Spatial Analysis of Storms Using GIS

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Abstract

Point data from rain gages have been historically used to develop depth-area relationships, design storm sizes and depths, average storm vectors, etc. The results are often adversely influenced by the lack of data between the gages, resulting in design storms that do not reflect the true spatial structure of storms. In essence, point data were used to solve a spatial problem. OneRain calibrated sixty months of radar rainfall data over 100,000 sq. mi. centered over St. Louis, Missouri, and ingested those results into TITAN, a program developed at NCAR (National Center for Atmospheric Research) that identifies and analyzes individual storm cells at every time step. For the sixty months, TITAN identified almost 900,000 individual storm cells. These results were ingested into ArcGIS to help determine the design characteristics of storms over the St. Louis region. In essence, spatial data were used to solve a spatial problem.

Introduction

Until recently, depth area reduction factors (DARF) and general storm statistics were based upon the spatial interpolation of point estimates at a number of sparsely placed rain gages. The conclusions based upon these results are heavily influenced by the method of the spatial interpolation and the number of gages used in the analysis. OneRain first created a long-term (60 months) gage-adjusted radar rainfall dataset for the greater St. Louis area then ingested these results into TITAN (Dixon 1993), a computer program that analyzes spatial data. The outputs from TITAN can be used to determine DARFs and various other storm statistics (size, speed, etc.) for a variety of rainfall intensities.

The resultant storm statistics, including the DARF and average storm motion vector, were ingested into ArcGIS, and point depth-duration-frequency (DDF) estimates were created at a fixed location based on the moving storm statistics. The goal of this paper is to use GIS to examine if there is a relationship between the DDF calculated at a single point from published rainfall frequency studies and the resultant design hyetograph calculated using a dynamic storm over a given point.

Depth-Duration Frequency (DDF) and Depth-Area-Reduction Factors (DARF)

Rainfall frequency analyses are used extensively in the design of systems to handle storm runoff, including roads, culverts and drainage systems (Smith 1993). Smith states that the "the precipitation frequency analysis problem is to compute the amount of precipitation *y* falling over a given area in a duration of *x* min with a given probability of occurrence in any given year." In other words, a 24-hour, 100-year storm is the 24-hour rainfall depth that has a 1/100 chance of occurring in a given year.

For engineering design applications, it is necessary to specify the temporal distribution of rainfall for a given frequency, or return interval. Intensity-Duration-Frequency (IDF) or Depth-Duration-Frequency (DDF) curves "allow calculation of the average design rainfall intensity [or depth] for a given exceedance probability over a range of durations" and is the result of the rainfall frequency analysis (Stedinger et al. 1993). For instance, over Washington, D.C., the 100-year, 5-minute rainfall is 0.76 inches, the 100-year, 10-minute rainfall is 1.21 inches, and the 100-year, 15-minute rainfall is 1.52 inches (Bonnin et al. 2003). For a design application, the maximum 5-minute rainfall is stated: 0.76 inches. The next highest 5-minute rainfall total would be 0.45 inches, which is 1.21 minus 0.76. The lowest 5-minute rainfall total for the 100-year storm would be 0.31 inches (1.52 minus 1.21). By disaggregating the rainfall frequency analysis, one is able to create a typical design hyetograph shown in Table 1:

Table 1: 100-Year Design Storm Hyetograph for Washington, D.C. (Bonnin et al. 2003)

Time	Rainfall (in.)
00:05	0.45
00:10	0.76
00:15	0.31

DDF curves are ideal for estimating the return interval of a rainfall event at a single location. However, rainfall depths for a given return interval decrease with increasing area. In other words, the 100-year, 24-hour storm over a large basin will be smaller than the 100-year, 24-hour rainfall at a point location. To convert from a return frequency at a point location to a return frequency over an area, engineers and hydrologists use DARFs. For instance, the total volume of water falling over a 100 sq. mi. watershed for 30 minutes would have be about 61% of the peak rainfall at a point location within that watershed, according to TP-40 (Hershfield 1963).

The details of the development of DARFs are presented in Durrans et al. (2002) and the paper explains the difference between three different methodologies for developing a DARF: storm-centered, geographically fixed, and annual-maxima centered. The spatial interpolation of fixed point data can influence the creation of a DARF. Figure 1 shows a hypothetical example of rainfall at six gages. Two scenarios show different interpretations of the same data; both interpretations show the correct rainfall estimate at the gage location. In other words, both interpolations *could* be correct.

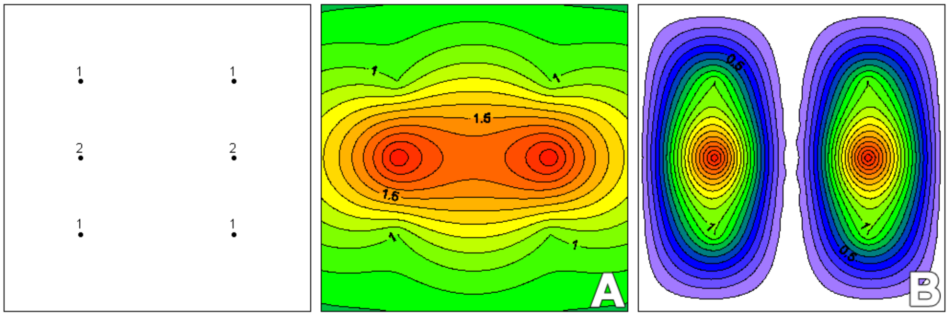

Figure 1: The Graphic on the Left Shows Rainfall at Six Gages; the Other Two Graphics (A & B) Show Different and Valid Ways to Interpolate the Rainfall Data at the Six Gage Locations.

The rainfall values at the six gage locations could have been the result of many (in fact, an infinite number of) spatial rainfall patterns. For example, scenario "A" and scenario "B" both generate the required values at the gage locations, yet they have drastically different spatial structures. The development of a DARF will vary based on whether one choses "A" or "B" in Figure 1 as the appropriate pattern. Since both scenarios could be correct, the resultant DARF is, at least partially, a function of the method of interpolation. Figure 2 shows the DARFs created from each interpolation option. Over an area of 700 relative units, the average rainfall is about 59% of the peak rainfall in scenario "A" and about 30% of the peak in scenario "B."

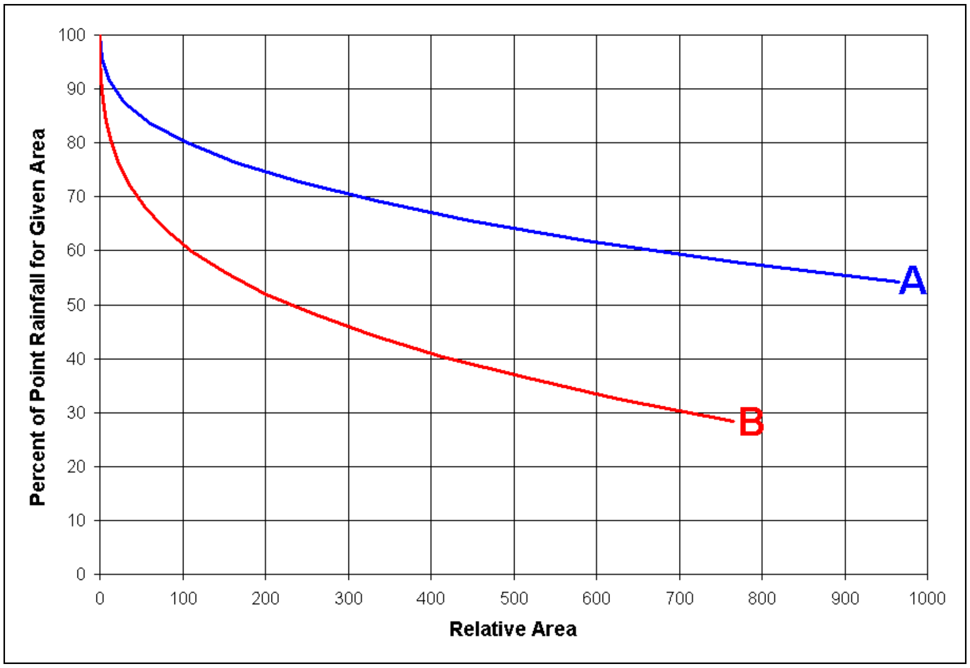

Figure 2: Depth-Area-Reduction Factors for Two Different Interpolation Options.

The increased use of gage-adjusted radar rainfall estimates and GIS over the past decade allows engineers to more accurately depict the size and shape of storms. Because there is less need to interpolate sparsely placed gages, the true DARF can be estimated using spatial data.

Radar Rainfall Analysis

Radar data were downloaded from OneRain's archives of 2-km, 15-minute radar data for the greater St. Louis study area for the 60-month period between 1998 and 2002. These data were reviewed and quality checked for anomalies such as ground clutter and discontinuities and these errors were eliminated using OneRain's GIS filters. In addition to correcting these errors, the radar data were adjusted using data from over 100 National Weather Service (NWS) rain gages. The resulting dataset contained five years of 15-minute gage-adjusted radar rainfall accumulations at almost 79,000 pixels at a spatial resolution of approximately 4 sq. km.

Figure 3 shows the total rainfall across the approximate 100,000 sq. mi. study area for a sample month, July 2002. Figure 4 shows the average rain gage rainfall from the gages with valid data (blue line) versus the unadjusted radar rainfall estimates at the pixels over the same gages (red line) and versus the gage-adjusted radar rainfall estimates at the pixels over the same gages (green line). Note that the figure depicts a running month-long accumulation. In this figure, the gage-adjusted radar rainfall line nearly matches the rain gage estimates, indicating a good fit for July 2002. The other 59 months showed similar results.

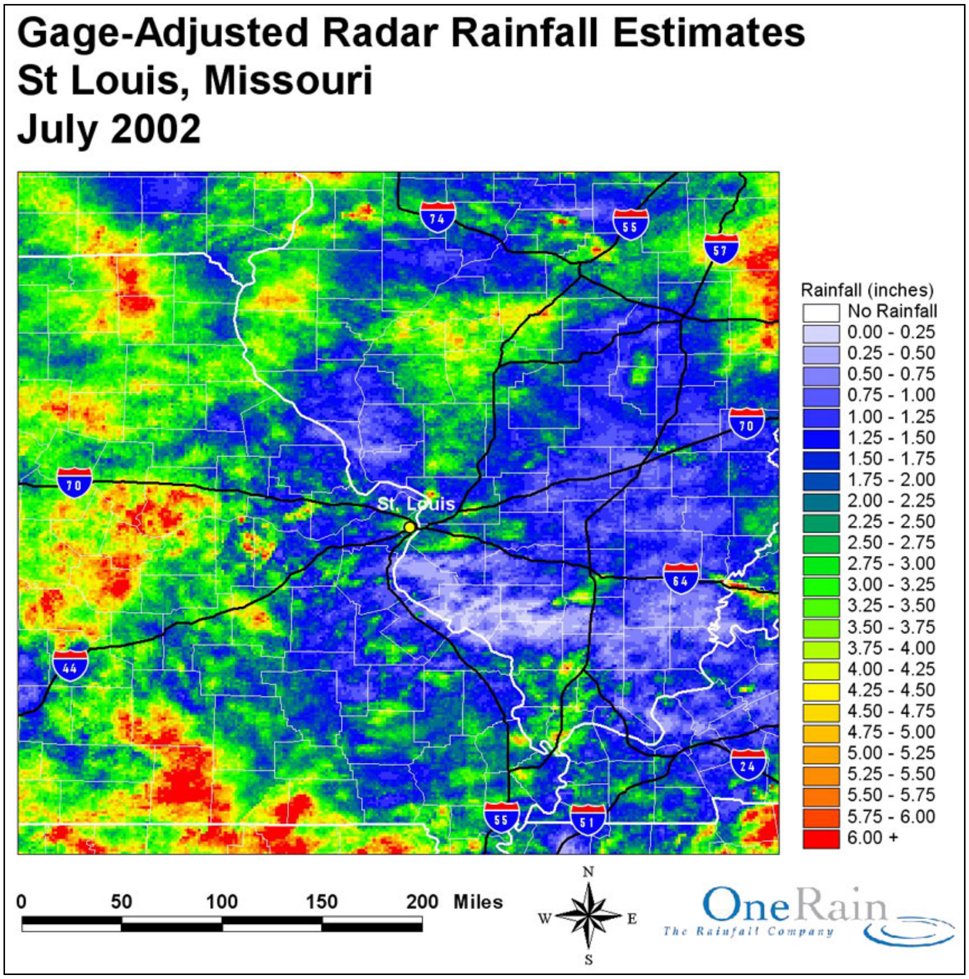

Figure 3: Gage-Adjusted Radar Rainfall Estimates for a Sample Month (July 2002).

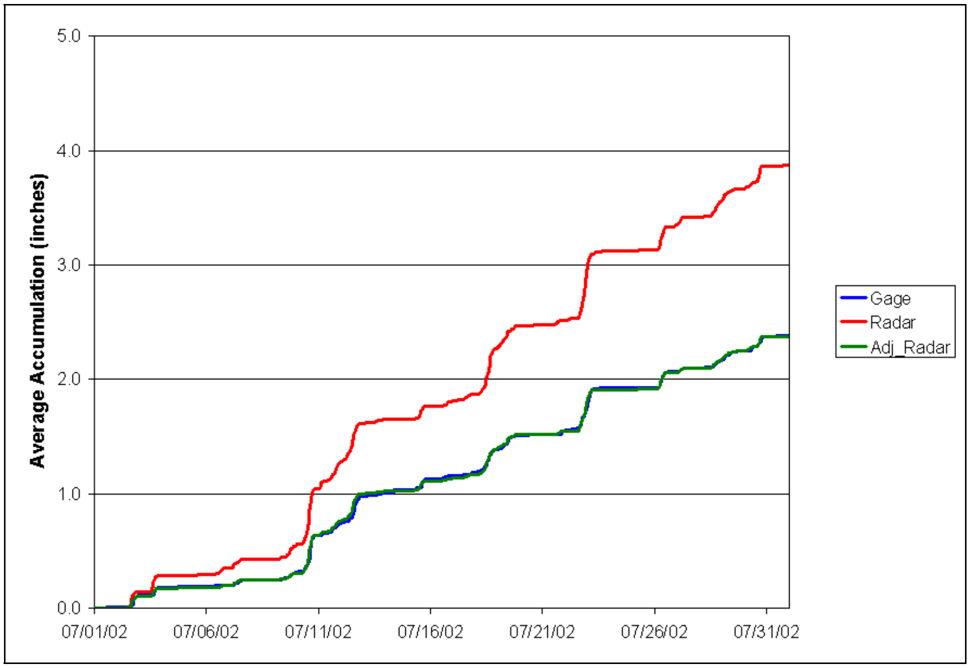

Figure 4: Plot Showing Average Accumulation at the Gages (Blue) and the Unadjusted Radar (Red) and the Gage-Adjusted Radar Rainfall at the Radar Pixels over the Rain Gages for July 2002.

Figure 5 shows the total rainfall measured each month at each gage versus the gage-adjusted radar rainfall estimates for the radar pixel over each gage. On average, about 67 gages were used in the adjustments each month out of more than 100 available gages. Gages were removed from the analysis because they contained missing data, did not report during the month, or because of a lack of correlation with the radar and/or nearby gage data.

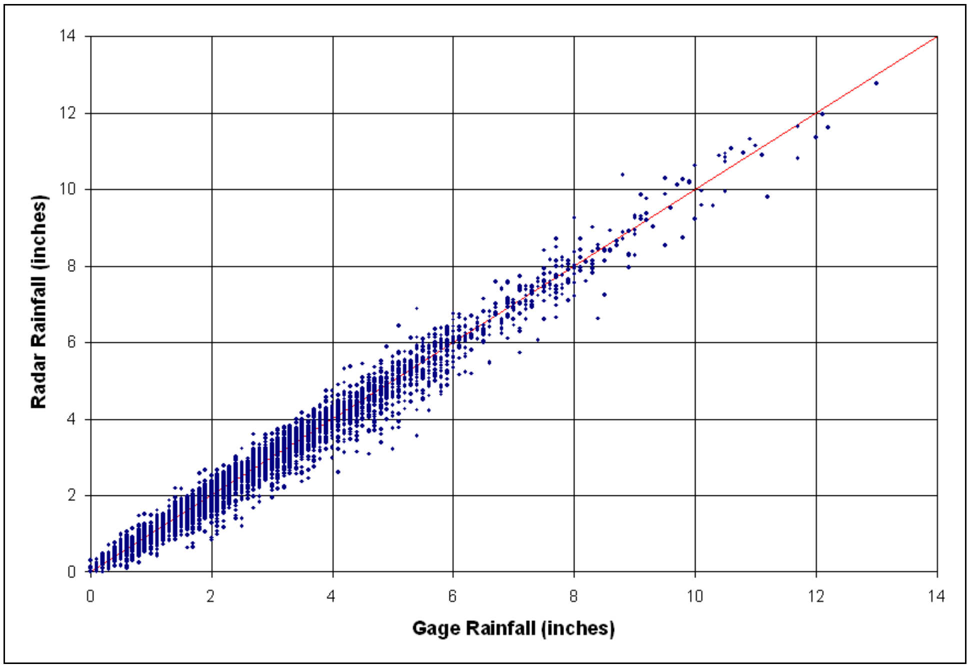

Figure 5: Scatterplot Showing Rain Gage Rainfall for Each Month vs the Gage-Adjusted Radar Rainfall Estimates for the Same Month.

The 60 months of gage-adjusted radar rainfall data were input into TITAN for further spatial analysis.

TITAN

The gage-adjusted radar dataset was ingested into the TITAN analysis package, a software package created at the National Center for Atmospheric Research to analyze spatial rainfall data. TITAN identifies contiguous areas of rainfall at different rainfall intensities and simplifies those areas by fitting an ellipse to areas of contiguous rainfall. Figure 6 shows how TITAN creates a simplified ellipse (in red) out of the more complex structures of gage-adjusted radar rainfall estimates. Each ellipse at each time step is termed a unique “storm.” For each identified storm, TITAN provides the percentage of storm area having an intensity contained within each particular rainfall intensity bin. By aggregating all of the associated areas and intensities for all of the almost 900,000 identified storms, one can create a DARF that is based upon spatial data. Outputs from TITAN can also be used to identify median storm size above a background intensity for a given peak intensity.

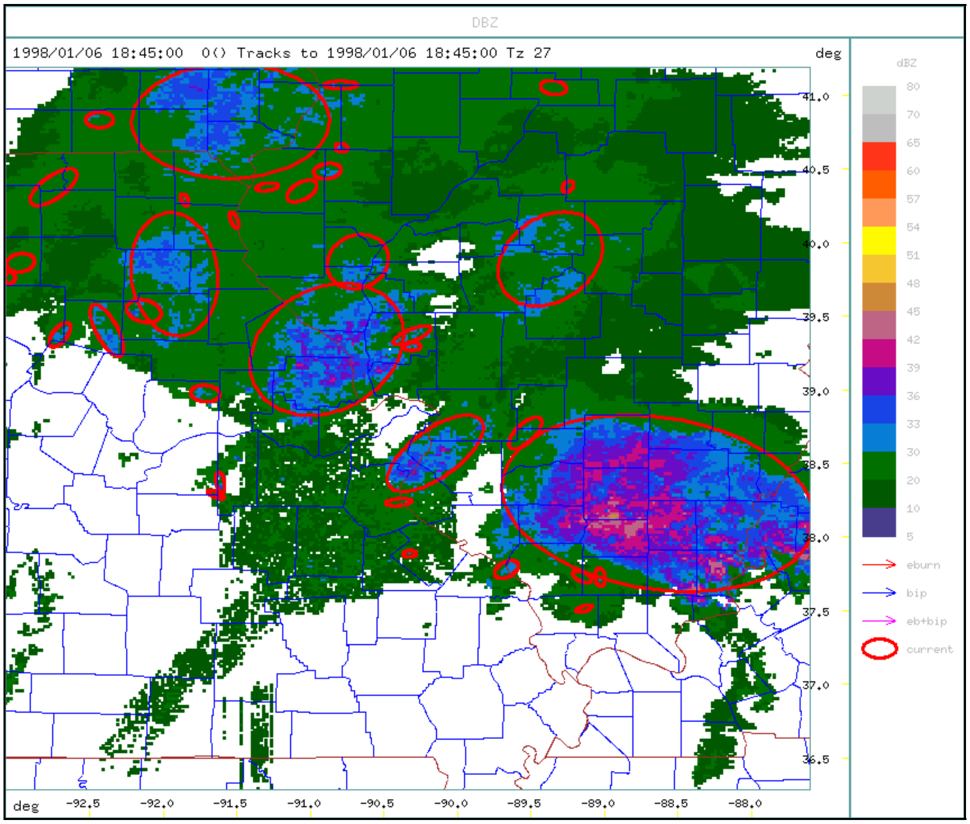

Figure 6: TITAN Image Showing Areas of Simplified Areas of Contiguous Rainfall (Red Ellipses).

TITAN tracks these ellipses from time step to time step, so it is able to estimate storm vectors and life spans. Other output statistics include: storm orientation, storm shape (major axis versus minor axis), and storm movement vectors (velocity and direction). TITAN can also group storms by season or month, and can output subsets of the full data according to specific queries (e.g. what was the average storm vector in July 2000 for storms with a peak intensity greater than 2.0 in/hr?).

The output data from TITAN were used to create a hypothetical design storm with a peak 5-minute duration derived from the latest National Weather Service frequency study (Bonnin et al. 2003). A DARF was developed based on the 60 months of data from the TITAN study. Outputs from TITAN were also used to develop average storm shape (size and aspect ratio) and storm movement vectors. In essence, TITAN is using the spatial rainfall data from the gage-adjusted radar rainfall estimates to estimate spatial variables.

Results

Over the St. Louis study area, the 5-minute, 100-year storm event is approximately 10.56 in/hr and the 1-hour, 100-year storm is approximately 3.16 in/hr (Bonnin et al. 2003). These estimates are derived from NOAA Atlas 14, which is now available on-line for Illinois (the estimates were derived from East St. Louis). NOAA Atlas 14 supercedes TP-40 (Hershfield 1963) and HYDRO 35 (Frederick 1977), among others, but the results are still "subject to change and not for official use," according to the web-site (http://hdsc.nws.noaa.gov/hdsc/pfds/). The 100-year rainfall rates from NOAA Atlas 14 were disaggregated into a temporal time series (Figure 7).

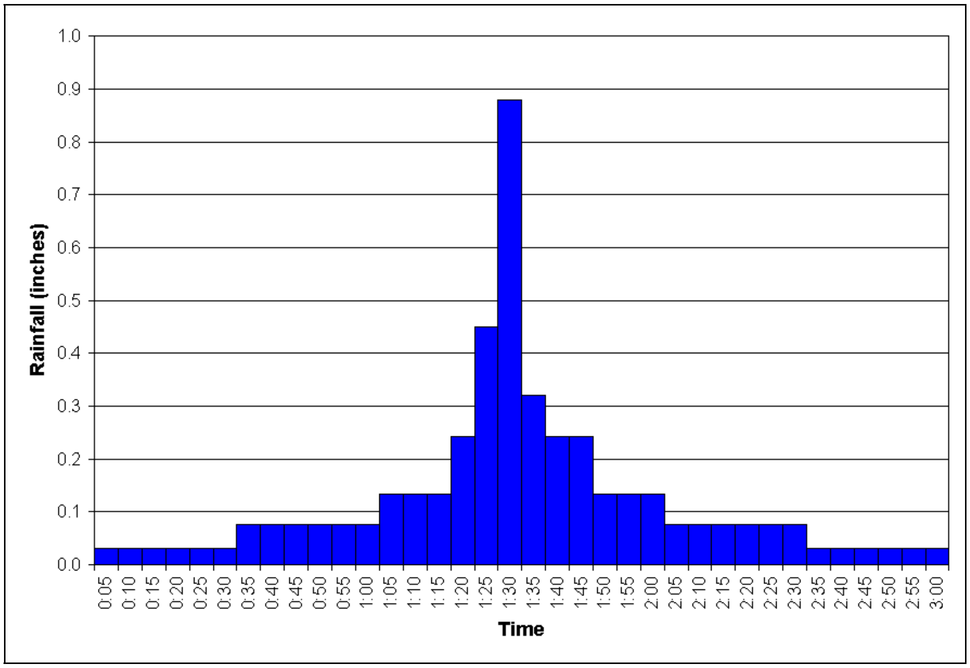

Figure 7: 100-Year Design Hyetograph for St. Louis (Bonnin et al. 2003).

Table 2 shows the storm property outputs from TITAN. The storm speed and direction were taken from the median storm direction of all storms. Using outputs from TITAN, OneRain determined the median storm area associated with a given peak intensity, the mean aspect ratio and average storm movement vectors, and these data were used for modeling the dynamic hypothetical storm. The aspect ratio is the ratio between the major and minor axis of the simplified ellipse. The storm direction is from slightly south of west and is headed slightly north of east.

Table 2: Storm Property Outputs from TITAN for St. Louis

Variable	Value	Units
Storm speed	10	mph
Storm direction	7.5	degrees N of E
Area	660	square miles
Aspect ratio	1.4	dimensionless

The results from TITAN were used to create a design storm. The storm was designed to move directly over a single point within the study area and a hyetograph of the storm was created at that location. The storm was a symmetrical storm; in other words, the leading and trailing edges of the storm were identical. It would be impossible to recreate the design hyetograph in Figure 7 with a symmetrical storm - a moving symmetrical storm, by definition, will create a symmetrical hyetograph over a given location. The moving storm also did not include a growth or decay function - the storm simply moved at the same size and intensity across the study area.

Figure 8 shows a single time step of the hypothetical design storm using the storm statistics derived from the TITAN analysis. The storm is moving just north of due east and just past the target location, which recorded the storm's hyetograph as it passed overhead.

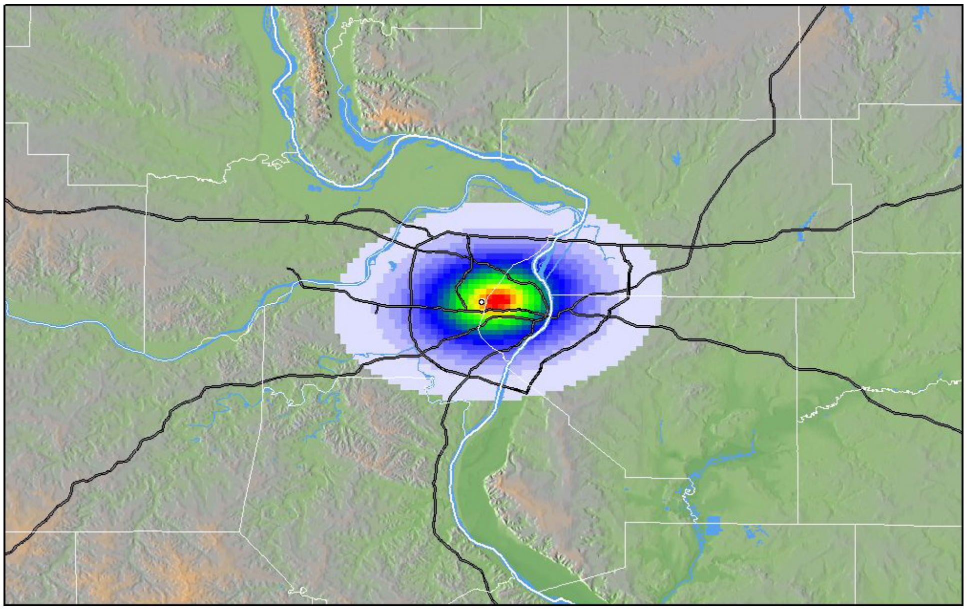

Figure 8: Hypothetical Design Storm Created Using Outputs from TITAN.

Figure 9 shows the results of the moving storm. The peak five-minute rainfall was set to match the peak five-minute rainfall from the frequency study. Over durations longer than five minutes, the storm showed more rainfall than the rainfall estimates from the frequency analysis. This suggests that the design storm depicted in Figure 7 is more typical of a faster moving storm.

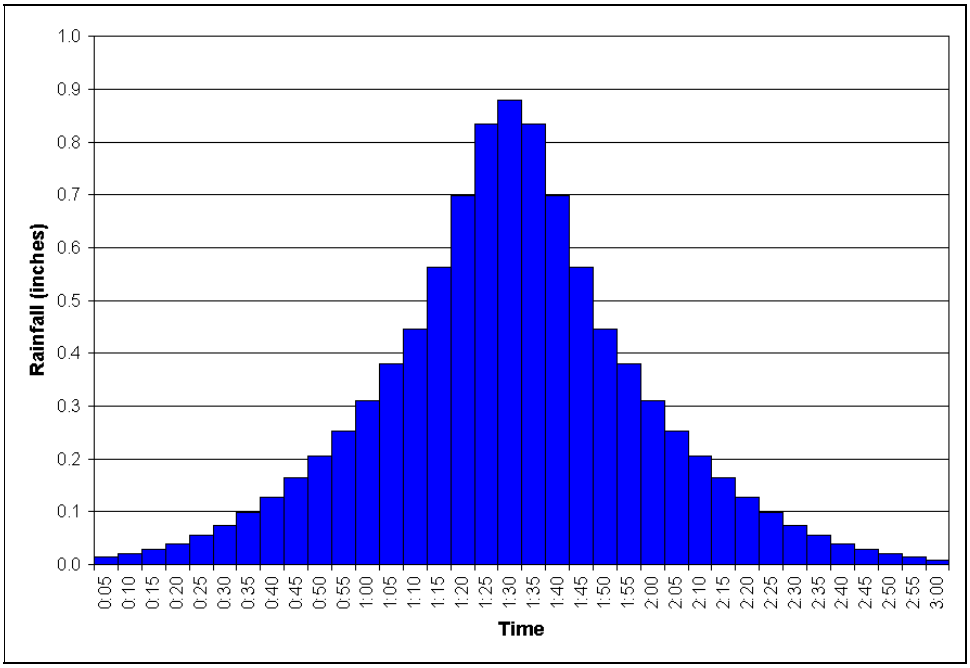

Figure 9: 100-Year Hyetograph Created from Output from TITAN.

OneRain increased the speed of the storm from 10 mph to about 30 mph to get the 1-hour rainfall to match the 1-hour rainfall from the design storm. These results are shown in Figure 10 and the results more closely match the design hyetograph in Figure 7. However, there still are some noticeable differences. Primarily, the peak 15-minute rainfall is considerably greater in Figure 10 and this is partially due to using a symmetrical storm.

While 30 mph is probably an unreasonably high storm velocity, the procedure does show the ability to adjust the variables based on the spatial data to produce a reasonable design hyetograph. Using a similar procedure, one could easily develop design hyetographs for a variety of parameters (intensity, time of year, shape, vector, etc.). The value of this approach is the ability to produce design storms with more realistic spatial patterns of rainfall.

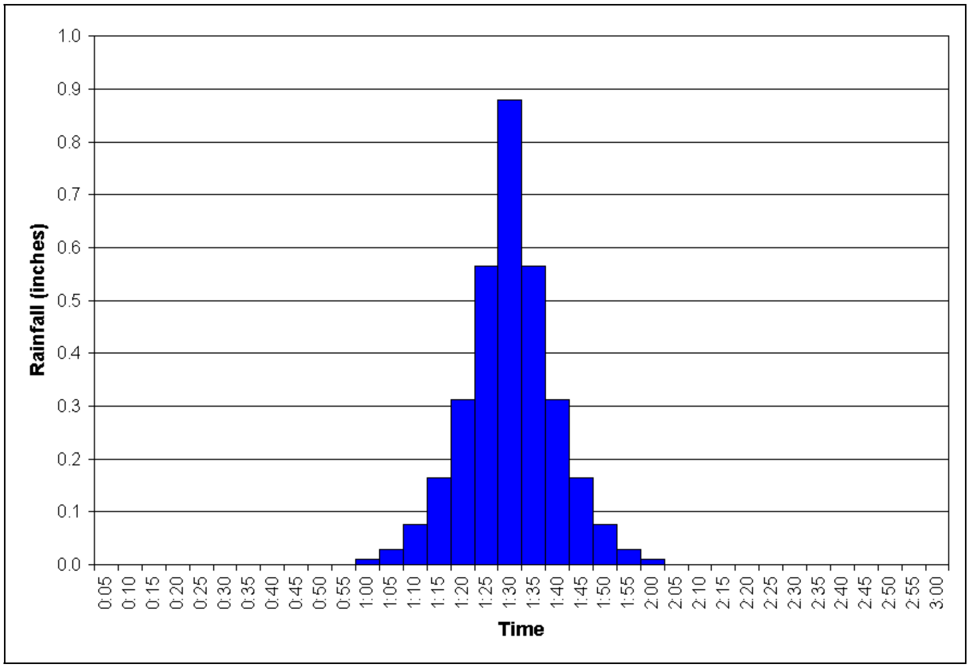

Figure 10: 100-Year Hyetograph Created from Output from TITAN with Increased Storm Speed.

Table 3 gives a summary of the results. For both TITAN studies, the peak intensity was set to match the five-minute intensity from the frequency analysis.

Table 3: 100-Year Design Rainfall Depths from Frequency Analysis, from TITAN and from another Run of TITAN with Increase Storm Speed. All Values are in Inches.

Duration (minutes)	DDF (Bonnin et al. 2003)	TITAN	TITAN w/ Increased Storm Speed
5	0.88	0.88	0.88
10	1.33	1.71	1.44
15	1.65	2.55	2.01
30	2.38	4.51	2.80
60	3.18	7.03	3.18
120	4.09	9.12	3.19
180	4.46	9.51	3.19

Conclusions

For years, engineers and hydrologists have been using point rainfall data to solve spatial problems. With the increased use of gage-adjusted radar rainfall estimates and GIS, spatial rainfall problems, such as the development of depth-area-reduction factors (DARF) can now be solved using spatial data.

The results show that there is promise in using gage-adjusted radar rainfall estimates to create more appropriate design rainfall based on spatial rainfall data. These procedures will be enhanced with the inclusion of storm growth and decay. These procedures will allow engineers and hydrologists to better use spatial data to solve a spatial problem.

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