Uncertainty analysis associated with Rainfall Spatial Distribution in an Experimental Semiarid Watershed, Northeastern Brazil

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Abstract: In this paper the main goal was to analyze the effect of spatial variability of rainfall on runoff in an experimental monitored watershed (2.108 km^2) located on a semiarid region (Seridó Potiguar), Rio Grande do Norte-Brazil. To accomplish this, a rainfall-runoff-sediment hydrologic model was used. The study area was divided into 143 elements (planes and channels). Rainfall spatial distribution, estimated using the inverse of distance method, was used as input to calculate rainfall spatial variability index for three observed storm events and different combinations of recording gauge arrangements. This index was considered in this study as an indicator used to evaluate the capacity of rainfall spatial characteristics measurement. The impact of spatial rainfall variability on catchment hydrologic response was analyzed and permitted to obtain the following conclusions: (a) rainfall data input provided by gage combination [1-2] best described rainfall distribution, although station 1 is located far from the outlet section. It confirmed that raingage spatial arrangement affects rainfall description capacity; (b) rainfall data input provided by combinations containing gage 3 poorly described rainfall distribution, although it is located near the outlet section. Presumably, it seems that gage 3 is the one that is impacted by the hillslope effect on northern part of the catchment; (c) catchment response of a relatively small catchment area is quite sensitive to the occurrence of high rainfall spatial variability.

Keywords: spatial variability, rainfall, modeling, semiarid.

1. INTRODUCTION

Semiarid regions are greatly affected by hydrological seasonal effects, notably rainfall events of high intensity. Rainfall is a key element for hydrologic processes comprehension at watershed scale. In this context, many studies have pointed out that rainfall spatial and temporal characteristics greatly influence runoff-generation, especially in regions of highly variable convective storms. Some studies have concluded that the reliability of rainfall-runoff models is mainly associated to its ability on representing spatial and temporal rainfall characteristics [Goodrich, 1990; Faurès *et al*., 1995; Chaubey *et al*., 1999]. Smith and Schreiber [1973, 1974] concluded that the variable nature of rainfall events in semiarid regions requires a statistical analysis involving factors such as spatial field rainfall as a function of time based on observed data distributed within the watershed area.

Creutin and Obled [1982] concluded that more sophisticated interpolation techniques might result in an improved estimation of rainfall behavior, especially in cases of high spatial variability. On the other hand, Goodrich *et al*. [1995] observed that rainfall could be considered uniformly distributed for hydrologic modeling of small basins, where usually a single rainfall station exists. In such cases, model parameters would be calibrated assuming uniform rainfall distribution within the watershed.

Faurès *et al*. [1995] investigated the impact of rainfall variability on runoff modeling by using a dense rain gage network on a small semiarid catchment. A distributed rainfall-runoff model was used; catchment was divided in elements (planes and channels) by considering physical characteristics. Rainfall intensities as a function of time and space were computed for each element using a linear interpolation method considering the three nearest stations [Goodrich, 1990]. Model calibration was performed by adjusting saturated hydraulic conductivity and Manning coefficient parameters. Results indicated that the uncertainty on runoff estimation for small semiarid catchments is greatly affected by rainfall spatial variability.

Goodrich [1990] used rainfall data of two gages approximately 300 m apart as input for a rainfall-runoff model in three small catchments (Walnut Gulch), areas varying from 0.4 to 4.4 ha. He observed that for each group of data different hydrographs were generated on simulation. He concluded that the uncertainty on runoff estimation would be reduced as the number of gages increased, due to the improvement on rainfall spatial characteristics representation.

In this context, important questions can be asked: a) under what conditions can rainfall spatial variability be neglected? That is, its effect on runoff modeling would be small and rainfall would be considered uniform on basin area; b) how can a rainfall-runoff model be reliably calibrated taking into account rainfall data available within the basin?

The aim of this study is to analyze the impact of rainfall spatial variability on runoff modeling using a semi-distributed runoff-erosion model to a 2.108 km^2 catchment in northeastern Brazil semiarid area dominated by convective storm rainfall events. Rainfall measurements were obtained from three gage stations on the catchment; runoff was measured on a *Parshall* flume installed at the basin outlet section.

2. HYDROLOGIC MODELING REPRESENTATION

Hydrologic models can have a generic representation described as follows,

$$S(t) = f(E, P) + \varepsilon(t) \tag{1}$$

where S is a matrix of the modeling hydrologic responses, E is a matrix of model input data, f is a collection of functional relationships, P is a vector of parameters whose values are obtained by calibration, ε is a matrix of errors and t is time. In general, parameters uncertainty sources are related to: a) limited capacity of simulating physical catchment processes; b) parameters calculation techniques; c) input data quality. The term (ε) represents the deference between hydrologic processes (S) and simulated results.

Even when input data and model parameters are well known, predicted output is often different from the observed data, because models are simplified approximations of complex natural processes. Furthermore, the level of reliability on runoff modeling depends on the consistency of input data.

3. UNCERTAINTY OF MODEL PARAMETERS

According to Chaubey *et al.* [1999], the variability in the model parameters provoked by the rainfall spatial distribution can be defined as one of the main contributors to parameter uncertainty. It can be quantitatively described using the following statistical parameters: medium error (EM), relative error (ER), standard error (EP) and coefficient of variation (CV), as following,

$$EM = \frac{1}{n}\sum_{1}^{n}\left(\left|P_i - O\right|\right) \tag{2}$$

$$ER = \frac{EM}{Obs} \tag{3}$$

$$EP = \sqrt{\frac{1}{n}\sum_{1}^{n}\left(P_i - O\right)^2} \tag{4}$$

$$CV = \frac{EP}{Obs} \tag{5}$$

where P_i represents the predicted value, O is an observed parameter value, Obs is the mean of the observed data, n is the number of data pairs, ($i=1,\ldots,n$).

4. STUDY SITE

The study was conducted in Serra Negra do Norte Experimental Watershed, located in the Brazilian northeastern semiarid region. The 2.108 km^2 catchment (coordinates 6°34'42" S; 37°15'56" W) is representative of approximately 1 million km^2 area where annual precipitation is less than 600 millimeters. Vegetation cover is composed of xerophytes brush and grass rangeland over shallow poorly sorted bimodal chromic luvisoils (fine and coarse modes present in the bulk sample). An efficient natural intermittent channel network reflects a potentially high erosion capacity. Catchment geometry and relief (hillslope upstream area is approximately 15%) produces a catchment rapid hydrologic response. Topographic survey of the catchment area provided information to produce a GIS-platform Digital Elevation Model, shown in Figure 1. Daily rainfall data statistical analysis revealed that approximately 25% of the annual depth occurs during the maximum daily precipitation, giving rise to erosion processes of high magnitude. Further information about study site characteristics is available in Moreira *et al.* [2004].

Point rainfall measurements were automatically recorded with a time interval of one minute by three raingage stations. One of them (station 3) is located near the outlet section; the other ones are located near the catchment boundary (station 2) and outside the catchment on the western side (station 3). While two of them are outside the

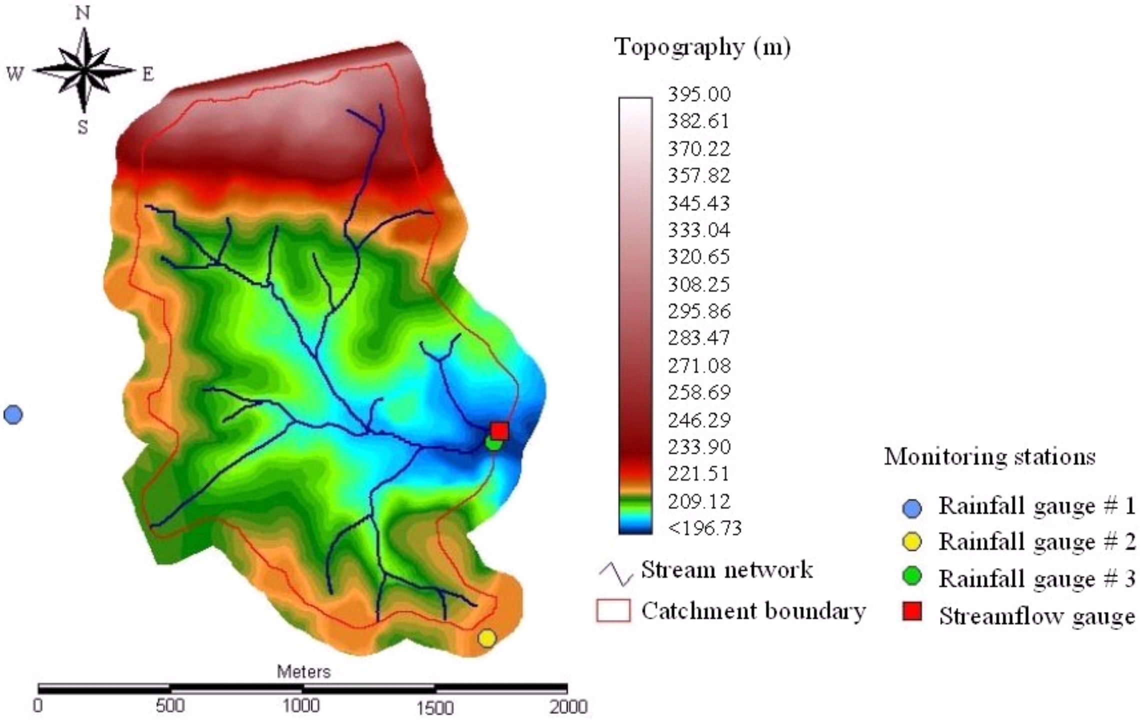


Figure 1. Digital Elevation Model

catchment area, they are sufficiently close to give a good indication of the rainfall behavior. An ultrasonic automatic system was connected to a *Parshall* flume structure at the basin outlet to monitor the hydrological processes on the storm event basis. During each storm water level readings were transferred to a *data-logger* with one minute time interval.

Soil hydraulic properties were measured by considering the different geological formations within the catchment area. In this way, hydraulic conductivity at saturation was obtained through infiltration experiments, ranging from 1.34×10^{-4} to 4.3×10^{-3} cm/s. Soil samples were collected at 0.15 m depth in different points within the basin area. Infiltration experiments were performed by using a constant head disc infiltrometer. At each location, experiments were performed until steady state infiltration was attained. The time required for attaining this condition varied as a function of soil characteristics, with 40 minutes on average. Some of the infiltration experiments showed a marked dispersion of infiltration capacity as a function of time, indicating the existence of preferred flow pathways and local biological activity.

The analysis is based on monitored data of three events of high magnitude that occurred in the catchment between 2004-january and 2004-february. Table 1 presents the precipitation and the hydrologic basin response (delay time, time of concentration, peak discharge and runoff coefficient) for each event. Important differences on hydrologic response can be seen between event #1 and the others. This may be due to the fact that this particular event occurred during the beginning of the rainy season. A high soil moisture deficit and the dry vegetation may be the main factors responsible for the high storage capacity of the basin, reflected by the runoff coefficient of 6.6%.

5. HYDROLOGIC MODELLING

Catchment runoff modeling was performed by using CHDM (Catchment Hydrology Distributed Model), an event-based semi-distributed model developed by Lopes *et al*. [1992, 1993 and 1996]. CHDM estimates runoff and sediment yield in an event basis and represents the processes of interception, depression storage, infiltration-excess overland flow, channel flow and non-equilibrium sediment transport. It has the advantage of having been developed for semiarid regions, considering the Hortonian concept of flow generation as a result of infiltration excess.

The model calculates one-dimensional overland and channel flows by using Saint-Venánt equations. Channel flow is calculated by considering the continuity equation for a channel with distributed lateral inflow from planes.

Table 1. Hydrologic data on catchment

Hydrologic Parameters	EVENT		
	1	2	3
Date	30/01/04	31/01/04	04/02/04
Time	17:20	23:20	20:10
Duration (min)	35	185	45
Precipitation (mm)	93.7	88.0	126.7
Lag time (min)	43	21	28
Time of Concentration (min)	47	38	39
Maximum discharge (mm/h)	3.8	9.3	6.3
Runoff coefficient (%)	6.6	14.8	9.9

Overland flow is considered as the difference between instantaneous rainfall intensity and infiltration. Rainfall excess is computed by using an infiltration model based on the Green and Ampt equation.

In the model, the catchment was represented by 102 overland flow planes and 41 channels elements. Each plane was described by its topography, soil and vegetation cover; each channel by its geometric properties. Catchment discrimination was made taking into account the digital elevation model generated by using IDRISI32 computational tool. Additionally, GIS-based thematic maps for soil and vegetal cover were used in this study. An electronic spreadsheet in MSExcel® was created to both identify each element by a code as a function of its individual properties and allow a more direct link with model input and output data. Precipitation was considered as spatially uniform on each element. In the same way, each plane was described by homogeneous hydrologic parameters. For purposes of catchment representation scheme, each plane can receive at the upstream boundary a maximum of three contributions. A channel can receive the contribution of a maximum of two other channels at the upstream boundary.

6. RAINFALL MODELING

Rainfall interpolation was performed using point rainfall measurements on three raingage stations. Additionally, in the analysis of rainfall characteristics rainfall intensity between stations was assumed to have a linear variation. The rainfall input to each element was computed as following: a) computation of the plane center of gravity in geographic coordinates; b) the inverse of distance method was used to compute the weight of each station relative to the plane.

6.1 Model calibration

CHDM was calibrated for each storm event individually, using as input the spatial estimates of rainfall. Simulation runs were performed for different combinations of the three raingage stations network. Calibration was attained for each run by using an iterative statistical method of trial-and-error, where model parameters estimation produced the best adjustment between measured and computed hydrographs. In order to measure the level of fit, objective functions of relative error and coefficient of variation were used as criteria, Equations (2) to (5).

7. RESULTS

7.1 Rainfall variability

Spatial rainfall variability (RVI) greatly affects runoff generation processes and catchment hydrologic response. In order to measure rainfall variability on the catchment, it was used a rainfall variability index that considers the amount of precipitation of each station during the event, proposed by M. B. Smith *et al.* [2004], as following,

$$\sigma_t = \sqrt{\frac{\sum_1^N P_i^2}{N} - \frac{\left(\sum_1^N P_i\right)^2}{N^2}} \tag{8}$$

where σ_t is rainfall standard deviation estimated value at time step t, P_i is rainfall amount at grid cell i, N is the total number of grid cells within the basin. Thus, the index of rainfall variability over the entire flood event can be estimated as a weighted value, as following,

$$I_\sigma = \frac{\sum \sigma_t P_t}{\sum P_t} \tag{9}$$

Storm rainfall events indicated in Table 1 occurred in a time interval of six days, with area total mean depth and duration varying from 88 to 127 mm and 35 to 185 minutes, respectively. Maximum intensities were 210, 290 and 280 mm/h for events 1, 2 and 3, respectively. Differences in catchment hydrologic response may be due to the effect of the location of rainfall centroid relative to basin outlet. In this study, computed rainfall variability indexes are plotted in Figure 2 for different raingage spatial arrangement combinations. As mentioned by previous studies, it is assumed that the best estimate of area rainfall input is provided by the simultaneous combination of three raingage stations. The effect of the raingage spatial arrangement and density on describing the rainfall variability can be demonstrated in Figure 2. It can be observed that combinations [event 1; stations 2-3], [event 2; stations 1-3] and [event 3; stations 1-2] couldn’t describe satisfactorily rainfall distribution. Furthermore, rainfall description capacity is affected by raingage spatial arrangement. However, this seems to be an unpredictable effect, once it varies as a function of rainfall characteristics.

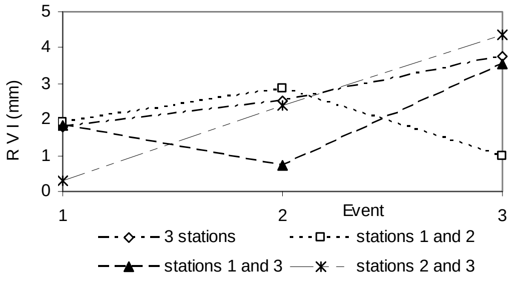


Figure 2. Rainfall variability index for different events and spatial arrangement combinations.

While catchment area is small, rainfall measurements revealed the presence of spatial rainfall gradients. Rainfall variability may be due to natural climatic processes related to the storm behavior in this region.

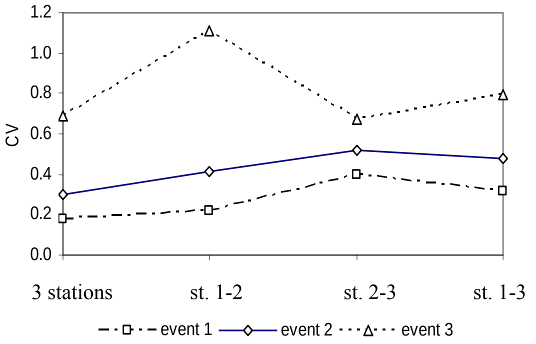
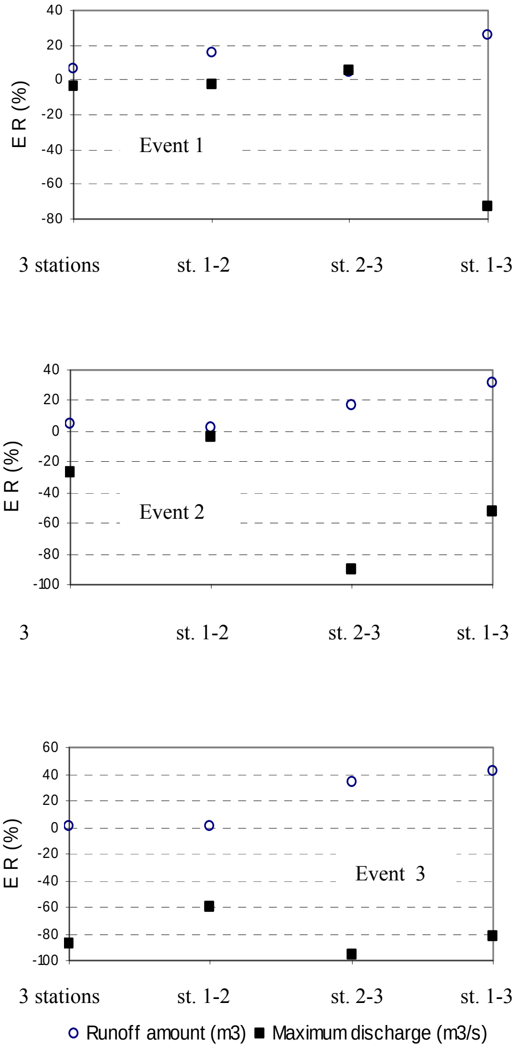


Figure 3. Coefficient of variation on runoff prediction

7.2 Effect of rainfall variability on runoff

Simulation runs using as input estimates of rainfall from a single raingage resulted in inaccurate rainfall spatial description on catchment. In fact, when the effect of variability was neglected, simulated hydrographs showed that modeling was unsatisfactory because of rainfall variability. Coefficient of variation was used as a measure of fit between observed and simulated hydrographs and reflects the level of uncertainty. Computed values of CV for each combination of event-spatial arrangement are presented on the plot of Figure 3. It can be observed that CV varied between 0.2 (event 1) and 1.10 (event 3), once its value is affected by rainfall characteristics and raingage spatial arrangement. The most satisfactory uncertainty levels (0.2) were obtained for the combinations event 1;3 stations and event 1; stations 1-2. On the other hand, a comparison between plots of Figures 2 and 3 revealed that for combination [event 3; stations 1-2] an unsatisfactory description of rainfall variability increased the level of uncertainty on runoff modeling. However, such tendency couldn’t be observed for other combinations that produced deviations on rainfall description [event 1; stations 2-3], [event 2; stations 1-3].



Figures 4 (a), (b) and (c). Relative error on catchment response prediction

7.3 Effect of rainfall variability on catchment response

Uncertainty analysis of rainfall variability on catchment response considered peak discharge (Qp) and runoff volume (ES). Uncertainty was defined as the failure on catchment response prediction. In this way, for each combination of event-raingage spatial arrangement, model simulations provided Qp and ES, whose values are plotted against relative errors in Figures 4 (a), (b) and (c). It can be observed a general overestimation of ES and underestimation of Qp. Large uncertainties were associated with events 2 and 3, 90% and 100%, respectively. Moreover, uncertainty is affected by raingage spatial location and rainfall distribution on a specific event.

A general tendency of increasing uncertainty with raingage density reduction was observed, which confirms previous studies. Least relative errors were obtained for the event 1 (combinations 1-2 and 2-3) and event 2 (combination 1-2). These results indicate that uncertainties increase on catchment response is influenced by the inability of rainfall model on describing rainfall spatial distribution.

8. CONCLUSIONS

The aim of this study was to analyze the effect of different levels of rainfall spatial variability affects catchment response modeling on a small semiarid catchment. In this context, there’s a need to evaluate rainfall-runoff model reliability as a function of the available rainfall data. The results of this study were obtained for a situation of convective storm rainfall regime. The use of the CHDM rainfall-runoff model implies that the conclusions reflect model’s assumptions and limitations on processes representation. The impact of spatial rainfall variability on catchment hydrologic response was analyzed and permitted to obtain the following conclusions: (a) rainfall data input provided by gage combination [1-2] best described rainfall distribution, although station 1 is located far from the outlet section. It confirmed that raingage spatial arrangement affects rainfall description capacity; (b) rainfall data input provided by combinations containing gage 3 poorly described rainfall distribution. Presumably, it seems that gage 3 is the one that is impacted by the hillslope effect on northern part of the catchment; (c) the relatively small catchment area makes it quite sensitive to the occurrence of high rainfall spatial variability.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

Chaubey, I, Haan, C. T., Grunwald, S. and Salisbury, J. M. Uncertainty in the model parameters due to spatial variability of rainfall. *Journal of Hydrology*, 220, 48-61, 1999.

Creutin, J. D., Obled, C. Objective analysis and mapping techniques for rainfall fields: an objective comparison. *Water Resources Research*, 18(2), 413-431, 1982.

Faurès, J. M., Goodrich, D. C, Woolhiser, D. A. and Sorooshian, S. Impact of small-scale rainfall variability on runoff modeling. *Journal of Hydrology*, 173 (1995), 309-326, 1995

Goodrich, D. C. Geometric simplification of a distributed rainfall-runoff model over a range of basin scales. Ph. D. Dissertation. University of Arizona. Tucson. AZ, 1990.

Goodrich, D. C., Faurès, J. M., Woolhiser, L. A. Lane, L. J. and Sorooshian, S. Measurement and analysis of small-scale convective storm rainfall variability. *Journal of Hydrology*, 173, 283-308, 1995.

Lopes, V. L. and Ffolliott, P. F. Modeling sediment processes on small watersheds: a conceptual framework. I. Broad shallow flow processes. *J. Sed. Res.,* 7, 21-44, 1992.

Lopes, V. L. and Ffolliott, P. F. Modeling sediment processes on small watersheds: a conceptual framework. II. Concentrated flow processes. *J. Sed. Res*., 8, 1-23, 1993.

Lopes, V. L. On the effect of uncertainty in spatial distribution of rainfall on catchment modeling. *Catena*, 28, 107-119, 1996.

Moreira, L. F. F., Righetto, A. M. and Medeiros, V. M. A. Soil hydraulics properties estimation by using pedotransfer functions in a Northeastern semiarid zone catchment, Brazil. iEMSs 2004 Proceedings, Osnabrueck, Germany, 2004.

Smith, M. B., Koren, V. I., Zhang, Z., Reed, S. M., Pan, J. J. and Moreda, F. Runoff response to spatial variability in precipitation: an analysis of observed data. *Journal of Hydrology*, 298, 267-286, 2004.

Smith, R. E., Schreiber, H. A. Point processes of thunderstorm rainfall. 1. Distribution of rainfall events. *Water Resources Research*, 9, 871-884, 1973.

Smith, R. E., Schreiber and H. A. Point processes of thunderstorm rainfall. 1. Rainfall depth probabilities. *Water Resources Research*, 10, 418-426, 1974.