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A Regional Methodology for Deriving Flood Frequency Curves (FFC) in Partially Gauged Catchments with Uncertain Knowledge of Soil Moisture Conditions

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Outlines

Goal of this research is to point out a Monte Carlo procedure for deriving frequency distributions of extreme discharges starting from a simplified description of rainfall and surface runoff processes and using regional data

- Problem overall
- Derivation of Flood Frequency Curve using a Monte Carlo stochastic technique
- Case study
- Application of methodology proposed
- Application of GLUE procedure to show the importance of the prior-to-storm conditions to derive the FFC and the sensitivity of the rainfall-runoff model to soil moisture variations
- Results
- Conclusions

Background

Methodologies for Flood Frequency Estimation

1. Derived Distribution Approach (Eagleson, 1972)

- *Analitical methods*: mathematical complexity, difficulties in parameter estimation, availability of hystorical data (Gottschalk & Weingartner, 1998; Yue et al., 1999; Iacobellis & Fiorentino, 2000; De Michele & Salvadori, 2002)
- *MonteCarlo Simulation tecnique*: mathematically simple, heavy computational efforts (Loukas et al., 1996, Rahman et al., 2002)

2. Continuous Simulation Approach (Boughton & Droop, 2003)

- Requires complex Rainfall-Runoff models to simulate hydrological response
- Availability of long continuous (and reliable) time series of hydrological variables (as rainfall and discharge)

FFC estimation methodology

Monte Carlo simulation technique

No continuous data → Derivation Distribution Approach

Few data → Monte Carlo simulation technique

} **Flood Frequency Curve**

The proposed methodology is based on two modules:

- A stochastic rainfall generator module
- A catchment response module to simulate the flood formation process

Stochastic rainfall generator module

- The storm *h* is assumed to follow the Two Components Extreme Value (TCEV) distribution (Rossi et al. 1984). The main advantage of this distribution lies in using two components (basic and outlying) to model the observed hydrological variable.
- The Cumulative Distribution Function (CDF) of the TCEV distribution written using a dimensionless variable h' equal to the ratio between *h* and the mean value μ of the distribution is the following:

$$F(h') = exp\left[-\Lambda_1 (exp\,\alpha)^{-h'} - \Lambda^* (\Lambda_1)^{\frac{1}{\Theta^*}} \left(exp\left(\frac{\alpha}{\Theta^*}\right)\right)^{-h'}\right]$$

In order to apply this distribution to ungauged catchments Cannarozzo et al. (1995) estimated the five parameters α, Λ_1, Λ^*, Θ^*, μ at regional scale for Sicily.

Stochastic rainfall generator module

- Parameters α, Λ_1, μ have been estimated using Maximum Likelihood (ML) method using the annual maximum rainfall with 1,3, 6, 12 and 24 hours duration recorded at raingauges located in each sub-region.
- The two parameters Λ^*, Θ^* have been estimated using the data recorded in the entire region.

For the entire region:

$$\Theta^* = 1.95 + 0.0285 \cdot t$$

$$\Lambda = 0.175 \cdot t^{0.301}$$

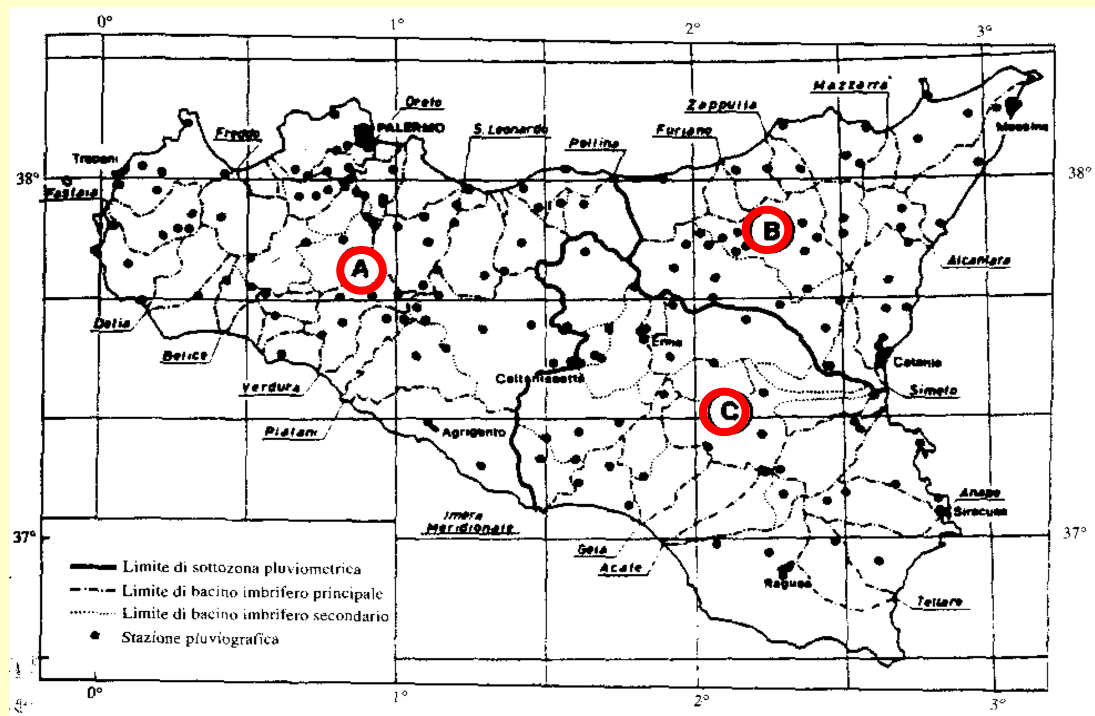
Depending on the sub- region:

$$\Lambda_1 = p \cdot t^q$$

$$\alpha = r \cdot t^s$$

Depending on raingauge site:

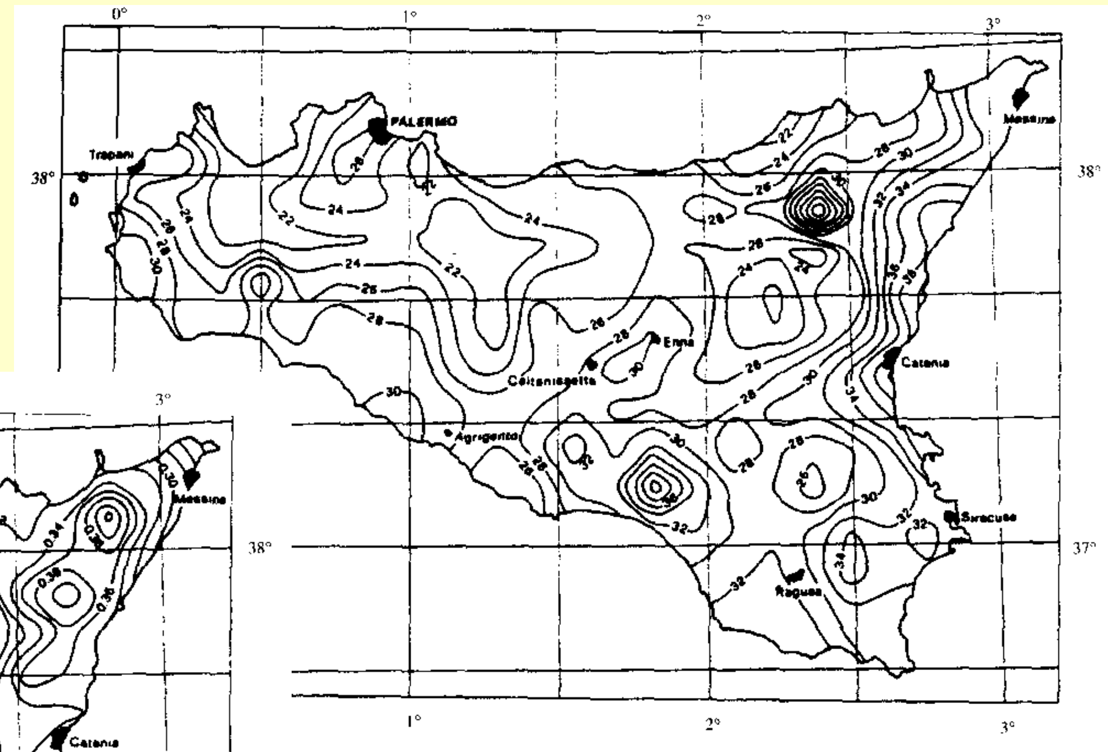
$$\mu = a \cdot t^n$$

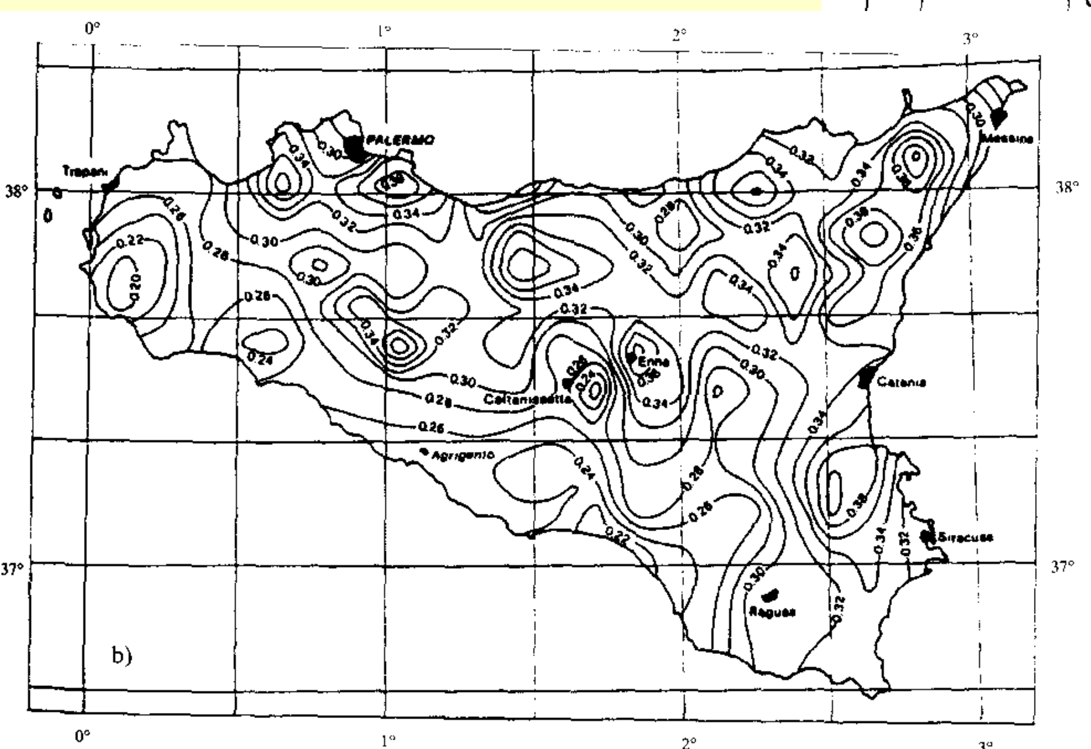


Stochastic rainfall generator module

To allow a simple estimation of the parameter μ in ungauged or partially gauged sites two maps reporting contour lines with constant *a* or *n* values were produced

Iso-a map





Iso-n map

Catchment response module

- Catchments generally characterised by a fast hydrological response
- Small areas
- Inadequate data

} **Parsimonious approach**

$$Q_{peak} = \frac{h_e(t_c)}{t_c} \cdot A$$

where:

$h_e(t_c)$ effective uniform rainfall for the critical duration t_c

A catchment area.

The total depth of effective rainfall h_e can be expressed in terms of the rainfall depth h using the SCS-CN method to incorporate information on soil type, land use, soil cover condition and antecedent soil moisture (AMC).

$$h_e = \begin{cases} \dfrac{(h - 0.2 \cdot S)^2}{(h + 0.8 \cdot S)} & h > 0.2 \cdot S \\ 0 & h \leq 0.2 \cdot S \end{cases}$$

$$S = 254 \cdot \left(\frac{100}{CN} - 1 \right)$$

Catchment response module

To take in account for the spatial variation of CN within the basin, a semi-distributed probabilistic approach was implemented for the modelling of the runoff production.

$$Q_{peak} = \sum_{i=1}^{N} \frac{h_{e,i}(t_c)}{t_c} \cdot a_i$$

$$h_{e,i} = \begin{cases} \dfrac{(h - 0.2 \cdot S_i)^2}{(h + 0.8 \cdot S_i)} & h > 0.2 \cdot S_i \\ 0 & h \leq 0.2 \cdot S_i \end{cases}$$

where:

$h_{e,i}$ runoff produced the ith CN class

S_i maximum soil potential retention in ith CN class

a_i area of the basin characterised by a particular value of CN

N number of CN classes in the GIS map

$$S_i = 254 \cdot \left(\frac{100}{CN_i} - 1 \right) \qquad A = \sum_{i=1}^{N} a_i$$

The catchment prior-to-storm conditions are taken in account by considering AMC as a random variable with a discrete probability distribution:

$$\begin{cases} \lambda_1 = Prob[AMC = I] \\ \lambda_2 = Prob[AMC = II] \\ \lambda_3 = Prob[AMC = III] \\ \sum_{i=1}^{3} \lambda_i = 1 \end{cases}$$

The distribution of peak flood conditioned by the AMC distribution

$$Q_{peak} = \sum_{i=1}^{3} \lambda_i \sum_{j=1}^{N} \frac{h_{e,i,j}(t_c)}{t_c} \cdot a_j$$

AMC estimation

Estimation of the uncertain knowledge of AMC affecting the predictions of the rainfall-runoff model →

GLUE procedure
(Generalised Likelihood Uncertainty Estimation)
Beven and Binley, 1992

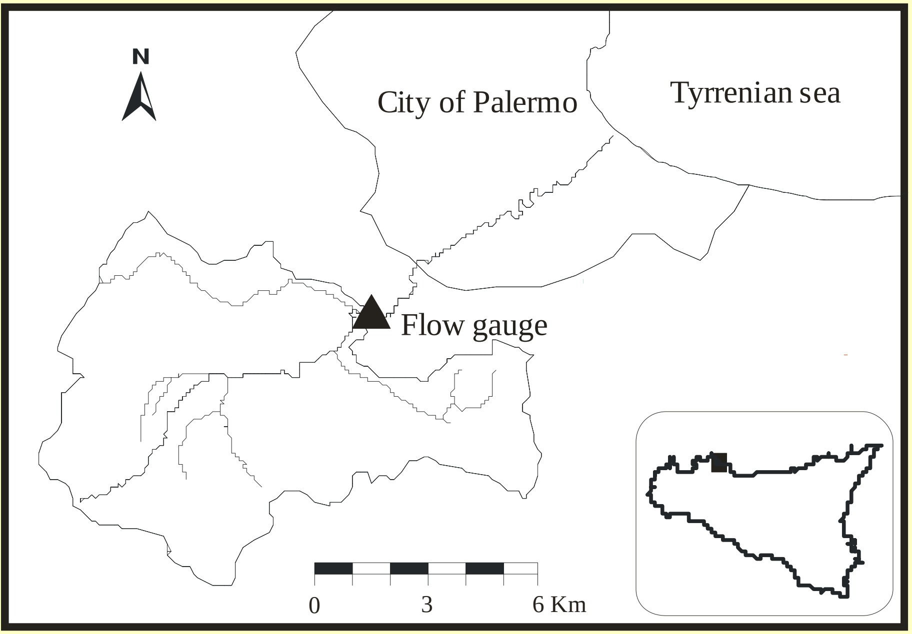
- It is a Monte Carlo based technique that allows for the concept of **equifinality** of parameter sets in the evaluation of modelling uncertainty;
- The performance of individual parameter sets are characterised by a likelihood weight, computed by comparing predicted to observed responses using some kind of likelihood measure. The model efficiency has been evaluated by the *Nash and Sutcliffe Efficienty Criterion*:

$$L(\theta_i / Y) = \left(1 - \sigma^2 / \sigma^2_{obs}\right) \quad \sigma^2 > \sigma^2_{obs}$$

where:
σ_i^2 error variance
σ_{obs}^2 observed variance
θ_i parameter vector
Y set of observation

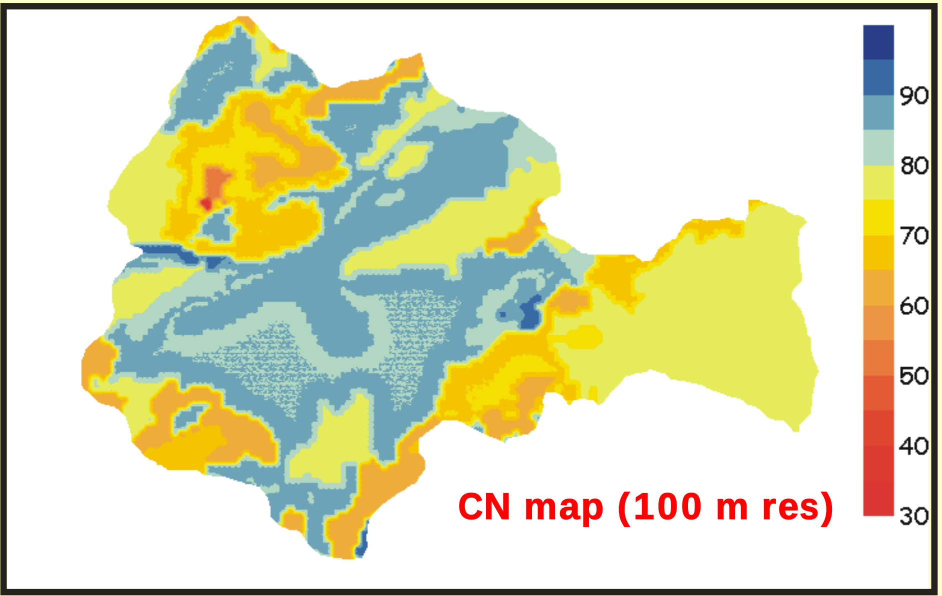
$\theta_i = [\lambda_1, \lambda_2, \lambda_3]$

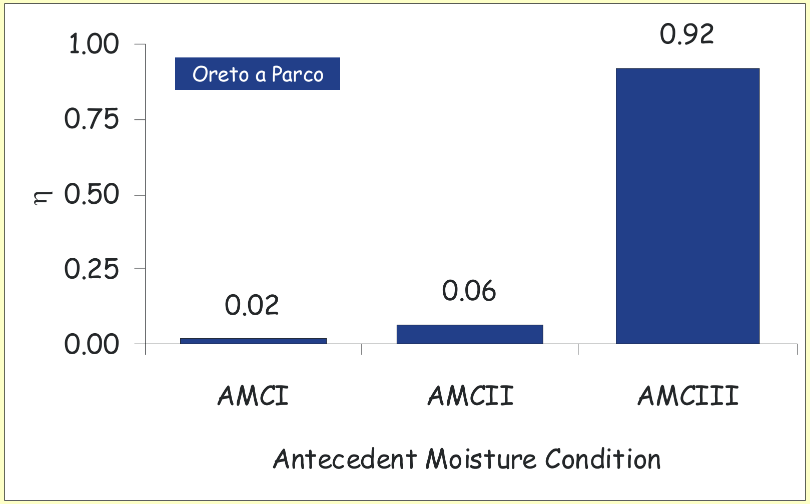
Case study



Oreto catchment (75.6 km²)

- Semiarid environment
- Mean annual rainfall 1030 mm
- Mean annual runoff 450 mm
- Extreme events (storms and floods) during wet season (October-April)
- 57 yrs continuous records at streamflow gauging station of Oreto a Parco allowed derivation of the AMC probability distribution using daily data





Case study

Oreto catchment (75.6 km²)

- The TCEV parameters have been estimated using Maximum Likelihood (ML) method with the parameters p, q, r, s, specified for the catchment sub-region and the parameters a, n obtained by the iso-a, iso-n contour lines.

- The critical storm duration t_c was assumed to be equal to the concentration time of the catchment. For its evaluation we used the simple relationship (Agnese and D'Asaro 1990) (t_c in hours, A in square kilometres and v = 1.5 $m \bullet s^{-1}$) :

$$t_c = 0.46 \cdot \sqrt{A} / v$$

Parameters	Values
p	14.55
q	0.2419
r	3.5208
s	0.1034
a	26.2
n	0.372
t_c (hours)	2.7

Application of proposed methodology

10000 Monte Carlo runs were performed to obtained synthetic FFC with a return time range from 1 to 500 years.

Procedure steps:

- 10000 values of total rainfall depth *h* for the storm duration t_c were randomly drawn from TCEV distribution;
- for the three AMC conditions (I, II, III) 10000 effective rainfall values have been calculated for each CN class;
- the final values of the peak flood discharges conditioned by the AMC distribution were obtained:
- the return time for each generated peak flood value has been computed from the plotting position formula:

$$T_m = \left(1 - \frac{m - 0.4}{NG + 0.2}\right)^{-1}$$

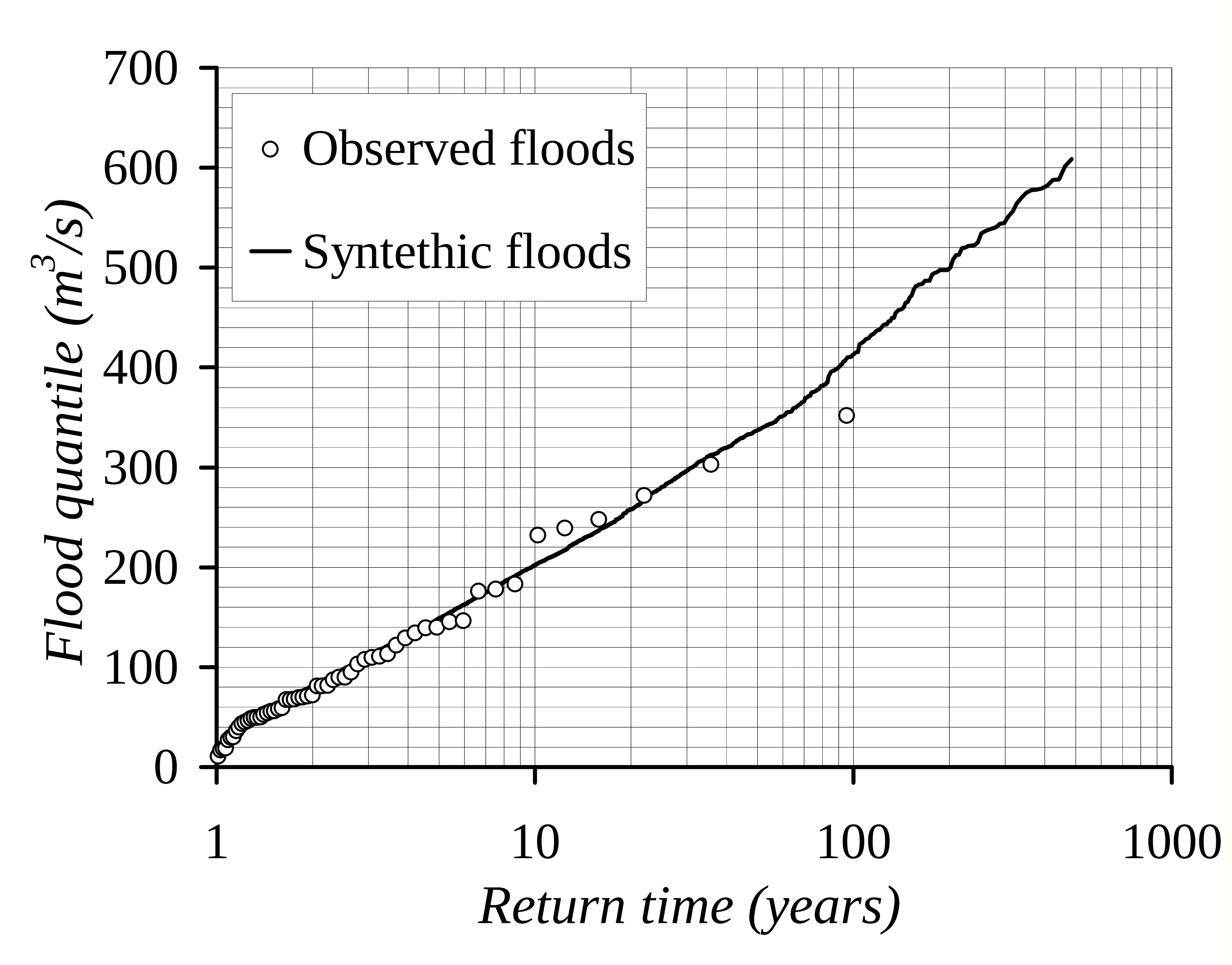
where:

NG is the number of simulated peaks

m is the rank of the m^{th} peak flood value arranged in increasing order of magnitude

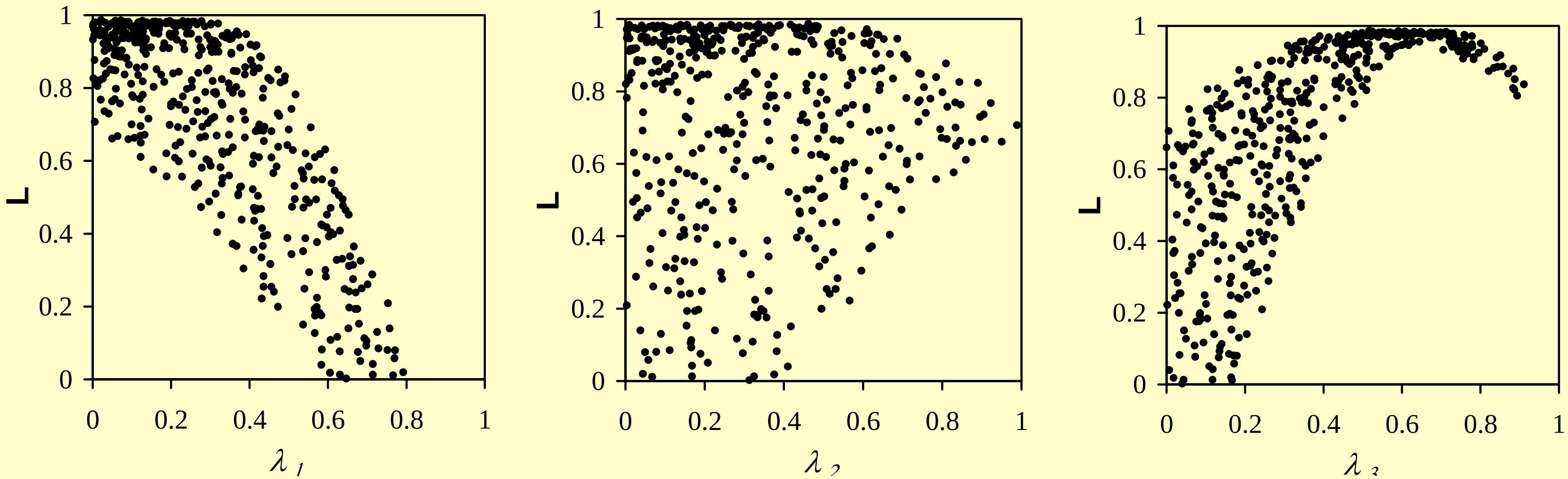
Results

Flood Frequency Curve derived vs. observed data



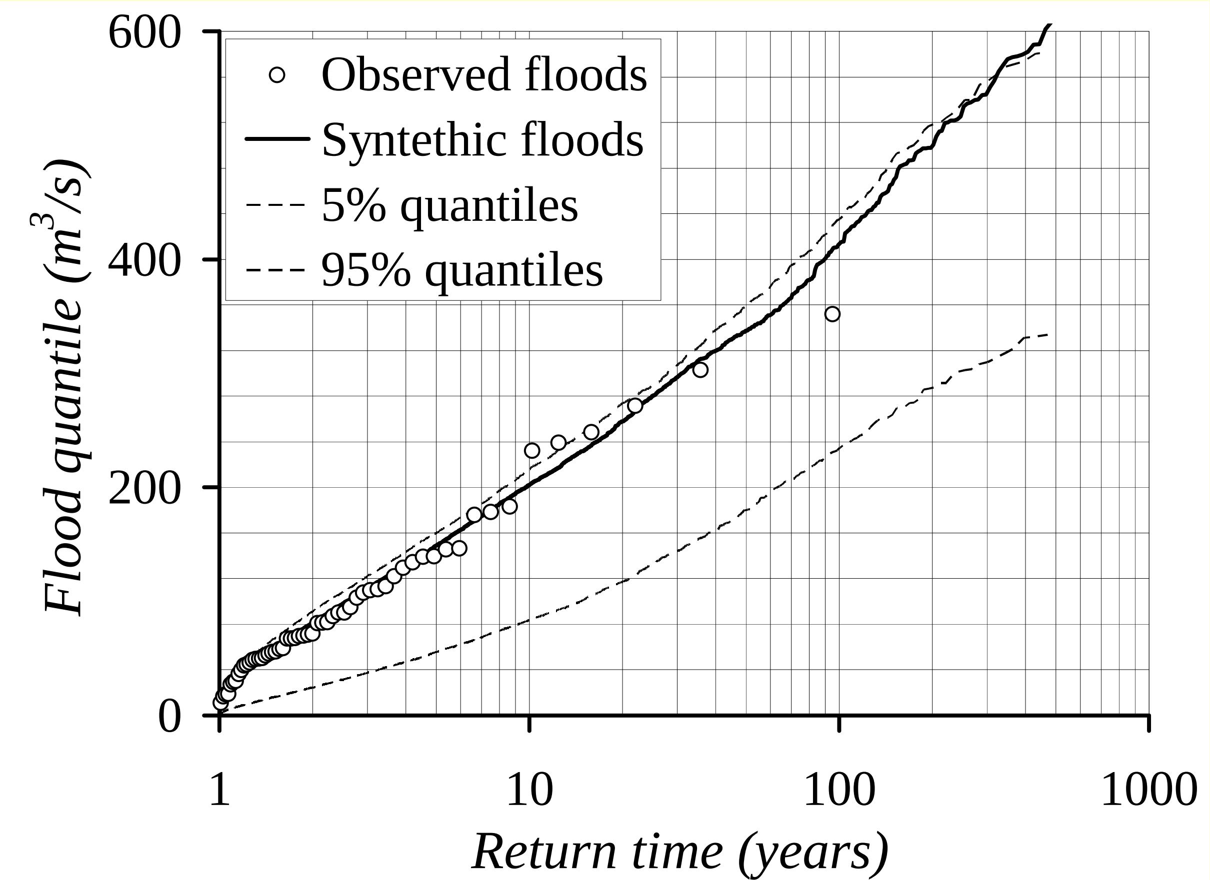
AMC uncertainty analysis

- 10000 numbers of λ_i values of (corresponding to different AMC conditions) were generated, each value being drawn within range from 0 to 1 with the condition $\sum_{i=1}^{3} \lambda_i = 1$
- Simulations were performed for each parameter set $\theta_i = \{\lambda_1, \lambda_2, \lambda_3\}_i$ for comparison with the measured flood peak values at catchment outlet
- The likelihood measure $L(\theta_i/Y)$ was evaluated for each parameter set and plotted versus the parameter values



AMC uncertainty estimation

Simulations that achieve a likelihood value less than zero are rejected as non-behavioural. The remaining are rescaled between 0 to 1 in order to calculate the cumulative distribution of the predictive variables from which the chosen discharge quantiles, 5 and 95%, have been calculated to represent the model uncertainty in the model predictions



Conclusions

- **A Monte Carlo procedure for deriving frequency distributions of extreme discharges starting from a simplified description of rainfall and surface runoff processes is proposed;**

- **The procedure is tailored for small-medium size ungauged or partially gauged catchments. It focuses on a parsimonious rainfall-runoff modelling approach and a stochastic rainfall generator both fed by data at regional scale;**

- **The application of this procedure to a Mediterranean catchment showed how Monte Carlo simulation technique can reproduce the observed flood frequency curves with reasonable accuracy over a wide range of return time;**

- **The application of GLUE procedure for exploring the uncertainty of the soil moisture conditions for flood formation process and the uncertainty in their knowledge showed the importance of the prior-to-storm conditions to derive the FFC and the sensitivity of the rainfall-runoff model to soil moisture variations**