# SPATIAL PATTERNS IN THUNDERSTORM RAINFALL EVENTS: CONCEPTUAL MODELING AND HYDROLOGICAL INSIGHTS

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## Abstract

The characteristic spatial patterns of rainfall systems evolve from underlying processes in the systems. The important role of these rainfall patterns in watershed hydrology has long been recognized. This paper presents conceptual modeling of the rainfall spatial patterns associated with air mass thunderstorm events using observed radar data. The modeled rainfall retains a relatively simple structure while including the primary spatial features of rainfall patterns such as location and magnitude of maximum rainfall, areal extent of rain - no rain, and small-scale variability. The model was applied to radar rainfall data from Arizona and evaluated using rainfall data from a dense gauge network. Through a case study we demonstrate the use of modeled rainfall as input to a distributed hydrological model. This approach allows a comprehensive linkage between the runoff response and spatial rainfall patterns. We suggest that conceptual rainfall modeling can help in the acquisition of new insights into the behavior of rainfall systems and their interaction with the environment.

**Key Words: spatial patterns, rainfall, weather radar, conceptual modeling, thunderstorms, distributed hydrological models**

## Introduction

Rain fields are characterized by spatial and temporal patterns. Through observations, scientists study these patterns to acquire a better understanding of the processes that underlie their creation. In hydrology, the resulting rain patterns are of special interest. It has been long recognized that rainfall patterns play an important role in runoff generation and many studies have described these patterns (e.g., Goodrich et al., 1995), and examine their effect on hydrological response (e.g., Singh, 1997).

During early hydrological research, the main obstacle to studying rainfall spatial patterns was limited rainfall data, usually from sparse gauge networks. With the development of rainfall remote sensing systems, observed spatial patterns became available and have been incorporated in studies investigating the physical and dynamical structure of rainstorms (e.g., Maddox et al., 1997). In hydrology, it is expected that the spatial patterns apparent in remotely sensed rainfall data will improve the capability of distributed hydrological modeling by using these data as model input (e.g., Collinge & Kirby, 1987). However, we have yet to see clear evidence for such improvements (for example, Carpenter et al., 2001). Among other difficulties reported are the accuracy of rainfall estimations (e.g., Krajewski & Smith, 2002) and runoff sensitivity to sub-pixel rainfall variability (e.g., Michaud & Sorooshian, 1994). Arguably, even though information on rainfall spatial patterns exists in remotely sensed rainfall data, there is a need to develop new ways to exploit this information and gain greater insight into rainfall and subsequent watershed response behaviour (Grayson & Bloschl, 2000). A possible approach, explored in this paper, is to use rainfall modeling to represent the essential aspects of spatial rainfall patterns.

Conceptual models have been used in stochastic rainfall models in order to represent the statistical structure of observed rainfall data (Waymire and Gupta, 1981). While these models attempt to reproduce rainfall patterns that are statistically similar to observations, there is also a need to represent rainfall patterns on a storm event basis. The objective of this study is to use a conceptual rainfall model to represent rainfall spatial fields associated with air mass thunderstorm rain events. The motivation is to develop a concise representation of the rainfall field containing the essential spatial storm structural information. The model is applied to weather radar data and is evaluated using an independent dataset from a dense rain gauge network. We also explore the potential of using the modeled rainfall as input to a hydrological model and discuss the possible advantages of this approach.

## Background

The two study areas are located in the semi-arid climate regime of southern Arizona (Fig. 1), which characterized by summer weather of frequent air mass thunderstorms that are highly convective, intense, localized and of short duration. The 148 $km^2$ Walnut Gulch Experimental Watershed (WGEW; Goodrich et al., 1997) is located 50-70 km east-southeast of the Tucson WSR-88D weather radar, which is a part of the U.S. National Weather Service (NWS) weather radar network. Data from the third radar tilt were used in the study because the first two tilts are blocked by terrain. Thirteen convective storms from the 1999 and 2000 monsoon seasons (June-August) were selected. Rain data from 74 gauges located in the watershed area (Fig. 1b) were used for radar calibration and in the evaluation procedure. The second study area is the Phoenix metropolitan area, located northwest of the Phoenix NWS WSR-88D weather radar (Fig. 1). Data from a summer storm in 2002 were used for this study.

Radar reflectivity data ($Z$) [$mm^6m^{-3}$] are commonly converted into rain intensity data ($R$) [mm/h] using a power law relationship: $Z = aR^b$. In this study, the exponent parameter ($b$) was set to the value of 1.4 that is used by the NWS for convective rainfall (Fulton et al., 1998), while the multiplicative parameter ($a$) was adjusted based on comparison of gauge and radar storm depth data. The resulting $Z-R$ relationship, based on analysis of radar and gauge data for the selected thirteen storms over WGEW, was:

$$Z = 655R^{1.4} \tag{1}$$

An upper threshold of 100 mm/h was applied to the estimated rain intensity.

## Rainfall modeling

The conceptual rainfall model used in this study is a deterministic version of the model proposed by Rodriguez-Iturbe et al. (1986). Using rain gauge data, the model was found suitable for representing the spatial variability of storm rain depth in the WGEW (Eagleson et al., 1987). The model assumes that rain intensity fields are composed of multiple rain cells. Each rain cell is an isotropic circular element with maximum rain intensity at the center and a quadratic exponential decay with distance from the center:

$$R_i(d) = \beta_i e^{-2\alpha_i^2 d^2} \tag{2}$$

where $R_i(d)$ is rain intensity [mm/h] for rain cell $i$ at a distance $d$ [km] from the rain cell center at coordinates $(X_i, Y_i)$, $\beta_i$ is the rain intensity [mm/h] at the center of rain cell $i$, and, $\alpha_i$ is the decay parameter [$km^{-1}$] of rain cell $i$. Equation 2 defines a two-dimensional non-normalized Gaussian surface, where $\beta_i$ represents the amplitude and $\alpha_i$ represents the spatial extent.

Parameter $\alpha_i$ is equivalent to the inverse of two times the standard deviation of the Gaussian distribution.

A procedure was developed for estimating model parameters for each radar map (Fig. 2). The main computational steps in this procedure are: 1) Input radar reflectivity map, 2) Convert radar reflectivity to radar rainfall intensity, 3) Segmentation, 4) Eliminate or merge small and weak segments, 5) Determine the rain cell parameters, and 6) Model output: number of rain cells for each radar map and four model parameters for each cell. These steps are repeated for the series of radar maps of a given storm. The algorithm produces a description of the rain cells (number, location, and parameters) as they evolve throughout the storm.

The algorithm was applied to radar data from thirteen storms over the WGEW. A summary of the model results for all storms is presented in Fig. 3. The algorithm was also applied to radar data for one storm over the Phoenix region using the same $Z-R$ relationship used for the WGEW study area. Modeling results at different radar tilts are compared for the Phoenix data (Fig. 4). The first tilt data was found to be contaminated with ground clutter. Comparison of the second and third tilt data indicated relatively good agreement between the identified rain cells (in terms of their number and parameters) suggesting that the third tilt data are suitable for the analysis presented in this paper.

The modeled radar rainfall was evaluated using an independent data set from the dense gauge network in WGEW. Details about the evaluation results are available at the full length paper.

## Modeled rainfall as input to hydrological model

The above sections presented rainfall modeling in the form of rain cells. In this approach, each rainfall map is translated into a set of rain cells specified by their location, maximum rain intensity, and decay factor. Because this modeling process recognizes rainfall spatial patterns that may play an important role in runoff generation, we evaluated the possibility of using the modeled rainfall as input to a hydrological model.

The hydrological model used is the KINEROS2, a physically based, event oriented, rainfall-runoff model (Woolhiser et al., 1990; Smith et al., 1995). The model represents the watershed as a cascade of overland flow planes and channels, thereby allowing rainfall, infiltration, runoff and erosion parameters to vary spatially. Recently, a GIS-based tool (AGWA) was developed (Miller et al., 2002) for delineating watersheds into hillslope contributing areas (abstracted into overland flow plane model elements) and channels and generating model parameter files, based on topography, soil and land cover information. In this study, we used the KINEROS2 model with default parameters generated by AGWA for the WGEW (delineation of 53 planes - average area 2.8 km$^2$, and 21 channels). We analyzed the rainfall-runoff event of August 11, 2000, which totaled to 25 mm watershed average rainfall depth with a maximum gauge depth of 91 mm and a recorded runoff peak discharge of 154 cms at the watershed outlet.

Two rainfall inputs were analyzed using the hydrological model. The first was the radar-grid rainfall data and the second was the radar-modeled rainfall data. Fig. 5 presents the two computed runoff hydrographs at the watershed outlet. It should be emphasized that the radar rainfall estimations were based on the $Z-R$ relationship described above. If the default NWS $Z-R$ relationship for convective precipitation is used (Fulton et al., 1998), the computed runoff peak discharge is more than three times higher.

Comparing the two computed runoff hydrographs in Fig. 5 revealed only minor differences. This suggests that both inputs contain essentially the same information required for predicting the hydrological response (as represented by the hydrological model). We believe that by using the rain cell analysis representation a better understanding can be gained of the major factors that generate runoff.

A manual examination and tracking of the modeled rain cells in the August 11, 2000 rainfall-runoff event (Fig. 6) identified five rain cells (cells A-E) that developed close to or over the watershed. Two of the modeled cells (A and C) were intense (in terms of maximum intensity and volume) and lasted a relatively long time (more than 60 min). The modeled cell A initiated outside and north of the watershed and then moved southward into the watershed. The modeled cell C developed within the watershed and moved west-northwest toward and beyond the watershed outlet. The three other cells (B, D and E) moved generally northward, had shorter duration (15 min) and were less intense.

Comparison of the computed runoff response for each modeled cell separately indicates that only cell C contributed to the peak discharge at the watershed outlet (Fig. 5, dashed line). This is probably due to its location within the watershed for most of its life cycle. Another important factor is the specific configuration of rain cell C relative to the watershed. Examining the detailed response of each model element (overland flow planes and channels) revealed that the cell passed close to watershed tributaries at three locations, precipitating more than 25 mm of intense rainfall over their associated contributing areas. This generated significant excess rainfall over the associated runoff model elements and high peak flows at the tributaries to the main channel (Fig. 7). The flow towards and along the main channel was such that runoff peaks arriving from the tributaries were close in time to the runoff peak of the main channel, resulting in an intensification of the peak flow. Over the last 7 km of the channel, there was no lateral contribution to the flow from hillslope areas or tributaries, which resulted in reduction of peak flow due to channel transmission losses.

In view of the above description, it is clear that different configurations of rain cells relative to the watershed can yield different runoff responses. Using the rainfall input in the form of modeled rain cell representation enables examination of runoff sensitivity to realistic rain cell characteristics (such as location, direction, velocity, spread, and maximum intensity).

In the current section we explored the potential of using modeled rainfall as input to a hydrological model. Further research needs to be conducted to examine the advantages and disadvantages of this approach from a more general perspective.

## Conclusion

This paper presents conceptual modeling of rainfall spatial patterns associated with air mass thunderstorm events using remotely sensed rain intensity maps. Applying the model to radar data yields rainstorm representation as a set of convective rain cells with a limited set of characteristic variables. The modeled rainfall has a relatively simple structure but includes all the main spatial features of rainfall patterns: location and magnitude of maximum rainfall intensity, rain - no rain areas (rain cell coverage) and small-scale variability (within rain cells). These features are important characteristics of the rain system and are known to play a significant role in watershed response to rainfall. We suggest that, through conceptual rainfall modeling, new insights can be acquired in understanding the behaviour of the rain and hydrological systems and their interaction.

We explored the potential use of modeled rainfall as input to a distributed hydrological model. Although the original radar rainfall data produced a similar computed runoff hydrograph as the modeled rainfall, it is the added insights that can be acquired on the spatial watershed response behavior using the latter that, in our view, makes this approach beneficial. This is because there is an essential difference in the way spatial patterns are represented in modeled radar rainfall data versus the original radar rainfall data. In the modeled rainfall, the spatial patterns are explicitly represented through the model parameters. The modeling process enables the decomposition of complex rainfall patterns into modeled cells with defined parameters and trajectories. In the grid rainfall data, the patterns are implicitly represented but are not easily quantified into well-defined parameters or functions. The explicit representation of rainfall spatial patterns in hydrological model input allows derivation of a more comprehensive link between runoff response and spatial rainfall patterns.

## References


Carpenter, T. M., Georgakakos, K. P. & Sperfslagea, J. A. (2001). "On the parametric and NEXRAD-radar sensitivities of a distributed hydrologic model suitable for operational use". *J. Hydrol.*, **253**, 169-193.

Collinge, V. K. & Kirby, C. (1987). *Weather Radar and Flood Forecasting*, Wiley, New York.

Eagleson, P. S., Fennessey, N. M., Qinliang, W. & Rodriguez-Iturbe, I. (1987). "Application of spatial Poisson models to air mass thunderstorm rainfall". *J. Geophys. Res.*, **92(D8)**, 9661-9678.

Fulton, R. A., Breidenbach, J. P. , Seo, D. J. & Miller, D. A. (1998). "The WSR-88D rainfall algorithm". *Wea. and Forecasting*, **13**, 377-395.

Goodrich, D. C., Faures, J. M., Woolhiser, D. A., Lane, L. J. & Sorooshian, S. (1995). "Measurement and analysis of small-scale convective storm rainfall variability". *J. Hydro.*, **173**, 283-308.

Goodrich, D. C., Lane, L. J., Shillito, R. A., Miller, S. N., Syed, K. H. & Woolhiser, D. A. (1997). "Linearity of basin response as a function of scale in a semi-arid watershed". *Water Resour. Res.*, **33(12)**, 2951-2965.

Grayson, R. & Bloschl, G. (2000). *Spatial Patterns in Catchment Hydrology: Observations and Modelling*. Cambridge University Press, Cambridge, 3-16.

Krajewski, W. F. & Smith, J. A. (2002). "Radar hydrology: Rainfall estimation". *Adv. Water Resour.*, **25**, 1387–1394.

Maddox, R. A., Howard, H. W. & Dempsey, C. L. (1997). "Intense convective storms with little or no lightning over central Arizona: A case of inadvertent weather modification?". *J. Appl. Meteor.*, **36(4)**, 302-314.

Michaud, J. D. & Sorooshian, S. (1994). "Effect of rainfall-sampling errors on simulations of desert flash floods". *Water Resour. Res.*, **30(10)**, 2765-2775.

Miller, S. N., Semmens, D. J., Miller, R. C., Hernandez, M., Goodrich, D. C., Miller, W. P., Kepner, W. G. & Ebert, D. (2002). "GIS-based hydrologic modeling: the automated geospatial watershed assessment tool". Proc. of the Second Federal Interagency Hydrologic Modeling Conference, Las Vegas NV, July 28 - August 1.

Rodriguez-Iturbe, I., Wang, Q., Jacobs, B. L. & Eagleson, P. S. (1986). "Spatial modeling of total storm rainfall". *Proc. R. Soc. London, Ser. A*, **403**, 27-50.

Singh, V. P. (1997). "Effect of spatial and temporal variability in rainfall and watershed characteristics on stream flow hydrograph". *Hydrol. Process.*, **11**, 12, 1649-1669.

Smith, R. E., Goodrich, D. C., Woolhiser, D. A. & Unkrich, C. L. (1995). "KINEROS - a kinematic runoff and erosion model". In *Computer Models of Watershed Hydrology*, edited by V. P. Singh, Water Resources Publications, Highlands Ranch, Colorado, 697-732.

Waymire, E. & Gupta, V. K. (1981). "The mathematical structure of rainfall representation, 1, A review of the stochastic rainfall models". *Water Resour. Res.*, 17, 5, 1261-1272.

Woolhiser, D. A., Smith, R. E. & Goodrich, D. C. (1990). KINEROS, A kinematic runoff and erosion model: Documentation and user manual, U.S. Dept. of Agriculture, Agricultural Research Service, ARS-77.

## Appendix A - Figures

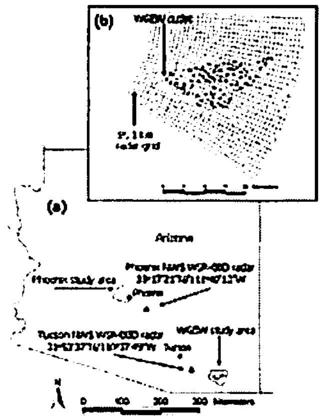

**Fig. 1.** a) Location map of the two study areas and the radar stations. b) The radar segment encompassing the 148 km$^2$ WGEW study area and the 74 gauges in the watershed. Radar polar grid resolution is of 1° x 1 km.

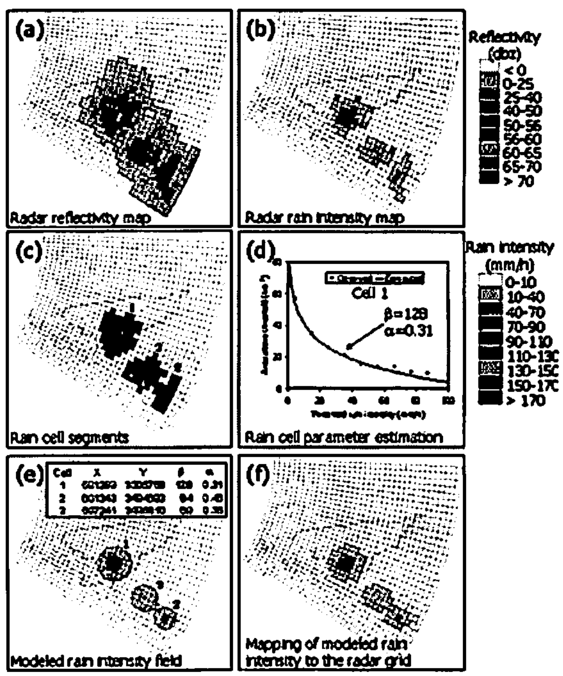


**Fig. 2.** Illustration of model application for radar data from the storm of July 6, 1999 at time 14:45 (LTC). a) Radar reflectivity map. b) Radar rain intensity map upon application of the $Z-R$ relationship described above. c) Rain cell segments. Black dots shows the center of maximum pixels and are considered as the rain cell center locations. d) Parameter estimation for rain cell 1. Observed area above threshold ($A^{\tau}$) for threshold values ($\tau$) between 5 and 100 mm/h are indicated (circles). The $\alpha$ parameter is estimated based on these values. The $\beta$ parameter is estimated from the resultant $\alpha$ and the estimated rain cell integral. The computed curve resulting from the estimated $\alpha$ and $\beta$ parameters is shown. d) Model results for the given radar rainfall map. The four parameters for each rain cell are shown in table. Figure shows the resulting rain intensity field. e) Mapping of the modeled rain intensity field to the radar grid pixels for comparison with the observed radar rain intensity map (b).

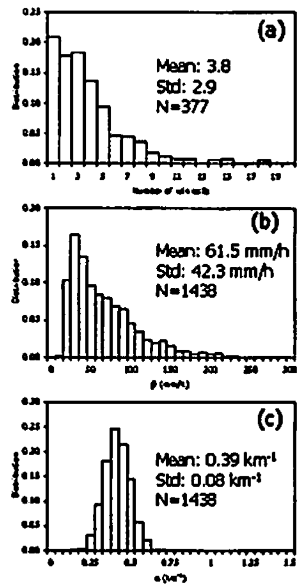


**Fig. 3.** Histograms of computed model parameters for thirteen storms over the WGEW study area: a) number of rain cells, b) $\beta$ parameter, and, c) $\alpha$ parameter.

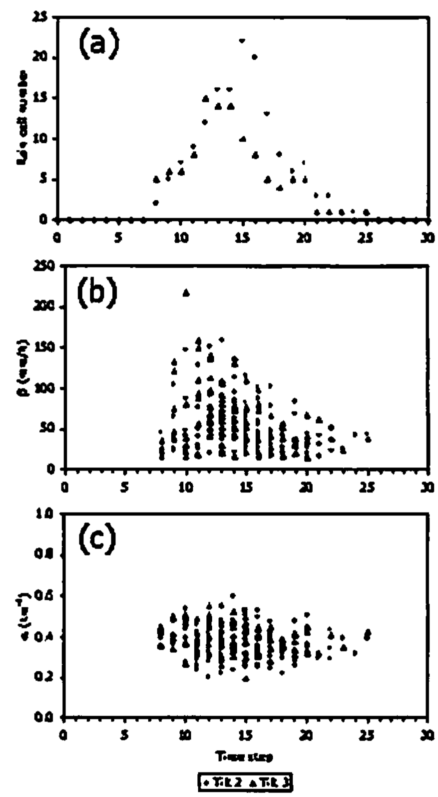


**Fig. 4.** Modeling results for the storm of July 14, 2002 over the Phoenix study area for the second radar tilt (1.45° elevation angle) and the third radar tilt (2.4° elevation angle). The model was applied with the same $Z-R$ and threshold values as for the WGEW study area. The figure shows time series of: a) rain cell number, b) $\beta$ parameter, and, c) $\alpha$ parameter.

**Fig. 5.** Computed runoff hydrographs at the WGEW outlet using the KINEROS2 rainfall-runoff model for the 8/11/2000 storm with different inputs: radar-grid rainfall (thick solid line), radar-modeled rainfall (thin solid line), and radar-modeled rainfall with only rain cell C (see Fig. 6) active (thin dashed line).

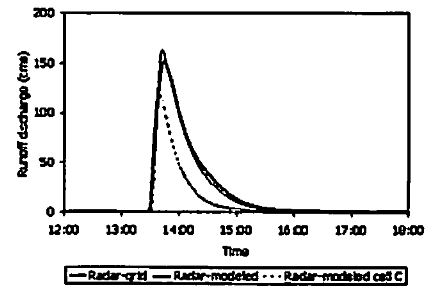


**Fig. 6.** Modeled rain cells locations and trajectories over WGEW for the 8/11/2000 storm. Rain cell tracking was done manually.

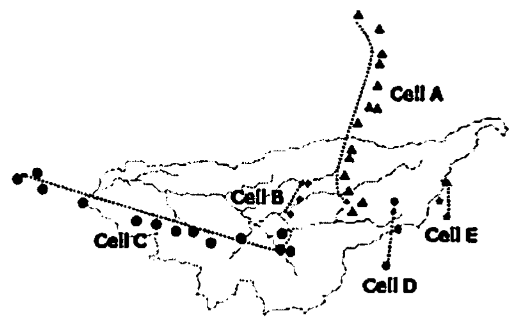


**Fig. 7.** Computed response of model elements in relation to rain cell location and trajectories for the 8/11/2000 storm over the WGEW. Averaged rain depth contributed by the modeled rain cell C (see Fig. 6) to each overland flow plane is shown. For selected points along the channel network the time of peak discharge (Tp) and peak discharge (Qp) are presented.