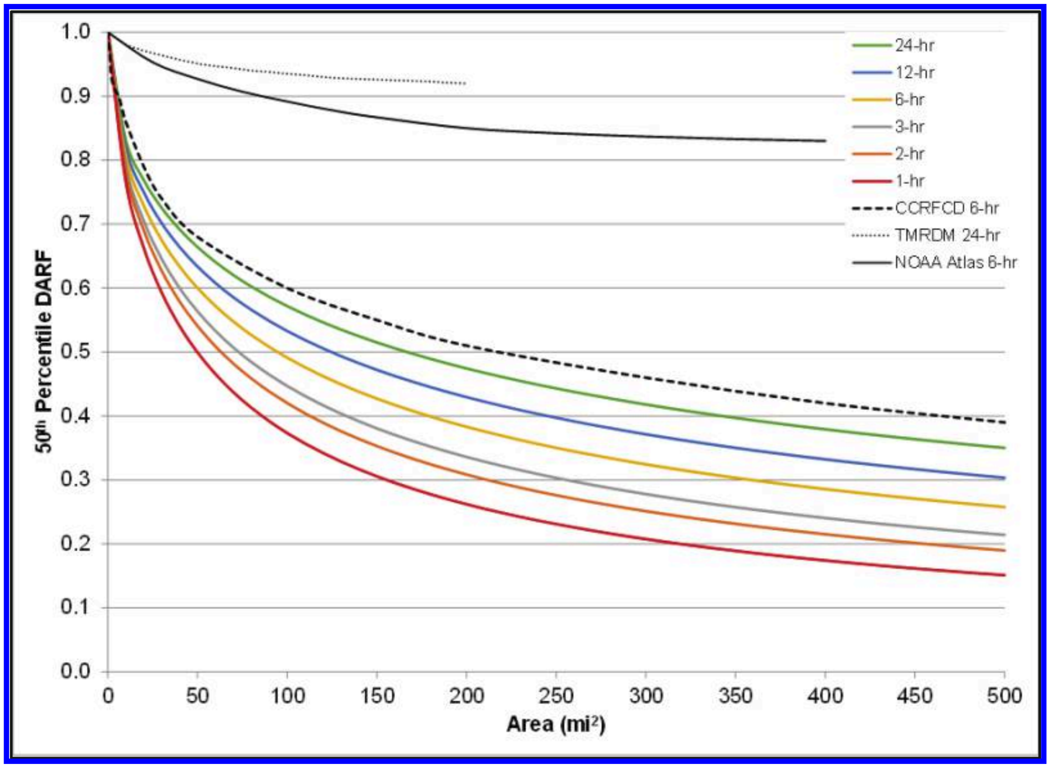

Figure 5a Smoothed 50th percentile depth area reduction factors (DARFs) for storm durations 1-through 24-hours

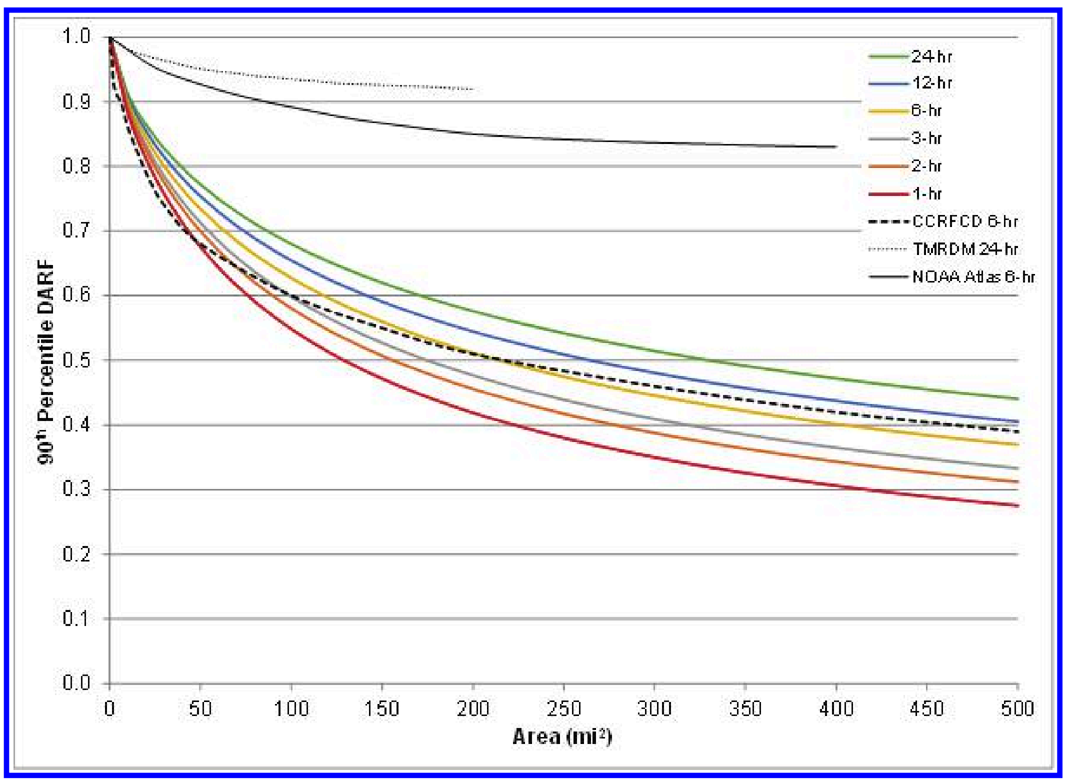

Figure 5b Smoothed 90th percentile depth area reduction factors (DARFs) for storm durations 1-through 24-hours

Depth-Area Reduction Factors (DARFs)
Evaluation of the use of the median versus the 90th percentile DARFs determined by this research is considered. Specifically, the 6-hour duration DARFs for three selected locations with an area of 100 mi^2 are summarized in Table 1. For both Ely and Sparks, NV, the jurisdictional DARFs were determined from NOAA Atlas 14 and are based on TP-29 since the TMRDM only provides 24-hour DARFs for Sparks, NV. The 6-hour storm duration is most typically used in Nevada, and is representative of most storms. The 24 hour duration was included for detention pond storage volume calculations performed by NDOT.

Table 1. Depth-Area Reduction Factors (DARFs) for Ely, Las Vegas, and Sparks NV

		6-hour DARF, Area = 100 mi^2		
Location	**HHA**	**Jurisdictional**	**50th Percentile**	**90th Percentile**
Ely, NV	5	0.89[1]	0.49	0.63
Las Vegas, NV	8	0.60[2]	0.49	0.63
Sparks, NV	1	0.89[1]	0.49	0.63

[1]TP-29, [2]CCRFCD Table 502

Hyetograph Development
The results of this research recommend the hyetograph shape be determined as a function of the maximum intensity. The generalized logistic equation (GLE) is a useful fitting procedure applicable to the dimensionless cumulative hyetographs. Two geographical distributions of maximum intensity are provided, the MMI and the 90th percentile maximum intensity (Figure 1 and Figure 2). As for hyetograph shape, the median cumulative hyetograph shape is similar to a general logistic curve seen Figure 6.

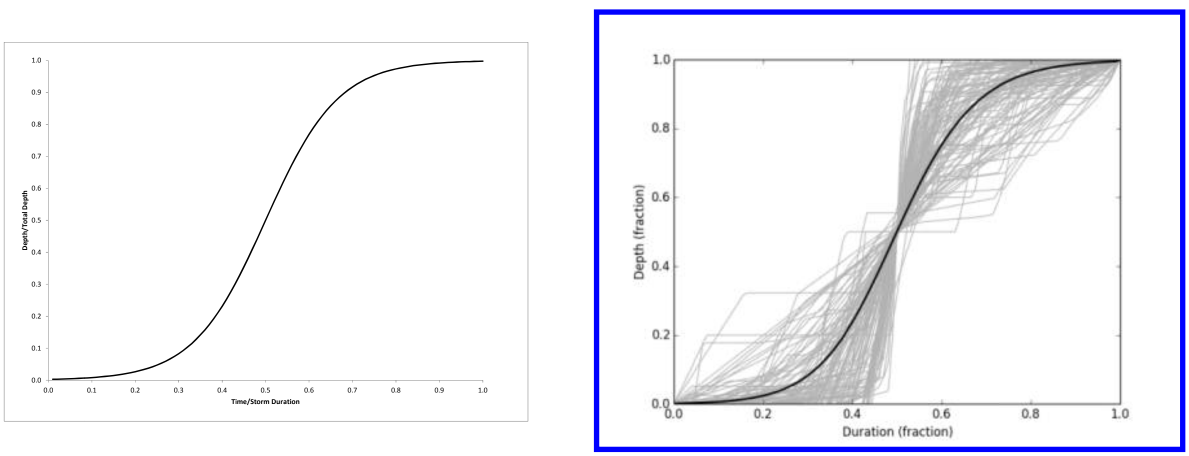

Figure 6 Shape of logistic curve (GLE) (left) and smoothed cumulative hyetograph (right).

The MMI and 90th percentile maximum intensities were sampled from the maps in Figure 1 and Figure 2 for the three locations, Ely, Las Vegas, and Sparks, as presented in Table 2. The DARFs in Table 1 were then applied to the storm hyetograph generated with the MMI and 90th percentile intensities summarized in Table 2 and hydrographs produced and analyzed as described below.

Table 2. Median Maximum Intensity (MMI) and 90th Percentile Maximum Intensity at each location.

Location	Maximum Intensity 50th Percentile (MMI)	90th Percentile
Ely, NV	4.49	5.61
Las Vegas, NV	3.61	5.60
Sparks, NV	2.79	3.65

Hydrologic Evaluation

A hydrologic evaluation was performed to test the sensitivity of three watersheds to design storm hyetograph and DARF characteristics at three locations, Ely (HHA 5), Las Vegas (HHA 8), and Sparks (HHA 1). For comparative purposes, hyetographs at each location are based on the existing jurisdictional methodology as provided by NDOT, CCRFCD, and TMRDM for Ely, Las Vegas, and Sparks, respectively and the jurisdictional depth defined by jurisdictional return frequency rainfall input. At Ely and Sparks, the jurisdictional hyetographs are based on a balanced storm, determined using HEC-HMS. Outflow hydrographs were generated using each hyetograph within HEC-HMS for a hypothetical 100 mi^2 watershed. The hydrologic analysis revealed that the balanced hyetograph produced using current NDOT procedures with HEC-HMS produces higher response than even the 90th percentile maximum intensity. Within the CCRFCD jurisdiction (HHA 8), the jurisdictional hydrograph (without losses) falls between the hydrographs from this study. With losses, the jurisdictional hydrograph falls closest to the hydrograph generated by the MMI and 90th percentile DARF hyetograph. The 6-hour, 100 mi^2 DARF from CCRFCD (0.60) is closest to the 90th percentile DARF (0.63) from this research. Interestingly, there is little difference in hydrograph peak, whether the MMI or 90th percentile hyetograph is chosen.

SUMMARY

For this research we conducted a detailed analysis of storm events in the State of Nevada to develop design storms for use by NDOT throughout the state, excluding Clark County. The design storm includes a hyetograph shape and DARF relationships for the 1-, 3-, 6-, 12-, and 24-hour storm durations. The recommended hyetograph shape is a general logistic curve determined as a function of the maximum intensity and cumulative rainfall depth. Two maps of maximum intensity were provided, one representing the MMI (50th percentile maximum intensity) and the other representing the 90th percentile maximum intensity. One set of DARF curves representing the median (50th percentile) and 90th percentile DARF relationships were provided for the entire state.

RECOMMENDATIONS

Recommendations for design storm parameters developed herein are as follows:

- Depth-areal reduction factor at the 90th percentile, and
- Hyetograph at the 90th percentile maximum intensity smoothed by the GLE and centered within the storm duration.

Procedures for applying the DARF and hyetograph are under development, and consist of determining the design storm depth and temporal distribution for a watershed. From the statewide 90th percentile DARF curves, a reduction factor is selected for the watershed area. A large watershed typically > 500 sq. mi. may need to be broken down to subwatersheds and the DARF applied to these subareas. Storm centering should also be considered since there are multiple cells typically found in thunderstorms, and even wintertime frontal storms have limited spatial extent. For watershed areas less than 5 mi^2, no reduction is recommended. The hyetograph should be selected for a watershed or subwatershed from the 90th percentile maximum intensity CAI interpolated map of values. Values can be selected at the centroid of the watershed area. The temporal distribution should be centered with the maximum intensity occurring at the center of the storm duration.

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Latest Perspective on Extreme Storm Precipitation Analysis

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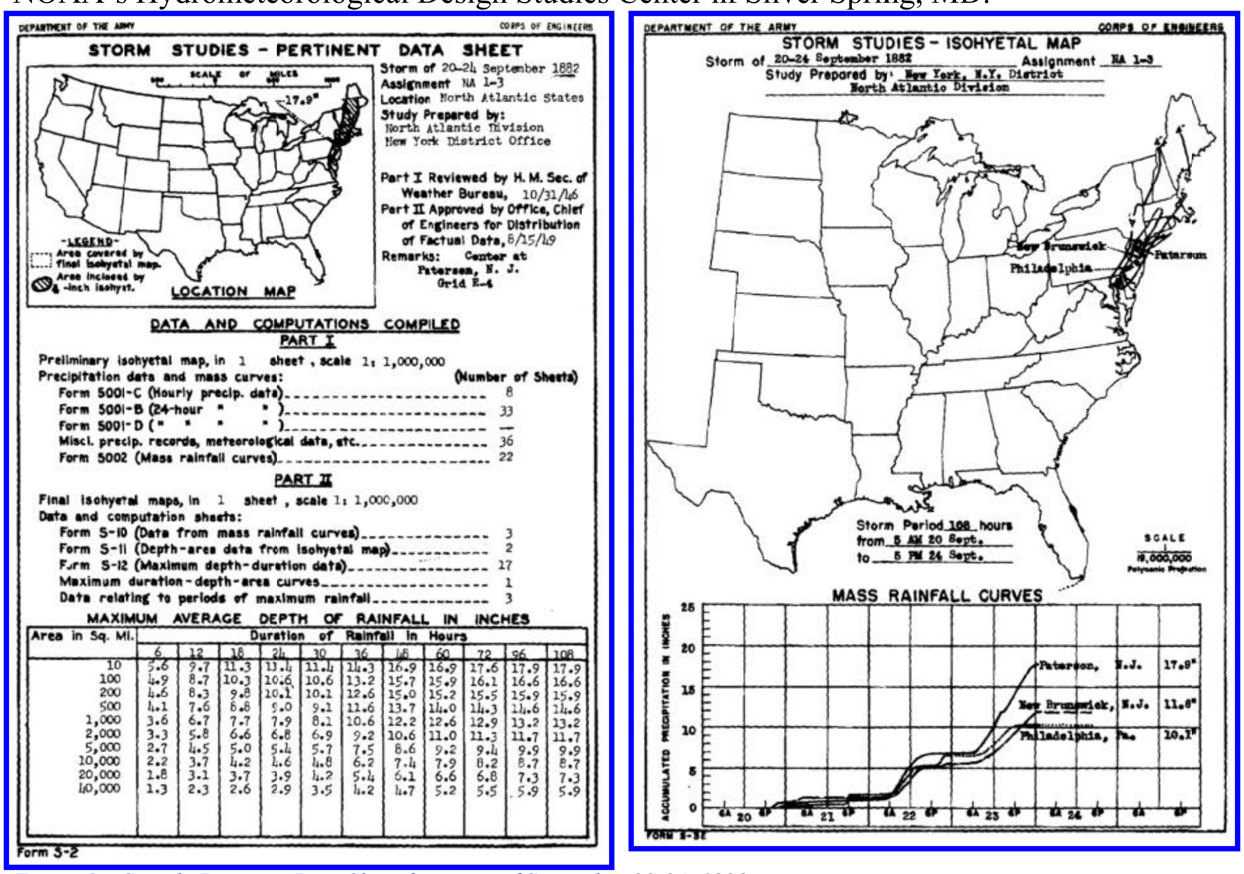
Abstract:

Historically, a systematic means of providing accurate, detailed analyses of precipitation associated with a recent extreme storm event has been difficult to achieve given lack of reliable data, particularly in near real-time. Enhanced radar data, improved satellite data, consolidated rain gauge observations, and innovative method for integrating these sources are making detailed storm analyses faster and more accurate than in the past. We help, manage, and maintain the largest known consolidated and quality-controlled precipitation gauge dataset in the United States, which is vital in "ground truthing" precipitation associated with extreme storms. Dual-polarization radar-estimated precipitation has shown to quantify extreme rainfall more accurately than traditional radar and has provided a significant increase in extreme event analysis accuracy. Meanwhile, satellite-estimated precipitation data continues to improve and provide "gap filling" in areas lacking gauge and/or reliable radar data. Using these datasets and a series of innovative algorithms makes near real-time near real-time, systematic storm analyses possible. Storm analyses of this nature support media inquiries, hydrologic modeling calibration and validation, flood responses, forensic cases, insurance claims, emergency management, situational awareness, and help build a storm database for use in future engineering design applications. This presentation will provide an overview of our efforts to advance the state-of-science associated with extreme precipitation event analysis.

INTRODUCTION

Efficient, safe and optimized design of infrastructure, flood control structures and other high-hazard structures (e.g. nuclear power plants) require thorough analyses of precipitation from extreme storms. In 1937 the U.S. Corps of Engineers (USACE) and United States Army organized an extreme storm analysis program to study extreme storms throughout the United States. The program supported the analysis of approximately 1000 storms occurring between 1878 (storm #NA 1-3, Patterson NJ) and 1969 (storm #NA 2-23, Tyro, VA). The original, hard-copy storm analyses exist today in archives at USACE, NWS and USBR offices around the country. Some of the reports have been electronically scanned as part of the Climate Database Modernization Program (CDMP) and accessible through the National Center for Environmental Information (NCEI) Environmental Document Access and Display System, Version 2 (EV2) application (NCEI, 2016). Meanwhile, summary statistics of the storm analyses also appear in Hydro-Meteorological Reports (HMRs) published by NOAA's National Weather Service and in collection of Pertinent Data Sheets (see Figure 1) stored at NOAA's Hydrometeorological Design Studies Center in Silver Spring, MD.



DEPARTMENT OF THE ARMY CORPS OF ENGINEERS

STORM STUDIES - PERTINENT DATA SHEET

Storm of 20-24 September 1882
Assignment NA 1-3
Location North Atlantic States
Study Prepared by:
North Atlantic Division
New York District Office

Part I Reviewed by H. M. Sec. of Weather Bureau, 10/31/46
Part II Approved by Office, Chief of Engineers for Distribution of Factual Data, 8/15/49
Remarks: Center at Patersen, N. J. Grid E-4

-LEGEND-
Area covered by final isohyetal map.
Area inclosed by -inch isohyet.

LOCATION MAP

DATA AND COMPUTATIONS COMPILED

PART I

Preliminary isohyetal map, in 1 sheet, scale 1: 1,000,000
Precipitation data and mass curves: (Number of Sheets)
Form 5001-C (Hourly precip. data) ---- 8
Form 5001-B (24-hour " ") ---- 33
Form 5001-D (" " " ") ---- —
Miscl. precip. records, meteorological data, etc. ---- 36
Form 5002 (Mass rainfall curves) ---- 22

PART II

Final isohyetal maps, in 1 sheet, scale 1: 1,000,000
Data and computation sheets:
Form S-10 (Data from mass rainfall curves) ---- 3
Form S-11 (Depth-area data from isohyetal map) ---- 2
Form S-12 (Maximum depth-duration data) ---- 17
Maximum duration-depth-area curves ---- 1
Data relating to periods of maximum rainfall ---- 3

MAXIMUM AVERAGE DEPTH OF RAINFALL IN INCHES

Area in Sq. Mi.	Duration of Rainfall in Hours										
	6	12	18	24	30	36	48	60	72	96	108
10	5.6	9.7	11.3	11.4	11.4	14.3	16.9	16.9	17.6	17.9	17.9
100	4.9	8.7	10.3	10.6	10.6	13.2	15.7	15.9	16.1	16.6	16.6
200	4.6	8.3	9.8	10.1	10.1	12.6	15.0	15.2	15.5	15.9	15.9
500	4.1	7.6	8.8	9.0	9.1	11.6	13.7	14.0	14.3	14.6	14.6
1,000	3.6	6.7	7.7	7.9	8.1	10.6	12.2	12.6	12.9	13.2	13.2
2,000	3.3	5.8	6.6	6.8	6.9	9.2	10.6	11.0	11.3	11.7	11.7
5,000	2.7	4.5	5.0	5.4	5.7	7.5	8.6	9.2	9.4	9.9	9.9
10,000	2.2	3.7	4.2	4.6	4.8	6.2	7.4	7.9	8.2	8.7	8.7
20,000	1.8	3.1	3.7	3.9	4.2	5.4	6.1	6.6	6.8	7.3	7.3
40,000	1.3	2.3	2.6	2.9	3.5	4.2	4.7	5.2	5.5	5.9	5.9

Form S-2

Figure 1. Sample Pertinent Data Sheet for storm of September 20-24, 1882.

The statistics, maps, reports, and data complied as part of these analyses is the basis for an invaluable extreme storms database. The NWS, USACE, USBR, TVA, and other government agencies continued intermittent storm analyses through 1973, while in 1959 NOAA began its monthly Storm Data publication. Storm Data provides a listing of storm occurrences and unusual weather phenomena; each storm listing contains storm paths, deaths, injuries, property damage, local storm reports, and a brief synopsis of the event. Although helpful, these storm reports and Storm Data do not contain the summarized data needed for meteorological engineering applications such as PMP determination. In the 1970s, systematic storm analyses all but ceased, except for some extreme flood-producing events, leaving hundreds of meteorologically-significant storms un-analyzed. This left a void of statistically summarized extreme storms from 1973 through present day.

The onset of site-specific PMPs in the late 1990s prompted a need to analyze "newer", significant storms. This necessitated the development of storm analysis programs, such as StormView and the Storm Precipitation Analysis System (SPAS). StormView, developed by Meteorological Solutions Inc, never gained notoriety or wide use in the industry. However in 2002, SPAS was developed to produce Depth-Area-Duration tables for PMP studies, but quickly became a trusted hydro-meteorological tool providing accurate gridded precipitation data at a high spatial and temporal resolution for use in a variety of sensitive hydrologic applications (Faulkner et al., 2004, Tomlinson et al., 2006 and 2008).

Later, in 2014, the next-generation of storm analysis software (MetStorm®) was designed to leverage new dual-polarization radar-estimated precipitation, satellite-estimated precipitation, quality-controlled rain gauge data, improved algorithms, richer output and more automation. (Parzybok and Laro, 2015 and 2016) In order to maintain a high-degree of constancy among the growing extreme storm database, SPAS and MetStorm® were designed to analyze storms similarly to those manually analyzed by the USACE. This helps in efforts to coordinate with Federal agencies, universities, and the private sector through an Extreme Storm Events Work Group under the Federal Subcommittee on Hydrology the establishment of a national inventory and database of extreme storms. (Sankovich and Caldwell, 2011) Furthermore, extreme storm analyses are a critical element of stochastic flood modeling efforts that support Risk-Informed Decision Making Approaches. (Federal Energy Regulatory Commission, 2016)

METHODS

During the pre-computer era, storm analyses were a laborious exercise that took several weeks (or months) to compete for a single storm. The analysis procedure was divided into two parts. Part I consists of the compilation of precipitation data, mass curves of the precipitation, and a preliminary total storm isohyetal map. Part I also includes all available ancillary data from miscellaneous storm reports, "bucket surveys", newspapers, etc. Given the lack of radar or satellite data, "bucket surveys" – the comprehensive collection of precipitation measurements following an extreme storm – were invaluable for accurately quantifying the storms' precipitation. After consolidating, quality controlling and plotting all of the observed precipitation data, a hand-analysis was conducted to produce the total storm isohyetal map. Using large-format drafting tables, tracing paper was overlaid on pre-existing maps of mean annual precipitation to help the hand-analyst draw contour lines consistent with the gauge data and orographics. In areas without significant topography, the analysis was driven by the expertise of the analyst, weather maps, and the gauge data. The total storm isohyetal map dictated the patterns of hourly precipitation patterns. The magnitude of hourly precipitation was govern by true hourly precipitation observations and hourly estimated precipitation from the disaggregation of daily-reported precipitation observations based on inferences from nearby hourly gauges. This allowed the analyst to create hourly precipitation maps and subsequent DAD analyses. Once Part I was quality controlled and evaluated for consistency against an independent meteorological analysis, the preparation of the final results were conducted in Part II. Part II contains the final total storm isohyetal map, tabulation of hourly precipitation values, tabulation of maximum precipitation values for all stations at defined intervals, computation of mass precipitation depths and the average depth of precipitation over selected area sizes (i.e. a DAD analysis). Part I and Part II were subsequently summarized into the Pertinent Data Sheets (Figure 1) for easy reference. The USACE storm analysis approach was applied on over 1000 storms and in fact, was mimicked at the National Weather Service Hydrometeorological Design Studies Center (HDSC) as recent as 1998 when a few storms were being analyzed as part of NOAA Atlas 14 Volume 1 (Bonnin, et. al, 2004); the storm analysis effort was later dropped and never completed.

Regular storm analyses in the U.S. remained infrequent through the 1960s, 70s, 80s, and 90s, except for high-impact events when various government agencies (e.g. Bureau of Reclamation) took the initiative to conduct storm reports. These included the Big Thompson, Colorado flood of 31 July 1979; In fact, this was among a few storms where limited radar data were available to help define the storms' areal extent and movement. (McCain, Shroba, et. al, 1979)

Rarely did any storms from the 1960s through the 1990s include a DAD analysis, the crux of a PMP analysis. Given the onset of regional and site-specific PMP studies around 2002, SPAS was designed to leverage computer software and hardware technologies to automate and expedited thorough storm analyses, including a complete DAD table/plot. SPAS was modeled after the traditional USACE storm analysis methodology to instill constancy in how new and old DADs were computed. In order to demonstrate this, SPAS was used to re-analyze several USACE storms; The DAD results between the two analyses were within +/-5%. (Parzybok and Tomlinson, 2006) The spatial interpolation of point data to gridded rainfall leverages the GRASS Geographic Information System (GIS)

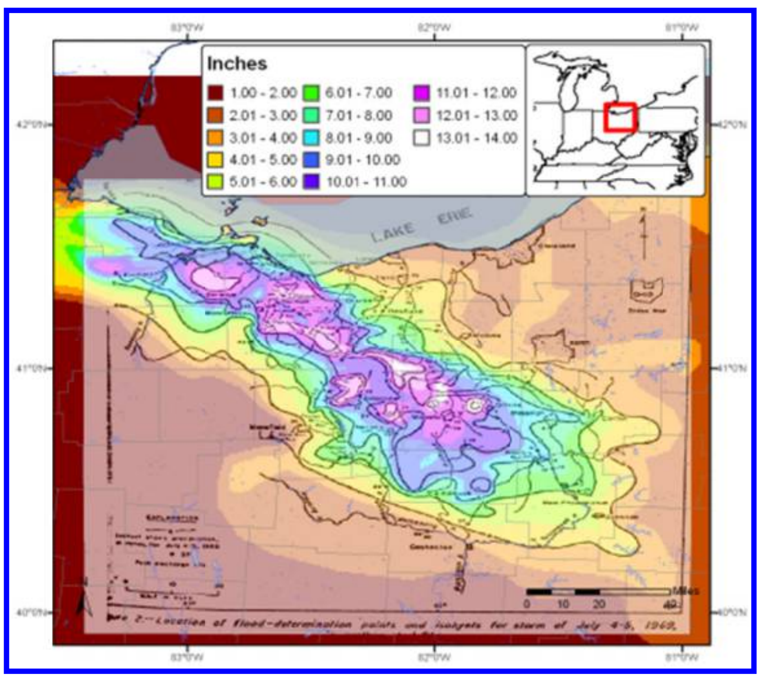


Figure 2. Sample basemap (color) based on a USGS hand-drawn isohyetal analysis.

engine and a slightly modified "climatologically-aided interpolation" technique (Richard and Ross, 2005). The climatologically-aided interpolation approach uses "basemaps," which are independent grids of spatially distributed weather or climate variables that are used to govern spatial patterns like hourly precipitation. Basemaps such as PRISM mean monthly/annual precipitation or NOAA Atlas 14 precipitation frequency grids are particularly useful in complex terrain given they resolve orographic enhancement areas. Climatological basemaps of this nature in flat terrain are not as effective given weak precipitation gradients, therefore basemaps in flat terrain are often developed from pre-existing (hand-drawn) isohyetal maps, radar imagery (if available), or nothing in some cases. The climatologically-aided interpolation approach, also known as the "isopercental" technique, remains as the most accepted method for interpolating random point values of precipitation to a uniform grid.

In 2008 SPAS was modified to integrate NEXRAD radar data, thereby increasing accuracy in the spatial patterns of precipitation. One of the unique capabilities of SPAS is the automatic calibration of the radar reflectivity to rainfall rate, known as the Z-R algorithm. Instead of adopting a standard Z-R, which can severely underestimate the precipitation, SPAS utilizes a least squares fit procedure for optimizing the Z-R relationship each hour of the analysis as shown in Figure 3. Concurrent 1-hour precipitation and radar reflectivity data are statically analyzed to derive an optimized Z-R. If insufficient concurrent radar-gauge pairs are available, then SPAS adopts a user-defined Z-R relationship. The resulting best-fit, one hour-based Z-R is subjected to several tests to determine if the Z-R relationship is within a certain tolerance before it is applied. This methodology helped SPAS resolve extremely heavy precipitation rates and improve the accuracy of the final results. SPAS produces high-resolution (1-km^2) GIS grids at a temporal resolution of 5-minutes or 1-hour, from which a host of deliverables are created including a DAD analysis, a total storm grid and mass curves.

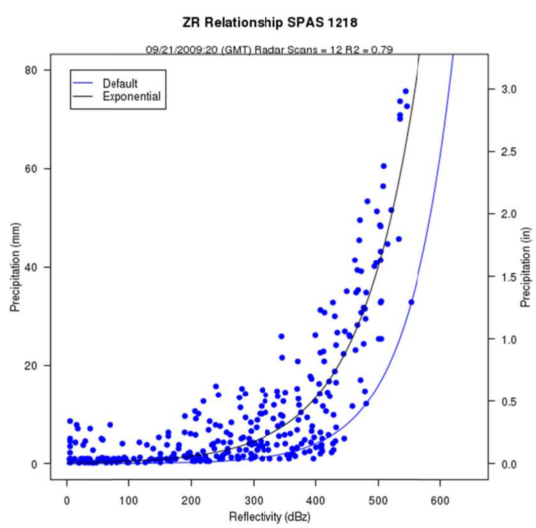


Figure 3. Example SPAS (denoted as "Exponential") vs. default Z-R relationship (SPAS #1218, Georgia September 2009).

Between 2002 and 2011, SPAS underwent several upgrades and version changes, ending with version 10.0. During this time, SPAS became a widely trusted and accepted storm analysis tool used to analyzed nearly 700 storm centers. In fact, in 2015 SPAS underwent a successful technical audit by the U.S. Nuclear Regulatory Commission. From 2002 through today, storm analyses are being regularly conducted with SPAS to support numerous PMP studies taking place across the US. Similarly, the high-resolution, gridded precipitation from SPAS has been utilized in hydrologic modeling efforts and forensic cases involving flooding. (Parzybok, et.al, 2009)

The increasing demand of detailed storm analyses, coupled with a wave of technological advances and data availability, prompted the development of the next generation of storm analysis software. Initially developed to rapidly analyze recent storms, MetStorm® evolved into an all-encompassing storm analysis tool for any storm, including those in the pre-radar era. (Laro, 2015; Parzybok, 2015) A generalized flowchart of MetStorm's processing is shown in Figure 5.

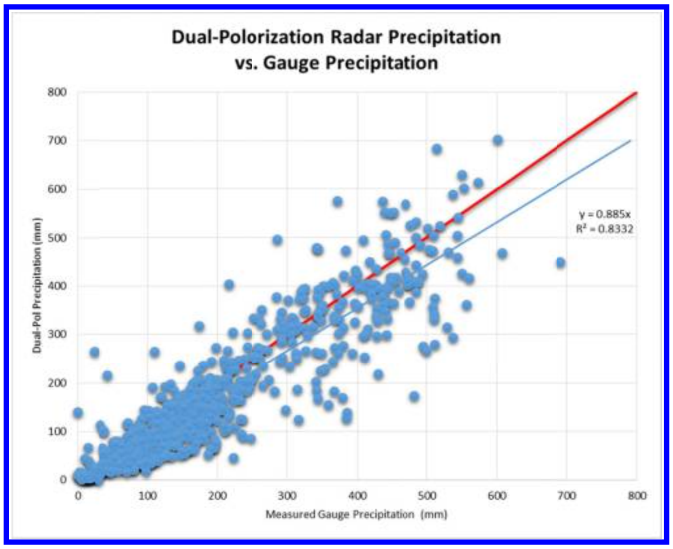


Figure 4. Dual-pol estimated precipitation vs. gauge precipitation for Oct 1-7, 2015 storm in South Carolina.

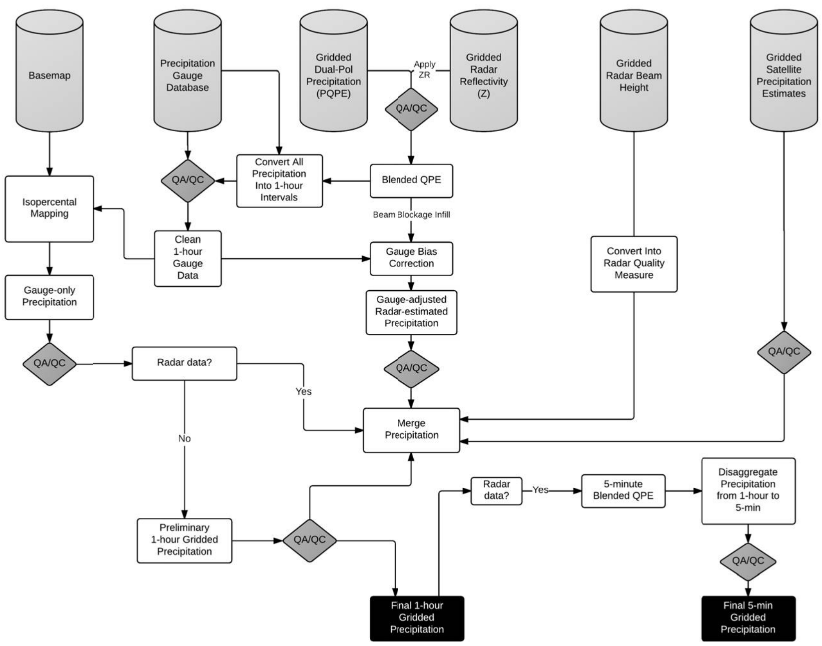


Figure 5. Generalized MetStorm flowchart.