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Effects of runoff thresholds on flood frequency distribution

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ABSTRACT

Runoff generation during extreme floods usually occurs whenever rainfall forcing exceeds a given threshold. In many cases, different thresholds may be identified as responsible of the hydrological losses during ordinary events or extraordinary events at the basin scale. Runoff thresholds are related to the dynamics of soil saturation of the river basin and may affect the skewness of the annual flood distributions. In basins where ordinary floods are mostly due to a small portion of the surface which is particularly prone to produce runoff, depending on soil permeability and characteristic antecedent soil moisture conditions, severe rainfalls may exceed a second, basin-wide soil storage threshold and produce the so-called outlier events responsible of the high skewness of flood distribution. In this context, the derived theoretical model based on the concept of variable contributing area to peak flow proposed by Iacobellis and Fiorentino (2000) was generalized with the aim of incorporating such kind of dynamics in the description of the phenomena. The work produced a new formulation of the derived distribution where the two runoff components are explicitly considered. The analysis focused on a group of basins in Southern Italy characterized by flood distributions with high skewness. The application of the proposed model provided a good fit to the observed distributions. Moreover, model parameters were found to be strongly related to physiographic basin characteristics giving consistency to the modeling assumptions.

Two Component IF Model (TCIF)

In the present work, we focus on the role of soil losses in runoff generation emphasising the way they are affected by rainfall amount and intensity. The goal is to improve the descriptive properties of theoretically derived distributions with particular attention on their ability of coping with the Matalas condition of separation. With this aim we generalize the theoretical probability distribution proposed by Iacobellis and Fiorentino (2000) (IF Model) introducing a two component derived distribution where the role of rainfall thresholds is emphasized and reconnected to the analysis of soil-vegetation dynamics. In particular, two different mechanisms of runoff generation are considered, and their non-linear effects on the flood frequency distribution is explained and parametrized. A new two-component probability distribution is proposed based on a generalization of the IF model. It has been given the name of Two Component IF Model (TCIF), based on the hypothesis that runoff is produced according to **two different threshold mechanisms**:

•L-type" mechanism activated by a lower threshold: $u_{a,L} = \xi\ (i - f_{a,L})$ $\quad f_{a,L} = f_{A,L}\,(a/A)^{-\varepsilon'}$

•H-type" mechanism activated by a higher threshold: $u_{a,H} = \xi\ (i - f_{a,H})$ $\quad f_{a,H} = f_{A,H}\,(a/A)^{-\varepsilon''}$

with $\quad f_{a,H} > f_{a,L}$

For any component the probability distribution of flood-peak is

$$G_{Q,L}'(q) = \int_0^A \int_{\frac{q}{a}}^{\infty} g(u \mid a_L)\, g(a_L)\, du\, da_L \qquad G_{Q,H}'(q) = \int_0^A \int_{\frac{q}{a}}^{\infty} g(u \mid a_H)\, g(a_H)\, du\, da_H$$

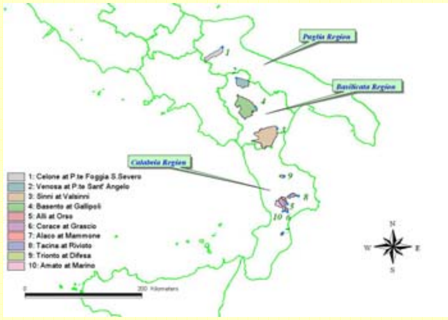
Two variables a_H and a_L are introduced, with different expected values, which allow to define two dimensionless parameters r_L = E[a_L]/A and r_H = E[a_H]/A, with $r_H > r_L$. Then, considering a Poisson process of exceedances of the introduced thresholds, the *cdf* of the flood annual maximum is:

$$F_{Q_p}(q_p) = \exp\left\{ -\Lambda_L \left[G_{Q,L}'(q_p) \right] - \Lambda_H \left[G_{Q,H}'(q_p) \right] \right\}$$

$$\Lambda_q = \Lambda_L + \Lambda_H = \Lambda_p \exp\left(-\frac{f_{A,L}^{\ k}}{E[i_{A,\tau}^k]} \right) \qquad \Lambda_H = \Lambda_p \exp\left(-\frac{f_{A,H}^{\ k}}{E[i_{A,\tau}^k]} \right)$$

The proposed distribution includes, among others, 6 parameters, $f_{A,L}$, $f_{A,H}$, r_L, r_H, ε', ε'', strictly related to the occurrence of the two main different mechanisms of runoff generation. They have a strong physical meaning and much about their behaviour is known from previous applications of the IF model.

The investigated basins



In order to investigate the thresholds effect on the flood probability distribution we focused on series of annual maximum flood characterized by high skewness coefficient (Ca > 1.75). Thus records of ten gauged sites in the area were selected including 8 humid basins in Basilicata and Calabria and two arid basins in Puglia. In Table 1 main characteristics of the investigated basins, as well as some significant statistics of their recorded annual maximum flood series, are reported.

n.	Basins	A (km^2)	I	Runoff coefficient "C"	ψ	Λ_p	Ca	τ_A (h)	p_1 (mm/h)	n	q_o (m^3/s)
1	Celone at P. Foggia S. Severo	233	-0.24	0.48	0.98	44.60	2.43	5.20	23.33	0.27	2.20
2	Venosa at P. S. Angelo	263	-0.17	0.52	0.85	44.60	2.26	5.60	24.13	0.26	1.40
3	Sinni at Valsinni	1140	0.57	0.40	0.41	21.00	2.42	5.60	23.13	0.40	45.00
4	Basento at Gallipoli	853	0.28	0.52	0.40	21.00	2.25	4.80	21.00	0.31	25.00
5	Alli at Orso	46	1.26	0.18	0.98	20.00	2.74	3.00	33.20	0.52	2.34
6	Corace at Grascio	182	0.90	0.24	0.94	20.00	1.83	3.80	29.80	0.45	8.84
7	Alaco at Mammone	15	1.66	0.13	1.00	10.00	1.76	1.30	39.60	0.63	0.96
8	Tacina at Rivioto	79	1.43	0.12	0.97	10.00	2.79	3.00	32.70	0.59	3.40
9	Trionto at Difesa	32	0.90	0.22	0.99	20.00	3.18	2.80	31.00	0.50	1.17
10	Amato at Marino	113	0.86	0.29	0.95	20.00	2.43	4.60	28.80	0.43	5.32

Table 1. Climatic and morphological features of the investigated basins.

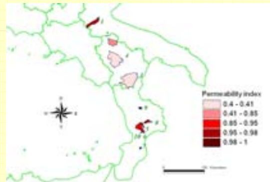


Figure 3. Map of permeability index "ψ" for the investigated basins.

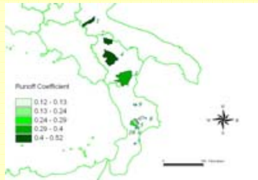


Figure 2. Map of mean runoff coefficient "C" for the investigated basins.

Fig. 2 and 3 provide a description of the spatial variability of the mean runoff coefficient "C" and the permeability index "ψ" computed for all the investigated basins. The estimates of "C" and "ψ" were computed within a GIS environment by means of lythological, pedological, land cover and local slope maps. In particular for Puglia and Basilicata regions "C" and "ψ" values are those reported respectively in Fiorentino at al., (2003) and in Fiorentino and Iacobellis (2001). For basins in Calabria they are estimated using Corine Land-Cover map, geological map (scale 1:50000) and a DTM of Italy (250 m).

Model Application to Gauged Basins

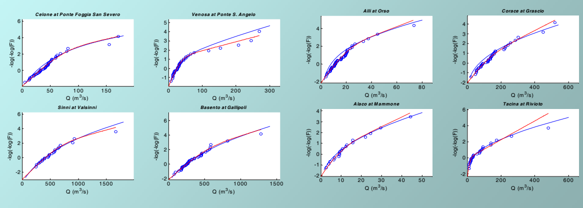
We exploit the TCEV model (Rossi et al., 1984) in order to obtain reliable estimates of some important distribution parameters and for comparison purposes. We use at-site estimation of TCEV (Two Component Extreme Value) parameters performed by Maximum Likelyhood Estimator.

$$F_x(x) = P[X \le x] = \exp\left[-\Lambda_1 \exp\left(-x/\theta_1\right) - \Lambda_2 \exp\left(-x/\theta_2\right) \right]$$

and assume $\Lambda_L = \Lambda_1$ and $\Lambda_H = \Lambda_2$,

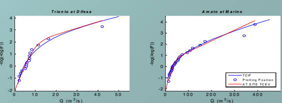
following Fiorentino and Iacobellis, (2001), we assume ε' = 0 for the L -type scaling relationship and ε' = 0.5 for the H-type mechanism. Parameters r_L and r_H are found as heuristic estimates providing the best fitting of the theoretical Annual maximum flood distribution to the observed time series.

The comparison between the CDFs obtained by the TCEV and TCIF models (whose parameters are reported in Table 2) for all 10 basins with corresponding plotting positions is below reported. The skewness of the observed distributions is always captured by the TCIF model.



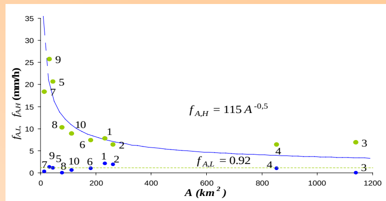
		TCIF Parameters					TCEV Parameters			
n.	Basins	$f_{A,L}$ (mm/h)	$f_{A,H}$ (mm/h)	r_L	r_H	k	Λ_1	θ_1	Λ_2	θ_2
1	Celone at Ponte Foggia San Severo	2.07	7.83	0.07	0.60	0.80	6.61	15.64	0.19	67.93
2	Venosa at Ponte Sant' Angelo	1.93	6.35	0.05	0.70	0.80	6.74	11.10	0.38	103.41
3	Sinni at Valsinni	0.00	6.90	0.15	0.50	0.80	20.51	127.52	0.49	481.35
4	Basento at Gallipoli	0.95	6.34	0.22	0.67	0.80	8.33	110.11	0.38	337.22
5	Alli at Orso	1.13	20.67	0.02	0.05	0.53	8.18	4.94	0.38	18.43
6	Corace at Grascio	0.95	7.37	0.10	0.28	0.53	6.52	39.63	1.19	114.14
7	Alaco at Mammone	0.31	18.33	0.03	0.04	0.53	6.65	3.23	1.11	11.29
8	Tacina at Rivioto	0.00	10.24	0.02	0.25	0.53	8.90	6.52	1.10	85.15
9	Trionto at Difesa	1.26	25.75	0.02	0.10	0.53	7.75	2.26	0.21	19.05
10	Amato at Marino	0.60	8.92	0.06	0.52	0.53	8.30	11.71	0.70	102.90

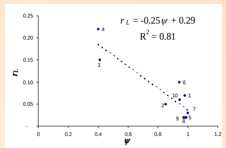
Table 2. Parameters of the investigated models.

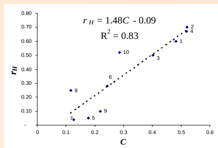


With the aim of investigating the effect of the two thresholds on flood frequency we analyze the **regional behavior of $f_{A,L}$, $f_{A,H}$, and r_L, r_H** in order to characterize their variability and dependence on measurable factors related to climate-soil-vegetation dynamics.

Within the investigated region, the first mechanism threshold corresponds to a low and constant infiltration rate practically independent from basin area, while the second runoff threshold follows, with a good approximation, a scaling law relationship with exponent equal to 0.5 representative of a soil water storage control.







Further analyses are carried out with the aim of investigating main physical controls on model parameters r_L and r_H. In particular we search for significant dependence between the estimated parameter values and physical features of the investigated basins. Although these analyses are affected by the approximation used in the estimation procedure, we would like to remark that parameter r_L shows a linear dependence on the permeability index, for area ranging between 2% and 22 % of the entire basin area and obviously decreases for higher values of permeable bedrocks. For the H-type mechanism, instead, the expected value of the contributing area ratio (r_H) ranges between 4% and 70% and is linearly related to the runoff coefficient "C" confirming that hydrological losses mainly depend on soil type and land cover.

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