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INFLUENCE OF RAINFALL OBSERVATION NETWORK ON MODELED HYDROLOGICAL RESPONSE

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ABSTRACT

Precipitation data, one of the most important input required in hydrological modeling and forecasting, are usually recorded using raingauges which are classical and fundamental tools able to provide an estimate of rainfall at a point. The consistency of precipitation monitoring network in terms of spatial scale (network density and location of raingauges) and time resolution has to be capable to reproduce, with acceptable accuracy, the characteristics of the flood phenomenon. In this context, over the last thirty years, several studies concerning the influence of point measurement of rainfall for the estimation of total runoff volume have been carried out. Aim of this paper is using a physically based and distributed-parameter hydrologic model in order to investigate the influence of the raingauges network configuration, in terms of number and spatial distribution, on the estimation of hydrograph peak discharge considering also the spatial distribution of soil types in the basin. The hydrologic model has been applied to the catchment of Baron Fork located in Oklahoma. The radar measurements, available in the area, have been assumed as representative of the "real" distribution of precipitation. Its hydrological response is compared with that obtained from interpolated precipitation fields, which, in turn, are obtained by varying the distribution of the raingauges network. The analysis has been first carried out assuming a simplified spatial distribution of soil characteristics and then considering the real spatial distribution of soil types.

1. INTRODUCTION

In the past years numerous field experiments have revealed that most of the hydrological processes are characterized by a considerable spatial variability (Schuurmans et al, 2007). In this context the distributed hydrologic models try to represent most of the natural processes occurring in a basin, but their capability to model the catchment hydrological response is often compromised by large uncertainties in the knowledge of spatial distribution of rainfall input. Particularly rainfall is often defined as the key variable in hydrological systems because of its important role in determining surface hydrological processes.

Precipitation is governed by complicated physical processes which are inherently nonlinear and extremely sensitive (Bardossy and Plate, 1992). It is significantly variable in space and time within a catchment (Krajewski et al., 2003) and this spatial variability has a dominant impact on runoff modeling (Schilling et al., 1986; Bell et al., 2000). The time-spatial variability of rainfall clearly affects every methods of rainfall estimation and influences the design of raingauge network (Sun et al., 2002). Raingauges provide punctual estimates of rainfall used, in turn, to obtain a spatial distribution of precipitation over the catchment through spatial interpolation techniques. Unfortunately, if the gauges network density is low or the distribution of gauges and the interpolated methods are not correct, the rainfall field obtained may be characterized by a large estimation error which is transferred, often amplified, to the runoff through the hydrological model.

The role of spatial distribution and temporal resolution of raingauges in the announcement of the flood has been discussed in scientific literature since 1960s, with the pioneeristic works of Eagleson and Shack (1966) and Eagleson (1967). Starting from these works Krajewski et al. (1991) forced a physically based distributed-parameter hydrologic model with synthetic rainfall generated using the Monte Carlo approach and applying it to the Ralston Creek watershed (7.5 km^2) for investigating the sensitivity of the model response at event scale with respect to different spatial and temporal rainfall-input sampling density. The input data were generated by a space-time stochastic model of rainfall and then sampled by the varied-density synthetic raingauges networks. The basin response, based on 5 minutes increment input data from a network of high density with about 1 gauge for 0.1 km^2, was assumed to be the "ground truth", and the other results were compared against it. The results indicated higher sensitivity of basin response with respect to the temporal resolution than to the spatial resolution of the rainfall data.

The sensitivity of hydrological models to spatial distribution of precipitation has been also assessed by Obled et al. (1994), who applied the semi-distributed version of TOPMODEL to an experimental medium-sized basin, considering two different patterns of rainfall point data given by 5 and 21 gauges respectively with simulations performed in continuous at hourly resolution. The authors showed that, although the use of a greater number of raingauges was irrelevant to the estimate of the precipitation, the small differences in terms of estimation of the precipitation become important when the response is assessed in term of runoff. In fact, increasing the number of raingauges causes an elevated improvement of the estimation of both runoff and flood peak.

Goodrich et al. (1995) showed also the influence, at the event scale, of the different positions of the gauge over the basin for the estimation of the runoff without providing any suggestions on how dispose the gauge correctly in the space. Runoff model runs performed with data from variable numbers of recording gauges demonstrated that the uncertainty in runoff estimation is strongly related to the number of input gauges. In the presence of elevated spatial rainfall gradients, observed in five of the eight observed events in this experiment, the location of the gauge becomes a crucial parameter in modeling the storm hydrograph.

The correlation between the scale of the basin and the effect of raingauges spatial density is explicitly studied in the work of Arnaud et al. (2001) who applied three different hydrologic models at the event scale in four basins characterized by a different spatial scale. The results showed that the sensitivity of models to precipitation spatial variability, that is a function of the spatial scale of the basin and of the type of model used, increases in the case of very extreme events.

Recently Bardossy et al. (2008) analyzed the performance of the hydrological model as a function of the raingauge density in continuous simulations. They showed that the number and spatial distribution of raingauges affect the simulation results pointing out that the overall model performances worsen radically with an excessive reduction of raingauges. However, the overall performances were not significantly improved by increasing the number of raingauges more than a certain threshold number specially if stations around but outside the catchments are considered.

As previously shown, in the past different studies have deeply analyzed the influence of the spatial distribution of raingauges on hydrological response while others the influence of the number of raingauges. Starting from these studies, our work aims to analyze the influence of the raingauges network configuration in terms of number and spatial distribution on the estimation of discharge hydrograph, taking into account the soil types spatial distribution within the basin as well. In fact, the soil distribution influences, through different hydrological properties, the rainfall-runoff transformation and then also the position of the "optimal" gauges for the estimation of runoff. The work is carried out applying a physically based distributed-parameter hydrologic model to the Baron Fork watershed in Oklahoma, USA. The analysis is performed at the event scale by considering nine precipitation events with different space-temporal characteristics, occurred during 1998. The influence of the gauges network configuration on the estimation of the runoff is thus assessed analyzing simultaneously the mutual relationship between spatial distribution of rainfall and soil types patterns within the study area. Analysis is first carried out assuming some simplified and fictitious spatial distributions of soil characteristics and then considering the real spatial distribution of soil types. In this way the dependence of the best raingauges configuration on the soil types distribution is investigated as well as the influence of the space-temporal characteristics of storm events on the choice of the gauges network.

2. MODEL

The model used in this study is the TIN-based Real-time Integrated Basin Simulator (tRIBS) (Ivanov et al., 2004a,b). The model stresses the role of topography in lateral soil moisture redistribution and accounts for the effects of a sloped, heterogeneous and anisotropic soil column. tRIBS explicitly considers the spatial variability in precipitation fields and land-surface descriptors and is capable of resolving basin hydrology at very fine temporal and spatial scales. An adaptive multiple resolution approach, discussed by Vivoni et al. (2004), is used to represent the complexity of the simulation domain.

Catchment topography, vegetation and soils are accounted for using triangulated irregular networks (TINs). Through the TIN implementation, the number of computational model elements is significantly reduced up to 90% or more as compared to high-resolution DEMs. The direct implication of the multiple resolution approach is a high computational efficiency which makes feasible real-time applications over large basins.

3. CASE STUDY

3.1. BASIN DESCRIPTION

Since the tRIBS model was successfully calibrated and verified at the Baron Fork basin at Eldon by Ivanov et al. (2004a, b), the study was made at the same catchment.

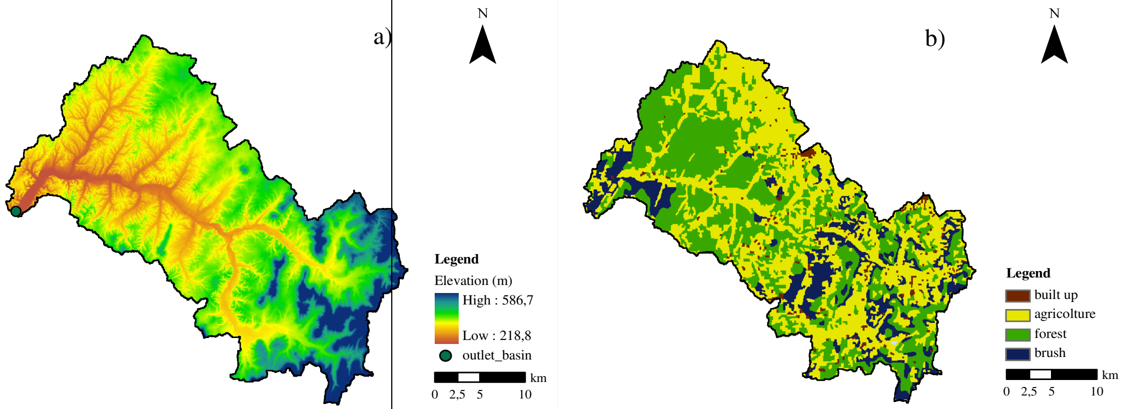

Figure 1. DEM of the Baron Fork at Eldon (a) - Land use map (b).

The basin, located in the north-eastern of Oklahoma (USA), is 800 km^2 in size and its elevation is between 200 and 600 m a.s.l.. Most of the basin is characterized by steep slopes (15% - 40%) with gently rolling relief at the basin headwater (east) and quite rugged terrain in its lower areas (west) (Fig. 1a). Vegetation covers about 52% of the area with deciduous and evergreen forests and 46% with croplands and orchards (Fig. 1b). The surface soil texture is primarily silt-clay (47%), sandy-clay-loam (40%) and loam (13%). For a more detailed description of the basin, the reader can refer to Ivanov et al. (2004a, b).

3.2. DATA

3.2.1. PRECIPITATION

Simulations were driven both with radar rainfall estimates from the NWS Next-Generation Weather Radar (NEXRAD) system and with fictitious raingauges measurements. Data by the NEXRAD radar (Vivoni et al., 2006) are available for the case study and used to obtain spatial distribution of precipitation fields over the basin in the form of hourly NEXRAD 4 km gridded estimates.

Following the approach used by many authors, the analysis of the effect of the raingauges position has been performed at the event scale by considering nine precipitation events, occurred during 1998 and classified as function of their average intensity and spatial variability. This allowed us to analyze the influence of the raingauges network configuration on hydrological response as a function of the precipitation characteristics. The nine events were chosen according to the average (in time and space) of precipitation event intensity i_m classified as H - high ($i_m > 2.5$ mm/h), M - medium (1.5 mm/h $< i_m <$ 2.5 mm/h) and L - low ($i_m < 1.5$ mm/h), and to the spatial variability of the average of rainfall evaluated in terms of coefficient of variation CV_S (i.e. the ratio between the standard deviation of the mean intensity grid and the spatial average value of the same grid) ranked as H - high ($CV_S > 0.5$), M - medium ($0.25 < CV_S < 0.5$) and L - low ($CV_S < 0.25$).

Figure 2 represents the spatial pattern of the precipitation average intensity for each event. The range of event duration is from 4 hours (event 5) to 74 hours (event 6) and the total event rainfall amount is between 6,09 mm (event 5) and 116,11 mm (event 6). The event 3 shows the greatest average precipitation intensity (i_m=3,49 mm/h) and the lowest precipitation spatial variability (CV_S=0,12), while the event 9 has the lowest average precipitation intensity (i_m=0,77 mm/h) and the event 7 the greatest spatial variability (CV_S= 0,92).

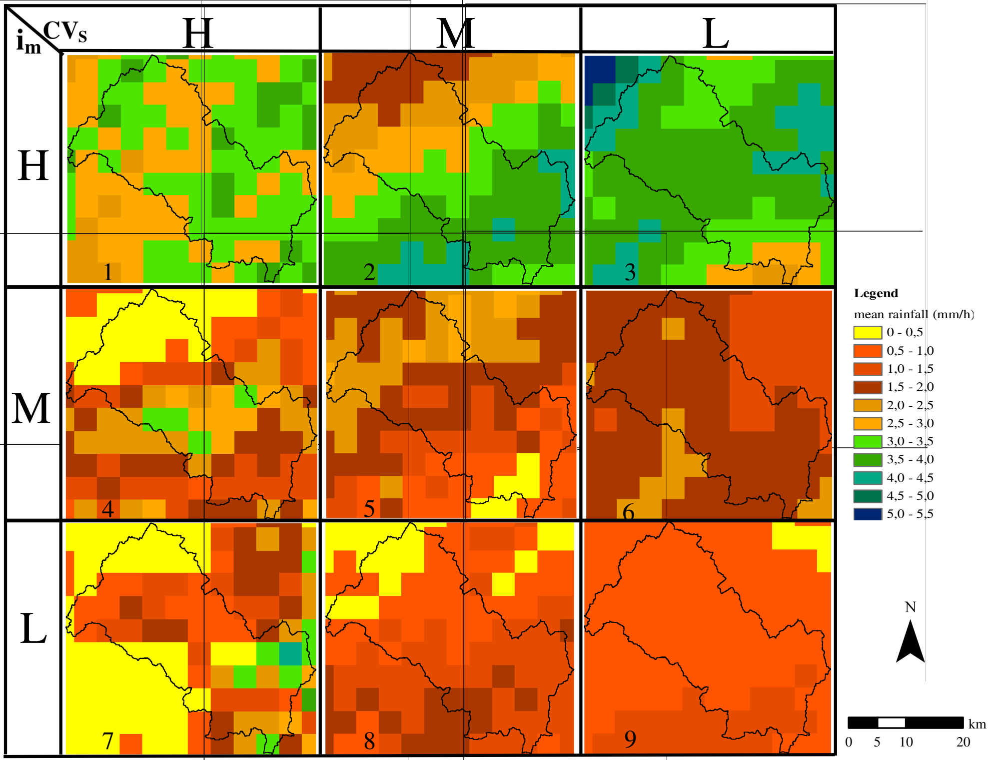

Figure 2. Spatial pattern of average precipitation intensity for each event. Events with the same average intensity class (H, M or L) are in the same row, while events with the same coefficient of variation class (H, M or L) are in the same column.

3.2.2. SOIL TYPES DISTRIBUTION

As mentioned above, since one of the goals of this analysis is to analyze the influence of raingauge network for a given spatial distribution of soil types, simulations have been performed considering first two synthetic configurations with a single soil type (silty-clay (*c*) and sandy-clay-loam (*s*)) and then using two synthetic configurations of the same two soil types differently distributed over the basin: silty-clay upstream the basin and sandy-clay-loam downstream the basin (*cs*) and vice versa (*sc*) (Figure 3). Finally, the real spatial distribution of soil types (*r*) with three soil types has been considered.

3.3. ASSUMPTIONS AND SIMULATIONS

In order to run all the simulations, the following assumptions have been done:

1. NEXRAD radar measurements, available in the area, have been assumed as representative of the “real” distribution of precipitation;
2. the “real” hydrological response of the catchment has been considered as obtained from the tRIBS using as climate forcing the “real” precipitation and then used as term of reference for the remaining simulations;
3. eight fictitious raingauges have been distributed in the basin randomly (Figure 4); 4 (1, 2, 3, 4) can be considered downstream and 4 (5, 6, 7, 8) upstream raingauges;
4. NEXRAD time series data have been sampled right by the eight fictitious raingauges in order to obtain the gauges time series;

5. tRIBS and soil parameters (section 3.2.2) used for running simulations come from calibration of Ivanov et al. (2004c).

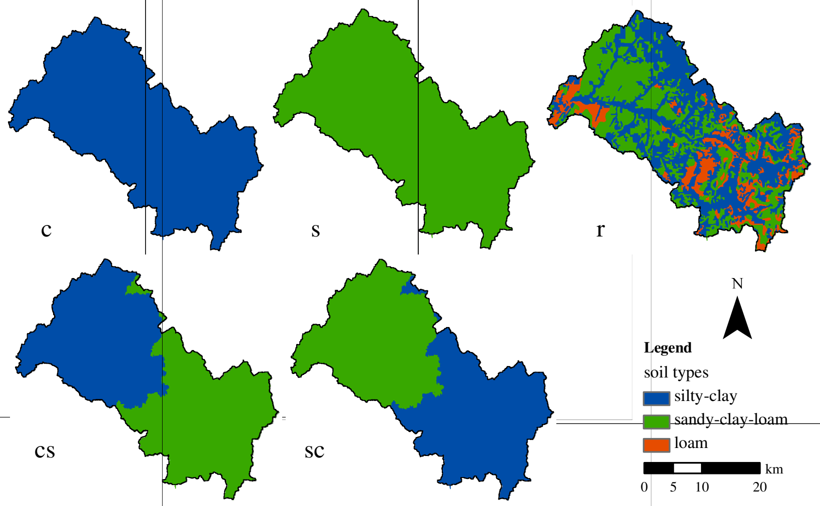

Figure 3. Different configurations of soil types distribution.

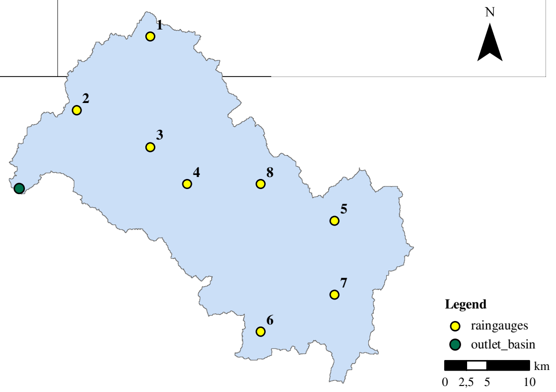

Figure 4. Raingauges placement inside the basin.

After simulation “zero” (model forced with NEXRAD precipitation - see points 1-2 of assumptions), 255 different simulations have been carried out for each soil type distribution and each event. Simulations use, as precipitation forcing, data coming from each single gauge, from the combinations of raingauges in pairs, three by three, four by four, five by five, six by six, seven by seven, and from the complete network spatially interpolated using Thiessen polygons. Considering all the events and all the soil types configurations, 11.484 simulations have been totally done. The flood hydrographs obtained for each combination of these raingauges have been compared with the “real” hydrological response. The performance of the model has been evaluated using as performance index the *Root Mean Squared Error* (RMSE). This index allows one to quantify the difference between discharge (or precipitation) values obtained with the precipitation measured by gauges and the true discharge (or precipitation) values obtained with the precipitation measured by radar during the considered event and it returns a good average estimation of the error for the considered event. *Normalized RMSE* (NRMSE) is here useful because the different events, characterized by different magnitude, have to be compared: it can be obtained normalizing RMSE to the average X_m of observed data (NRMSE=RMSE/X_m).

4. RESULTS AND DISCUSSION

The results have been analyzed considering firstly the "best raingauges network" for rainfall estimation and then the "best raingauges network" for runoff estimation (i.e. the network that for fixed number of raingauges and soil type distribution minimizes the RMSE for precipitation ($RMSE_P$) and runoff ($RMSE_Q$)).

Considering the case of rainfall estimation, the distribution of precipitation obtained for each combination of raingauges has been compared with the "real" distribution of precipitation. For fixed number of raingauges composing the network, the network of raingauges with the smallest $RMSE_P$ ($RMSE_{min,P}$) has been chosen as the "best network" for rainfall estimation while, for each soil types configuration, the network of raingauges with the smallest $RMSE_Q$ ($RMSE_{min,Q}$) has been chosen as the "best network" for the hydrograph reconstruction.

In Table 1, the "best networks" for each event are summarized as a function of the number of gauges in the network. The corresponding $RMSE_{min,P}$ values can be also read in the table. Networks with the minimum $RMSE_{min,P}$ are highlighted in bold italic; for each event, the minimum $RMSE_{min,P}$ is not obtained with the complete network but with a fewer number of raingauges.

number of gauges	**event 1**		**event 2**		**event 3**	
	$RMSE_{min,P}$ (mm/h)	**gauges**	**$RMSE_{min,P}$** (mm/h)	**gauges**	**$RMSE_{min,P}$** (mm/h)	**gauges**
1	0,946	4	0,964	8	1,655	8
2	0,306	1,8	0,387	3,5	0,686	3,7
3	0,179	1,5,8	0,309	1,3,5	0,487	2,4,7
4	***0,169***	***1,5,6,8***	0,241	3,4,5,6	0,342	2,4,6,7
5	0,170	1,5,6,7,8	0,231	2,3,5,6,8	0,302	2,4,5,6,7
6	0,261	1,4,5,6,7,8	***0,207***	***1,2,3,5,6,8***	0,271	2,3,4,5,6,7
7	0,339	2,3,4,5,6,7,8	0,211	1,2,3,5,6,7,8	***0,267***	***2,3,4,5,6,7,8***
8	0,421	ALL	0,219	ALL	0,323	ALL
number of gauges	**event 4**		**event 5**		**event 6**	
	$RMSE_{min,P}$ (mm/h)	**gauges**	**$RMSE_{min,P}$** (mm/h)	**gauges**	**$RMSE_{min,P}$** (mm/h)	**gauges**
1	0,975	3	0,575	8	1,252	8
2	0,754	3,7	0,162	1,8	0,400	3,5
3	0,204	3,7,8	***0,100***	***3,6,8***	0,340	3,7,8
4	0,244	2,4,5,6	0,107	2,3,6,8	0,288	1,3,7,8
5	0,193	2,3,4,5,7	0,114	1,2,3,6,8	***0,212***	***1,2,3,7,8***
6	***0,185***	***1,2,3,4,7,8***	0,183	1,2,3,4,6,8	0,236	1,2,3,6,7,8
7	0,226	1,3,4,5,6,7,8	0,342	1,2,3,4,5,7,8	0,283	1,2,3,5,6,7,8
8	0,406	ALL	0,393	ALL	0,334	ALL
number of gauges	**event 7**		**event 8**		**event 9**	
	$RMSE_{min,P}$ (mm/h)	**gauges**	**$RMSE_{min,P}$** (mm/h)	**gauges**	**$RMSE_{min,P}$** (mm/h)	**gauges**
1	1,132	8	0,803	8	0,198	4
2	0,556	3,8	0,338	7,8	0,126	4,8
3	0,178	1,4,7	0,236	2,3,5	***0,071***	***2,4,5***
4	***0,154***	***1,3,6,7***	0,165	2,3,7,8	0,086	2,3,4,5
5	0,164	1,2,3,4,7	0,166	1,2,3,7,8	0,085	2,3,4,6,8
6	0,164	1,3,4,6,7,8	***0,164***	***1,2,3,5,7,8***	0,079	2,3,4,5,7,8
7	0,321	1,2,3,4,6,7,8	0,197	2,3,4,5,6,7,8	0,092	2,3,4,5,6,7,8
8	0,681	ALL	0,215	ALL	0,112	ALL

Table 1. $RMSE_{min,P}$ and optimal raingauges network for a fixed number of gauges for each event. Networks with the minimum $RMSE_{min,P}$ are highlighted in bold italic.

Analyzing all the events simultanously, it is not easy to understand the exact position of raingauges for rainfall estimation. In fact, since the reconstruction of the rainfall volume is strongly influenced by the spatial pattern of precipitation, the network performance varies for each event.

Results previously shown in Table 1 can be summarized by averaging the NRMSEs relative to the nine events. Figure 5 shows the average NRMSE values ($\overline{NRMSE}$) as a function of the number of used gauges. If only one raingauge is used, the lowest value of $\overline{NRMSE}_P$ is obtained by raingauge #8 that is placed in the central part of the basin. If two raingauges are used, the $\overline{NRMSE}_P$ is obtained with the gauges #3 and #7, and the #8 becomes less important because its importance is replaced by a gauge upstream (#7) and a gauge downstream (#3). In the three raingauges configuration the "best network" is 3-7-8, while in the four gauges configuration the best one is 2-3-7-8 and there are two gauges upstream the basin and two downstream. In the cases of five raingauges there are three gauges downstream (#2, #3, #4) and two downstream (#7, #8). The minimum $\overline{NRMSE}_P$ is obtained with five gauges. Adding more raingauges causes an increase of the $\overline{NRMSE}_P$.

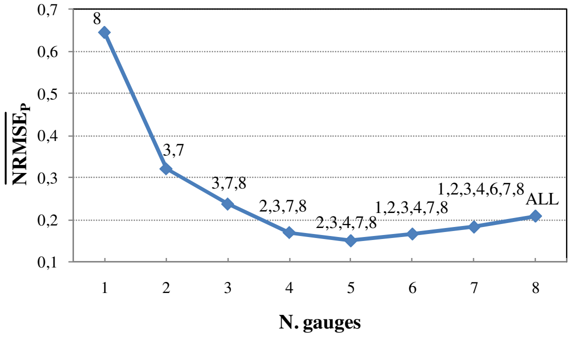

Figure 5. Relationship between $\overline{NRMSE}_P$ and number of gauges for the average event.

Considering the performances of networks relative to runoff estimation, the results have been evaluated by analyzing firstly the single events, and then trying to summarize the overall knowledge provided by the analysis of each single event.

In Table 2 the optimal networks for the event 1 are summarized as a function of the soil types configuration and the number of gauges within the network. Table 2 shows the $RMSE_Q$ values of each "best network" as well. For a fixed soil type configuration the network with the minimum $RMSE_{min,Q}$ is highlighted in bold italic.

A first important observation can be done by comparing the "best gauges network" for precipitation estimation (Table 1) with the "best gauges network" for runoff estimation(Table 2 – relative just to the 1st event): the network aimed to the best rainfall field estimation rarely coincides with the network aimed to the reconstruction of the best flood hydrograph, according to Eagleson (1967) and Goodrich et al. (1995), because the best gauges position for runoff estimation is influenced also by the rainfall-runoff transformation as a function of the soil distribution.

Event 1 (Table 2) has a duration of 5 hours and the precipitation is higher upstream than downstream. With one raingauge, the lowest value of $RMSE_Q$ is obtained by raingauge #5, for the soil configurations *c* and *cs*. Instead for *s* and *cs*, the "best" raingauge is the #7. In particular, the best single raingauge is placed in the area with higher precipitation. If two raingauges are used, the best $RMSE_Q$ is obtained with an upstream raingauge and a downstream raingauge for *c* and *cs*, and with two upstream gauges for *s*, *cs* and *r*. In the three raingauges configuration , two raingauges have to be located downstream the basin (#1, #4) and one raingauge upstream (#8) in all soil configurations. In a network with four raingauges, there are always two gauges upstream and two raingauges downstream. The number of raingauges placed upstream is usually greater than the number of raingauges located downstream, because of the spatial pattern of precipitation. For the sake of brevity, the tables summarizing the results relative to the other eight events are here omitted, providing only the comments to the results.

$RMSE_{min,Q}$ (m^3/s)						**Raingauges**				
	s	**c**	**sc**	**cs**	**r**	**s**	**c**	**sc**	**cs**	**r**
1	0,464	1,387	0,989	0,848	0,837	7	5	7	5	7
2	0,397	0,982	0,758	0,882	0,705	5,6	4,8	4,8	5,7	5,6
3	0,328	***0,662***	0,568	0,556	0,470	1,4,8	***1,4,8***	1,4,8	1,4,8	1,4,8
4	***0,308***	0,768	***0,419***	***0,552***	***0,442***	***1,4,6,8***	1,4,6,8	***2,3,6,8***	***1,4,6,8***	***1,4,6,8***
5	0,380	1,026	0,438	0,645	0,587	1,4,6,7,8	1,4,6,7,8	1,2,3,6,8	1,4,6,7,8	1,2,3,4,8
6	0,382	1,157	0,544	0,707	0,564	1,2,3,4,6,8	1,2,3,4,6,8	1,2,3,4,6,8	1,4,5,6,7,8	1,2,3,4,6,8
7	0,423	1,175	0,788	1,124	0,674	1,2,3,4,6,7,8	1,2,3,4,6,7,8	1,2,3,4,6,7,8	1,2,3,4,5,6,7	1,2,3,4,6,7,8
8	0,477	1,323	1,139	1,152	0,828	ALL				

Table 2. $RMSE_{min,Q}$ and optimal network for a fixed number of gauges for each soil distribution and for event 1. Network with the minimum $RMSE_{min,Q}$ is underlined in bold italic.

Event 2 has a duration of 39 hours and precipitation is higher upstream than downstream. With one raingauge, the lowest value of $RMSE_Q$ is obtained by raingauge #4, for both the configurations with one soil type. Instead for the configuration with two soil types, the best raingauge is the #3 for *cs* and the #5 for *sc*. In particular, it seems that it is preferable to sample the precipitation where the soil is less permeable. If two raingauges are used, in all soil distribution configurations, the lowest $RMSE_Q$ is obtain with a raingauge upstream the basin and one downstream. In the configuration with three raingauges, two raingauges have to be located downstream the basin (#1, #3) and one upstream (#6) with *s* and *cs*, and vice versa in *sc* (#3, #5, #7). In a network with four raingauges, there are two gauges upstream the basin and two downstream in all cases except for *sc*, for which there are three raingauges upstream and one downstream (#2, #5, #6, #8). In a network with 5 raingauges, there are always three gauges upstream the basin and two downstream. The observed pattern seems to show a usual location of the raingauges where the soil is less permeable.

Event 3 has a duration of 29 hours and is characterized by high precipitation at the center and downstream. Using one raingauge the effect of precipitation distribution prevails and the best raingauge is always the #3. With two raingauges the "best network" is always located downstream except in *sc* (7-8). With three raingauges the influence of soil types distribution is negligible and the "best optimal network" is 1-7-8 in all the soil type configurations. With four raingauges, there are always two gauges upstream and two raingauges downstream.

Event 4 is representative of a precipitation with short duration (7 hours), high precipitation in the central area and lower downstream. When a single raingauge is used, the best estimate of the hydrograph is obtained with raingauge #7 for *r*, *s* and *cs* and with raingauge #5 for *c* and *sc*. When two gauges are placed, raingauges #3 and #8 return the minimum $RMSE_Q$ for *c* and *cs*, while the "best gauges network" is 5-7 when the less permeable soil is in the upstream part of the basin (*sc*) and 6-7 for *s*. Raingauges with the best performance are usually placed in the part of the basin with high precipitation and less permeable soils. With a network of three raingauges in *s*, there are two raingauges upstream (#6, #8) and one raingauge downstream (#1) because the rain intensity is higher upstream. In *c* and *sc*, there are a raingauge (#1) downstream and two raingauges upstream (#5, #8). With four raingauges, if the soil configuration is *c* the network is placed upstream the basin where precipitation is greater. In the soil configuration *sc* there are more raingauges upstream the basin since the effect of rainfall spatial distribution is greater.

For event 5 precipitation is higher downstream and lower upstream. With one raingauge and for *sc* and *cs*, the raingauge is placed where the soil is less permeable, while when a pair of raingauges is used, there is not the influence of the soil types distribution and the "best optimal network" is 3-5 for all the soil type configurations. Increasing the number of raingauges, the arrangement of raingauges varies little with the soil type configurations and the "best raingauges network" is obtained with the same gauges for all the soil configurations.

Event 6 has a duration of 74 hours, precipitation is higher downstream and lower upstream. If a single gauge is used, the #2 is always the best raingauge, except for *sc* (#5), while with two raingauges the couple is always given by raingauges 3-5. Varying the soil type distribution the position of raingauges varies little, due to the low value of rainfall spatial. For all the soil type configurations, the minimum value of $RMSE_Q$ is always obtained with the same number of gauges equal to five and with the same gauges (2-3-4-5-8).

Event 7 has a duration of 7 hours, with high precipitation in the upstream part of the basin and lower rainfall in the downstream area. With a single raingauge and when the less permeable soil is upstream the basin (*sc*) the raingauge is placed upstream (#7), whereas in *cs* the raingauge is placed downstream (#2). In a three raingauges network, the gauges are located upstream (#5, #7, #8) for *c* and *sc*, while in *cs* there are two gauges downstream (#1, #2) and a gauge upstream (#7).

Event 8 has a duration of 9 hours and precipitation is higher upstream and lower downstream. The single raingauge is placed in the less permeable soil for all configurations. Increasing the number of raingauges, the position of raingauges varies little with the soil type distribution.

Event 9 has a duration of 12 hours, low coefficient of variation and low average precipitation intensity. Varying the soil type distribution, the "best network" is the same for a fixed number of gauges: 3-5 with two gauges, 1-3-5 with three gauges, 3-5-7-8 with four gauges, due to the low value of precipitation spatial variability and the minimum value of $RMSE_Q$ is always obtained with the same number of gauges equal to four.

The above mentioned comments point out that the factors that mainly influence the distribution of raingauges are:

- soil type distribution, with a general trend to locate the raingauges where the soil is less permeable,
- precipitation spatial distribution, being the raingauges placed where there is more precipitation.

In the event with high precipitation average intensity and high spatial variability the raingauge is placed where the precipitation is higher (event 1). If the average precipitation intensity is medium but the spatial variability of rainfall is high, the influence of precipitation pattern is more considerable than that of soil types distribution and the gauge is placed where the precipitation is higher (event 4). In the event with low average intensity and high spatial variability the gauge is placed where the soil is less permeable, in fact the effect of the less permeable soil position prevails on the effect of precipitation distribution (event 7). If the spatial variability of precipitation is low then the position of the gauges is not influenced by the soil distribution (events 3-6-9) and the "best gauges network" is obtained with the same number of gauges for all the soil configuration. Moreover if the spatial variability of precipitation is medium the position of gauges varies little varying the soil type distribution (events 5-8).

In order to compare the different events, the $NRMSE_Q$ has been used. Figure 6 shows, for each event, the value of $NRMSE_{min,Q}$ as a function of the number of gauges and for fixed soil configuration.

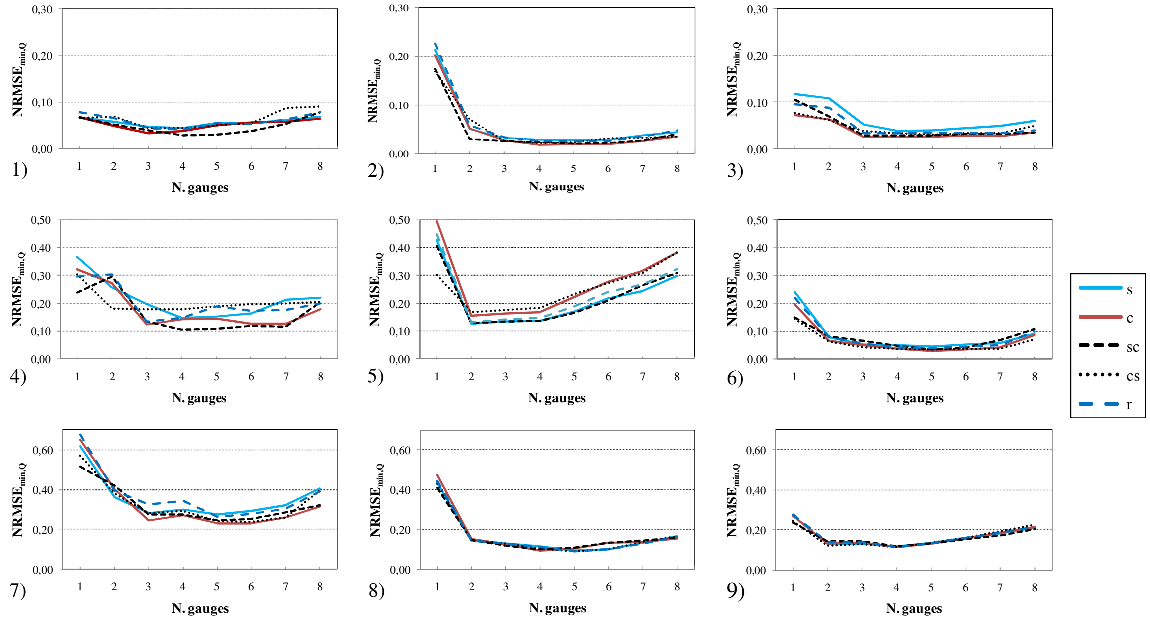

Figure 6. $NRMSE_{min,Q}$ as a function of the number of gauges and for fixed soil configuration, relative to each event.

When CV_S=H (events 1-4-7), there is an elevated influence of the soil configuration on the network performance, while for CV_S=M or CV_S=L, as the soil configuration changes, the NRMSE curves have a similar pattern (events 2-5-6-8-9). When CV_S=L, the distribution of raingauges varies little changing the soil distribution; one can observe a flattening of the curves and then the position of the gauges is not influenced by the soil distribution (events 3-6-9). The "best gauges network" is obtained, in this way, with the same number of gauges for all the soil configurations.

For a fixed number of gauges, the number of occurrences of single raingauges in the "best network" as function of the soil configuration can be analyzed (Figure 7). In the one gauge network (Figure 7a) the gauge #6 is never present while the #3 is the most important in *cs*, the #5 is important in *sc*; gauges #1, #2, #4 are never present in *sc*.

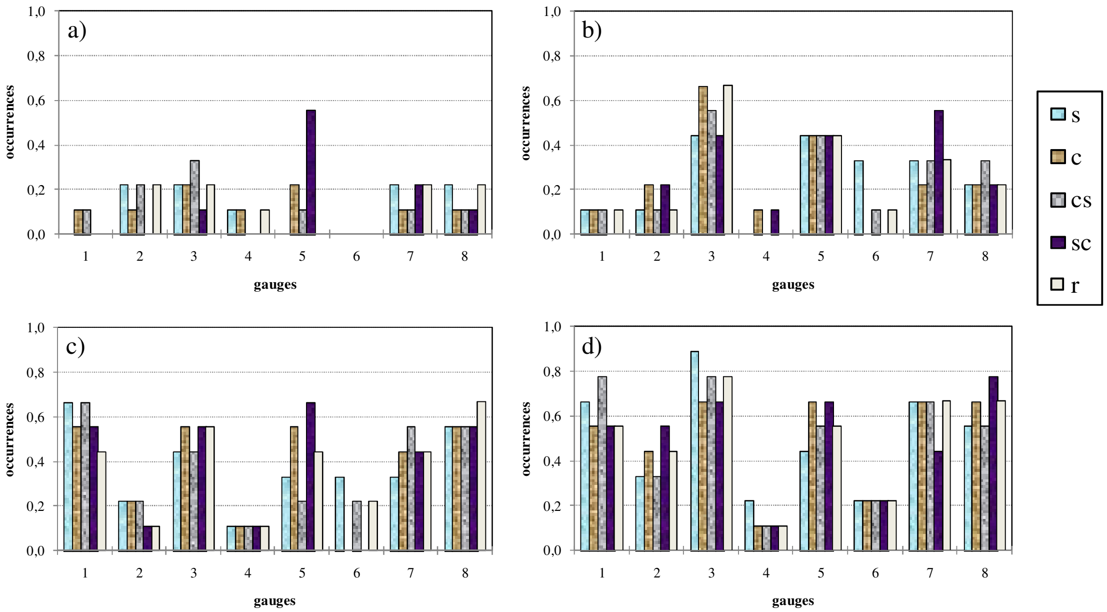

Figure 7. Number of occurrences of each single raingauge in the one gauge network (a), two gauges network (b), three gauges network (c), and four gauges network (d) for runoff estimation as function of the soil configuration.

Varying the number of gauges in the networks, gauges #3 and #5 are always present, while gauges #2, #4 and #6 are less important. Also the gauge #8 is important and, varying the soil distribution, it is usually present with the same frequency. Gauges #1 and #7 are less important in the network with one or two gauges but they become important in the network with three and four gauges. When a single raingauge is used in *cs* the best raingauge is placed downstream for six events and upstream for three events, whereas in *sc* the gauge is upstream for eight events and downstream only for an event. This observed pattern suggests that the best raingauge tends to be located where the soil is less permeable.

The results previously shown can be summarized in Table 3 by averaging the NRMSE_Q relative to single events. The best network, for average conditions, seems to not be influenced by the soil type distribution since the network is almost the same for each soil type distribution. This could be due to the removing of the influence of the spatial pattern of the precipitation by averaging the results relative to each event.

$\overline{\text{NRMSE}}_Q$ (m^3/s)						Raingauges					$\overline{\text{NRMSE}}_P$
n.gauges\soil	**s**	**c**	**sc**	**cs**	**r**	**s**	**c**	**sc**	**cs**	**r**	
1	0,416	0,451	0,429	0,347	0,447	3	3	8	3	3	8
2	0,248	0,279	0,257	0,237	0,271	3,7	3,7	7,8	3,8	3,7	3,7
3	0,175	0,192	0,175	0,188	0,174	3,7,8	3,7,8	3,7,8	3,7,8	3,7,8	3,7,8
4	0,153	0,154	0,136	0,175	0,158	2,3,7,8	3,5,7,8	3,5,7,8	1,3,7,8	3,5,7,8	2,3,7,8
5	***0,138***	***0,148***	***0,134***	***0,151***	***0,145***	***1,3,5,7,8***	***1,3,5,7,8***	***1,3,5,7,8***	***1,3,5,7,8***	***1,3,5,7,8***	***2,3,4,7,8***
6	0,142	0,155	0,138	0,164	0,152	1,2,3,5,7,8	1,2,3,5,7,8	1,2,3,5,7,8	1,3,5,6,7,8	1,2,3,5,7,8	1,2,3,4,7,8
7	0,150	0,160	0,152	0,174	0,163	1,2,3,5,6,7,8	1,2,3,4,5,7,8	1,2,3,5,6,7,8	1,2,3,5,6,7,8	1,2,3,5,6,7,8	1,2,3,4,6,7,8
8	0,174	0,163	0,161	0,180	0,173	ALL					ALL

Table 3. $\overline{NRMSE}_Q$ and “best network” as a function of the number of gauges and for fixed soil distribution. The network with the minimum $\overline{NRMSE}_Q$ is highlighted in bold italic. Last column shows the precipitation “best network”.

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As the number of raingauges increases, there is not a clear criterion for the best positioning of a new gauge. However, when in the network there are three or five gauges there is not influence of the soil distribution and the network is the same for each soil distribution. If the precipitation “best network” is compared with the discharge “best network” for a fixed number of gauges, one can observe that the two networks coincide rarely (only when three gauges are present, 3-7-8).

Results observed in Table 3 can be also analyzed considering the curve of $\overline{NRMSE}_Q$ varying the number of gauges for each soil configuration (Fig. 8). The minimum $\overline{NRMSE}_Q$ is obtained with five gauges in all the soil type configurations and the five curves rarely differ each other following the same pattern. €

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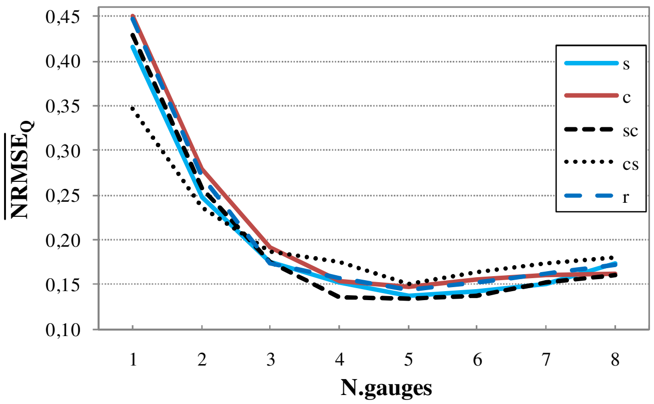

Figure 8. $\overline{NRMSE}_Q$ as a function of the number of gauges and for a fixed soil configuration.

5. CONCLUSIONS

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In this paper a deep investigation of the influence of raingauge network characteristics on hydrological response at catchment scale has been carried out. The use of tRIBS model has allowed us to investigate the influence of the raingauges network configuration in terms of number and spatial distribution on the estimation of flood hydrograph in the Baron Fork watershed at Eldon. Analysis has been performed at the event scale by considering precipitation events with different spatial variability and intensity and trying to take into account the effect of different soil types distribution as well.

One of the main outcoming of this work derives from the comparison of networks for precipitation and discharge estimations, which points out how the network aimed to the best reconstruction of rainfall field does not coincide with the network aimed to the best flood hydrograph estimation. This behavior is due to the fact that the best gauges position for runoff estimation is influenced also by the rainfall-runoff transformation as a function of the soil distribution.

Results of the analysis show the influence of the space-temporal characteristics of storm events on catchment response predictions and that, for a fixed event, the best raingauges configuration is strongly dependent on the soil types distribution. Then the main factors that influence the position of raingauges are the precipitation spatial distribution (i.e. the raingauges are placed where higher precipitation occur) and the soil types distribution (i.e. general trend to locate the raingauges where the soil is less permeable). If the average intensity of precipitation is high the influence of precipitation on catchment response is greater than the soil types distribution influence. Vice versa if the average intensity of precipitation is low or medium. When the spatial variability of precipitation is high, the location of gauge becomes very important for modeling the storm hydrograph. Moreover increasing the precipitation gradient, the effect of the soil type configuration becomes important. Vice versa if the rainfall spatial variability is low, the distribution of raingauges varies little with the change of the distribution of soils, then the position of the gauges is not influenced by the soil distribution and the “best network” is obtained with the same number of gauges for all the soil configurations.

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