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Effects of Rainfall and Soil/Land Use Spatial Distribution on Hydrological Response at Different Scales

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Abstract: The influence of spatial variability of rainfall and soil/land use on the accuracy of runoff simulation was investigated in order to define the optimal spatial discretization of the basin to be adopted in rainfall-runoff modeling. In particular, the effects of a uniform versus distributed spatial representation of both rainfall field and basin properties was analyzed by using a semi-distributed model. These effects were evaluated by comparing the observed and simulated flood hydrographs for different sub-basins of the Upper Tiber River basin at Ponte Felcino river section (drainage area of ~1800 km^2), located in Central Italy. On the basis of the obtained results, a dimension of about 300 km^2 for the homogeneous elements of the basin can be considered adequate for model applications addressed to flood forecasting and warning activities.

Keywords: Spatial variability, scale, rainfall-runoff modelling, semi-distributed scheme; flood forecasting.

1. INTRODUCTION

Several authors have emphasized the role of rainfall spatial distribution on estimating peak discharge and discharge hydrograph shape [Julien & Moglen, 1990; Beven & Hornberg, 1982; Syed et al., 2003]. In particular, Michaud & Sorooshian [1994] showed that significant errors in peak discharge can be found by using rainfall data of an inadequate hydrometeorological network. Ogden et al. [1995] and Singh [1998] investigated the effects of storm direction and velocity on peak discharge and discharge hydrograph shape. Syed et al. [2003] showed the influence of the interaction of basin area and shape with rainfall spatial structure in the runoff generation process.

The spatial distribution of soil/land use characteristics can also affect the hydrograph shape [Merz and Plate, 1997; Merz and Bardossy, 1998; Singh and Woolhiser 2002]. This issue has been investigated by using the Soil Conservation Service method for abstraction for which the soil/land use characteristics are parameterized through a dimensionless Curve Number (CN). Grove et al. [1998] underlined that runoff depth estimates using a distributed CN are as much as 100% higher than that obtained considering a uniform CN. Underestimation of runoff depth due to CN compositing is most severe for wide CN ranges, low CN values and low precipitation depths. For two watersheds in South Africa, Hope and Schulze [1982] concluded that a distributed CN approach furnished estimates of stormflow more accurate than those derived by adopting a lumped CN method.

The selection of the optimal spatial discretization for the above mentioned quantities represents a key factor in the development of reliable rainfall-runoff models [Hellenbrand and van den Bos, 2007]. This issue becomes fundamental when the models are involved in real-time flood forecasting systems, such those developed and managed by the Italian network of regional "*Functional Centres*", coordinated by the National Civil Protection Department in Rome. In fact, the availability of accurate forecasts allow to minimize false/missed alarms [Ravazzani et al., 2007].

Based on the above issues, the main purpose of this study is to analyze the influence of rainfall and soil/land use spatial representation on the estimation of the hydrologic response for sub-basins of the Upper Tiber River (Central Italy), that is concern of Umbria region Functional Centre. Specifically, the effects of a uniform versus distributed spatial account of these quantities are analyzed through the comparison of simulated flood hydrographs for different river sections. At the purpose a freely available event-based hydrological model of semi-distributed type (Hydrologic Engineering Center - Hydrologic Modeling System, HEC-HMS) is applied to simulate four significant flood events occurred in the last five years. Moreover, the spatial discretization of the basin is addressed in view of model applications for flood warning purpose.

2. SEMI-DISTRIBUTED RAINFALL-RUNOFF MODEL

The freely available semi-distributed event-based hydrological model HEC-HMS, coupled with HEC-GeoHMS module, was used for the analysis. HEC-GeoHMS is a public-domain extension of ESRI ArcMap 9.1 GIS program which is useful to perform terrain pre-processing, delineate sub-basins and streams, compute hydrologic parameters and directly produce the geographical input data for the HEC-HMS model.

HEC-HMS is the updated version of the United State Army Corps of Engineering (USACE) rainfall-runoff model HEC-1 and it was chosen for this study because of its flexibility. In fact, many of the most common formulations used in hydrologic engineering for runoff volume, base flow, direct runoff and channel flow assessment, are included in the software [USACE, 2000]. The geometric representation of the basin is based on the main elements implemented in HEC-HMS: subbasin, reach, junction and source. In the following, a brief description of the model components formulation adopted in this study is given.

Specifically, losses are estimated by using the Soil Conservation Service - Curve Number (SCS-CN) for which the direct runoff depth, P_e, is:

$$P_e = \frac{(P - I_a)^2}{(P - I_a + S)} \qquad P \geq I_a \tag{1}$$

where P is the rainfall depth, S is the potential maximum retention and I_a is the initial abstraction which can be expressed as a function of S. The SCS expressed $I_a = 0.2S$ on the basis of the results obtained for several experimental watersheds [Ponce and Hawkins, 1996]. The potential maximum retention, S, is related to a dimensionless Curve Number (CN) defined as a function of land use, soil type and antecedent wetness conditions (AWC).

The rainfall-runoff transformation is represented by using the SCS - Unit Hydrograph (SCS-UH) method incorporating only one parameter. This parameter is assumed to be the basin lag time, defined as the time shift between the centroids of effective rainfall and direct runoff [Singh, 1975; 1988]. Specifically, for each homogeneous elements (sub-basin), the lag time, L, is estimated by using the lag-area relationship proposed by Melone et al. [2002]:

$$L = \eta 1.19 A^{0.33} \tag{2}$$

with L basin lag time (in hours), A drainage area (in km^2) and η a parameter to be calibrated. Equation (2) with $\eta = 1$ was obtained considering 26 watersheds in Central Italy ranging in area from 12 km^2 to 4147 km^2. However, this result refers to the effective rainfall hyetographs determined by the extended form of the two-term Philip infiltration equation and the use of the geomorphological unit hydrograph for the rainfall-runoff transformation. Therefore, η is considered here as a calibration parameter to take into account of the differences due to the use of the SCS-CN method and the SCS unit hydrograph.

Finally, flood routing along the natural channels is simulated through the lag routing method which represents the simple translation of flood waves neglecting the attenuation or diffusion processes. The method requires the estimation of only one parameter, the channel lag time, L_C, that can be determined as a function of reach length and slope and mean flow velocity, v_m.

3. STUDY AREA AND DATA SETS

The model was applied to the Upper basin of the Tiber River located between the hydrometric sections of Gorgabuia and Ponte Felcino with an area of ~1800 km^2 (see Figure 1). The catchment has a complex topography that can significantly enhance the widespread frontal rainfalls causing the major flood events. A geolithological map (scale 1:100000) and the soil/land use map defined in the CORINE – LAND COVER European project are available. Accordingly, the study area is characterized by terrigeneous facies and flysch deposits mainly consisting of clayeyschistose and clayey-marly sediments; 57% of the total watershed area is covered by wood, the remaining area is 37% agricultural crop and 5% pasture. The forests are generally located in headwater areas and cropping in valley floors. The area is affected by Mediterranean climate with average annual precipitation of about 900 mm and mean annual temperature of 11 °C; the mean annual potential evapotranspiration, computed with the Thornthwaite formula [1948], is almost 800 mm. The 50 years return period peak discharge is equal to 490 m^{3}s^{-1} and 1020 m^{3}s^{-}1 at Santa Lucia and Ponte Felcino section, respectively.

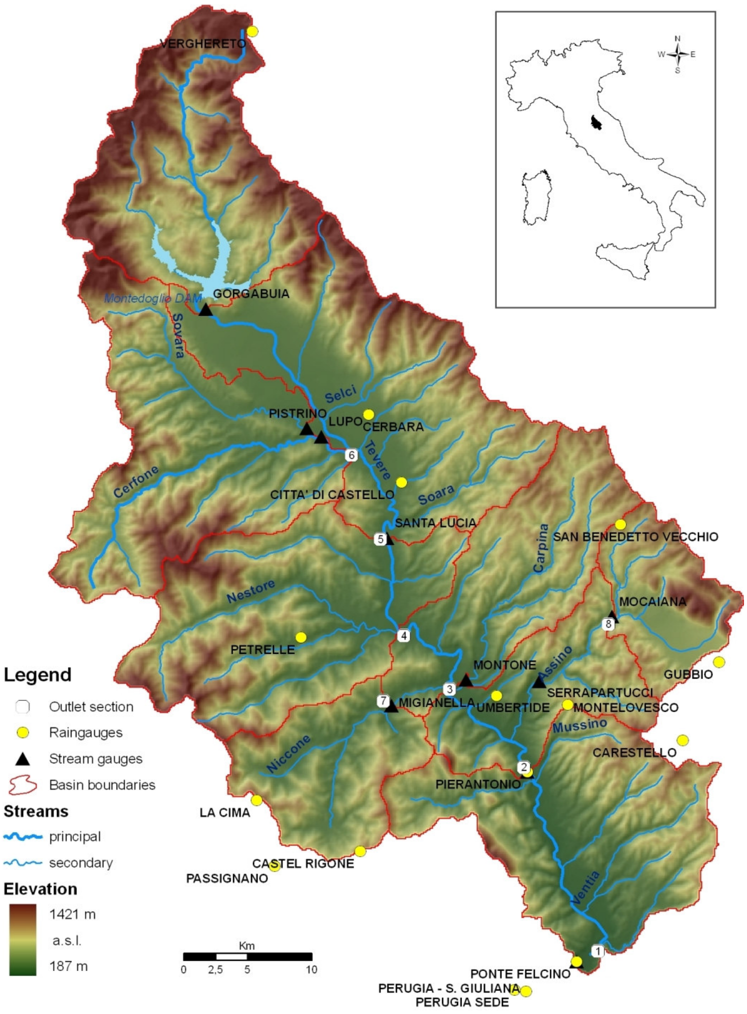

Figure 1. Study area: topographic characteristics and operating hydrometeorological network. The eight selected sections are also shown as white circles.

A dense real time hydrometeorological network (1 station every 150 km^2) has been operating in the Upper Tiber River basin for more than 20 years and the data are recorded with a time interval of 30 minutes. The hydrometric sections are located along the main channel and the secondary streams (see Figure 1), the corresponding stage-discharge relationship is frequently updated so allowing reliable discharge estimates. For this study the data recorded during the period December 1998 - December 2003 by 13 rain gauges and 10 hydrometric gauges were considered. In this period the four more significant flood events were selected, their main characteristics are summarized in Table 1.

Table 1. Main characteristics of selected flood events for the Upper Tiber basin at Ponte Felcino.

Event Date	Rainfall Depth (mm)	Initial Base Flow (m^3 s^{-1})	Observed Direct Runoff Peak (m^3 s^{-1})
December 14, 1996	31.4	26	315
June 01, 1997	98.2	10	399
December 04, 1998	33.9	43	254
December 27, 2000	53.8	148	365

4. METHODOLOGY

In order to define the optimal rainfall and soil/land use spatial distribution, the hydrological model was implemented considering two different configurations for both rainfall and CN parameter. Table 2 summarizes the four different configurations considered for the analysis. In particular, for the distributed Cases (Case 1-3) the rainfall and the CN values were assumed variable from one sub-catchment to another according to the rainfall spatial pattern and soil/land use characteristics. For Case 4 the model can be considered as a lumped model. It has to be noted that the comparison of Case 1 and Case 2 (distributed versus uniform rainfall) and between Case 1 and Case 3 (distributed versus uniform CN) is used to highlight, separately, the effects related to the assumption on the rainfall and the CN spatial distribution, respectively. From the other hand, the comparison between Case 1 and Case 4 allow us to define the optimal spatial discretization.

Table 2. Case study combinations for different rainfall and CN spatial distribution.

		Rainfall	
		Distributed	*Uniform*
Soil/Land Use	*Distributed*	Case 1	Case 2
	Uniform	Case 3	Case 4

To implement the model the study catchment has been subdivided into 70 homogeneous elements (sub-basins) characterized by a drainage area ranging from few square kilometers to 120 km^2 and a mean basin slope ranging from 4% to 28%. It has to be underlined that there is an artificial reservoir in the upper part of the selected catchment formed by the Montedoglio dam (Figure 1). Therefore, the upstream drainage area has been simulated by using a source element in the HEC-HMS model represented by the discharge observed at Gorgabuia hydrometric station.

For the analysis, eight river sections, whose location is shown in Figure 1, were selected. Table 3 summarizes the main properties of each sub-catchments subtended by the eight cross sections including the drainage area, the main basin slope and length and the CN values for intermediate antecedent wetness conditions, CN$_{\text{II}}$.

The four selected flood events were simulated by the HEC-HMS model considering all the combinations of Table 2 and the flood hydrographs estimated at several river sections within the basin were compared. For each flood event the antecedent wetness conditions were assessed scaling by a correction factor, C_f, the CN$_{\text{II}}$ values in order to reproduce the observed direct runoff volume at the outlet river section. In this way, the CN spatial distribution was kept on and only the absolute CN values were modified without loosing the spatial variability described by the soil/land use characteristics [Frances et al., 2007].

Table 3. Main characteristics of the sub-catchments selected for the analysis. CN_{II} represents the Curve Number value for intermediate antecedent wetness conditions.

ID	Outlet Section	Drainage Area (km^2)	Mean slope (%)	River length (km)	CN_{II}
1	Tiber R. at P.Felcino section	1791	1.00	107	70.6
2	Tiber R. at Pierantonio section	1511	1.19	93	71.4
3	Tiber R. at Niccone R. confluence	1280	1.34	83	71.6
4	Tiber R. at Néstore R. confluence	948	1.50	71	71.7
5	Tiber R. at S. Lucia section	652	1.83	63	72.0
6	Cerfone Str. at Tiber R. confluence	301	3.13	34	72.0
7	Niccone Str. at Migianella section	134	2.35	16	70.5
8	Assino Str. at Mocaiana section	99	0.83	15	71.0

5. RESULTS AND DISCUSSIONS

The hydrological model was calibrated for the Case 1, i.e. distributed rainfall and CN values. The discharge data of the two first events observed at the outlet station Ponte Felcino were used to estimate model parameters. In particular, the model parameters related to the rainfall-runoff transformation, η, and channel routing, v_m, were optimized considering the agreement of the overall shape of the discharge hydrograph. Then, the optimal correction factor, C_f, for the CN values was determined for each event in order to reproduce the direct runoff volume at Ponte Felcino section; the C_f values are equal to 1.23 for December 1996, 0.55 for June 1997, 1.11 for December 1998 and 1.12 for December 2000. Figure 2 shows the comparison between observed and simulated flood hydrographs for the Ponte Felcino section and for the upstream section of Santa Lucia.

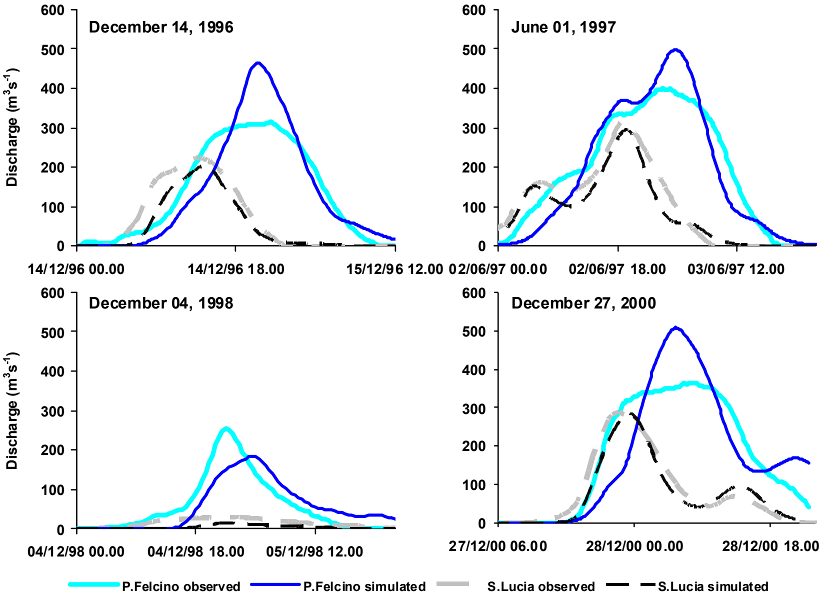

Figure 2. Comparison of the observed and simulated flood hydrographs for the Santa Lucia and Ponte Felcino river sections.

As the model parameters are estimated through the flood hydrograph observed at the outlet of the catchment, the results obtained for Santa Lucia section have to be considered for model validation. As it can be seen in Figure 2, the model predicts a narrow flood hydrograph shape for Ponte Felcino section both for calibration and validation events. This can be due to the fact that the model does not take into account of flooding, that occurred for the flood events of December 1996 and 2000, and of the diffusion process in the channel routing module. However, the model was able to reproduce with a fair accuracy the hydrograph shape and timing both for Ponte Felcino and Santa Lucia river section. Similar results were obtained for other equipped river sections, not shown here for sake of brevity.

In order to investigate the effects of rainfall and CN spatial distribution on hydrologic response, the hydrological model was then applied considering the different configurations of rainfall and soil/land use characteristics summarized in Table 2. For the flood occurred on June 1997 Figure 3 shows the discharge hydrographs estimated at the eight selected river sections for the four different configurations and, if available, the observed discharge hydrograph.

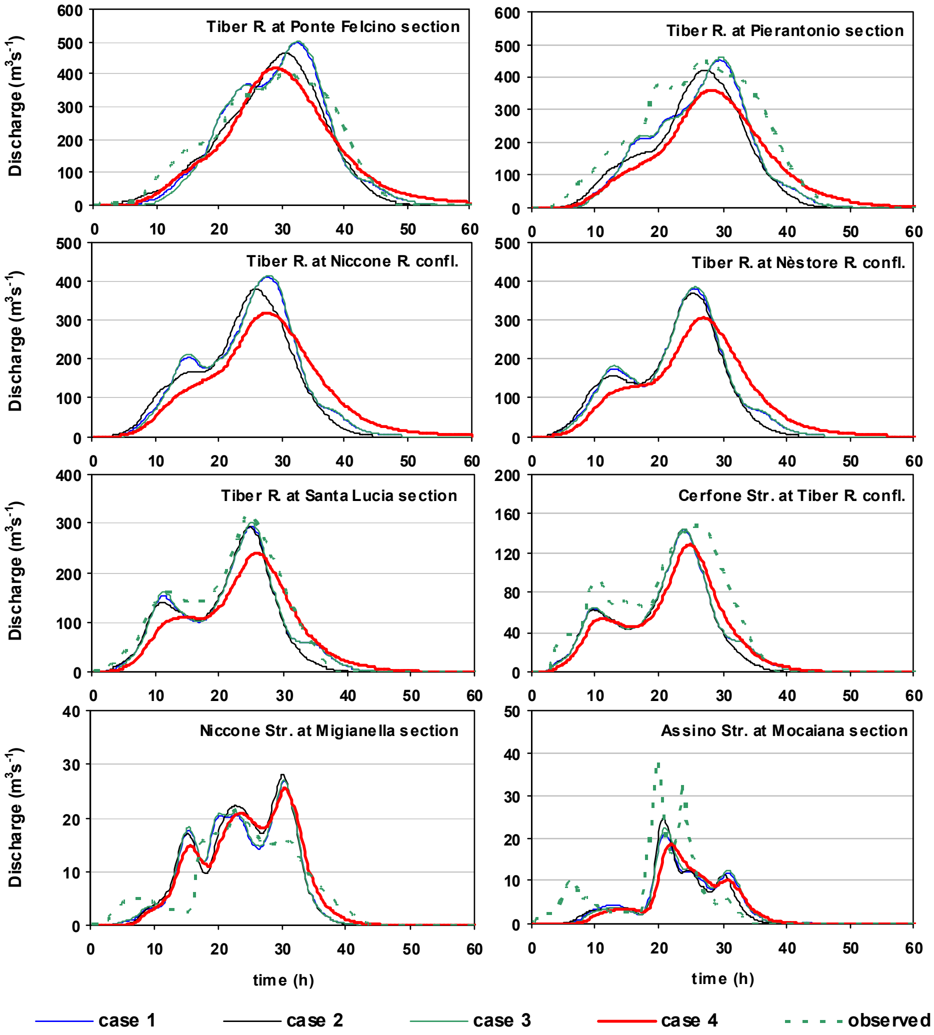

Figure 3. Event of June 1997: comparison between simulated discharge hydrographs for different rainfall and soil/land use spatial pattern (Case 1-4 of Table 2). The observed discharge, if it is available, is also shown.

As it can be seen, Case 1 and Case 3 furnish very similar results for all sections denoting that, for the study area, the CN representation does not significantly affect the hydrologic response. This result is in accordance with Grove et al. [1998]. In fact, the CN values vary in a limited range (Table 3) and the flood events are characterized by high rainfall depths. Moreover, Cases 1 and 3 reproduce the observed discharge hydrograph more accurately than Cases 2, particularly for the Tiber River sections. From these observations it can be derived that, for our study area, the knowledge of the rainfall spatial pattern is more important than the soil/land use spatial distribution. Moreover, for all the selected river sections the discharge hydrographs simulated by the lumped approach (Case 4) were significantly different from those of the other three Cases with a general underestimation of peak flow.

To define the optimal rainfall and soil/land use spatial distribution it was used the Root Mean Square Error (RMSE) and the Nash-Sutcliffe coefficient (NS) [Nash & Sutcliffe, 1970] computed between simulated and 'observed' discharge hydrographs. In particular, the 'observed' hydrograph refers to discharge computed by the hydrological model under the hypothesis of heterogeneity on rainfall and CN values (Case 1), whereas the simulated hydrographs correspond to Case 2-4. For the four selected events, Figure 4 shows the RMSE as a function of contributing drainage area. As it can be seen, Case 3 provided simulated hydrographs very similar to those 'observed' for every basin scale. On the contrary, Case 2 and mainly Case 4 furnished quite different discharges with error values increasing significantly with the contributing drainage area. Analyzing the slope of the RMSE curve for Case 4, it can be inferred that, for most of the investigated flood events, the RMSE starts to increase quickly when the basin drainage area becomes greater than ~300 km^2. Analogous considerations can be inferred for the NS values which is greater than 82% for basin drainage area smaller than ~300 km^2 and rapidly decrease for larger areas. This threshold value can be assumed as the minimum areal extension of the homogeneous elements for partitioning the basin in order to maintain the spatial variability of rainfall and soil/land use which can affect significantly the basin response. This result was corroborated by the RMSE computed between the simulated hydrographs and those observed at the eight gauged sections, subtending a drainage area from 100 to 1800 km^2 (not shown here for sake of brevity). In fact, the RMSE of Case 4 starts to move away from that computed for Case 1-3 for a drainage area of about 300 km^2.

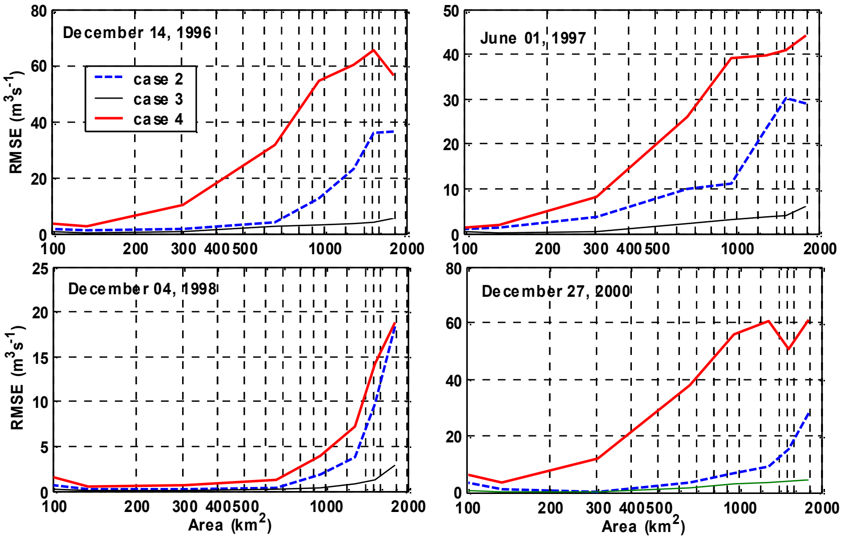

Figure 4 Root Mean Square Error (RMSE) computed between the discharge hydrograph of Case 2-4 and that of Case 1 for the four selected events as a function of contributing drainage area.

6. CONCLUSIONS

In this study a semi-distributed event-based hydrological model was applied to four significant flood events occurred in the Upper Tiber River basin. Model performance was found fairly accurate in reproducing both flood hydrograph shape and timing at the basin outlet and for different equipped sub-basins.

The comparison between the discharge hydrographs provided by different configuration of rainfall and soil/land use spatial pattern was carried out in order to analyze the effect of heterogeneity of these quantities on the hydrological response at different scales. In particular, a uniform versus distributed spatial representation of these quantities was analyzed. The obtained results highlighted the importance of the rainfall spatial distribution knowledge to determine the runoff response in our study area and, the low influence of the soil/land use spatial characterization due to its low variability in the study area. Moreover, a threshold value for the sub-catchment area of 300 km^2 was identified as the optimal spatial discretization to be adopted for rainfall-runoff models designed for flood warning purposes. However, further investigations on other basins with different areal and physiographic characteristics should be carried out in order to verify the reliability of the results obtained in this study.

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