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Analysis on flood generation processes by means of a continuous simulation model

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Abstract. In the present research, we exploited a continuous hydrological simulation to investigate on key variables responsible of flood peak formation. With this purpose, a distributed hydrological model (DREAM) is used in cascade with a rainfall generator (IRP-Iterated Random Pulse) to simulate a large number of extreme events providing insight into the main controls of flood generation mechanisms. Investigated variables are those used in theoretically derived probability distribution of floods based on the concept of partial contributing area (e.g. Iacobellis and Fiorentino, 2000). The continuous simulation model is used to investigate on the hydrological losses occurring during extreme events, the variability of the source area contributing to the flood peak and its lag-time. Results suggest interesting simplification for the theoretical probability distribution of floods according to the different climatic and geomorfologic environments. The study is applied to two basins located in Southern Italy with different climatic characteristics.

1 Introduction

The main purpose of the present research is to investigate the behaviour of flood generation processes in order to improve or simplify the structure of theoretically derived probability distributions of floods such as those based on the concept of variable runoff contributing area proposed by Iacobellis and Fiorentino (2000). Recent results regarding the comparison of continuous simulation models and theoretical derived distributions of floods encourage the application of numerical simulation models to investigate on flood generation mechanisms with the aim of incorporating this knowledge in probabilistic theoretical models (Manfreda et al., 2004).

The continuous hydrological simulation is considered by many authors (e.g. Cameron et al., 1999, 2000; Blazkova and Beven, 2004) to be one of the most promising tool for flood risk prediction. Such methodology can also be extended to ungauged basins with a deep knowledge about physical characteristics such as soil texture, morphology, vegetation status, the rainfall regime, etc (e.g. Blazkova and Beven, 2002).

In this paper, we adopt a distributed hydrological model called DREAM (Manfreda et al., 2005) which was conceived with the purpose of exploiting as much as possible the available knowledge and database of Mediterranean basins. The DREAM model in cascade with a rainfall generator, called IRP (Iterated Random Pulse) model (Veneziano and Iacobellis, 2002), is used to simulate a large number of extreme events and provides insight into the main controls of flood generation. This scheme is adopted to analyse the behaviour of hydrological variables such as infiltration, runoff per unit contributing area, lag-time, and partial contributing area. Particular emphasis is given to the study of this last variable and its influence on the remaining others.

2 Continuous flood simulation

The DREAM model is realized in a GIS-based approach that explicitly takes into account the spatial heterogeneity of hydrological variables using distributed data contained in digital elevation models (DEMs), land use and soil texture maps. DREAM is developed to ensure a proper description of (*i*) the runoff production; (*ii*) the surface storage effect; (*iii*) the chronologic sequence of state variables as soil moisture and base-flow discharge; (*iv*) the surface and subsurface routing. The model includes two sub-models operating at distinct time scales with a grid-based representation of the river basin of 240 m resolution. The D-DREAM module is designed to reproduce daily runoff and soil dynamics, while H-DREAM is the module aimed to reproduce flood events at an hourly steps.

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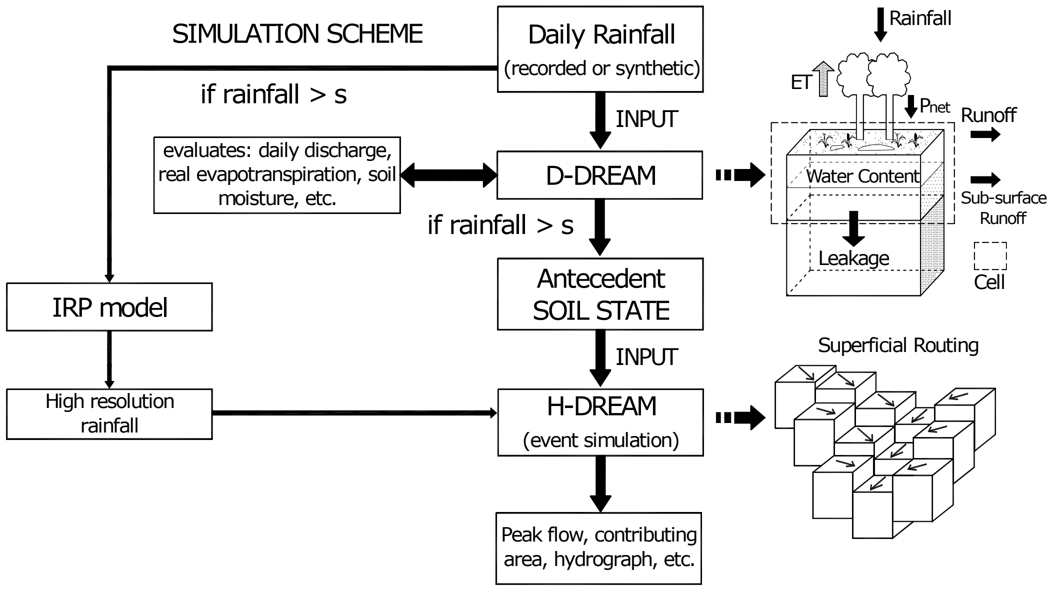

Fig. 1. The simulation scheme.

The hydrological simulation scheme adopted is sketched in Fig. 1. According to it, the simulation process is activated by means of daily rainfall series inputs, which are required to run D-DREAM with the main purpose of providing the initial condition for flood event hourly simulations. This module runs as long as a daily rainfall greater than a threshold s [mm/day] does not occur. Whenever s is exceeded, the simulation switches to the H-DREAM in order to reproduce the flood event.

In this work, 800 years of synthetic streamflow are used exploiting the continuous simulation model DREAM applied to two basins located in Southern Italy with different climatic and physical characteristics.

3 The model for the theoretical derivation of the probability distribution of floods

The theoretical model proposed by Iacobellis and Fiorentino (2000), is based on the hypothesis that the peak of direct streamflow Q, is given by the product of two random variables: runoff per unit contributing area u_a and a the portion of the basin area that contributes to direct runoff. The runoff, u_a, is expressed as a fraction of the excess rainfall, which is assumed as the exceedance of total rainfall above a threshold $f_a$that represents the basin adsorption. Thus, it follows

$$u_a = \xi(i_{a,\tau} - f_a), \tag{1}$$

where ξ is a constant routing factor, $i_{a,\tau}$ is the areal rainfall intensity fallen on the contributing part of the basin a and occurring in a duration equal to a characteristic response time τ_a of the same contributing area a and f_a is the average water loss rate within the duration τ_a and the area a. The water loss f_a takes into account both initial absorption and infiltration and it is assumed independent from rainfall intensity, while τ_a is assumed to scale with a according to the following power law

$$\tau_a = \tau_1 a^{\nu}. \tag{2}$$

The expected value of the areal rainfall intensity is supposed to scale with a according to the power law

$$E\left[i_{a,\tau}\right] = i_A (a/A)^{-\varepsilon}, \tag{3}$$

where i_A is the expected value of the space-time averaged intensity of the rainfall occurring on the total basin area ε is a constant scaling parameter (see Iacobellis and Fiorentino, 2000).

The variable f_a represents the threshold responsible for the difference between mean annual number of flood events and mean annual number of rainfall events. In this model, a power law relationship between f_a and a, is also assumed

$$f_a = f_A (a/A)^{-\varepsilon'} \tag{4}$$

where f_A is water loss of the total basin area. Fiorentino and Iacobellis (2001) assumed for Bradano and Agri Basins values of ε' equal to 0.5 and 0, respectevely.

The variables a and u_a are gamma and Weibull distributed, respectively. Since u_a and a are supposed to be stochastic dependent variables, the cumulative distribution function of peak streamflow (base process) is derived integrating the joint density function $g(u_a, a)$ over the region $R(q)$ within the peak streamflow is smaller then q depending on u_a and a.

The *cdf* (cumulative density function) of the annual maximum values of Q_p is then obtained, under the hypothesis that flood occurrence is of Poisson type. Thus, Iacobellis and

Fiorentino (2000) derived an analytical formulation of probability distribution function with parameters directly correlated to climatic and geomorphologic characteristics.

4 The study area

The methodology is applied to Bradano at Ponte Colonna and Agri at Tarangelo river basins (Fig. 2). Both are located in the region of Basilicata in Southern Italy. The Basilicata is characterized by a strong climatic gradient and a low anthropic pressure. For this reasons the region constitutes a natural hydrological laboratory to investigate on climate-soil-vegetation interactions.

The Bradano basin is located within the North-West side of the region and it is characterized by a Thornthwaite climatic index (Thornthwaite, 1948) equal to −0.08, surface area equal to 462 km^2, mean altitude equal to 560 m and mean annual rainfall equal to 680 mm. The Agri river basin is located within the South-West side area and it is characterized by the Thornthwaite climatic index equal to 0.47, surface area equal to 511 km^2, mean altitude equal to 870 m and mean annual rainfall equal to 1100 mm.

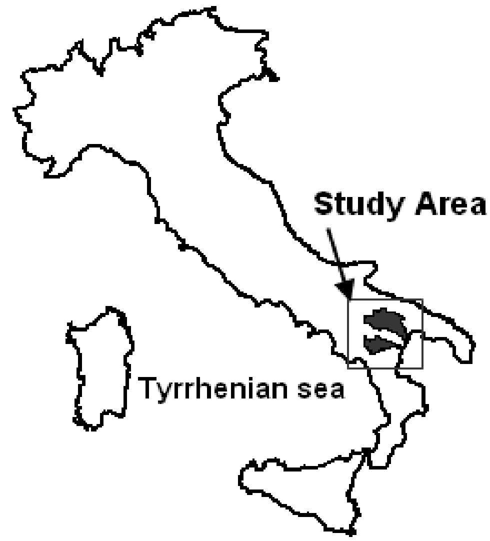

Fig. 2. The study area.

5 Results of the continuous hydrological simulation

In this section, we describe the results obtained through application of the continuous hydrological model over 800 years of simulation. In particular, investigations are focused on: infiltration, lag-time and peak unit runoff, as a function of contributing area.

It is necessary to point out that both synthetic rainfall and streamflow were compared satisfactorily with recorded data for validation purposes. Such comparisons are not reported in the present paper for sake of brevity, but major details can be found in Manfreda (2004).

5.1 The infiltration during flood events

For each flood event, f_a is computed as the space-time average infiltration over the grid cells contributing to the surface flow and over a duration equal to the lag-time of the same contributing area.

Figure 3 describes the values of infiltration intensity as a function of the contributing area for the semi-arid basin (A) and the sub-humid basin (B). The circles are the mean values of f_a conditional on a and the continuous line represents a power law fitted to the simulated data.

The infiltration behaviour confirms the semi-empirical relationship proposed by Fiorentino and Iacobellis (2000). Moreover it is worth nothing that for both basins there is a prevailing constant trend especially for high contributing areas and the dispersion around mean of the data decreases with the increase of the contributing area: this is due to a saturation effect that reduces the variability of the infiltration.

5.2 The lag-time

The lag-time of contributing area to peak flow is computed as the average flow time of the cells that contribute to the peak flow producing surface runoff.

Lag-time values show a strong dependence on the contributing area to peak flow (Fig. 4). Nevertheless, the two basins have remarkable differences that are commented below. In particular, the relationship between the two variables seems to be well represented by a power law in the case of the sub-humid basin (Fig. 4b) according to the hypothesis of Fiorentino and Iacobellis (2000). In this case, the Dunne process is prevailing, because of the dense vegetation and forested hillslopes, so only a portion of the area close to the channel network contributes to surface runoff. Consequently, the contributing area increases along the river network remaining a compact area that increases during the rain event producing a contemporary increase of the lag-time. Furthermore, the lag-time as well as the contributing area are strongly controlled by the antecedent soil moisture conditions as shown in the same figure.

Conversely, in the arid basins, where the soil moisture is often lower than field capacity, the typical short rainfall events of the area occur frequently over a non-organized soil moisture pattern. Therefore for small values of contributing area, the mechanism of runoff generation is spatially random and the lag-time shows a high dispersion that becomes smaller for growing values of contributing area. When the contributing area increases, the spatial pattern of runoff starts to be organized along the stream network and the dispersion of lag-time decreases. Furthermore, for events with low frequency and high values of contributing area, the runoff spatial pattern involves the hillslope cells and the lag-time increases following the same behaviour observed in the sub-humid case (Fig. 4a, for $a > 200\,\mathrm{km}^2$). It can be also noticed that the dispersion of points, observed for $a \leq 200\,\mathrm{km}^2$,

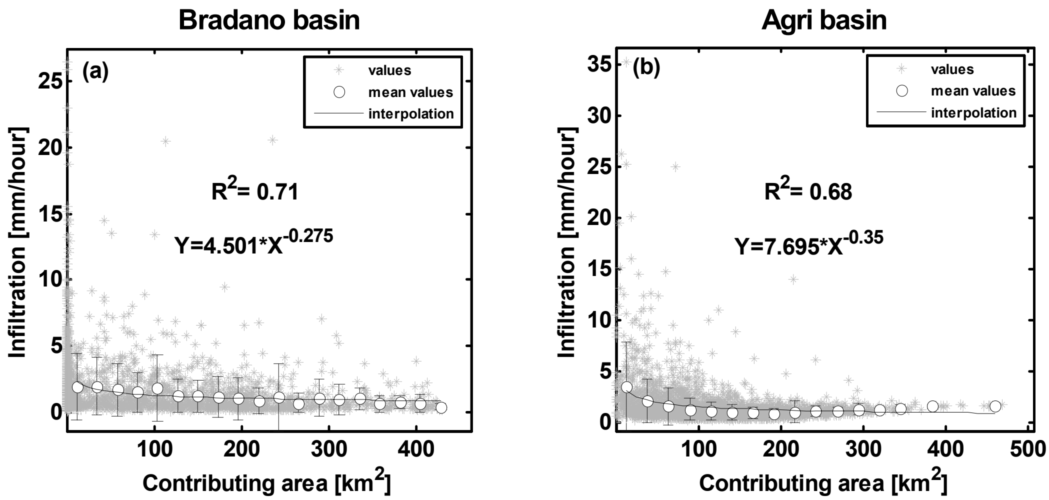

Fig. 3. Mean value of the infiltration at the event scale as a function of contributing area for the semi-arid basin **(a)** and sub-humid basin **(b)**.

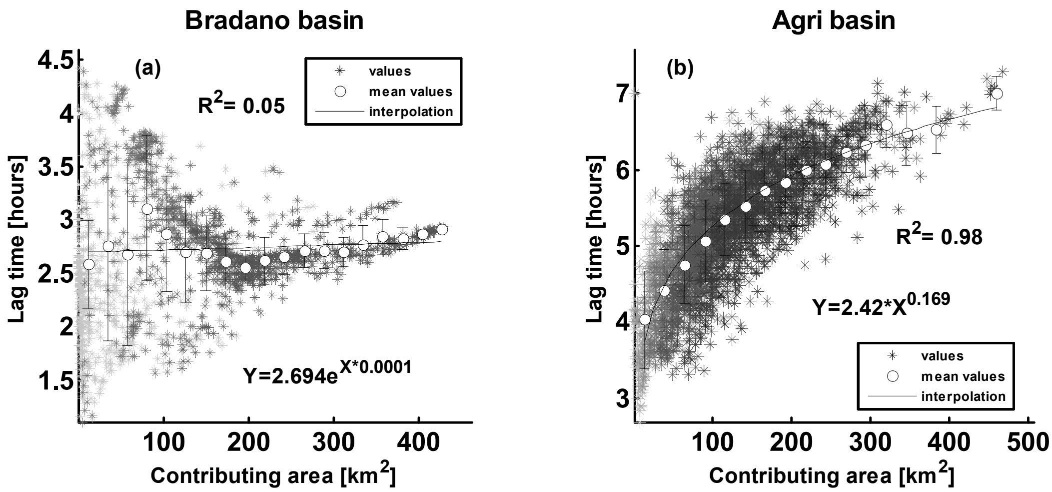

Fig. 4. Simulated values of the lag-time at the event scale as a function of the contributing area for the semi-arid basin **(a)** and sub-humid basin **(b)** corresponding to different initial soil moisture conditions (ligth gray corresponds to low values of mean areal soil moisture). The circles represent the mean value of the lag-time as a function of contributing area.

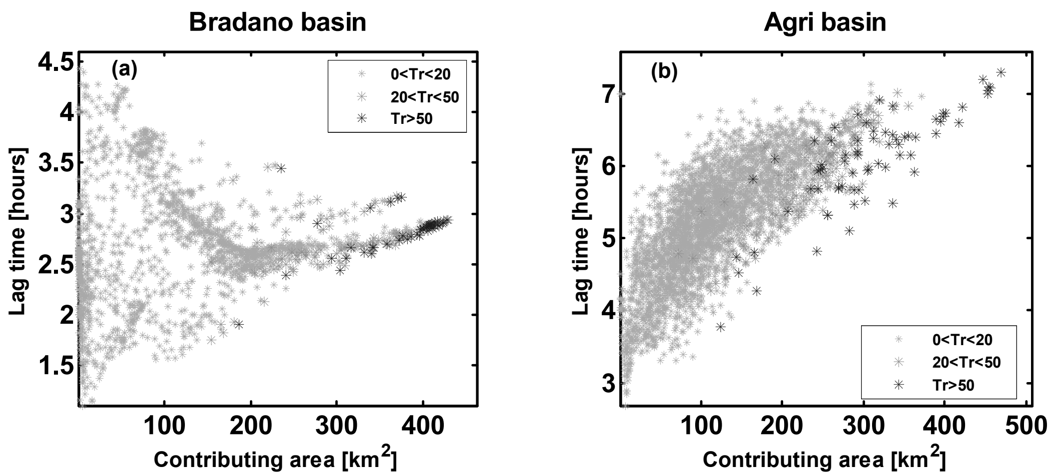

Fig. 5. Lag time at event scale as a function of contributing area for different return periods for the semi-arid basin **(a)** and sub-humid basin **(b)**.

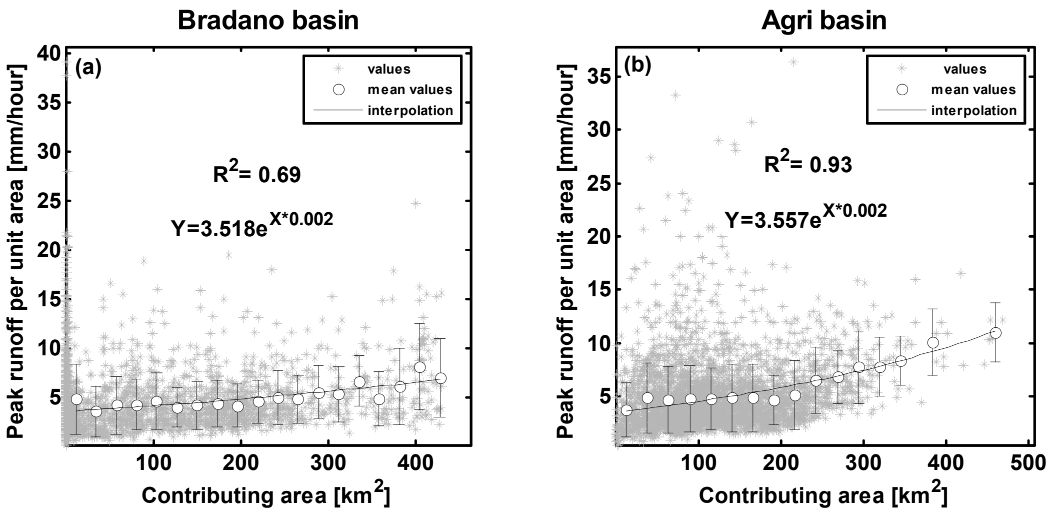

Fig. 6. Mean value of the peak runoff per unit area at the event scale as a function of contributing area for semi-arid basin **(a)** and sub-humid basin **(b)**.

Table 1. Parameters of lagtime-contributing area relationship for different return periods.

Bradano Basin				Agri Basin			
Return Time (years)	τ_1 (hours)	ν	R^2	Return Time (years)	τ_1 (hours)	ν	R^2
0<TR<20	2.68	0.004	0.01	0<TR<20	2.38	0.17	0.97
20<TR<50	0.76	0.22	0.29	20<TR<50	1.03	0.32	0.70
TR>50	0.71	0.23	0.25	TR>50	0.86	0.34	0.69

is strongly controlled by the antecedent soil moisture conditions whose increase reduces the dispersion of data.

Analyzing the relationship between lag-time and contributing area at different return periods (Fig. 5), it seems that the semi-arid basin, for peak flow with high return periods, assume a behaviour similar to that of the sub-humid basin. This can be better understood by taking a look at Table 1 that describes the coefficients of the power law regression at differents return periods for both basins.

5.3 The peak runoff

Figure 6 reports u_a as a function of the contributing area a. The peak runoff per unit area seems to be slightly dependent on the contributing area for the lower values of a. Such dependence increases significantly at the higher values of contributing area especially in the sub-humid basin. The graphs of Fig. 6 show a good exponential relationship between mean value of the peak runoff per unit area and contributing area. These results are consistent with the assumptions of the theoretical model.

For both basins the peak runoff per unit area, u_a, increases with the contributing area as supposed in the theoretical model. Being the infiltration rate (f_a) independent from the contributing area, this result may be due to the dependence between rainfall intensity and contributing area.

6 Conclusions

In the present paper, the continuous flood simulation is used to analyse the behaviour of hydrological variables exploited in the theoretically derived probability distribution proposed by Iacobellis and Fiorentino (2000). Particular emphasis is given to the study of contributing area and its influence on the hydrological quantities such as infiltration, runoff per unit contributing area, lag-time with the aim to improve the understanding of physical controls characterizing dynamics of flood events in different climatic environments.

Part of the analyses presented confirm the hypothesis of the scheme proposed by Iacobellis and Fiorentino (2000), while others may help to simplify the structure of the theoretically derived probability distributions of floods. For instance, it is possible to assume the infiltration rate (f_a) independent from the contributing area to peak flow in different climatic conditions. In fact for both basins, the application of the continuous simulation model suggests a prevailing constant trend when the contributing area increases. A similar result was also found by Fiorentino and Iacobellis (2001) and

Claps et al. (2000) in the case of humid basins. Such a simplification may be used to derive an explicit function easy to apply for the probability distribution of the of floods.

The behaviour of the lag-time for the sub-humid basin is consistent with assumptions made by Iacobellis and Fiorentino (2000). Conversely, in the semi-arid basin, the values of lag-time assume a more complex dynamic that are not simple to be incorporated in the framework of the theoretical model, but should be carefully taken into account for the definition of new schemes.

The numerical simulation shows that in a semiarid basin, for small values of contributing area, the lag-time assumes higher dispersion due to a spatially random runoff generation. This result does not affect the flood generation mechanisms at the higher return period where the lag-time behaviour is similar to that of the sub-humid basins.

Finally, the runoff per unit area displays a dependence on the contributing area that is remarkable in the sub-humid basin. This is certainly due to a mutual interaction between rainfall and basin saturation that may be modelled using an appropriate schematization of the relationship between basin relative saturation and contributing area.

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