Evaluation of the Spatial Structure of Storms and the Development of Design Storms

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Abstract

Traditional analyses defining the spatial structure of design storms are interpreted from point rain gage data. However, rarely are rain gage networks dense enough to provide accurate assessments of the very storms these networks are intended to monitor. Furthermore, rainfall topologies interpolated from point data may be quite different from the actual storm shapes.

For the past decade, large scale databases of radar rainfall estimates have been created and archived providing a rich store of information that has never existed before. These databases can be mined for detailed information regarding the spatial characteristics of storms.

This paper will present findings on the spatial structure of storms from Florida and other locations in the United States. Example frequency distributions of storm parameters will be presented. In addition, information will be presented on how these data are being used to develop more realistic design storms.

Introduction

Traditional analyses defining the spatial structure of design storms are interpreted from point rain gage data. However, rarely do rain gage networks have sufficient density and cover enough area to provide accurate assessments of the very storms these networks are intended to monitor. For example, Florida's average rain gage density is only on the order of one gage in 100 square miles, hardly dense enough to fully characterize the extreme spatial variability of rainfall common to Florida. In fact, at the 15-minute level, approximately 75% of individual storm cells in Florida may have areas less than 100 square miles. Furthermore, the spatial interpretation of point gage data is as much a function of gage network geometry as the geometry of storms which distorts our understanding of the true structure of rainfall distribution.

Design storm parameters are often drawn from studies where a dense rain gage network existed at another location and the results transferred with little regard to potential impact of local weather and climate conditions. These assumptions are imbedded in the current generation of standards for critical metrics such as design storm size, shape, orientation, depth-area reduction factors etc. Current commonly used design methods, based on standards such as uniform system-wide application of design storm rainfall often result in unrealistic and unaffordable design capacities.

For the past decade, large scale databases of radar rainfall estimates have been created and archived providing a rich store of information that has never existed before. The databases can be mined for detailed information regarding the spatial characteristics of storms. For example, a 15-minute, 2 km x 2 km resolution statewide dataset of gage adjusted radar rainfall over the State of Florida has been created over the past 11 years. It is also possible to create and analyze similar data from other locations across the country.

Methodology

Radar Rainfall Estimation. Since the early 1990's, National Weather Service WSR-88D data have been used to estimate rainfall. While promising high resolution rainfall estimates, experience has shown that radar data can provide good representations of the spatial distribution of rainfall but is an inconsistent estimator of rainfall volumes. Calibrating the radar rainfall estimates using point rainfall measurements from rain gages overcomes this limitation. Gage-calibrated data are often referred to as gage-adjusted radar rainfall (GARR) estimates.

With more than a decade of radar rainfall estimates available, a growing volume of gage-adjusted radar rainfall datasets are now available for analysis. For example, the five water management districts in Florida initiated the development of gage-adjusted radar rainfall data covering the entire state. While each district receive and archive data to meet their individual specifications, the base gage-adjusted radar rainfall estimates are processed at 15-minute, 2 km x 2 km resolution. Similar data sets, some with even higher resolution, now exist for other regions of the country as well, including central Texas, Missouri/Illinois, central Indiana, southwest Pennsylvania and northern Kentucky to name a few. In addition, National Weather Service River Forecast Centers produce hourly 4 km x 4 km gage-adjusted radar rainfall datasets. These databases contain detailed information regarding the spatial characteristics of storms.

Spatial Analysis. To analyze the spatial properties of storm cells time period by time period, a software package called Thunderstorm Identification, Tracking and Nowcasting or TITAN (Dixon, 1993) was used. TITAN is licensed by the National Center for Atmospheric Research (NOAA).

TITAN defines a storm cell as an area of contiguous rainfall above a user-defined threshold radar reflectivity value and identifies storm cells in a two-step process. The first step identifies individual cells at each time step; that is, separate storm cells are identified with an area of precipitation. The second step tracks the cell as it moves, grows, decays, splits into multiple cells or merges with other cells.

TITAN identifies contiguous areas of rainfall at different rainfall intensities and simplifies those areas by fitting an ellipse to the rainfall. Figure 1 shows an example of how TITAN creates simplified ellipses of contiguous rainfall from the more complex radar rainfall estimates. Figure 2 presents and example of 15-minute storm cell ellipses defined by TITAN for a single day.

For each identified storm cell ellipse, TITAN computes a variety of spatial measures including: storm cell size, peak rainfall intensity, distribution of rainfall intensities within each cell, the cell aspect ratio (length vs. width), cell orientation, and the direction and speed of cell movement.

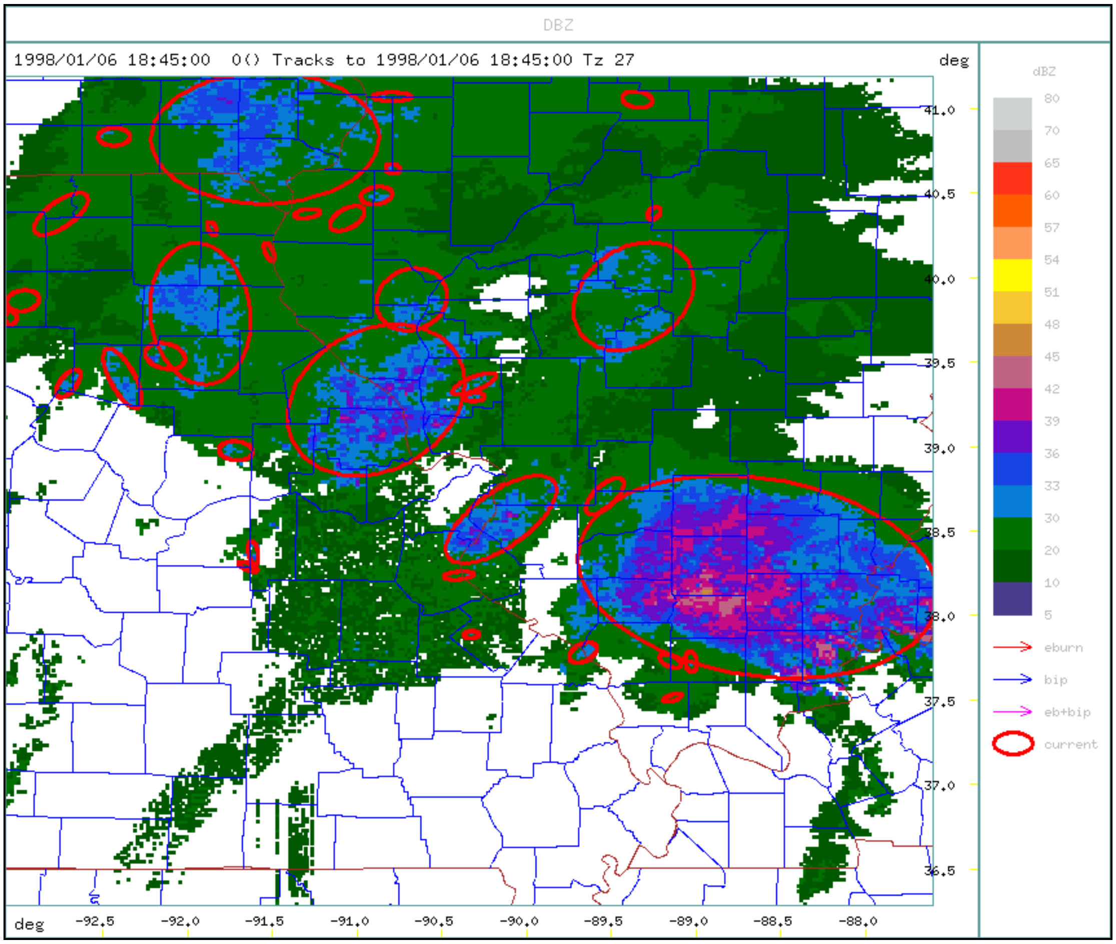

Figure 1: Example of TITAN's Automated Storm Cell Identification for One Time Period (Ellipses indicated identified storm cells.)

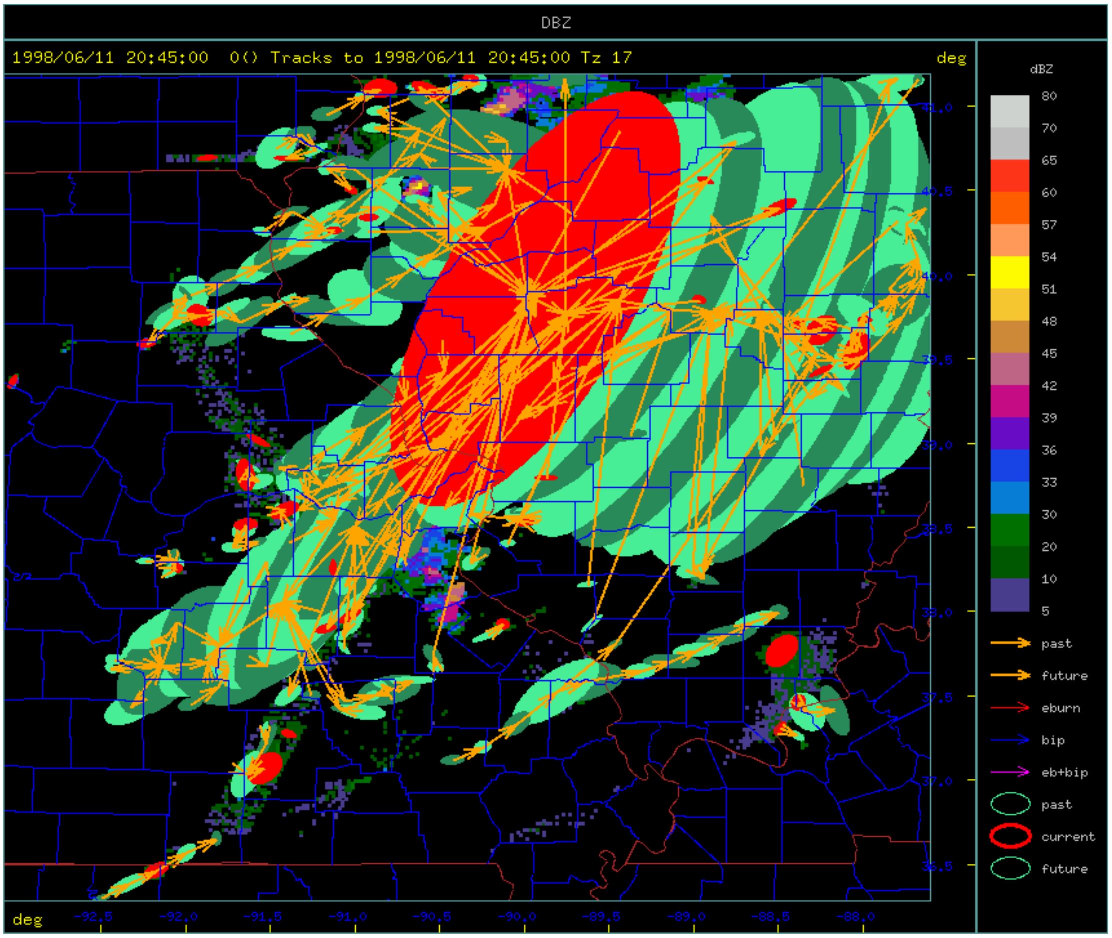

Figure 2: Example summary of 15-minute storm cells identified in one day.

One of the intriguing outcomes from a TITAN analysis is the shear number of storm cells available for analysis. TITAN analyzes storm cells within an area. The TITAN study domain must be large enough to capture entire storm cells in order to preserve credible measurement of cell properties. A 250,000 square kilometer (100,000 square miles) area can yield sample sizes on the order of several hundred thousand storm cells or even millions of cells in a relatively short period of time, say five years. Granted, the same cell may be included in the analysis from one time step to the next, but storm cells are highly dynamic. An active cell can change shapes rapidly, and may only survive as an identifiable cell for 45 minutes, on average, before dying, dividing in to multiple cells, or merging with other cells.

With large numbers of storm cell data available for analysis, it is possible to develop a variety of statistical measures to assess and categorize the geometric properties of storms. Figure 3 shows an example of a distribution of 15-minute storm cells in the Missouri/Illinois area over a five year period. Figure 4 shows the frequency distribution of storm cell aspect ratio or the ratio of the major and minor axes of the TITAN storm cell ellipses for the same five-year period.

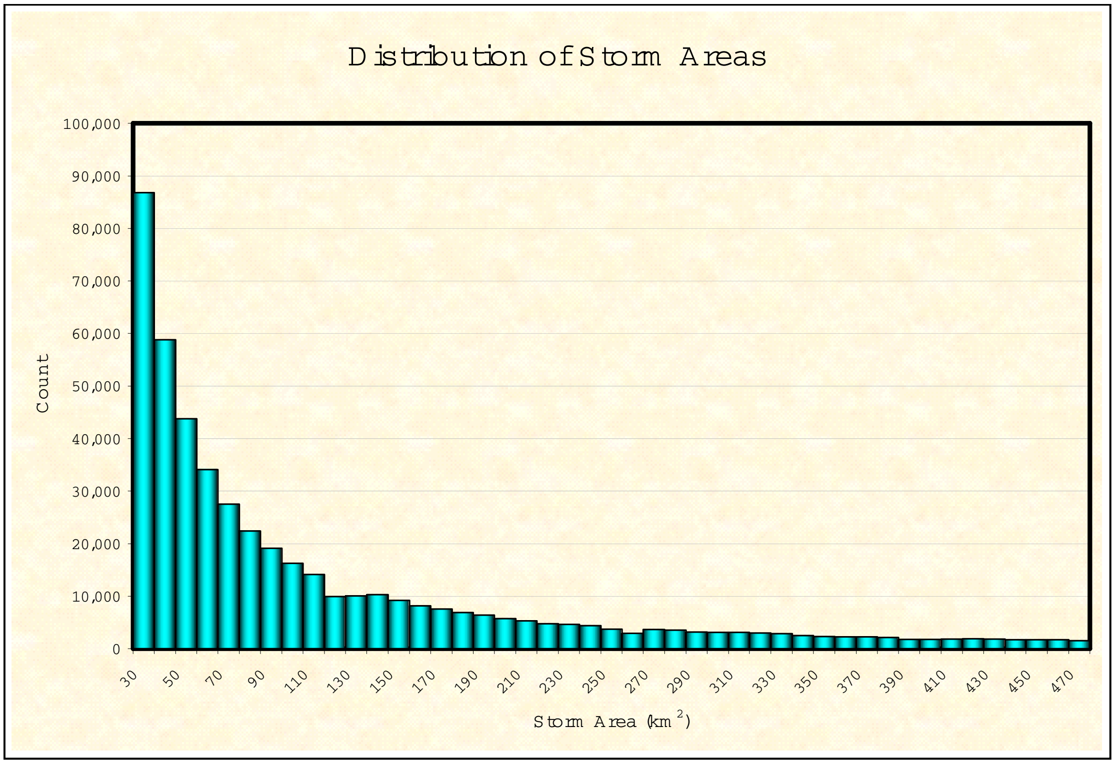

Figure 3: Distribution of storm cell areas.

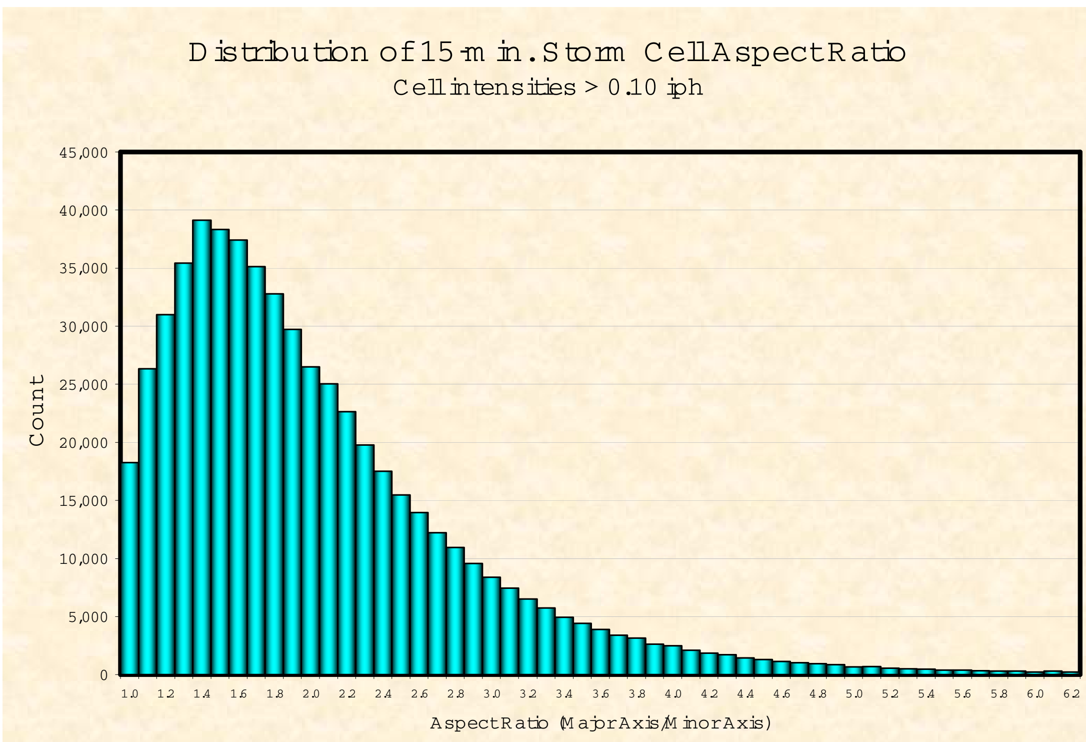

Figure 4: Distribution of 15-minute storm cell aspect ratios.

An improved understanding of the spatial structure of storms, not only at the storm total level, but time step by time step can lead to important hydrologic design insights. Rain gage network, drainage systems, and storm water treatment facilities are just a sample of the design questions potentially affected. The collection of statistics defined for storms cells is particularly important to the development of design storms.

Design Storm Development

Most hydrometeorological analyses for design storms use a relatively simple concept of stationary storms, with fixed areal depth derived from annual Depth-Duration-Frequency (DDF) statistics of representative precipitation data records. (Humphrey, et al, 2004) Typically, the response frequency of a system (i.e. peak flows, daily volumes, overflows, pump requirements, etc.) has been assumed to equate to the design storm frequency. This is rarely the case, especially in sanitary sewer systems with high levels of inflow/infiltration. System response may also be significantly different for short-duration (1-3 hours) compared to long-duration events.

The common practice of nesting short-duration depth statistics within a longer duration storm (i.e. 24 hours or longer) has been found to produce unrealistic results for many systems. The high-intensity short-duration depths cover a very limited area compared to the long-duration events. The short-duration events require Depth-Area-Reduction-Factors (DARF) to adjust for the limited area of high intensities. However, these DARF adjustments are not appropriate for longer-duration general rainstorms or antecedent rainfall or for the portions of the system that experience the peak core rainfalls. Furthermore, commonly used DARFs developed solely from analysis of point rain gage data such as those published by the National Weather Service (Figure 5), may underestimate how sharply rainfall intensities drop off from the peak. This implies that commonly used DARFs may spread heavy rainfall over a larger area than necessary resulting in too much rainfall volume over a watershed. Too much volume may yield overly conservative and expensive designs.

Using the results of TITAN analyses of gage-adjusted radar rainfall estimates, idealized storm cells can be created for each natural cell analyzed. (Figure 6) By examining hundreds of thousands such idealized cells, depth area relationships for each intensity range can be developed as indicated in Figure 7. Normalized depth area curves ranged from 0.15 inches per hour to nearly eight inches per hour are shown in Figure 7. Most of the curves shown represent relatively light rain.

Figure 8 shows only the curves for storm cells with peak rainfall exceeding the 2-year 15-minute intensity, including curves for intensities greater than the 100-year event. Remarkably, the normalized depth area curves for the 2 to 100-year event and beyond are essentially identical. This suggests that individual storm cells from the 2-year event and above have essentially the same characteristic shape, on average.

Even more remarkably, similar results have been obtained by the author for studies in Florida, Texas, Missouri/Illinois, and the arid southwest. The size of storms change as peak intensity changes but the characteristic shape stays the same.

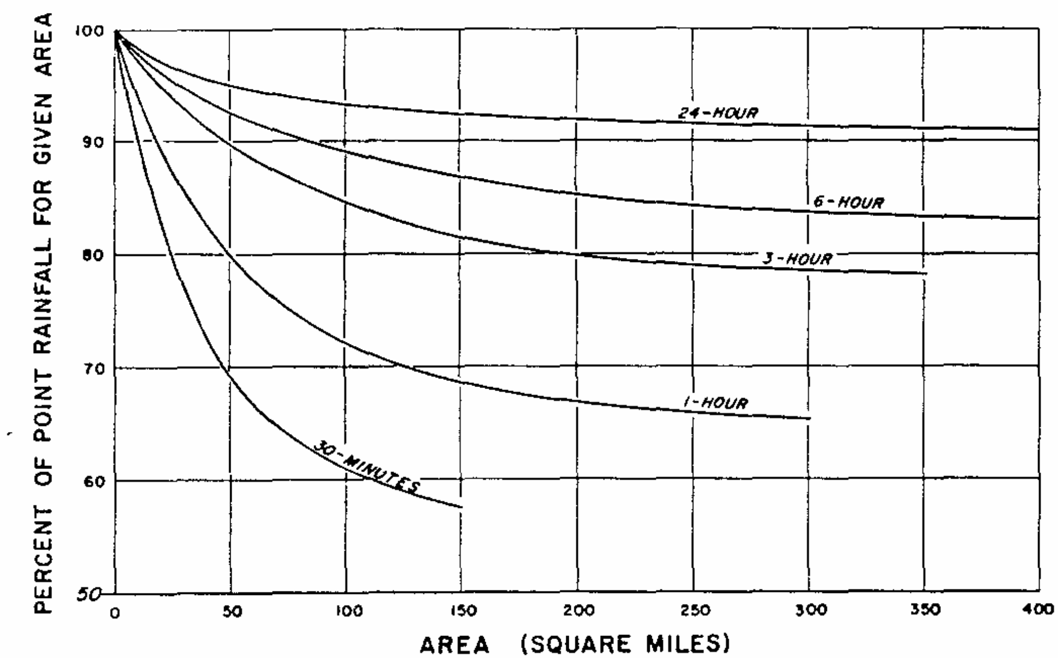

Figure 5: Depth area reduction factors (NWS Technical Paper 40).

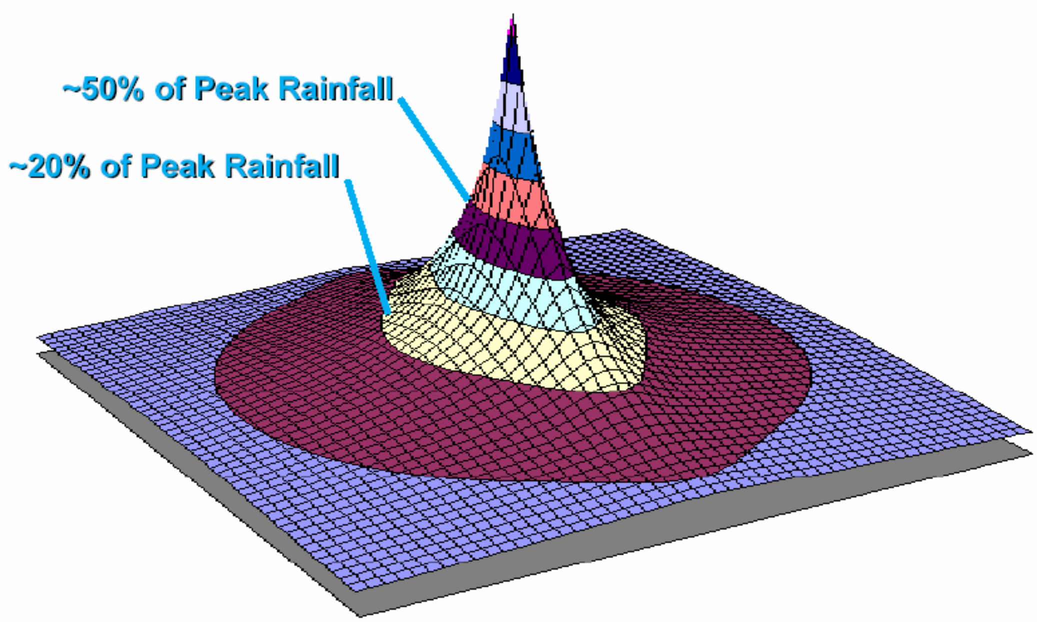

Figure 6: Idealized storm cell.

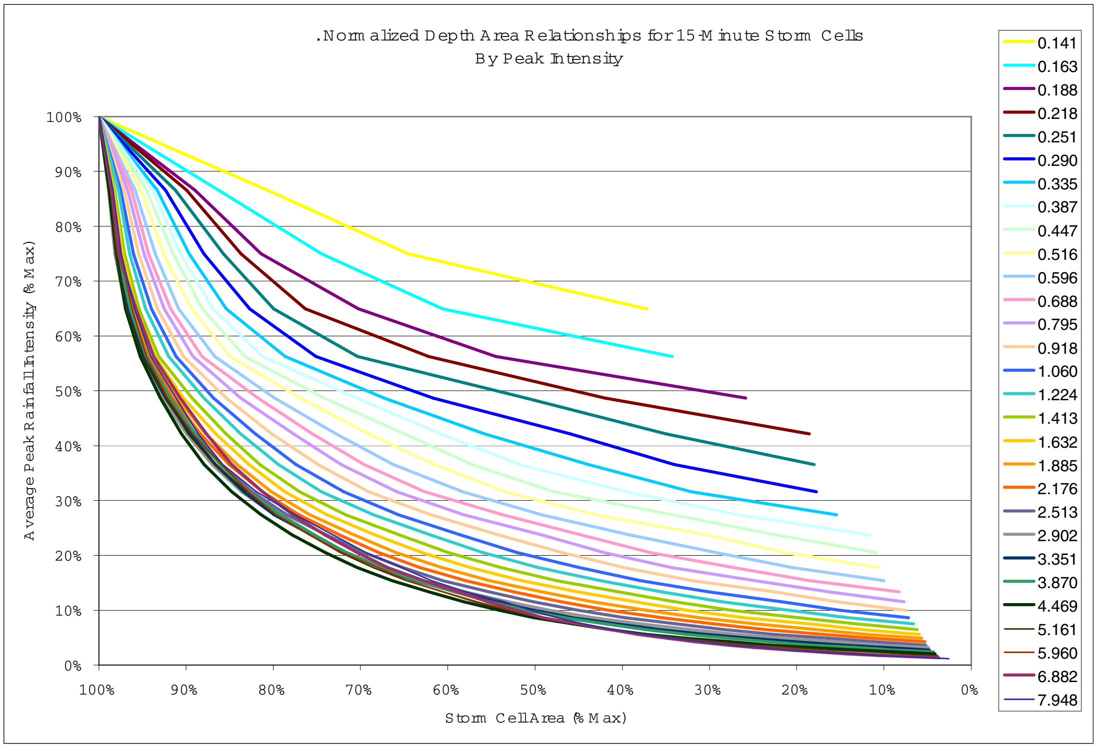

Figure 7: Normalized depth area relationships for 15-minute storms cells by peak intensity.

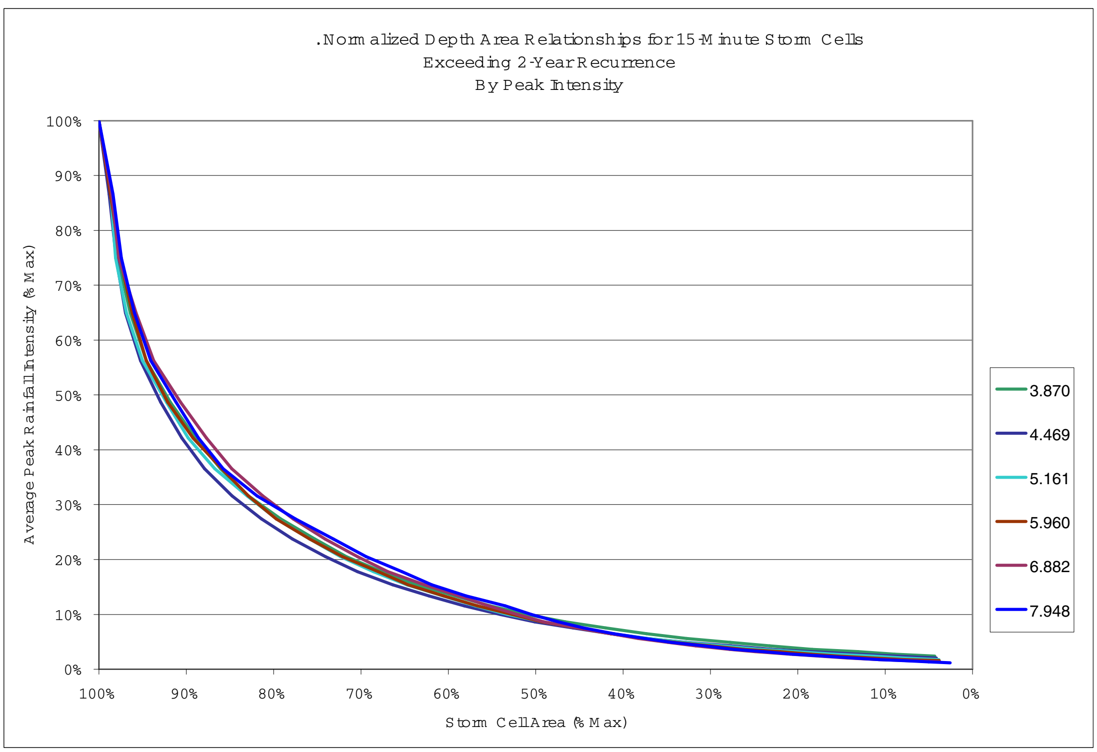

Figure 8: Normalized depth area relationships for 15-minute storm cells exceeded 2-year recurrence.

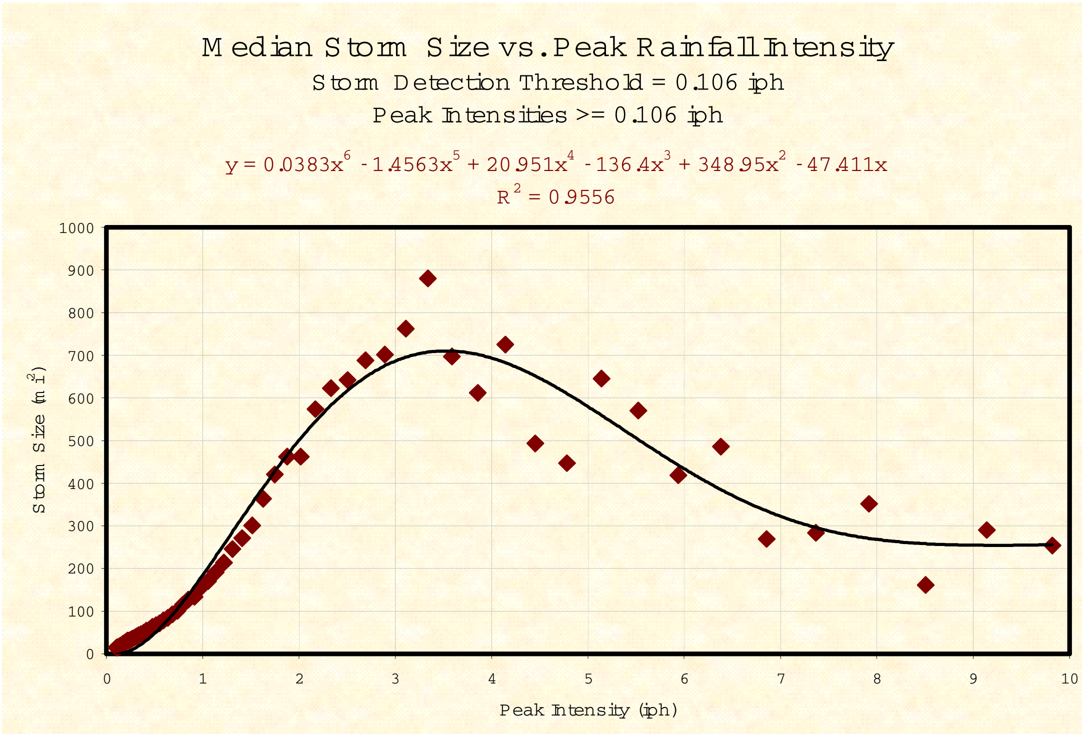

Figure 9: Relationship between storm cell area and peak rainfall intensity.

The analysis of the spatial structure of storm cells also suggests that 15-minute storm cell peak intensities and cell area may be related in a predictable way. Figure 9 presents peak rainfall intensity plotted against mean 15-minute storm cell size for the Missouri/Illinois area. Storm size appears to increase with peak cell intensity up to approximately the 2-year event. Above the 2- year event, storm cell size appears to decrease to the point where the size of the 100-year is less than half the size of the 2-year event. Very similar results have been obtained in a range on locations and climates in the U.S. including Florida.

Summary and Conclusions

Radar-rainfall records for the past 10-years or more are available for many locations in the U.S. These data, when calibrated to local rain gages, provide valuable insights to the spatial distribution of rainfall which affects many applications in hydrologic design.

The results from Figures 4, 8, and 9, in particular, provide insight to the appropriate size and shape of potential design storms for a wide range of return periods. Further information is available from distributions of storm speed, direction, and orientation. Seasonality impacts can also be discerned. Collectively, these statistics form the foundation for the derivation of design storms specific to a given location. In addition, there is enough information to develop both static and dynamic design storms.

References

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