at the outlet of the draining stream, and it is thus an essential component of flash flood warning systems.

Over the last decade, many studies have developed rainfall thresholds for flash floods occurrence using different physical process-based models [1, 3]. [4] used GIS tools and digital elevation model developing a national system for the determination of the threshold runoff for several locations in the United States. Analysis of the results indicated the importance of channel geometry in flash flood applications.

[5] have addressed the possibility of providing flood warnings at given river outlet based on the direct comparison of the quantitative precipitation forecast with critical rainfall threshold values. This approach, applied to a tributary of the Arno river (Italy), leads to a simplified alert system to be used to supplement the traditional flood forecasting systems in case of system failures. The critical rainfall threshold values, incorporating the soil moisture initial conditions, resulted from statistical analyses using long hydrological time series combined with a Bayesian utility function minimization.

[3] proposed a method to use a distributed hydrological model in conjunction with threshold frequencies to improve the accuracy of flash flood forecasts at ungauged basins. The model produced high-resolution grids of peak flow forecast frequencies during rainfall events. Forecasters can compare these grids to locally derived threshold frequency (TF) grids for warning decisions. TF grids may be derived from several sources of information such as known flood frequencies at selected river locations and local hydraulic engineering design standards. Simulation results for 10 basins in Oklahoma and Arkansas, US, were analyzed to (1) improve understanding of distributed hydrologic model accuracy in small basins, when forced by operational quality radar-based precipitation data, and (2) demonstrate that the method can provide an inherent bias correction using available operational data archives to develop statistical parameters.

[1] used a semi-distributed conceptual rainfall-runoff model, following the structure of the *probability distributed model* (PDM), to evaluate a threshold-based flash flood warning method, by considering a wide range of climatic and physiographic conditions based on data from 11 basins located in Italy and France. The method was derived from the flash flood guidance (FFG) approach. The FFG is the rainfall depth of a given duration, taken as uniform in space and time on a certain basin, necessary to cause minor flooding at the outlet of the considered basin. This rainfall depth, which was computed based on a hydrological model, was compared to either real-time-observed or forecasted rainfall of the same duration and on the same basin. If the nowcasted or forecasted rainfall depth was greater than the FFG, then flooding in the basin was considered likely.

[2] provided an operative methodology for rainfall thresholds definition, in order to provide optimal flood warnings at river outlet. The procedure for the definition of the critical threshold was based both on the observed precipitation and the hydrological response of the basin. Thresholds rainfall values that generated critical discharges at given outlets were estimated by modeling the hydrological response for several configurations of different initial soil moisture conditions.

In this framework, the objective of this work was to derive rainfall thresholds for the hydraulic risk for the Oreto river basin, located in Sicily, southern Italy, using the calibrated conceptual hydrological model TOPDM [6]. Specifically, the model was used to estimate, for given duration and hydrological initial conditions, the amount of rainfall that causes the critical flow at the basin outlet. To reduce the uncertainty associated with the non-linearity of the rainfall-runoff process, different initial conditions, in terms of soil moisture, were considered for each event. Moreover, in order to take into account the effect of the hyetograph types, three different types of synthetic hyetographs were taken into account, characterized respectively by: linearly increasing rainfall intensity, decreasing intensity and linearly increasing-decreasing intensity (isosceles triangular shape), which are typical of rainfall events occurring in temperate climates. As a result, rainfall thresholds for the hydraulic risk have been obtained as a function of the hydrological initial conditions and of the hyetograph type

2. Hydrological model TOPDM

The TOPDM (*TOPography based probability Distributed Model*) [6, 7] is a lumped conceptual model based on the PDMs (*Probability Distributed Models*) [8]. It can be used to simulate runoff and analyze hydrological processes at the catchment scale using a daily time-step. As part of the PDM family models, TOPDM represents the basin as a series of storages of capacity c variable within it. Each of these storages takes up water from rainfall and loses water by evaporation and vertical drainage, until either the storage fills and spills, generating direct runoff q', or empties and ceases to lose water by evaporation and vertical drainage. The water lost by evaporation, from the storage, simulates the complex process of evapotranspiration. The storage capacity c can be considered as a random variable with probability density function $p(c)$; the portion of the basin characterized by capacities in the range (c, $c+dc$) is thus equal to $p(c)dc$.

TOPDM represents the basin as two different types of buckets: the soil moisture system, represented by a series of storages with capacity c; and a bucket representing the groundwater storage, which interacts with the sub-surface system (i.e. soil moisture storage) by receiving water volumes from it exclusively.

The direct runoff in the soil moisture system can occur according to two different mechanisms: *Hortonian* and *Dunnian*, according to which saturation of the soil column occurs from above and below, respectively. The *Dunnian mechanism* occurs when, during a generic rainfall event, the smallest storages, i.e. those with a storage capacity lower than a dynamic threshold capacity c^*, are totally filled and begin to produce direct runoff as a result of exceeding storage capacity. The *Hortonian mechanism*, instead, occurs in the storages not yet saturated, i.e. the storages greater than threshold capacity c^*; these storages maintain a residual capacity which can be filled by infiltrating water, while the infiltration excess produces just the second component of direct runoff.

Vertical drainage to groundwater, represented as a storage with unlimited capacity, is simulated as well. This storage does not exchange water with the sub-surface system, and it generates the slow response of the basin. On the whole, two runoff components can be identified in such model schematization: the surface direct runoff, which represents the "fast response" of the system; and the "slow response" given by the subsurface runoff, which comes from the soil moisture system, and by the groundwater runoff, which comes from the groundwater storage. 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*. For a complete description of the TOPDM, interested readers are referred to [6].

The spatial distribution of the capacity c is estimated on the basis of the catchment morphology through the topographic index, λ, which is, as the capacity c, an indicator of the catchment capability to produce runoff:

$$\lambda = \ln\left(\frac{a}{tg\beta}\right) \tag{1}$$

where a is the cumulative area drained through a unit length of contour line and β is the local surface slope. Specifically, a linear relationship is imposed between the two variables:

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

where c_{min} is here set equal to 0 and c_{max} is a model parameter.

3. Case study: the Oreto river basin

The case study has been carried out on the basin of the Oreto river at Parco. The watershed of this ephemeral river is located in the northern coast of Sicily, it covers an area of about 129 km^2, and spans an elevation range from 125 m to 1300 m a.s.l., with an average slope of 17.5% (10°). In the recent decades, an increasing transformation of the river due to intense urbanization and to water exploitation for civil and hydraulic uses occurred. Climatic data have been recorded from six weather stations of OA-ARRA (*Osservatorio delle Acque - Agenzia Regionale per i Rifiuti e le Acque*) from 1924. The mean annual precipitation (MAP) is ~1072 mm, with a dry season from May to September and a wet season from October to April. The mean annual temperature is 18 °C. Since 1924, the hydrometric station of 'Oreto a Parco' (608 m a.s.l.) have measured an average annual runoff of 497 mm.

4. Model Calibration

In order to calibrate the TOPDM model, first, the spatial distribution of the topographic index λ (eq. 1) was obtained from a DEM of 100 m resolution using spatial analysis techniques in ESRI ArcGIS. The next step was deriving the distribution of the storage capacity c through eq. (2) which requires the calibration of the parameter c_{max}. The theoretical gamma distribution has been fitted to the empirical frequency distribution of the storage capacity c. The three parameters of the gamma distribution have been estimated through the "maximum likelihood method". Other model parameters (i.e., maximum infiltration rate, saturated hydraulic conductivity, baseflow time constant, exponent of baseflow non linear storage, soil tension storage capacity, exponents of the infiltration and evapotranspiration processes) were first assigned starting from values of literature and then adjusted to the case study through a sensitivity analysis using the GLUE procedure. The GLUE (*Generalised Likelihood Uncertainty Estimation*) procedure [9], based on a Monte Carlo approach, recognizes and explicitly quantifies the uncertainty associated with the model's simulations. The approach assumes that all the parameters are acceptable estimators of the system. The first step was to generate many sets of parameters belonging to specified range by using Monte Carlo simulations. Subsequently, the performance of the single set is evaluated through the efficiency index *Nash and Sutcliffe*. During the calibration phase, the average Nash-Sutcliffe coefficient resulted equal to 0.78, while in the validation phase, we obtained an average coefficient equal to 0.67. Both the obtained efficiency values can be considered as representative of a satisfactory result following the classification of [10].

5. Set up modeling

The hydrological response in terms of discharge at the basin outlet was evaluated by forcing the TOPDM model with different rainfall events and starting from different initial conditions.

5.1 Generation of rainfall hyetographs

The response of the basin at the outlet was analyzed using synthetic rainfall events that, for a fixed duration and cumulative rainfall value, can be characterized by different temporal distributions. In this study, three different synthetic hyetograph types were used:

- Hyetograph - 1 (*H1*), triangular hyetograph with positive gradient;
- Hyetograph - 2 (*H2*), triangular hyetograph with negative gradient;
- Hyetograph - 3 (*H3*), isosceles triangle hyetograph.

The effect of each hyetograph type on the hydrograph at given rainfall volume is depicted in Fig. 1, which highlights that for this case study, the hyetograph that generates the maximum flow peak is the one characterized by a peak of storm at the end of the event, in agreement with other studies [11].

5.2 Initial conditions

The initial soil moisture conditions are taken into account in the model by imposing an initial value of discharge, Q_{init}. Starting from this value, the model is able to derive the initial conditions in terms of surface $S(0)$ and groundwater $W(0)$ storages. The effect of different initial conditions is analyzed by varying the initial discharge Q_{init} in the model simulations. For each simulation, Q_{init} was derived from the historical duration curve of the basin for a fixed value of the not exceeding probability $P(Q)$ of the average daily discharge. Ten values of $P(Q_{init})$ between 0 and 1, at step 0.1, were fixed obtaining ten initial discharge values Q_{init}.

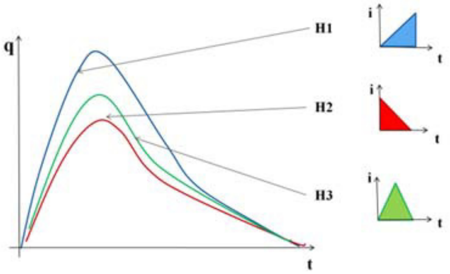

Fig. 1. Example of the selected synthetic hyetograph types *H1*, *H2*, *H3* and the derived hydrographs.

5.3 Derivation of rainfall thresholds

The scheme of the model simulations is described in Fig. 2 and is based on the generation of hydrological responses for rainfall events at fixed cumulative value, duration and hyetograph type. Specifically, 22 different values of cumulative rainfall, E_c, were chosen between 40 mm and 250 mm at step of 10 mm. Each of the E_c value was then used to create 24 events of different durations, d, varying from 1 to 24 hours, at hourly time-step. For each of the 22x24 E_c-d combinations, the 3 types of hyetographs described in section 5.1 were generated, for a total of 22x24x3 different rainfall events. Finally, the hydrological response of the basin (peak of the hydrograph, Q_{max}) to each event was evaluated starting from the 10 initial conditions identified by the 10 initial discharge values, Q_{init}.

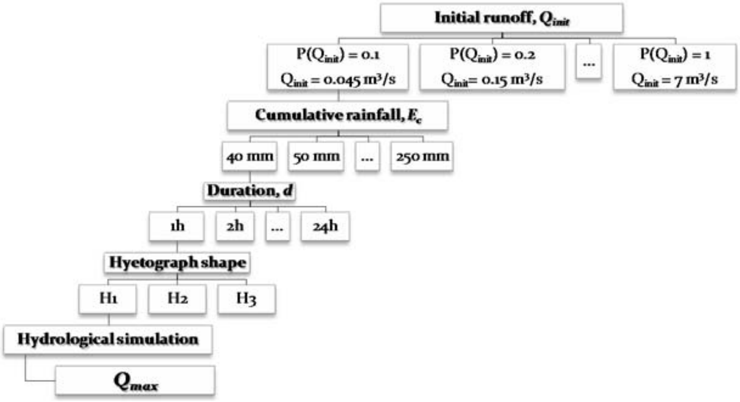

Fig. 2. Scheme of the model simulations.

The obtained maximum discharge values, Q_{max}, were then interpolated to derive "iso-discharge" curves on a E_c-d plot for each hyetograph type and initial discharge Q_{init}. The curves identify the cumulative value of precipitation for a given duration required to generate a fixed discharge. The adopted strategy led to a total of 16,000 simulations, and 30 E_c-d graphs.

6. Results and Discussions

6.1 Rainfall thresholds analysis

For sake of brevity, we show here the results of some selected simulations. Fig. 3 shows the rainfall thresholds for fixed Q_{max} (from 200 to 1600 m^3/s), P(Q_{init}) equal to 0.1 (i.e., dry initial conditions) and for the three hyetograph types (Fig.3a, 3b, 3c). Clearly, as the Q_{max} increases, the thresholds are higher in all cases. The hyetograph type *H1* tends to determine rainfall thresholds lower than the other cases; this is clearly highlighted in Fig. 3d in which the thresholds obtained with the three hyetographs and for only two values of Q_{max} (i.e., 200 and 400 m^3/s) are compared. Specifically, up to a duration of 5 h the results are similar, whereas at higher durations the differences are even more significant.

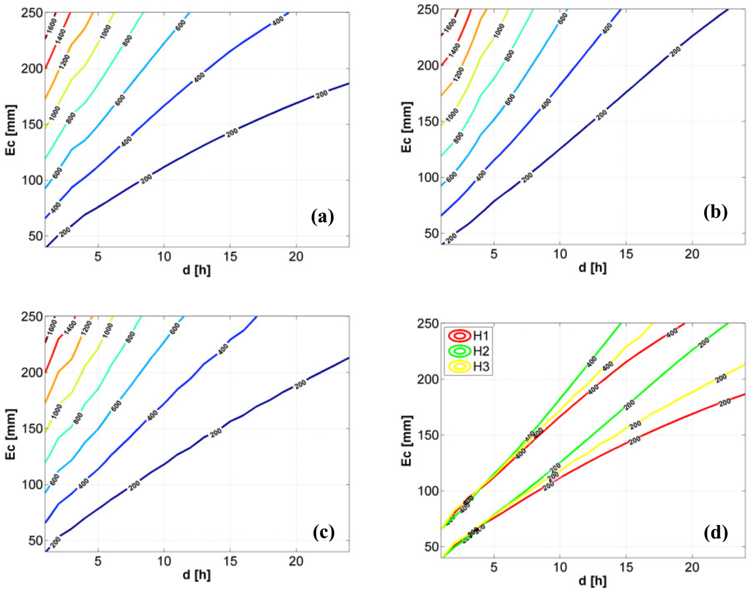

Fig. 3. Rainfall thresholds for fixed discharge ranging from 200 to 1600 m^3/s obtained using P (Q_{init}) equal to 0.1 and different hyetograph type: a) *H1*; b) *H2*; c) *H3*; d) comparison of the rainfall thresholds for Q_{max} equal to 200 and 400 m^3/s.

Fig. 4 instead compares the rainfall thresholds for the same Q_{max} values obtained at varying initial conditions and for the hyetograph *H1*. Compared to the previous case, the increase of the Q_{init} value clearly leads to lower rainfall thresholds. The comparison among the rainfall thresholds obtained with three P(Q_{init}) values is shown in Fig. 4d for Q_{max} equal to 200 and 400 m^3/s.

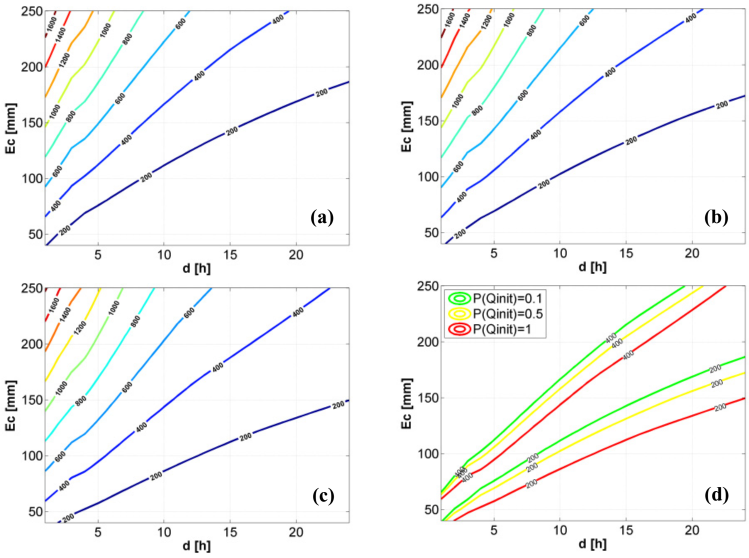

Fig. 4. Rainfall thresholds for fixed discharge ranging from 200 to 1600 m^3/s obtained using hyetograph type *H1* and different values of initial conditions, P(Q_{init}): a) 0.1; b) 0.5; c) 1; d) comparison of the rainfall thresholds for Q_{max} equal to 200 and 400 m^3/s.

In this case, for events of low duration and intensity, the method is more sensitive to the initial conditions of the system (Fig. 4d) then to the hyetograph types.

6.2 Model evaluation

In absence of observed historical flood events in the Oreto river basin, we evaluated the performance of the model system by verifying whether the E_c-d couples of values of the obtained thresholds generate a maximum discharge $Q_{\max}$ comparable with observed maximum discharge determined in the past by a historical similar event, i.e. E_c and d, and for the same initial conditions and similar hyetograph shape. In particular, we used discharge data observed in the period 1998-2009, for the Oreto at Parco, and relative to twenty different events. The hyetograph type was selected based on the cumulative rainfall distribution of the selected event. Specifically, the choice was based on the assessment of the "major similarity" between the observed rainfall event and the previously defined hyetograph types.

For sake of brevity, we present here only the results for one event occurred in December 1998. The event is characterized by a cumulative rainfall value of 36.31 mm and duration equal to 8 hours, while the maximum discharge of the recorded hydrograph was equal to 84.34 m^3/s. The comparison between the cumulative rainfall and the three hyetographs types (Fig. 5a) shows that the cumulative rainfall curve is similar to the hyetograph type *H3.* The initial conditions were evaluated based on the value of discharge measured by the hydrometric station before the rainfall event, and equal to 1.58 m^3/s. According to the historical duration curve of the basin introduced in section 5.2, this value of discharge is characterized by a not exceeding probability P(Q) equal to 0.8. The observed cumulated rainfall (blue line in Fig. 5b) was then compared with the rainfall thresholds obtained with the hyetograph *H3* and P(Q_{init}) equal to 0.8 (Fig. 5b). The intersection between the historical event (blue line) and the rainfall threshold at 80 m^3/s (red line), indicates that the E_c-d couple of the modeled threshold is similar to the E_c-d of the historical event that generated a similar maximum discharge (80 m^3/s vs 84.34 m^3/s), demonstrating a good model performance.

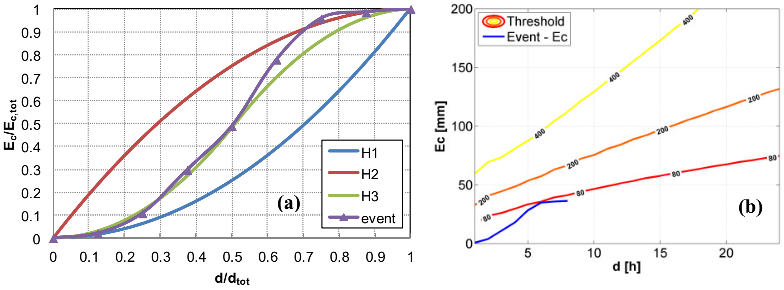

Fig. 5. (a) Cumulative rainfall event, E_c, of the selected historical event compared with the three hyetographs types; (b) comparison between the E_c event and the rainfall thresholds for fixed Q_{max} ranging from 80 to 400 m^3/s.

For all the analyzed events, the comparison between the historical E_c-d events and the rainfall thresholds showed that the $Q_{\max}$ generated by the rainfall events identified by the modelled thresholds is generally similar to the $Q_{\max}$ measured by hydrometer and determined by a similar event, even if a slight underestimation has been observed.

According to the hydraulic modeling study of [12], the critical discharge value for the Oreto basin at Parco can be fixed equal to 400 m^3/s. Fig. 6 shows the rainfall thresholds corresponding to the critical discharge (i.e., to 400 m^3/s) obtained with different initial conditions and hyetograph types. In order to estimate the possible return period of the events that may cause the critical rainfall, the cumulative rainfall of different events, taken from Fig. 6, were compared with the values of the *depth duration frequency* (DDF) curves (source: *Dipartimento Regionale della Protezione Civile-Servizio Rischi Idrologici e Ambientali*). For short durations (i.e., 2 hours), the critical events have a return period ranging from 20 to 50 years. While for long duration events (i.e., 18 hours), the return period is significantly higher, ranging from 100 years to values higher than 200 years.

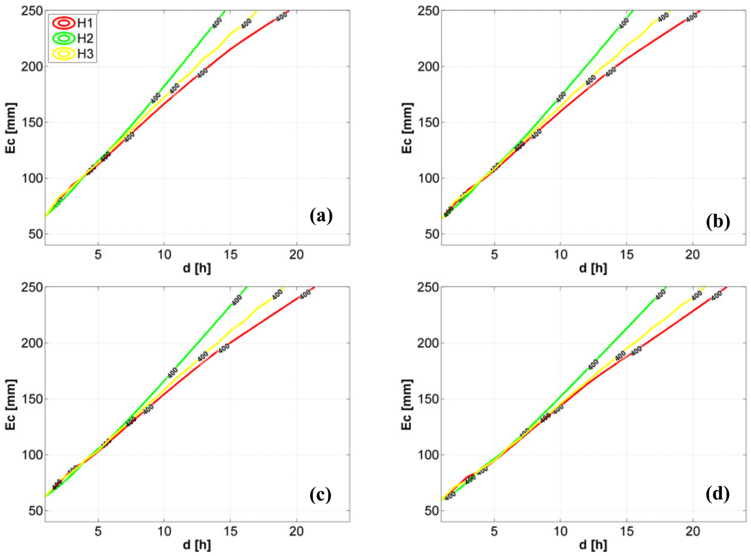

Fig. 6. Rainfall thresholds relative to the critical discharge value (400 m^3/s) for different hyetograph types and different initial discharge values P(Q_{init}): a) 0.1; b) 0.4; c) 0.7; d) 1.

7. Conclusions

The aim of this work was to obtain the rainfall thresholds for flash flood risk for a Sicilian basin through a deterministic approach. The hydrological model TOPDM was calibrated and used to estimate the amount of rainfall that, for fixed duration and initial conditions, causes the maximum discharge at the basin outlet. Moreover, the rainfall thresholds have been parameterized taking into account three different hyetographs types.

The methodology demonstrated to be efficient and provided interesting and useful results. The comparison between the cumulative rainfall of the analyzed events and the modeled rainfall thresholds showed that the rainfall events expected by the thresholds generate a peak of the hydrograph that is similar to the maximum observed discharge, even if a slight underestimation has been observed. However, given the restricted availability of data which have caused floods in the past, a rigorous validation was not possible and further analyses are necessary.

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