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Synthesis of Extreme Storm Rainfall and Probable Maximum Precipitation in the Southeastern U.S. Pilot Region

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Synthesis of Extreme Storm Rainfall and Probable Maximum Precipitation in the Southeastern U.S. Pilot Region

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ABSTRACT

Data and analyses of ten recent extreme storms in North and South Carolina have been completed by Caldwell et al. (2011). These new storms may influence Probable Maximum Precipitation (PMP) estimates in the region. This report builds on the storm analyses to illustrate some potential impacts to design precipitation estimates and to introduce some alternative, risk-based perspectives, including precipitation frequency. The major objectives of the work were to: (1) describe potential impacts of new storms on existing PMP estimates; (2) present some sensitivities of PMP estimates; and (3) provide preliminary probability estimates of PMP.

The approach that is used is to examine in finer detail the impacts of Hurricanes Floyd and Fran on PMP estimates, based on new Depth-Area-Duration (DAD) and in place storm maximization results from these storms. Brief comparisons are made to 2011 storms. The sensitivity of PMP estimates to several factors is illustrated, including examination of potential climate influences and trends in moisture and surface observations. Approximate PMP exceedance probabilities for example sites within the Carolinas Pilot Region are estimated using regional precipitation frequency analysis.

New data analyses of ten tropical cyclones (TC) suggest that Hydrometeorological Report 51 (HMR 51) PMP values are too low for durations greater than 12 hours and area sizes greater than 5,000 mi^2 (12,950 km^2) along the coastal Carolinas, based on analysis of Hurricanes Floyd and Fran (Caldwell et al, 2011). Other durations and area sizes are unaffected in this location. HMR 51 may need to be updated for coastal areas in Carolinas. There are unknown impacts in the Carolinas because envelopment, transposition and orographic effects are unclear due to the limited sample. These factors, if included, would tend to increase PMP estimates in some locations. Storm Depth-Area Duration maximized values are somewhat sensitive to radar rainfall biases and use of maximized moisture. Using a median moisture maximization ratio, Floyd is still close to HMR 51 PMP. No significant trends were found in sea surface temperature (SST) and dew point grids. This suggests stationary series for storm maximization. There is a potential for increased temporal clustering of TC events in August-September based on recent storms in 1999, 2004, and 2011. Longer-duration rainfalls (> 72 hr) and soil moisture for runoff may be changing factors.

PMP ratios to 1/1000 Annual Exceedance Probability (AEP) 24 hour rainfall ranged from 2 to 6 times. PMP 24 hour, 10 mi^2 (26 km^2) return periods ranged from 10^{-5} to > 10^{-7}. HMR 51 PMP estimates might be high in the Piedmont region based on NOAA 14 point frequency estimates. Existing regional precipitation frequency methods exist and can be used for a transition from a design maximum, PMP-focused assessment to probabilistic assessments. Considerations for future work should address several critical aspects, including orographics with the use of numerical models (e.g. WRF); transposition effects; and larger-scale community efforts on data collection and synthesis.

FOREWORD

This report (NUREG/CR-7133) documents work sponsored by the U.S. Nuclear Regulatory Commission (NRC) as part of the Office of Nuclear Regulatory Research (RES) project "Research to Develop Guidance on Probable Maximum Precipitation (PMP) Estimates for the Eastern United States". The original objective of the project was to provide the NRC with data and analyses to assess whether PMP estimates for the Eastern United States contained in Hydrometeorological Report 51 (HMR 51) published by the National Oceanic and Atmospheric Administration (NOAA) in 1978, could be exceeded if information on more recent storms is considered. However, due to limited resources, the research focused on a pilot region in the Carolinas[1]. The work and recommendations presented in this report will be considered by the NRC as it revises Regulatory Guide 1.59, "Design Basis Floods for Nuclear Power Plants," which was last updated in 1978.

NUREG/CR-7133 examines in finer detail the impacts of hurricanes Floyd and Fran first examined in NUREG/CR-7132 on PMP estimates for the Carolinas. The sensitivity of PMP estimates to several input factors is illustrated, including examination of potential climate influences and recent trends in moisture and surface observations. Regional precipitation frequency estimation methods are discussed in order to provide risk-informed perspectives on PMP estimates. Approximate PMP exceedance probabilities for example sites within the Carolinas pilot region are estimated.

This report provides useful information that NRC can consider during the revision of Regulatory Guide 1.59. The report does not make detailed, site-specific recommendations or draw conclusions regarding PMP estimates used for licensing of specific power plants. It would not be appropriate to draw conclusions about the adequacy of flood protection for existing plants based on the work presented in this report since precipitation is only one aspect of flood hazard assessment. It should be noted that, as part of its overall response to the March 2011 Fukushima accident, the NRC has issued a request for information to all power reactor licensees and holders of construction permits under 10 CFR Part 50 on March 12, 2012. The March 12, 2012 50.54(f) letter includes a request that respondents reevaluate flooding hazards at nuclear power plant sites using updated flooding hazard information and present-day regulatory guidance and methodologies.

[1] Reducing the project scope to focus on the Carolinas pilot region does not compromise the applicability of the study. The pilot region has experienced several very large precipitation events in recent years. Analysis of these storms provides a sufficient basis for assessing the possibility that recent storms can challenge the existing PMP estimates for other regions provided in the HMRs.

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EXECUTIVE SUMMARY

This report synthesized research on extreme storm rainfall for a North Carolina and South Carolina pilot region. The major objectives of the work were to: (1) describe potential impacts of new storms on existing PMP estimates; (2) present some sensitivities of PMP estimates; and (3) provide preliminary probability estimates of PMP. Key findings of the research are as follows, and center on the use of radar-rainfall estimates from Multisensor Precipitation Reanalysis.

1. New data analyses of ten tropical cyclones suggest HMR 51 PMP values are too low for durations > 12 hrs and area sizes > 5,000 mi^2 (12,950 km^2) along coastal Carolinas, based on analysis of Hurricanes Floyd and Fran. Other durations and area sizes are unaffected in this location. HMR 51 may need to be updated for coastal areas in Carolinas. There are unknown impacts in the Carolinas because envelopment, transposition and orographic effects are unclear due to the limited sample. These factors, if included, would tend to increase PMP estimates in some locations.

2. Storm Depth-Area Duration maximized values are somewhat sensitive to radar rainfall biases and use of maximized moisture. Using a median moisture maximization ratio, Floyd is still close to HMR 51 PMP.

3. No significant trends were found in SST and dewpoint temperature grids. This suggests stationary series for storm maximization.

4. There is a potential for increased temporal clustering of TC events in August-September based on recent storms in 1999, 2004, and 2011. Longer-duration rainfalls (> 72 hr) and soil moisture for runoff may be changing factors.

5. Regional precipitation frequency techniques were used to estimate PMP ratios and probabilities. PMP ratios to 1/1000 AEP 24hr rainfall ranged from 2 to 6 times. PMP 24hr, 10mi^2 (26 km^2) return periods ranged from 10^{-5} to > 10^{-7}. HMR 51 PMP estimates might be high in the Piedmont based on NOAA 14 point frequency estimates. Additional efforts are needed to address orographics and decreases in Piedmont areas.

A risk-based perspective suggests the following points. NOAA 14 extrapolations suggest PMP point values may be exceeded at 10^{-5} along the coast and less frequent inland. There are problems with the use of different distributions in space and extrapolations, especially generalized logistic distribution (GLO) in Western South Carolina. Point frequency estimate confidence intervals need to be utilized (e.g. observed events). PMP amounts are estimates and can be exceeded. Uncertainties of PMP estimates can be quantified for point values. Further work is needed for areal estimates and uncertainties. Existing regional precipitation frequency methods exist and can be used for a transition from a design maximum, PMP-focused assessment to probabilistic assessments.

From a design/maximum perspective, we suggest the following. The database behind HMR 51 is severely outdated and needs to be comprehensively updated. Use of recent gridded data sets is extremely valuable. The resolutions of recent products (NOAA 14) are superior to HMR 51 smoothed estimates. A coastal multiplier for HMR 51 PMP estimates could be considered in design concepts. An open design question is should one focus on specific locations, versus generalized or regional PMP estimates.

Future work should consider several critical aspects. These include orographics with the use of numerical models (e.g. Weather Research and Forecasting model (WRF)); transposition effects; and larger-scale community efforts on data collection and synthesis.

ABBREVIATIONS AND ACRONYMS

AEP	Annual Exceedance Probability
AWA	Applied Weather Associates
CAD	Cold air damming
COOP	NCDC Cooperative Center
CPP	Core precipitation periods
DAD	Depth Area Duration
ET	Extratropical transition
FI	Flood Index
FRT	Extratropical cyclone near a front
GCIP	Global Energy and Water Cycle Experiment Continental-Scale International Project
GCM	Global climate model
GEV	Generalized extreme value distribution
GLO	Generalized logistic distribution
GNO	Generalized normal distribution
HMR	Hydrometeorological Report
HPC	Hydrometeorological Prediction Center
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory Model
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
IPMF	In-place maximization factors
MPR	Multisensor Precipitation Reanalysis
MPE	Multisensor precipitation estimation algorithm
NA	North Atlantic
NARR	North American Regional Reanalysis
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NC	North Carolina
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NHDS	NOAA Hydrologic Data Systems Group
NOAA	National Oceanic and Atmospheric Administration
NLCD	National Land Cover Database
NRC	U.S. Nuclear Regulatory Commission
NRC	National Research Council
NWIS	U.S. National Geographic Survey National Water Information System
NWS	National Weather Service
NWS COOP	National Weather Service Cooperative Network
NWS-HDSC	National Weather Service Hydrometeorological Design Studies Center

OH	NCDC Office of Hydrology
PFDS	Precipitation Frequency Data Server
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
PRE	Predecessor rain events
PW	Precipitable water
RAMS	Regional Atmospheric Modeling System
RES	Office of Nuclear Regulatory Research
SA	South Atlantic
SACSMA	Sacramento Soil Moisture Accounting model
SC	South Carolina
SE US	Southeast United States
SNOTEL	Natural Resources Conservation Service Snowpack Telemetry
SST	Sea surface temperature
TC	Tropical cyclone
Td	Dewpoint temperature
USACE	U.S. Army Corps of Engineers or Corps
WRF	Weather Research and Forecasting model
WSI	Weather Services International Corporation

1 INTRODUCTION

The Nuclear Regulatory Commission (NRC) requested assistance in potentially improving estimates of Probable Maximum Precipitation (PMP) in the Southeastern United States. Probable Maximum Precipitation is the key factor in developing Probable Maximum Floods (PMFs), that are needed for evaluating early site permits and license applications for Nuclear Power Plants (Prasad et al., 2011). Some Federal agencies design their structures to the PMP, the theoretical upper limit of precipitation for a specified area and duration. Other agencies use a risk-based approach (Swain et al., 2006; Reclamation, 2010; Reclamation, 2011) where the probability of occurrence of precipitation events (e.g. 1 in 1,000-year storm) is determined using statistical methods, and the structure is assessed according to the appropriate risk. The risk-based approach still considers PMP in their calculations; PMP is the operational upper limit of the precipitation frequency curve.

For the United States, the most current methodology used to determine PMP is provided in Hydrometeorological Reports (HMRs) published by the National Weather Service. For example, HMR 51 (Schreiner and Riedel, 1978) provides guidance to determine design rainfall estimates for the eastern United States. However, HMR 51 was published in 1978 from a storm database that was last updated in the early 1970s. This report presents a synthesis of research results on extreme storms and PMP estimates for a North Carolina-South Carolina Pilot region in the U.S., to assess the impacts of newly-analyzed storms on HMR 51 PMP estimates, and provide approximate probability and uncertainty estimates to PMP.

1.1 Authorization

This work was completed by the Bureau of Reclamation (Reclamation) for the NRC, Office of Nuclear Regulatory Research (RES), via an Interagency Agreement. The work was performed under NRC Agreement RES-08-127, Job Code N6570. A pilot study region, including the states of North and South Carolina, was used. This report documents work from Task 3 of the agreement, including a synthesis of new storm data, PMP results and uncertainties. England et al. (2011) provide a literature review conducted as Task 1 of the agreement. Caldwell et al. (2011) present new storm data and analysis, as part of Task 2 of the agreement.

1.2 Objectives and Approach

Caldwell et al. (2011) present data from and analyses of ten recent extreme storms in North and South Carolina. These new storms may influence PMP estimates in the region. This report builds on the work of Caldwell et al. (2011) to illustrate some potential impacts to design precipitation estimates and to introduce some alternative, risk-based perspectives, including precipitation frequency. The major objectives of the work are to: (1) describe potential impacts of new storms on existing PMP estimates; (2) present some sensitivities of PMP estimates; and (3) provide preliminary probability estimates of PMP.

The approach that is used is to examine in finer detail the impacts of Hurricanes Floyd (1999) and Fran (1996) on PMP estimates, based on results presented in Caldwell et al. (2011). Potential impacts of Floyd and Fran are described. Brief comparisons are then made to 2011 storms that occurred post analysis. The sensitivity of PMP estimates to several factors is illustrated, including examination of potential climate influences and trends in moisture and surface observations. Approximate PMP exceedance probabilities for example sites within the proposed Pilot Region are estimated using regional precipitation frequency estimates based on L-Moments (Hosking and Wallis, 1997). The focus is to use the existing National Weather Service Cooperative Network (NWS COOP) stations and National Oceanic and Atmospheric Administration (NOAA) Atlas 14 (Bonnin et al., 2006). Regional frequency distributions are used to extrapolate to PMP magnitudes.

2 POTENTIAL IMPACTS OF NEW EXTREME STORM DATA ON PMP ESTIMATES

Some Federal agencies, state agencies, and others continue to utilize the extreme storm Depth-Area Duration (DAD) database and PMP estimates from HMR reports. Most importantly, examination of recent extreme precipitation events (Caldwell et al., 2011) suggests that several events have the potential to meet or exceed current PMP estimates, including Hurricane Floyd in 1999 and Hurricane Fran in 1996. It is problematic if storms are producing precipitation in excess of PMP, especially since nuclear power plants (NPPs) and dams consider PMP to be the absolute upper threshold. In the risk-based approach, if the precipitation frequency curve is calculated using an outdated storm dataset, then there is potential for the curve and subsequent risk estimates to be biased too low.

Based on recent observations of extreme precipitation events, it is possible that some PMP estimates may not be sufficient for design criteria. This section summarizes the findings of possible PMP increases due to Hurricanes Floyd (1999) and Fran (1996) from Caldwell et al. (2011), and describes potential implications in determining design precipitation criteria for NPPs and dams, particularly across eastern portions of South Carolina (SC) and North Carolina (NC).

2.1 Impacts from Floyd (1999) and Fran (1996)

Hurricanes Floyd and Fran impacted the eastern sections of NC and SC in the late 1990s. Based on the maximized depth-area-duration (DADx) estimates of Caldwell et al. (2011), the precipitation with both Floyd and Fran have the potential to challenge the values of PMP in that region, particularly at large area sizes (5,000 – 20,000 mi^2) at 6- and 24-hour durations (Figure 2-1). Since Floyd is considered to be the largest event in terms of magnitude and duration, a case study showing approximate magnitudes and probabilities (Chapter 4) of such an event on a hypothetical plant near Brunswick County is examined. Here, we provide a brief synopsis of Floyd. Fran comparisons to HMR 51 PMP show somewhat similar impacts for the 6-hour duration (Caldwell et al., 2011).

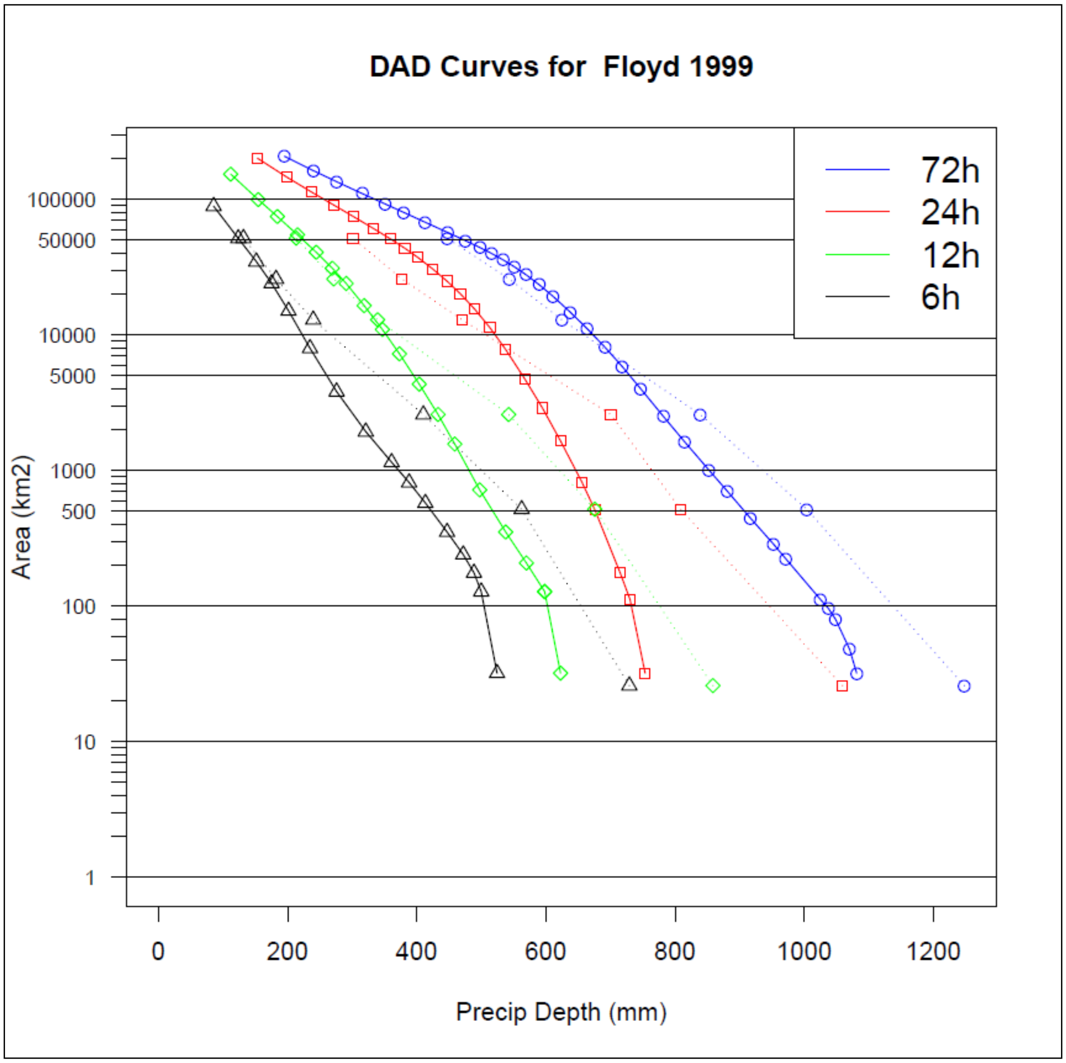

Figure 2-1 Comparison of DADx curves for Hurricane Floyd (solid) and PMP values extracted from HMR 51 (dotted)

A rain gauge at Southport 5N, NC, had the largest reported storm-total rainfall during Floyd of 24.06 in (61.11 cm). The Cape Fear River which flows into the Atlantic Ocean in eastern Brunswick County, near Southport, experienced some flooding during Floyd, but did not experience the record floods that occurred across other portions of eastern North Carolina (http://en.wikipedia.org/wiki/ Hurricane_Floyd). This was due, at least partially, to the spatial distribution of rainfall associated with the storm (Figure 2-2). Since the Cape Fear River Basin (CFRB) is large (~5300 mi2) and elongated from northwest to southeast (Figure 2-3), the upper reaches of the basin received much less rainfall, sparing Brunswick County from the catastrophic flooding experienced elsewhere. The potential exists, however, for a tropical storm to track up the CFRB from the coast to central North Carolina. In fact, the trajectory of Hurricane Fran (1996) can be used as an analogous storm track representative of this point (see Appendix A of Caldwell et al., 2011). Therefore, it is important to examine how a storm of Floyd's magnitude and duration may impact the estimates of PMP in the region.

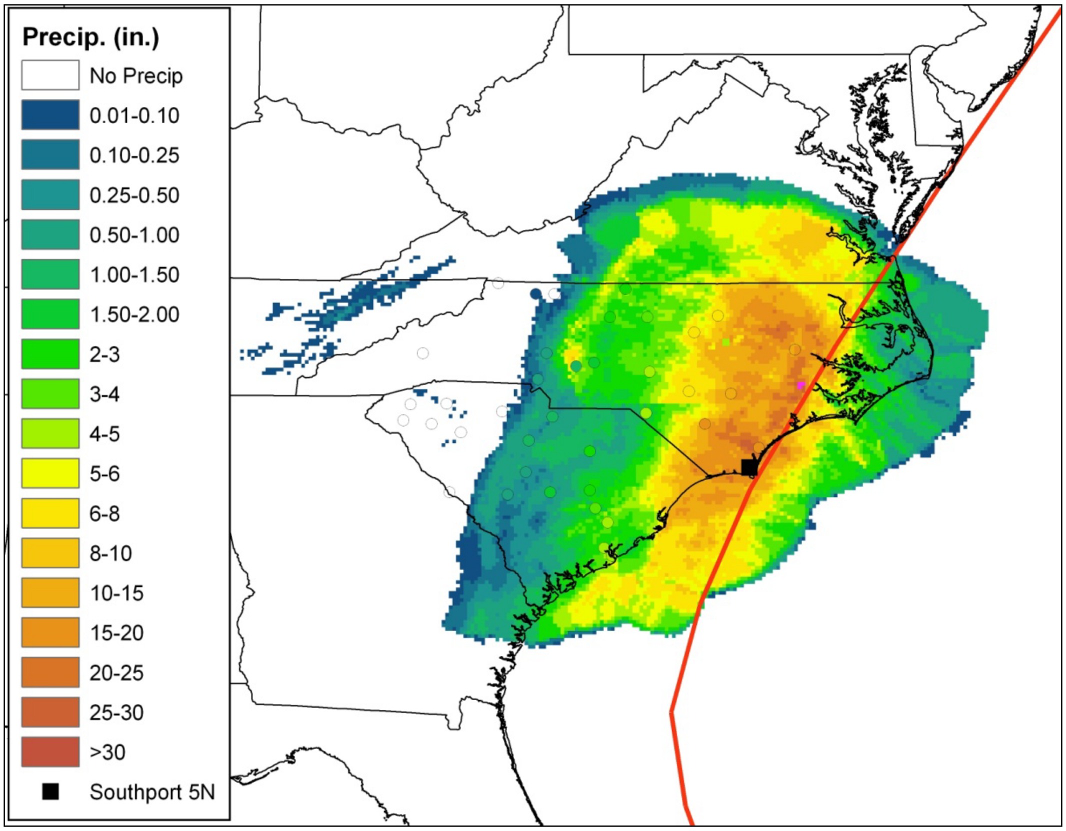

Figure 2-2 Storm total precipitation for Hurricane Floyd with best storm track from NOAA shown in red ***Hourly precipitation gauge accumulations are overlaid to indicate differences between gauge and radar estimates. The location of the maximum point rainfall at Southport 5N along the southeast coast of North Carolina is shown as a black square.***

Precipitation depth-duration plots using the DADx for Floyd at 5,000 mi^2 (12,950 km^2) and 10,000 mi^2 (25,900 km^2) indicate exceedance of PMP from HMR 51 generally above durations of 12 hours (Figure 2-4). Since PMP can be considered as the envelope curve which captures the largest potential rainfall amounts at each duration, Hurricane Floyd suggests that PMP may be underestimated across portions of eastern North Carolina. Storm envelopment, transposition and adjustments to orographics were not considered for the current study; so, the spatial extent of the impact on the PMP contours across the region is uncertain. Envelopment of observations would generally lead to PMP values larger than that depicted here. A rough estimate of the region in which the HMR 51 PMP contours may shift northward for the 5,000 mi^2 (12,950 km^2), 24-hour duration is provided in Figure 2-5. The PMP values may potentially increase from 3 to 13 percent, using full in-place maximization of Hurricane Floyd (see Table 3-2).

Figure 2-3 Map of the Cape Fear River Basin in eastern North Carolina ***Source: http://upload.wikimedia.org/wikipedia/commons/e/e4/Capefearrivermap.png***

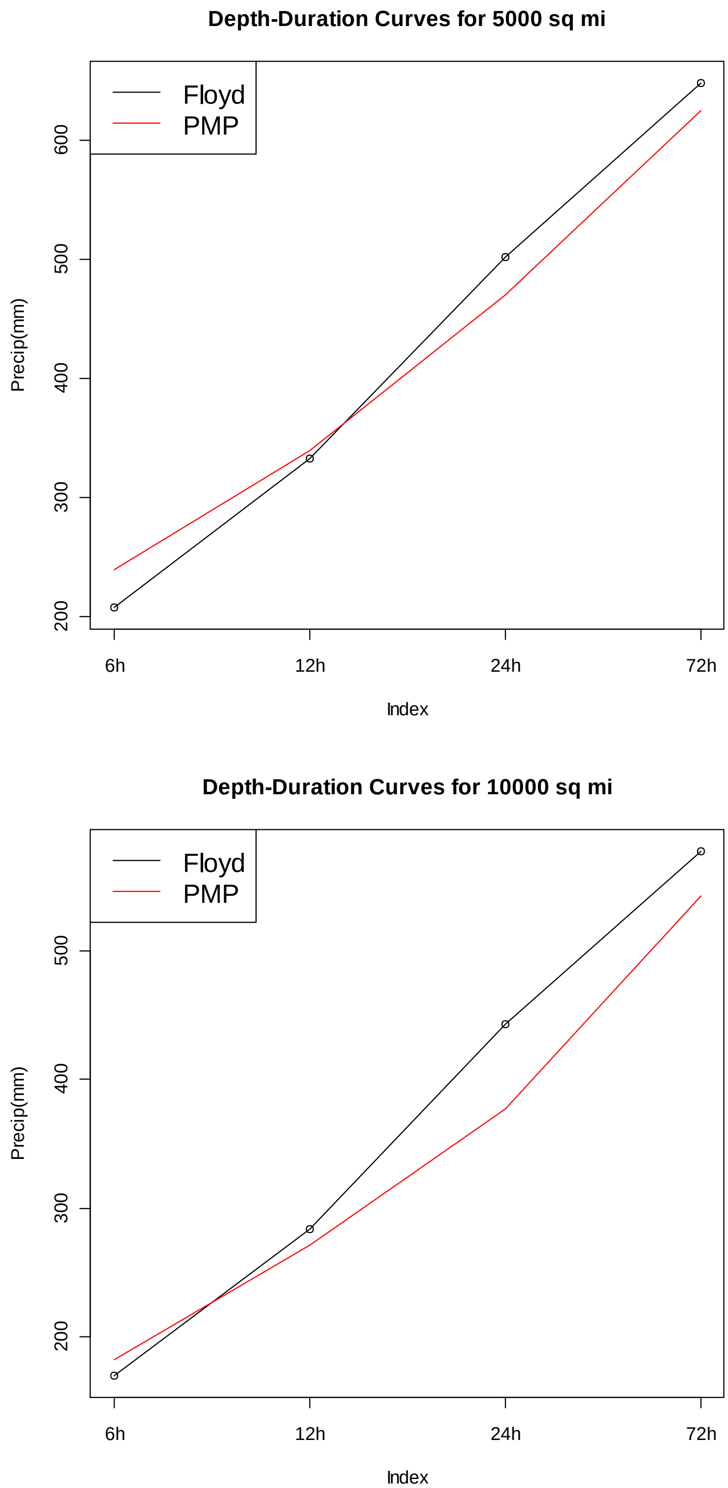

Figure 2-4 **Depth-duration curves for Hurricane Floyd at 5,000 (top) and 10,000 (bottom) mi^2** ***The red line indicates the PMP values at Southport 5N from HMR 51 for each duration at the respective area sizes.***

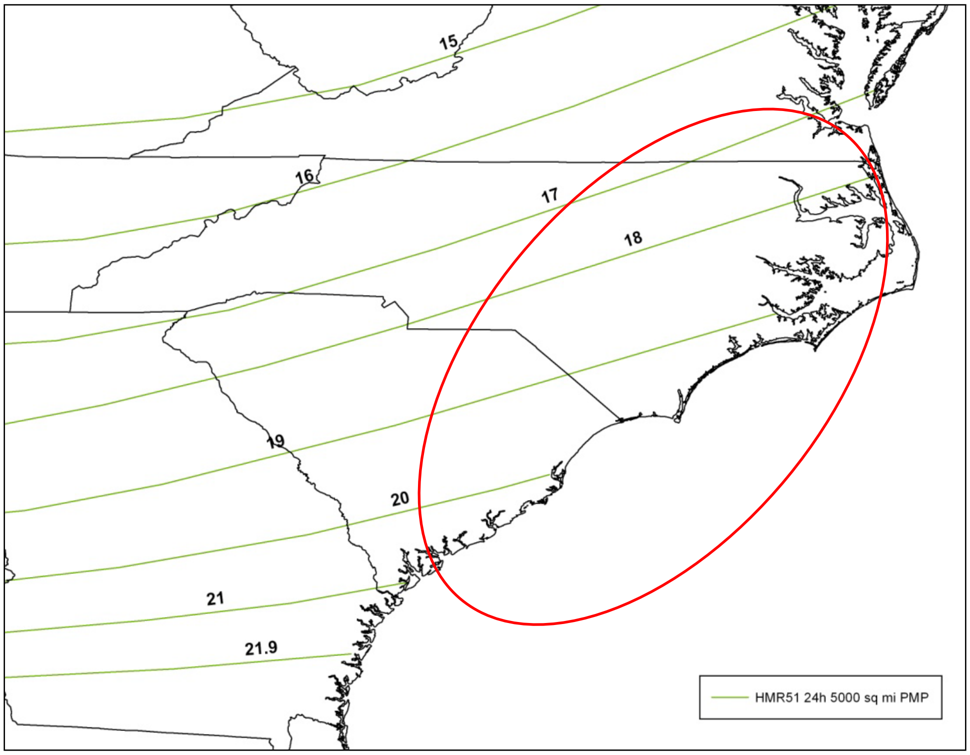

Figure 2-5 Depth Region of potential impacts on PMP due to Hurricane Floyd ***Green lines represent the 24-hour, 5000 mi² PMP values from HMR 51. The red oval indicates a rough approximation of the region of influence on PMP.***

The comparisons of 5,000 mi^2 (12,950 km^2) magnitudes at the Southport, NC location suggests that PMP design precipitation amounts for existing high-hazard facilities (nuclear reactors and dams) in this vicinity might need to be reassessed. A detailed analysis for a specific, individual watershed and facility would need to be conducted to assess the degree to which design precipitation magnitudes would increase along the coast. Caldwell et al. (2011) provide information and full electronic data to conduct such assessments. Extreme storm tracks and storm core precipitation start times are presented in Appendix A of that report, with hourly precipitation grids listed in Appendix C. These precipitation grids from Floyd (Figure 2-2) and Fran could be maximized, rotated, translated, and applied to specific locations of interest.

2.2 Recent 2011 Storms and Predecessor Events

There is a continuing need for new extreme storm data collection and synthesis. There is also a need to investigate the effects of predecessor rainfall events, described by Caldwell et al. (2011), on soil moisture and design flood assumptions. During the course of this study, two extreme rainfall events – Hurricane Irene and Tropical Storm Lee – occurred in 2011 over the eastern United States. Here, we briefly highlight extreme storm rainfall and predecessor rainfall event issues that need to be considered as part of potential design precipitation revisions.

During a two-week period from 26 August to 9 September 2011, a series of tropical cyclones produced heavy rainfall across much of the eastern United States (Figure 2-6). Hurricane Irene tracked from the coastal Carolinas to New England during the period 26-29 August dumping localized amounts of ~20 in (50 cm) of rain in eastern NC and southeast Virginia. Tropical Storm Lee formed on 1 September off the Louisiana coast and made landfall in the state on 3 September. The remnants of Lee tracked into the Tennessee and Ohio Valleys and merged with a cold front, which generated a large swath of precipitation from the Gulf Coast to the Mid-Atlantic States with gauge totals approaching 21 in (53 cm). The large region of heavy rainfall associated with Hurricane Irene over eastern North Carolina spurred a brief, preliminary analysis of the storm to see if the storm may have approached the rainfall values seen during Floyd.

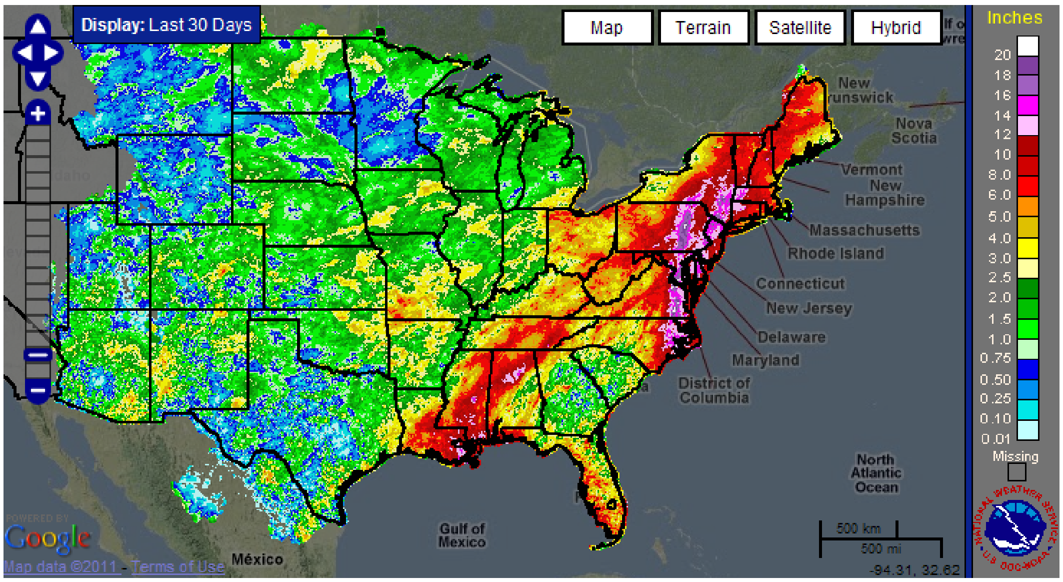

Figure 2-6 Gridded precipitation totals across the eastern United States for the 30-day period ending on 22 September 2011, including precipitation from Hurricane Irene and Tropical Storm Lee ***Source: http://www.srh.noaa.gov/ridge2/RFC_Precip/.***

Storm total precipitation (96 hours) for Floyd and Irene indicated a large volume of precipitation fell across eastern North Carolina (Figure 2-2 and Figure 2-7). Comparisons of the 10 in (2.5 cm) rainfall contours over the NC/SC domain from each storm are shown in Figure 2-8. The areal coverage of heavy rainfall during Irene ~7300 mi^2 (~19000 km^2) is about 1.5 times smaller than that from Floyd ~16600 mi^2 (~43000 km^2); however, the spatial pattern associated with each storm is similar. Since the heaviest rainfall occurred in the northeastern corner of NC and southeastern Virginia, these results are limited by the restricted domain over the Carolinas. Inclusion of rainfall across the Mid-Atlantic States and southern New England, and transposition of this rainfall southward, would be required to adequately determine if Irene approached PMP. In addition, a significant amount of dry air was entrained into the circulation of Irene potentially limiting the efficiency of precipitation production during the storm. Therefore, the effects of moisture maximization may also impact the final assessment of DAD relationships associated with Irene. Moisture maximization estimates for Irene were not conducted as part of the present study, but would need to be performed.

The occurrence of two major storms (i.e., Floyd 1999 and Irene 2011) over eastern North Carolina suggests that the frequency of heavy rainfall events is high and that recent events are influential and should continue to be investigated further. The fact that both Lee and Irene occurred during a two-week time frame indicates the potential for multiple storms of near-equal magnitude can occur over watersheds in the eastern United States. Current design precipitation procedures, such as HMR 51, focus on a 72-hour storm duration. While most design procedures consider antecedent events, the duration, magnitude and sequencing of these predecessor rainfall events needs closer examination and review. In addition to Irene and Lee, the top ten events examined in Caldwell et al. (2011), suggest that soil moisture and design flood assumptions may need to be revised. Temporal clustering of tropical cyclones may be a previously unrecognized issue. There is a need for stronger consideration of pre-storm events; not just 72hr PMP duration. Examples of tropical cyclone temporal clustering (Caldwell et al., 2011 Table 2) include: 1999 Dennis, Floyd Aug 28 - Sept 8 and Sept. 14-17; and 2004 Gaston, Frances, Ivan, Aug 25 – Sept 1, Sept 3-11, and Sept 13-26. Now in 2011, Irene and Tropical Storm Lee occurred Aug 22 – Sept 22 (Figure 2-6). These events potentially have a strong effect on precipitation frequency estimates.

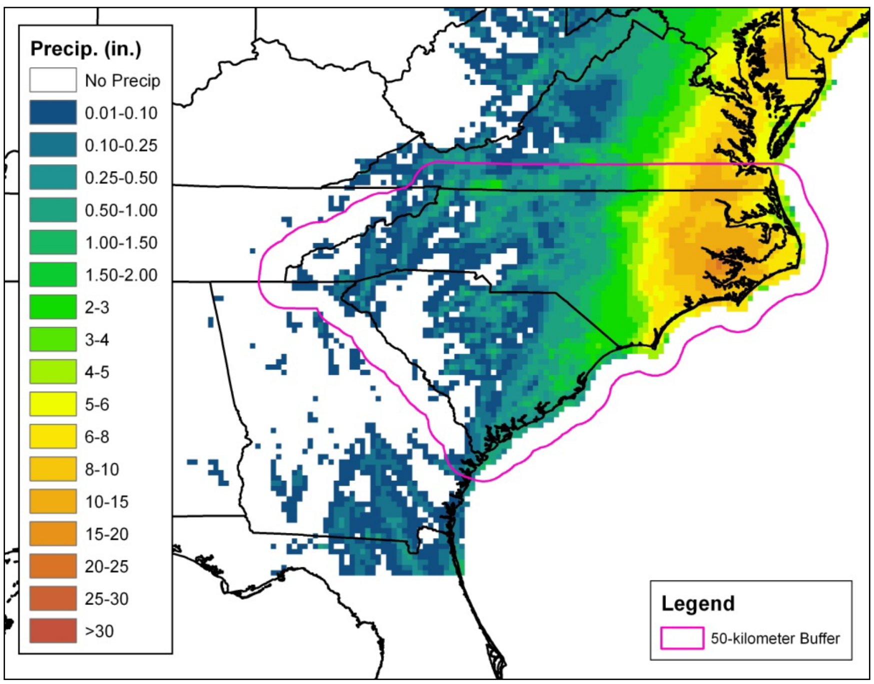

Figure 2-7 Storm total precipitation during Hurricane Irene (2011) for the period 26 – 29 August ***A buffer (in pink) was used to clip the grid to ensure direct comparison to Hurricane Floyd.***

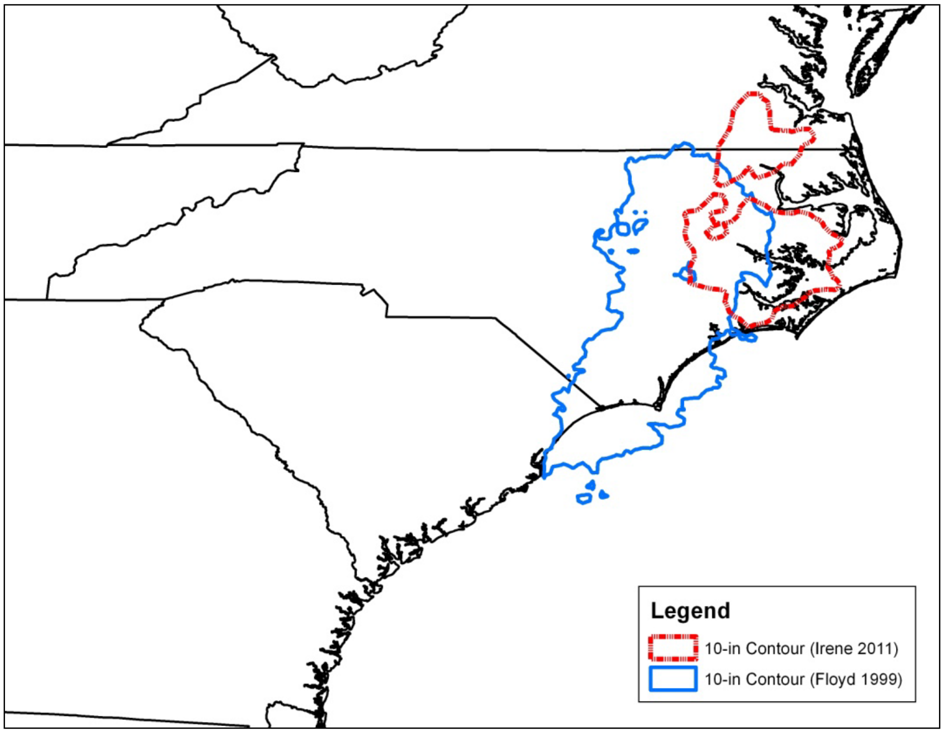

Figure 2-8 Domains of the 10-inch contours from Hurricanes Irene and Floyd to indicate the areal coverage and shape of the main region of precipitation from each storm

3 SENSITIVITY OF PMP ESTIMATES

The computation of PMP traditionally involves the use of spatial and temporal analyses of gauge-based precipitation to create DAD tables. In Caldwell et al. (2011), gauge-based analyses were supplemented with radar-estimated precipitation grids to compute the DAD relationships. These grids provide enhanced spatial and temporal resolution compared to most gauge data, but rely, at least partially, on these gauges to adjust for biases. Both gauge and radar data exhibit limitations that were described fully in Caldwell et al. (2011).

Once DAD tables are established for storms used in PMP estimation, maximization of these storms is determined using ratios of maximum and representative precipitable water derived from dewpoint or sea surface temperatures (SSTs). As with the precipitation analyses, the traditional method for acquiring dewpoint or SST is through gauge-based observations. Recent advances in technology and computing power have allowed the creation of gridded values of meteorological variables, including dewpoint and SST, that provide continuous surfaces over longer time frames than are consistently available in point measurements (see Caldwell et al., 2011 for additional details). The meteorological grids, however, are often at spatial resolutions of tens to hundreds of kilometers, which can result in over-smoothing of the values.

In this section, we reiterate the issues with both point and gridded datasets of precipitation and other meteorological variables by examining the potential impacts on PMP estimates. We conducted sensitivity analyses of PMP estimates in 3 areas: (1) radar and gauge uncertainty, estimation of DAD from radar and potential bias issues; (2) moisture maximization in-place, variation of maximization factors; and (3) trends in maximum moisture potential from SST and dewpoint analyses. We discuss these issues in turn in the following sections.

3.1 Radar Uncertainties

The multi-sensor precipitation reanalysis (MPR) data used in Caldwell et al. (2011) was available on a 4 x 4 km (2.5 x 2.5 mi) grid at hourly intervals. This high-resolution dataset allows the capture of spatial variability in rainfall amounts across time. For example, hourly gauge data during Hurricane Floyd is limited to a total of 30 sites with non-zero values across NC and SC (Figure 3-1). In eastern NC, there are only three gauges within the 10 in (25 cm) contour. The grid cell with the highest precipitation amount during Floyd indicates over 30 in (76 cm) of rainfall in a region of no gauge-based measurements. Whether this value is valid or not is impossible to determine; however, it does reflect the potential for the gauge network to miss important localized features in the precipitation pattern. The overlaid contours in Figure 3-1 support this point, suggesting an area of uniformly changing magnitudes of precipitation between each contour. The radar provides evidence that the rainfall is not uniformly distributed and in fact can vary significantly across short distances. The radar-estimated precipitation, however, is not without issue.

While the radar provides improved representation of the spatial pattern of a storm, the gauge data are still considered to be the best representation of true precipitation reaching the ground. Due to high wind and intense rainfall rates during tropical cyclones, these gauges often under-estimate the amount of precipitation. In addition, gauges are often lost midway through the storm to the extreme conditions and fail to report continuously. Despite the issues, gauges are still the only “ground truth” and are used to bias correct the radar estimates. As was shown in Caldwell et al. (2011), mean biases between the gauge and radar have a significant range. For the ten storms analyzed in that report, radar estimates ranged from nearly half to more than 120 percent of the gauge reported values (see Table 3-1). Differences at the individual gauge sites in Figure 3-2 show the spatial and temporal variation in the biases.

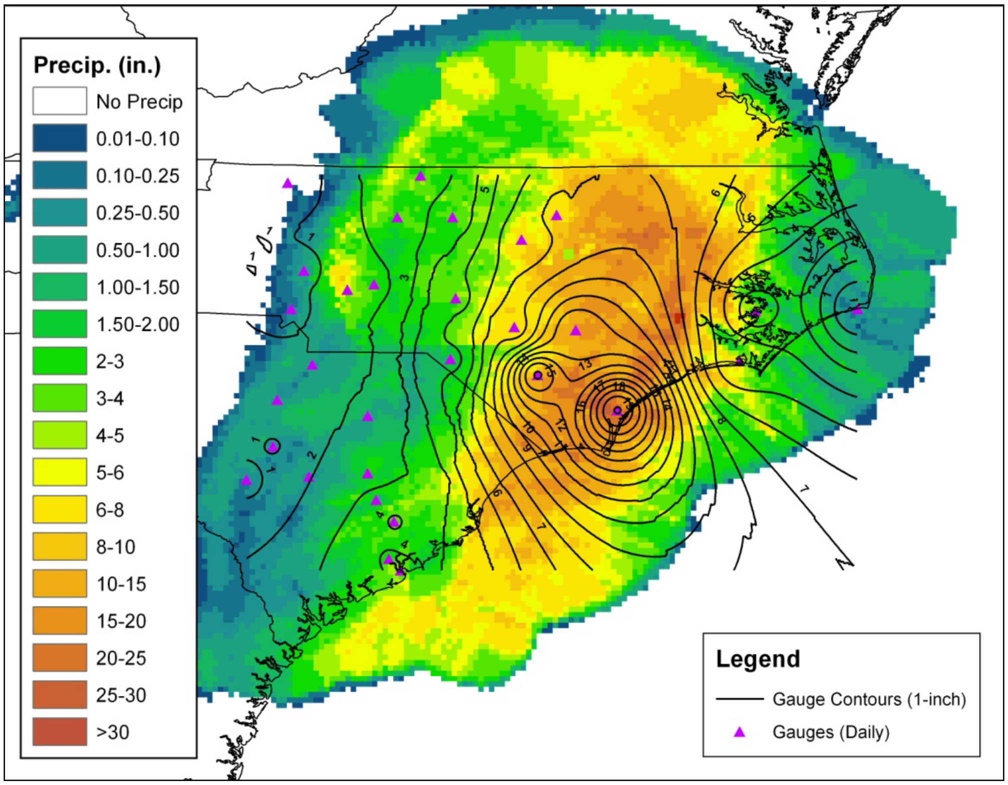

Figure 3-1 **Storm total precipitation for Hurricane Floyd with point locations of gauges used in the contour analysis** ***One-inch contours are shown and labeled in black. The contour analysis was performed on a grid developed from the gauge observations using inverse distance weighting.***

Table 3-1 **Comparison of gauge (g) and radar-estimated (r) precipitation** ***Ratio is calculated as r/g such that values less/greater than 1 indicate under/overestimates by radar, respectively***

Storm	Gauge (mm)	MPR (mm)	Ratio
Bonnie	71.0738	36.17	0.51
Dennis	79.7122	83.4479	1.05
Earl	65.9051	41.6814	0.63
Ernesto	68.5875	67.1569	0.98
Floyd	103.793	102.147	0.98

Frances	111.006	114.26	1.03
Fran	59.5086	72.4056	1.22
Gaston	46.4617	45.1394	0.97
Ivan	48.2801	55.7489	1.15
Ophelia	38.7985	37.5308	0.97

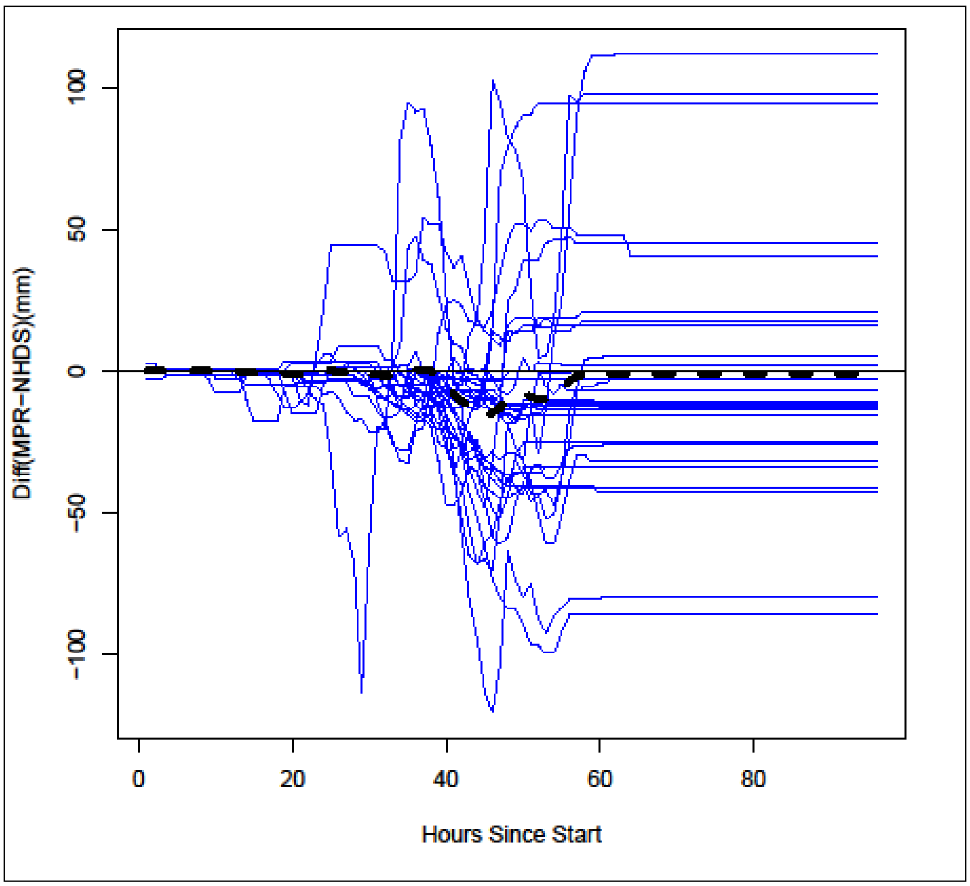

Figure 3-2 Plots of the differences between MPR and 30 NOAA-NHDS hourly gauges for Floyd ***The mean hourly bias (black dashed line) from all gauges is shown.***

Table 3-1 indicates that, for Floyd, the radar estimates were reasonable with a mean bias of 0.98; however, radar generally over-estimates precipitation for Fran (1996) with a mean bias of 1.22. This over-estimate may result in DADx values that are too large. For Fran, we reduced the rainfall magnitudes by 22 percent and recomputed DADx (Figure 3-3). When comparing the values from these curves to those from Table 9 in Caldwell et al. (2011), the 6-hour values no longer exceed PMP at large area sizes. The closest value is 7.43 percent below PMP at 10,000 mi^2 (25900 km^2). Despite the potential issue with the radar, the resulting DADx still approaches PMP and falls within the standard error range suggested in HMR 51 of +/- 10 percent.

As shown, the estimates of PMP can be highly sensitive to the type and quality of data used in the analysis. Radar-estimated and gauge-based precipitation both exhibit issues with quality and the decision on which is the most appropriate to use for individual storm analysis is subjective. Quality control of input datasets and adjustment to a benchmark (e.g., gauge measurements) should be performed prior to the application of new estimates of PMP in design.

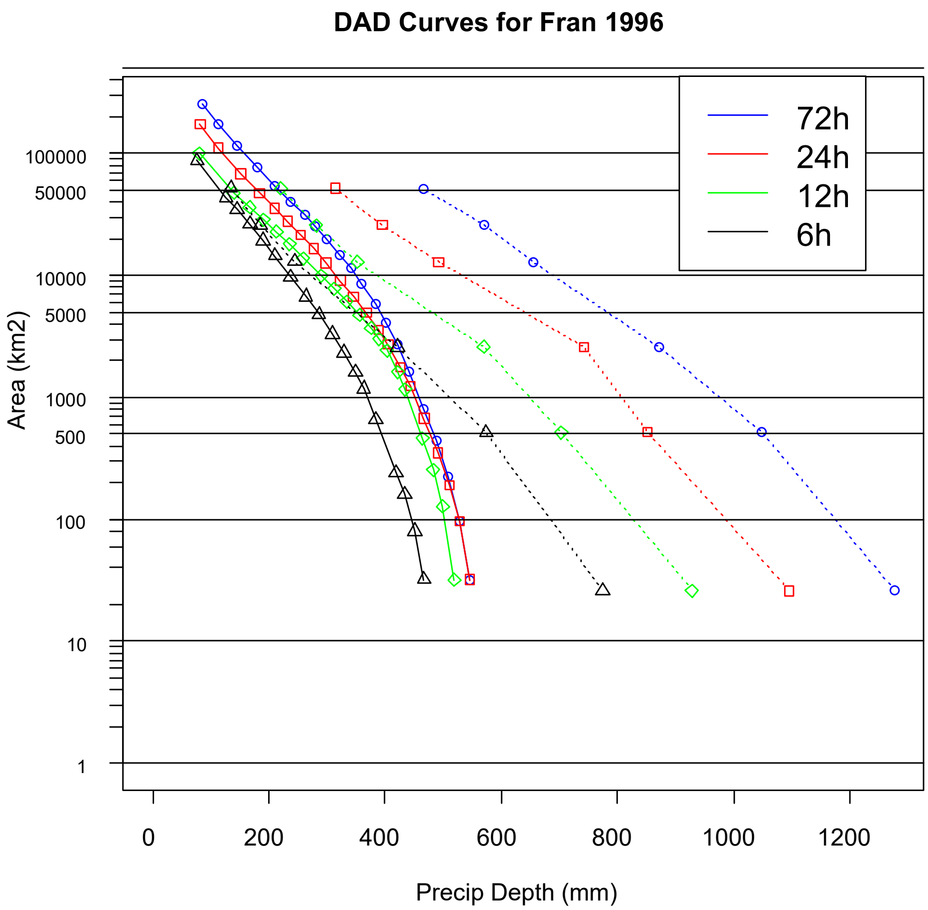

Figure 3-3 Comparison of DADx for Fran 1996 (solid) and PMP from HMR 51 (dashed) following adjustment for radar biases

3.2 Moisture Maximization Factors

Moisture maximization is typically applied to storms to adjust for the relative amount of available moisture for a storm compared to some reference value, usually a climatology-based maximum value. The equation for computation of the in-place maximization factor (IPMF) is defined as IMPF=PWx/PWr, where PWx and PWr are the maximum and reference precipitable water values, respectively. Both PWx and PWr are either determined directly from PW grids or are a function of SST. The value for PWx is computed using the mean SST plus two standard deviations, which is assumed to be equivalent to the 1-in-100 year value.

The source location of that moisture is typically determined through investigation of the meteorological environment associated with the storm. The selection of that site can be interpreted differently depending on the data available, resources available for the analysis, and depth of knowledge by the meteorologists and/or hydrologists studying the storm. For example, Applied Weather Associates (2008) and Chen and Bradley (2006) both performed an analysis of the July 1996 storm near Aurora, IL. Chen and Bradley utilized the upper-air sounding at Lincoln, IL, as the representative site. In contrast, AWA used a back-trajectory analysis tool, HYSPLIT, to determine the source of moisture at various levels in the atmosphere. The closest dewpoint sites, likely in northern Arkansas or southern Missouri (though not mentioned specifically in their report), were then used to represent the moisture source site. Since each location has a specific representative and maximum moisture value (e.g., dewpoint and/or SST), the IPMF ratio can vary significantly.

In Caldwell et al. (2011), the back-trajectory analysis using HYSPLIT was performed from the point of maximum rainfall observed during each storm. Rather than using a single point estimate for the source location, a matrix methodology was employed to provide potential source regions within a 3 x 3 degree latitude-longitude area centered on the point precipitation maxima. As a result, the representative and maximum values of either precipitable water or SST were gathered for a total of nine potential source locations. All potential combinations of the representative and maximum values yielded an array of potential maximization factors for each storm. While maximization ratios between different datasets differed slightly for individual storms, the IPMF boxplots derived from SST and PW grids provided similar results for Floyd with the entire range from PW incorporated in the SST boxplot (Figure 3-4). To be conservative, the maximum ratio was used for each storm in the computation of the original estimates of PMP in Caldwell et al. (2001).

To test the sensitivity of PMP estimates to the choice of IPMF ratio, the median value of 1.1 (instead of the maximum of 1.29) from the boxplot of SST-based IPMF for Floyd was used to recompute estimates of DADx (Figure 3-5). When using the median value of IPMF, the 24-hour duration does not exceed PMP at large area sizes. Table 3-2 shows a reduction compared to the maximum with the DADx only being slightly below the HMR 51 PMP at areas greater than 10,000 mi^2 (25,900 km^2).

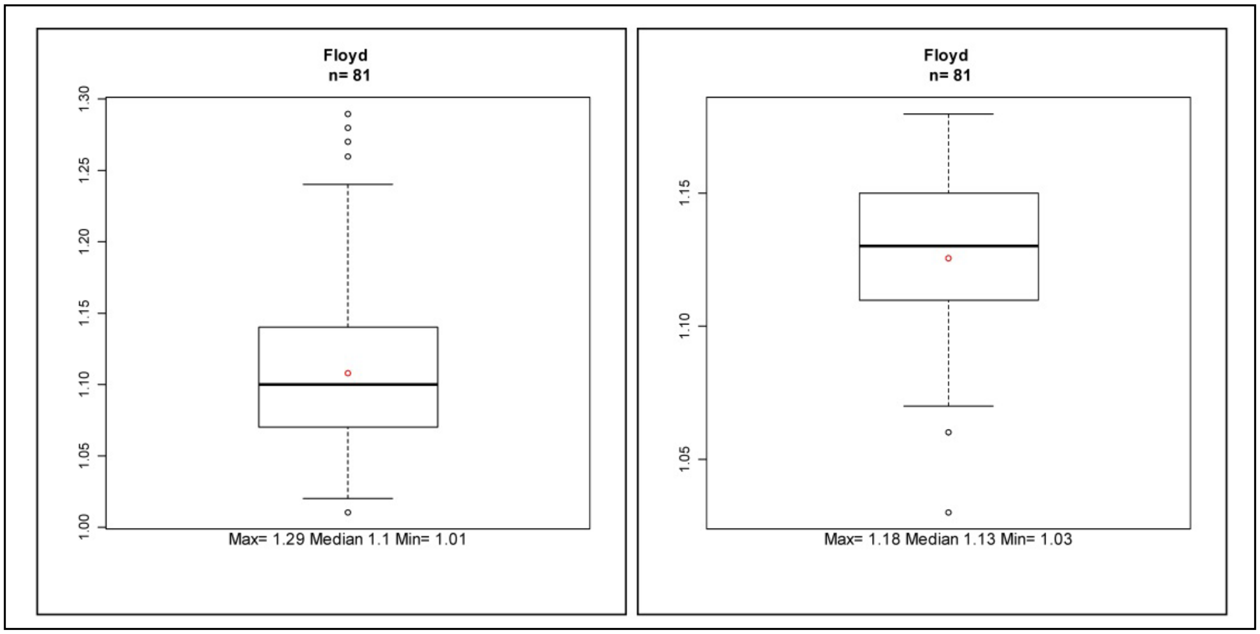

Figure 3-4 Boxplots of IPMFs for Floyd using gridded SST (left) and gridded PW (right)
Whiskers represent 5th and 95th percentiles, box represents interquartile range, solid black line represents median, and red dot represents the mean. Hollow points in black indicate outliers. The value of n represents the number of combinations from HYSPLIT back-trajectories.

DAD Curves for Floyd 1999

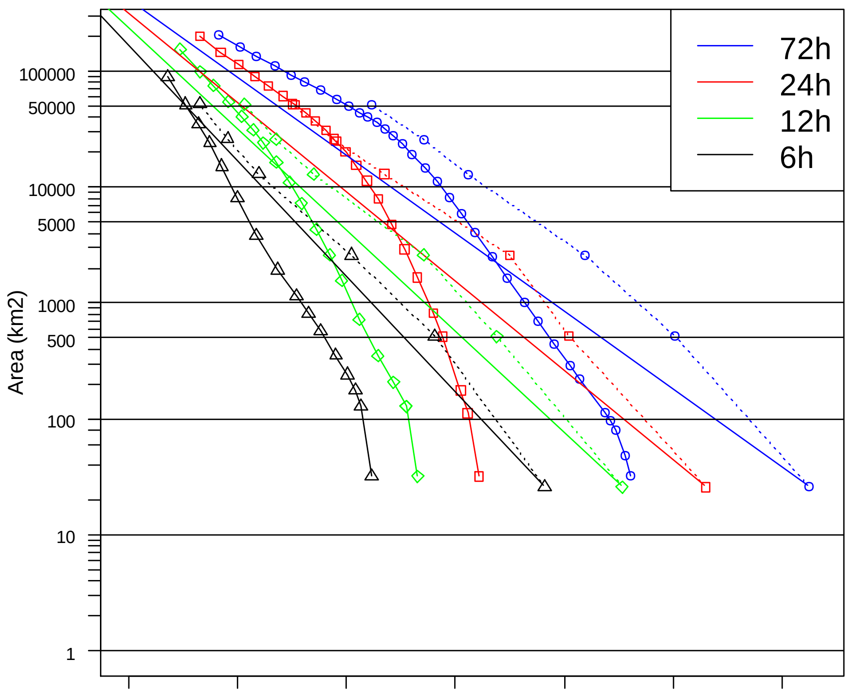

Figure 3-5 **DADx plot for Floyd using the median value of IPMF (solid lines) compared to PMP values from HMR 51 (dashed lines)** ***) IPMF was computed using SST.***

Table 3-2 **Comparison of computed DADx using the median and maximum and HMR 51 PMP**

Floyd1999			**24h**			
Area (km^2)	Area (mi^2)	HMR51 (mm)	MPR (max) (mm)	MPR (median) (mm)	% diff (max)	% diff (median)
25.9	10	1084.59	755.40	644.14	-43.58	-68.38
51.8	20	840.78	675.41	575.93	-24.48	-45.99
2589.99	1000	731.55	601.39	512.81	-21.64	-42.66
12949.94	5000	485.41	504.01	429.78	3.69	-12.95
25899.88	10000	388.75	443.13	377.86	12.27	-2.88
51799.76	20000	309.86	357.37	304.73	13.29	-1.68

Using a method that incorporates potential variability into the estimates of PMP (i.e., the HYSPLIT matrix method), provides a mechanism for incorporating uncertainty due to a variety of factors, including the selected moisture source location and dataset used. Gridded datasets do offer the advantage of providing continuous data over time and space; but often are regional in nature and can be overly smoothed (i.e., averaged across a large domain). The hope is that by using a distribution of maximization factors, a majority of the uncertainty is captured within the boxplot, though additional research is needed to adequately answer this question. The boxplots can also eventually be used for probabilistic estimates of in place extreme storm rainfall, as the calculations of PMP can be performed at fixed percentages of the IPMF ratios.

3.3 Maximum Moisture Trends

The moisture maximization techniques employed in Caldwell et al. (2011) utilize gridded datasets. As mentioned in Section 3.2, these datasets offer continuous data over both spatial and temporal domains. The grids are built from either ground-based measurements or in situ observations (e.g., satellite), or are a combination of both. The gridded nature of these data often results in the averaging of multiple observations to a single grid cell. This reduces the spatial representation of small-scale features and can result in over-smoothing of the field. Despite this limitation, gridded data are the only available dataset for performing spatially explicit analyses.

The trend analysis performed by Caldwell et al. (2011) on mean monthly dewpoint temperature indicates no significant trends over land areas. There is some evidence in both the mean monthly dewpoint temperature and SST analyses that there is a small increasing trend off the coast of NC during the month of September, when most of the tropical cyclones analyzed occurred (Figure 3-6).

Since the analysis performed by Caldwell et al. (2011) focuses on trends in the mean values of dewpoint and SST, it is possible to conclude that (at a first approximation) the value for PWx has been stationary over the past several decades. Therefore, a subsequent analysis on PWr would be required to conclude if the maximization factors have a trend. Given the assumption that PWx is constant, then positive trends in PWr would cause IPMFs to approach one, potentially indicating that tropical cyclones are becoming more efficient precipitation producers. However, if trends in PWr are negative, then IPMFs would increase, yielding storms that would be magnified further based on in-place moisture maximization. At this time, however, limited work has been performed to evaluate how moisture availability is changing over time and what impact this may have on PMP.

Due to the potential issues with gridded datasets, it would be helpful to perform subsequent analyses of trends on point data across the region to determine if gridded trends are supported by point measurements. In addition, a subsequent analysis of trends in the variance would help to substantiate the conclusion that SSTx is stationary. The authors of NOAA Atlas 14, Volume 2 (henceforth, simply NOAA 14) performed a point analysis on precipitation trends across the Ohio Valley region, including the Carolinas (Bonnin et al., 2006). A discussion on these trends is provided in Section 5.

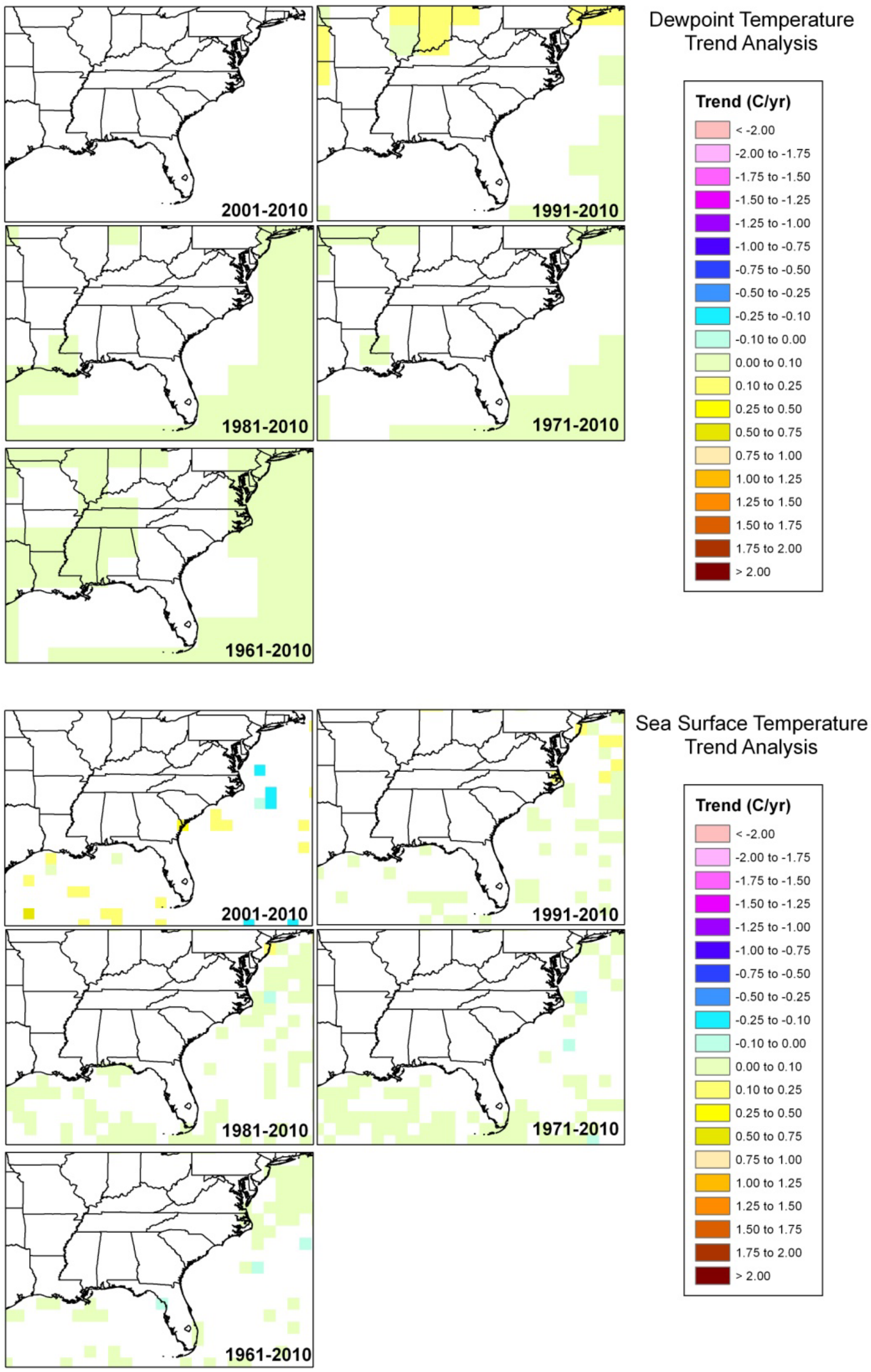

Figure 3-6 Trend analysis for Td (top) and SSTs (bottom) for the month of September for each decade during the respective periods of record for NCEP/NCAR (1948-2010) and ICOADS (1960-2010) ***Only significant trends (alpha > 0.10) are shown.***

4 FREQUENCY ESTIMATES OF PMP

The overarching goal of this section is to show how point estimates (i.e., 10 mi^2 (26km^2)) of PMP probabilities can be estimated using regional frequency analysis. Frequency estimates of PMP allow the consideration of risk (rainfall or load probabilities) when determining design criteria for dams and other structures. The data and methods used to compute the regional frequency analysis in NOAA 14 are described, followed by an analysis of PMP from HMR 51 relative to the regional frequency estimates from NOAA 14 (Bonnin et al., 2006). A point precipitation maximum observed during Hurricane Floyd is used to illustrate the variability associated with the frequency of such an event.

4.1 Data

The precipitation data used by the National Weather Service Hydrometeorological Design Studies Center (NWS-HDSC) in the creation of NOAA 14 Volume 2 (Bonnin et al., 2006) was analyzed. In particular, we focus on the annual maximum precipitation dataset. The annual maximum dataset lists the top precipitation event for each year that a National Weather Service Cooperative Observation Program (NWS COOP) rain gauge site was in operation. Here, year is defined as calendar year. The annual maximum precipitation data are available at the frequencies listed Table 4-1.

Table 4-1 Durations available within the NWS-HDSC annual maximum dataset

Hours	Days
1	1
2	2
3	4
6	7
12	10
24	20
48	30
	45
	60

Each annual maximum file lists all years of operation for the NWS COOP rain gauge sites and the associated annual maximum precipitation value with date of occurrence. For those frequencies that extend over multiple days, the start day of the precipitation is given. Missing values are reported as -999. Figure 4-1 and Figure 4-2 show the 1-day and 24-hour annual maximum precipitation values for the NWS COOP sites. Note that the 1-day maximum dataset contains enhanced spatial distribution of sites, due to the fact that few sites report on an hourly basis.

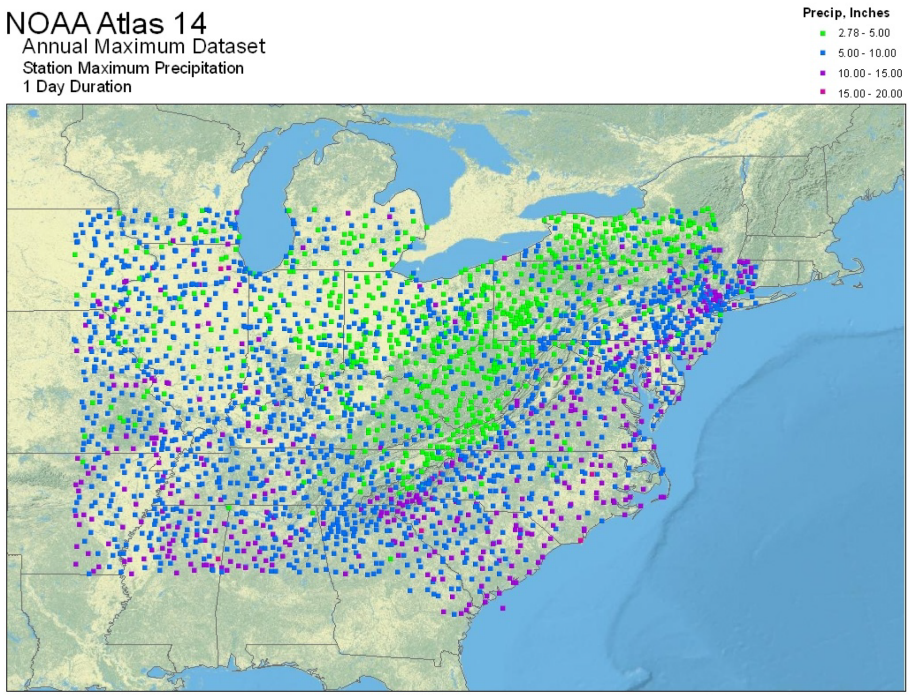

Figure 4-1 Annual maximum precipitation values for 1-day duration at each NWS COOP site

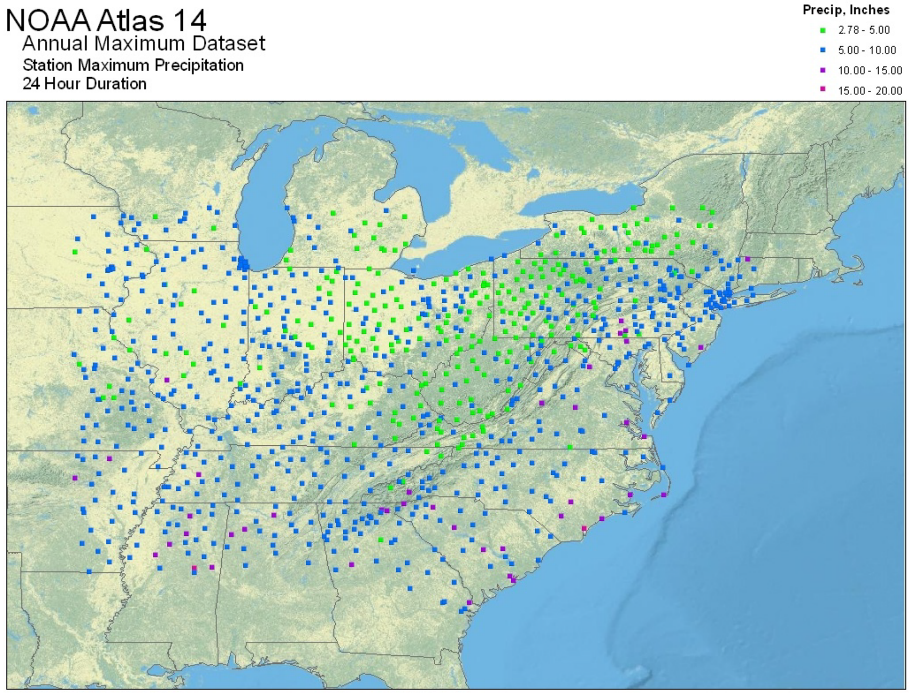

Figure 4-2 Annual maximum precipitation values for 24-hour duration at each NWS COOP site

The HDSC applied multiple quality control procedures to the point data prior to using in the determination of regional frequency distributions and analyses (Section 4.2). Initial quality control included a check for extreme values above thresholds, where the thresholds were established for 1-hour and 24-hour values based on climatological factors and previous precipitation frequency estimates in a given region. Observations above these thresholds were checked against nearby stations, original records, and other climatological bulletins. Daily stations in the project area (i.e., within 5 miles in horizontal distance and 100 feet in elevation) with records that contain an overlap of less than 5 years of data or a gap between records of 5 years or less were considered for merging to increase record length and reduce spatial overlaps. All longer duration annual maxima that exceeded the 1,000-year confidence limit estimates by more than 5% were investigated for data quality and appropriate regionalization. Finally, missing data were cleaned based on the duration of the precipitation event in question. Bonnin et al. (2006; pages 17-18) list these criteria in detail.

Once quality control was performed on the input datasets and maximum point precipitation amounts were determined for both partial duration (not included here) and annual maximum datasets, regional precipitation frequency analysis was performed by grouping sites together into homogeneous regions. Frequency estimates were derived out to a 1-in-1000 year threshold based on fitting a statistical model (e.g., generalized normal (GNO), generalized logistic (GLO), or generalized extreme value (GEV)) and selecting a model by comparing measures of model goodness-of-fit. The next section describes this process in some detail, relating specifically to the Carolinas, but the reader is directed to NOAA 14 (Bonnin et al., 2006) and Hosking and Wallis (1997) for additional details on the methodology.

4.2 NOAA 14 Precipitation Frequency Methods

NOAA 14 provides regional precipitation frequency information for the Ohio Valley and surrounding states, including NC and SC. At each duration listed in Table 4-1, NOAA 14 provides the precipitation amount associated with various return periods (e.g., Figure 4-3) in gridded format. The grids provide increased spatial discrimination relative to the PMP maps from HMR 51 (Figure 4-3). It should be noted that the 1-day durations are combined to a single 24-hour file using a conversion factor of 1.13. In order to make the daily and hourly data comparable, a conversion was necessary from 'observation day' (constrained observation) to 24 hours (unconstrained observation). Both NOAA Atlas 2 (Miller et al., 1973) and Technical Paper 40 used the empirically derived value of 1.13 to convert daily data to 24-hour data.

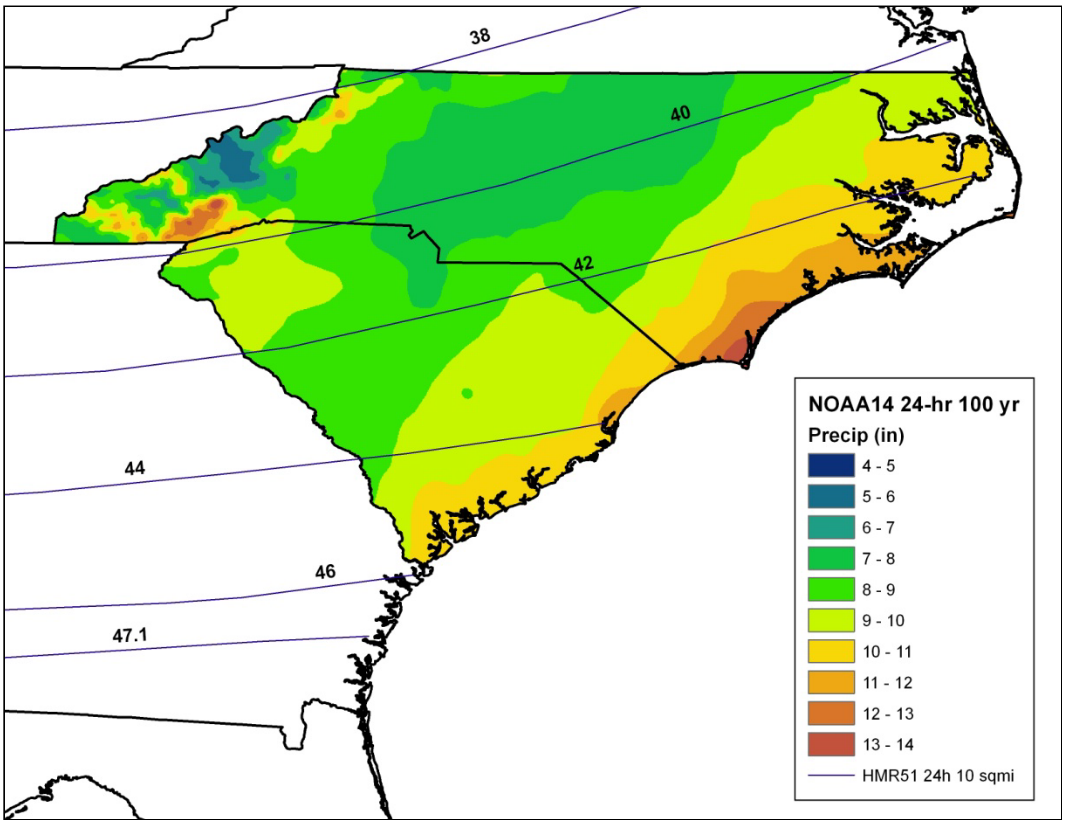

Figure 4-3 NOAA 14 24-hour, 100-year precipitation with 24-hour, 10 mi^2 PMP contours from HMR 51

The precipitation value for each return period is determined from a regional precipitation frequency analysis, where multiple sites from within a region of similar meteorological conditions (i.e., a statistically homogeneous region) are combined. The annual maximum time series from each of the points are then pooled to extend the record length in time, by making the assumption that the frequency distribution at each site within the region is similar, except for a scale factor (at-site mean). The at-site means for each of the NWS COOP sites can later be used to scale the resulting precipitation distribution relative to a regional mean. We use the data associated with NC and SC to further illustrate the process here.

There are a total of 296 NWS COOP sites across NC and SC with 24-hour annual maximum data available (Figure 4-4). A total of 14 homogeneous regions were determined for these two states (Bonnin et al., 2006) and subsequently used for computation of the regional frequency for these points, which includes two points that fall along or just outside of the border of the Carolinas in regions 36 and 83. For each of the 14 regions, the three distributions (i.e., GNO, GLO, GEV) were fit and model diagnostics were performed to select the preferred distribution (Figure 4-5; Table 4.5.1 in NOAA 14). The distributions selected were generally GNO or GEV, with the exception of a portion of the northwestern Piedmont of SC in region 12 (see Figure 4-6). Details on the model parameters for each region can be found in NOAA 14, Appendix A.7, Table A.7.1.

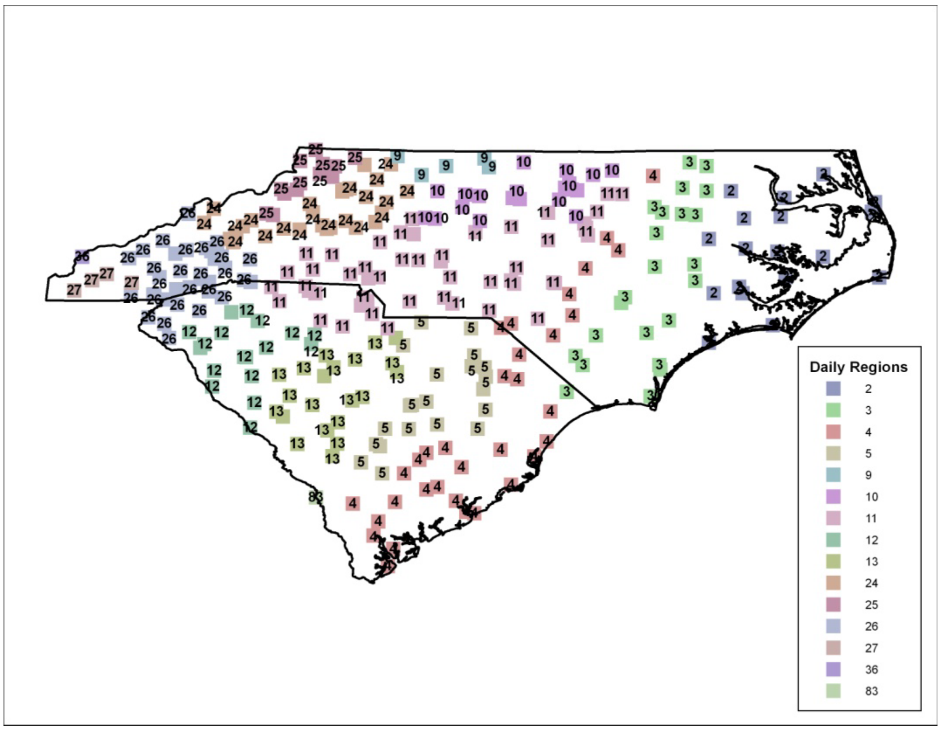

Figure 4-4 NWS COOP sites used in the NOAA 14 regional frequency analysis with the daily homogeneous region identification number indicated

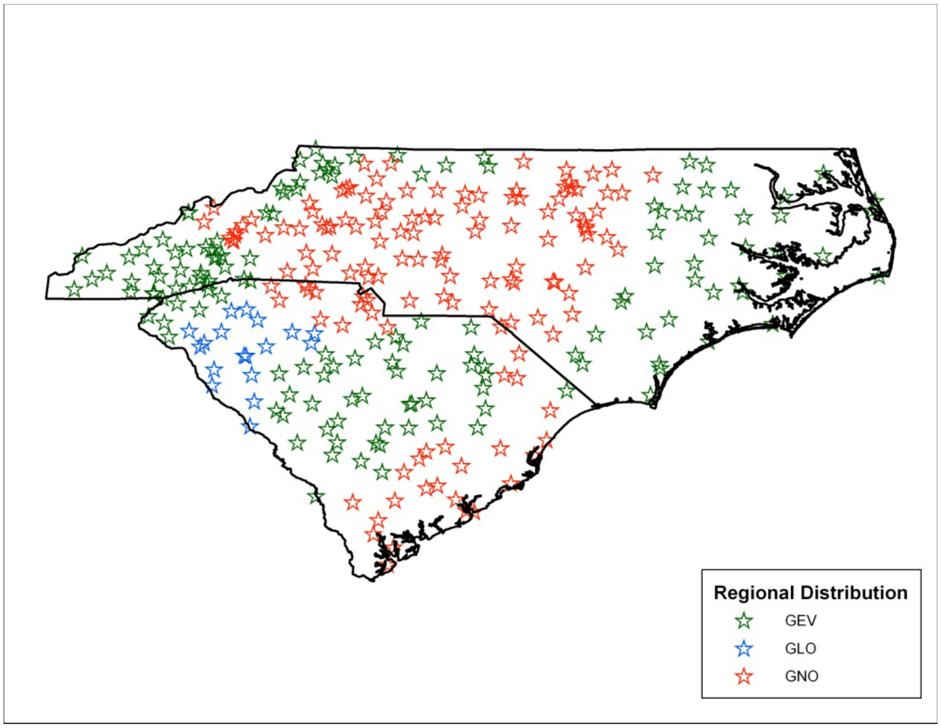

Figure 4-5 Regional frequency distribution type selected in NOAA 14

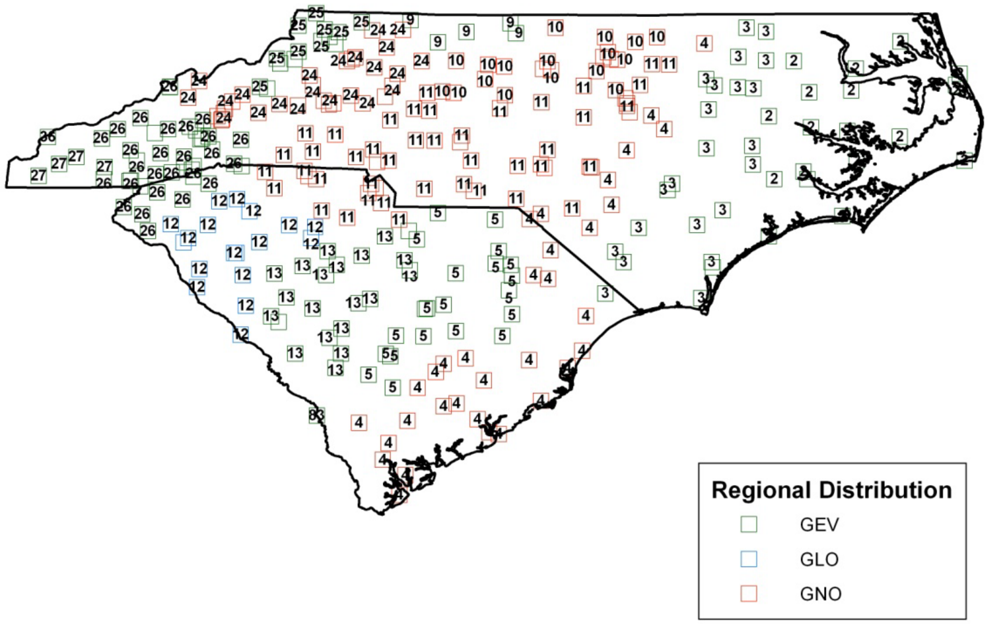

Figure 4-6 Regional frequency distribution type selected with region number overlaid

Using the model parameters and selected model, the dimensionless precipitation value for each of the regions in the Carolinas can be estimated at a variety of annual exceedance probabilities (AEP; i.e., return periods). Figure 4-7 shows that the distributions are clustered tightly through an AEP of 0.001, but diverge significantly at values less than 0.001 (or at return periods greater than 1-in-1000). The most notable deviation is for the GLO distribution in region 12 of SC, which indicates a dimensionless precipitation value of ~70 at 1E-07.

The regional distributions are then adjusted using the at-site mean as a multiplier. The at-site means are computed as the average of the annual maximum for all reporting years. It should be noted that the annual maximum time series provided by NOAA 14 contain values of -9.99 for years with missing data. Therefore, it is essential to remove these values and associated years from the computations, so that the estimate of the mean is not biased too low.

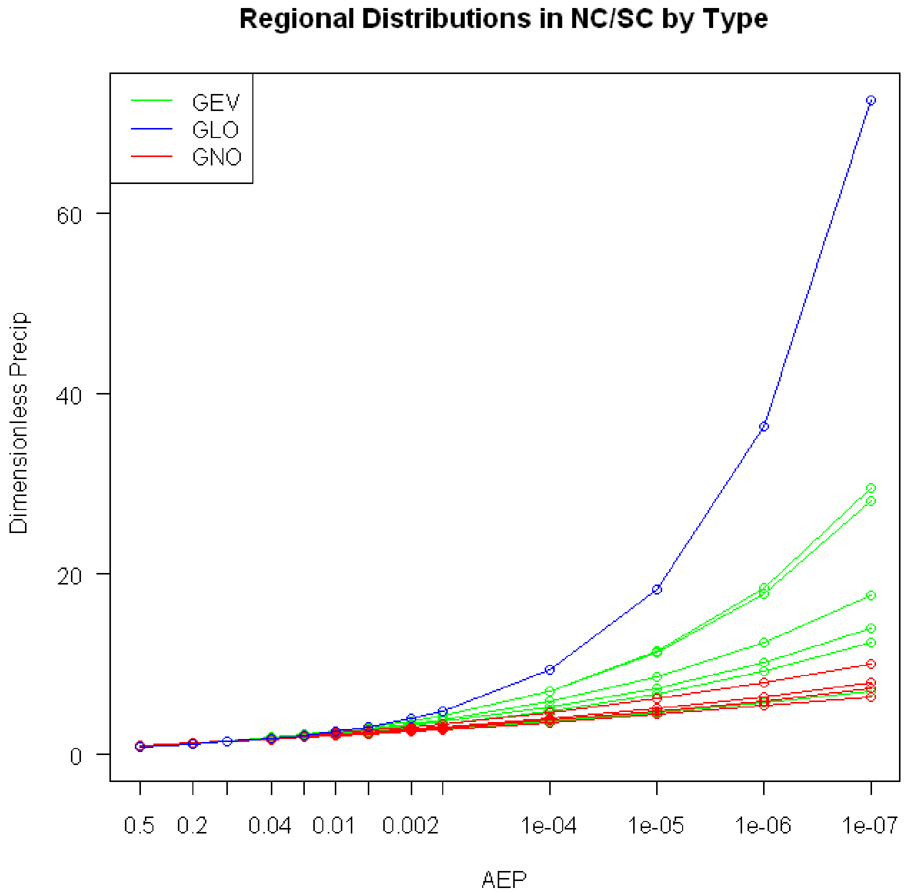

Figure 4-7 Regional precipitation frequency curves by distribution type in the Carolinas

4.3 Precipitation Frequency Ratios

The spatial representation of frequency information in NOAA 14 exceeds that from HMR 51. Figure 4-8 shows a similar plot to Figure 4-3, but for the 1-in-1000 year, 24-hour point precipitation values. Highest precipitation values from NOAA 14 exist along the coast of NC and in the favored upslope areas for precipitation in the Appalachians. A region of higher precipitation is also noted in northwestern SC in the location of region 12, which used the highly-skewed GLO frequency distribution (Figure 4-3). This section focuses on the magnitude of differences between the HMR 51 PMP and NOAA 14 24-hour values across the Carolinas.

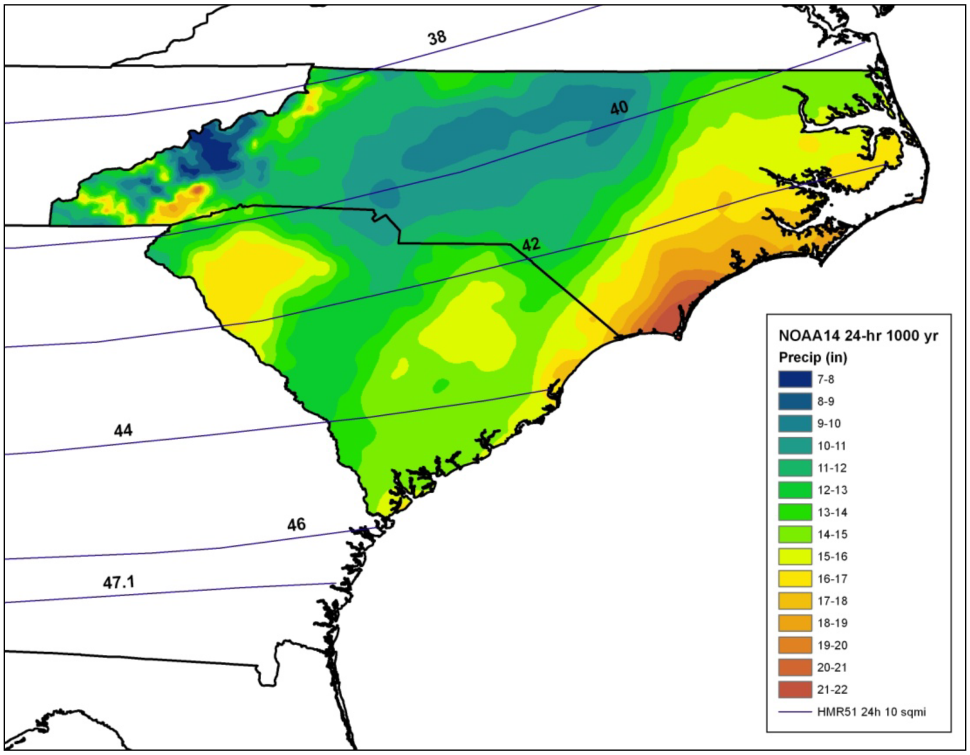

Figure 4-8 NOAA 14 24-hour, 1000-year precipitation with 24-hour, 10 mi^2 PMP contours from HMR 51

As in Figure 4-8, the design precipitation ratios indicate the marked contrast between the smooth PMP contours and the spatial variability of the NOAA 14 estimates (Figure 4-9). The spatial variability of NOAA 14 appears to define the ratios. This spatial variability in the ratios is a reflection of the actual precipitation frequency and distribution across the states, with the exception of northwest SC (i.e., region 12) where ratios range from 2 to 3. The lower ratio region across the central Carolinas is indicative of an observed minimum in precipitation due to downslope drying off the Appalachians coupled with distance from moisture supply. However, the region over northwest SC, mentioned above, corresponds to issues with the regional distribution selected. Precipitation in this region is likely not significantly different from nearby areas of central and extreme northwestern SC. The spatial variability over the mountainous regions may be related to under-representation by the gauge network or a function of the local orographic forcing of rainfall in the area.

Similar patterns are seen in the comparison of PMP to 1-in-100 year precipitation in Figure 4-8. The impact of the regional distribution in northwest SC is less evident, as the deviation from the other nearby distributions is less for higher frequency events. This is also reflected in Figure 4-7 where the frequency curve for region 12 is more tightly clustered with the other regions in the Carolinas. The coastal and mountainous areas of the Carolinas show the lowest ratios as precipitation is generally expected to be heaviest due to tropical influence and orographics.

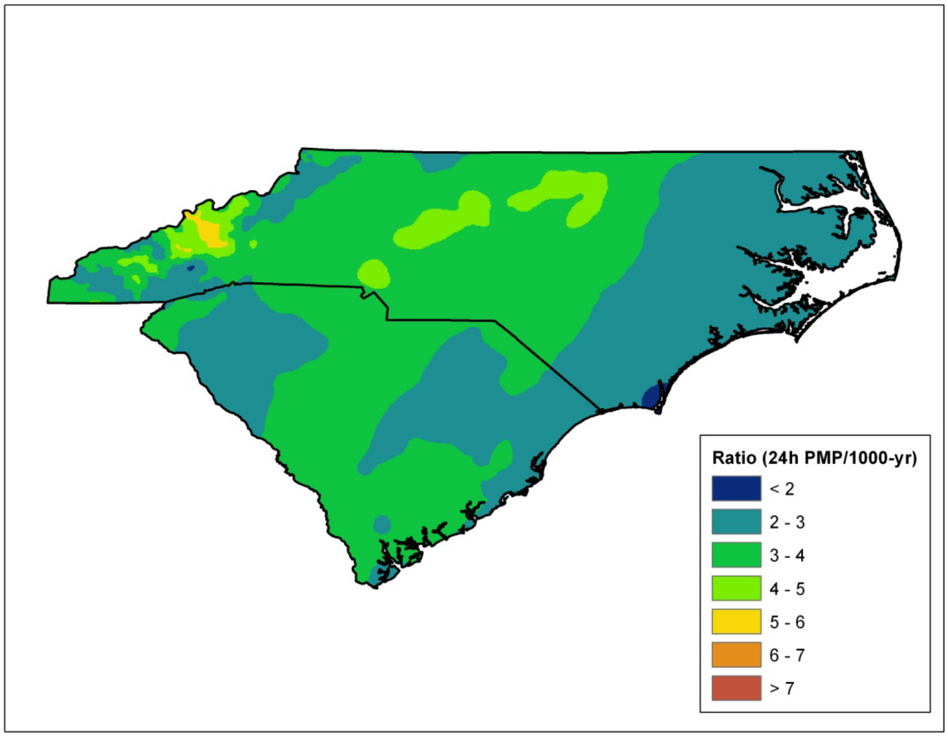

Figure 4-9 Ratios of the 24-hour, 10 mi^2 PMP from HMR 51 and NOAA 14 24-hour, 1000-yr precipitation

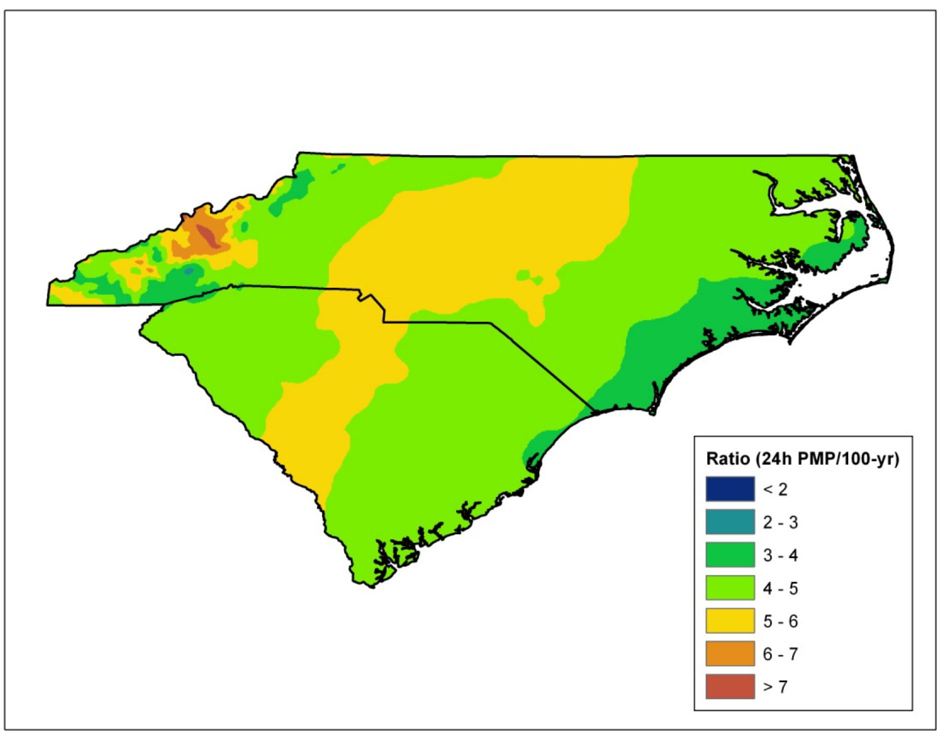

Figure 4-10 Ratios of the 24-hour, 10 mi^2 PMP from HMR 51 and NOAA 14 24-hour, 100-yr precipitation

4.4 PMP Frequency Estimates

For each of the NWS COOP sites in the Carolinas (see Figure 4-4), the 24-hour, 10 mi^2 ($26km^2$) PMP from HMR 51 was extracted from grids developed at Reclamation from the HMR 51 shapefiles of contoured PMP. The goal is to determine where the PMP value at each site lies within the regional distribution from NOAA 14. Using the regional distributions from Section 4.2, the AEP can be determined by calculating the quantile at which the PMP occurs on the frequency curve. Figure 4-11 and Figure 4-12 show the shape of the regional distributions for each region in NC and SC. In general, the regions are shown in the legend from east to west. Region 12 again shows the significant deviations at large return periods. The variability at AEP of 1E-07 in SC (ranges from less than 10 to over 70) is much larger than in NC (ranges from less than 5 to around 30). This variation across space means that the return period associated with the PMP varies significantly depending on the area investigated.

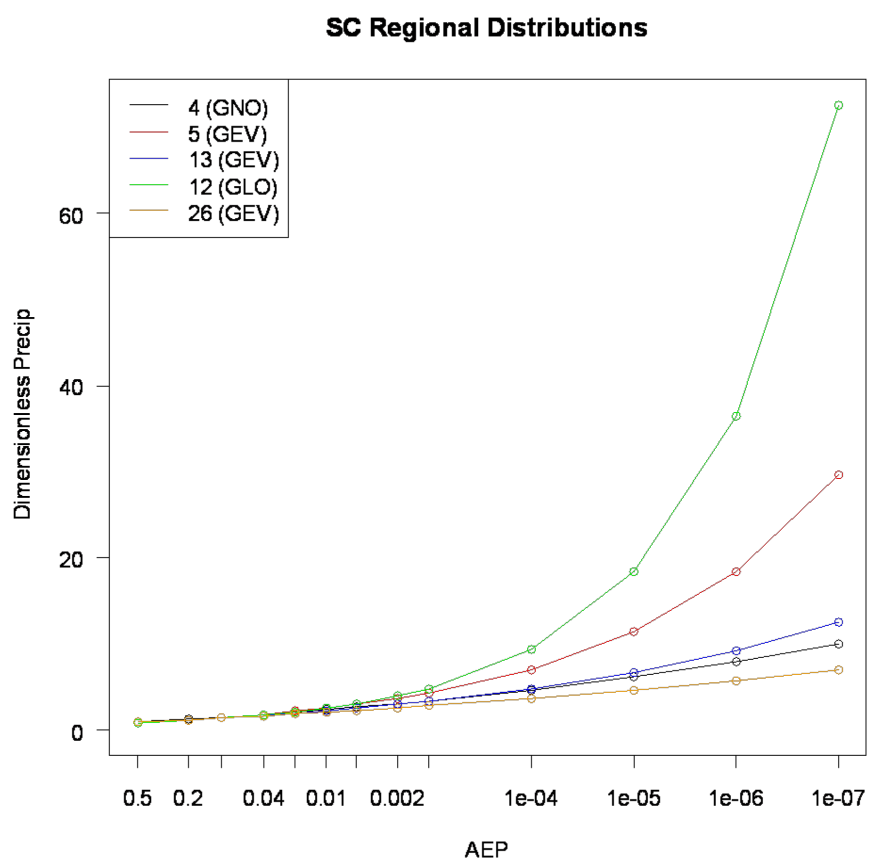

Figure 4-11 Regional precipitation frequency distributions for South Carolina regions

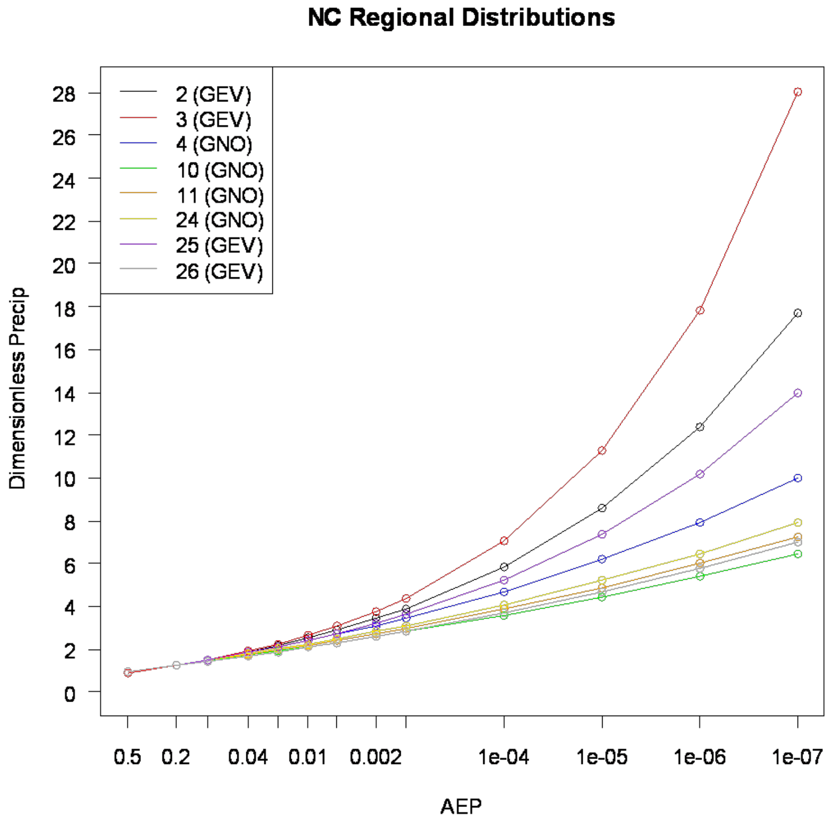

Figure 4-12 Regional precipitation frequency distributions for North Carolina regions

In general, the 24-hour, 10 mi^2 (26km^2) PMP has the lowest return periods over southeastern NC and across northwest SC in region 12 (Figure 4-13). Extreme precipitation is likely more frequent along the coast due to the regular intervals of tropical cyclone impacts in the region. Again, the low return periods in region 12 are a numerical artifact from extrapolation of the GLO regional distribution (Figure 4-11). The fact that these regions have PMP at return periods of less than 1-in-100,000 years may be of great interest in design studies.

4.5 Point Frequency Estimates

Using the 1-day annual maximum precipitation data (see Figure 4-1), the events were ranked to determine the dates of the top 10 storms (not shown). The top two precipitation-producing storms, based on 1-day totals, were Altapass, NC, in 1916 (19.32”) and Floyd in 1999 (18.30” at Southport 5N, NC). Figure 4-14 shows all the points in the Carolinas which had Floyd as the maximum 1-day total in 1999. The impact of Floyd extended farther north along the eastern seaboard (not shown), including areas in Virginia and New Jersey.

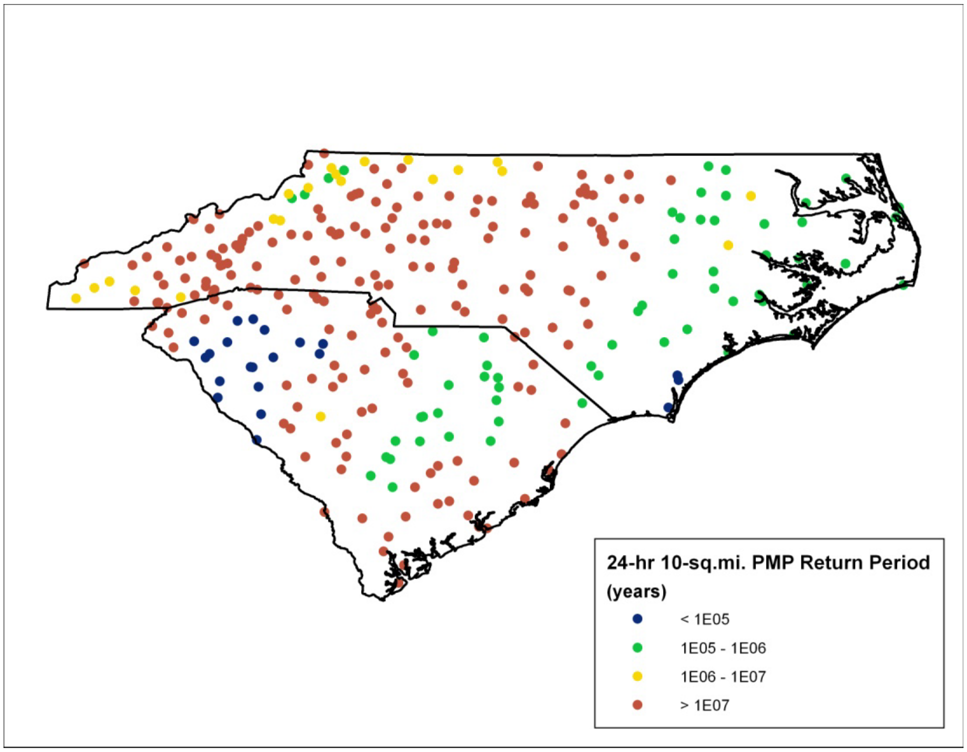

Figure 4-13 Return period estimates of the 24-hour, 10 mi^2 PMP using regional precipitation frequency distributions

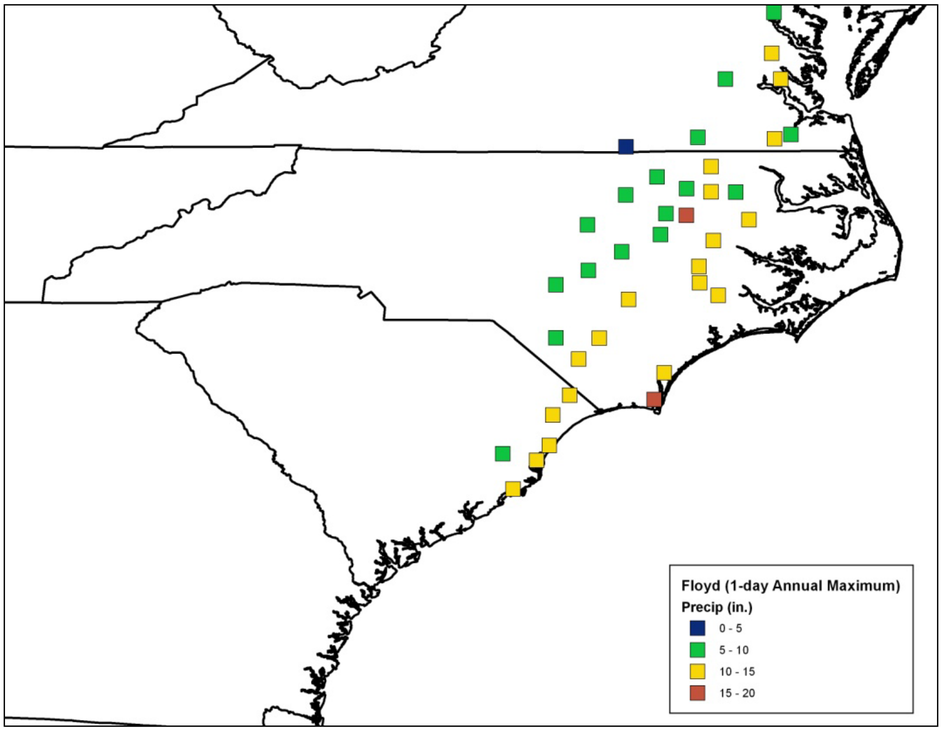

Figure 4-14 Annual maximum precipitation points at 1-day duration (extracted from Figure 4-1) that occurred during Hurricane Floyd in 1999

Using the Precipitation Frequency Data Server (PFDS) at NWS-HDSC, which provides online access to NOAA 14 data, the point specific estimates of precipitation frequency at various durations and AEPs can be downloaded in text format. In addition, the NWS-HDSC provides upper and lower confidence bounds for each precipitation frequency at the 90 percent confidence level.

Here we use the PFDS to access the precipitation frequency estimates at 24-hour duration for the Southport 5N site, since the aforementioned storm relates directly to the recent research related to Floyd. Figure 4-15 shows the 24-hour frequency curve, the upper and lower bounds, and the 18.30” value recorded at the gauge during Floyd. Note that the variability about the 24-hour mean value has a wide range. Using a linear interpolation scheme to estimate the actual AEP values along each confidence at 18.30” suggests that the return period may range from approximately 1-in-240 to 1-in-908 years, nearly an order of magnitude (Figure 4-16).

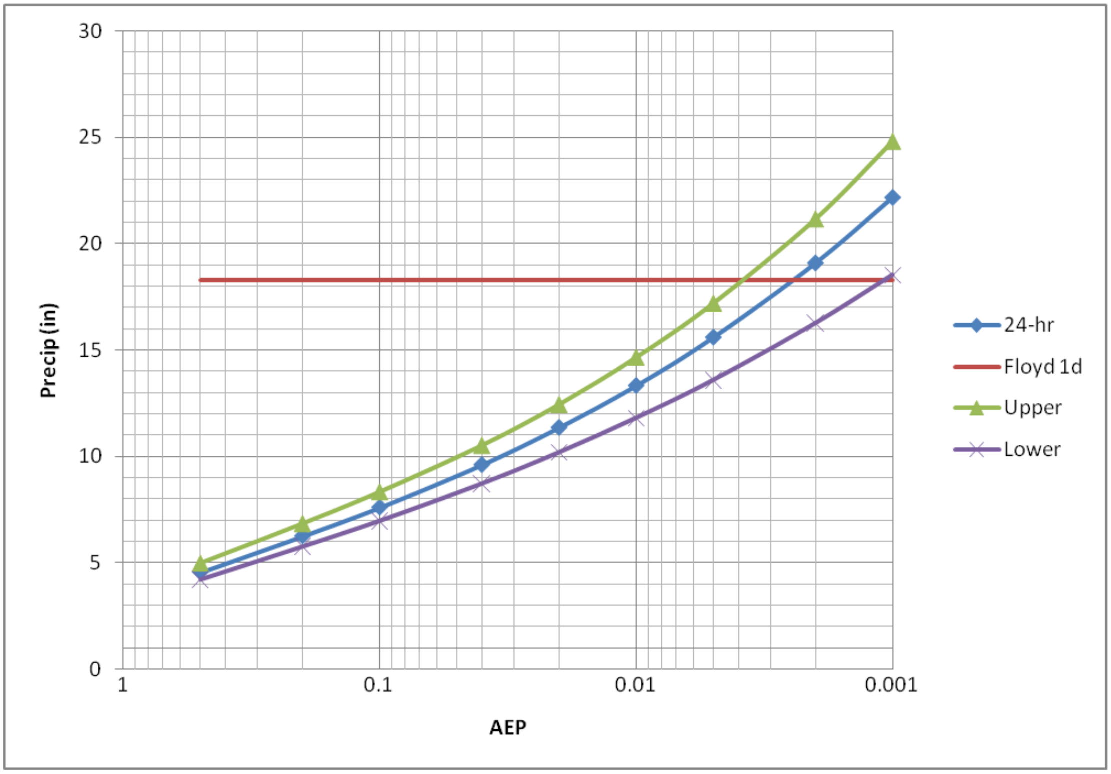

Figure 4-15 Precipitation frequency curves at Southport 5N, NC, for the 24-hour duration with upper and lower confidence bounds indicated ***The horizontal red line represents the annual maximum value of 18.30" during Hurricane Floyd in 1999***

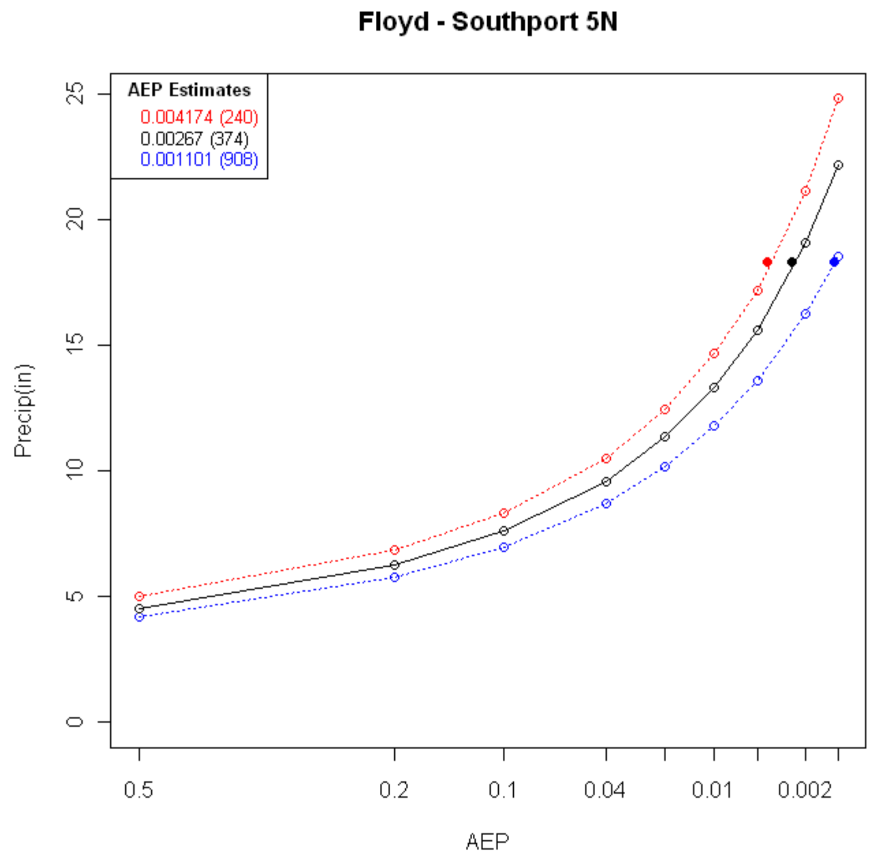

Figure 4-16 Precipitation frequency at Southport, NC ***Same as Figure 4-15, except that the linear estimates of return periods are indicated (solid dots) for the upper bound (red), mean (black), and lower bound (blue). The lines with hollow points represent the respective frequency curves based on color.***

5 DISCUSSION

Since the early 1970s, very few new storms have been analyzed for use in determining design precipitation magnitudes, up to and including PMP. In recent decades, the advent of new technologies offer the ability to perform storms analyses using gridded datasets (e.g., radar). The quality of these datasets must be considered due to the potential impacts on variability in PMP estimates. The same concept of variability is inherently included in the calculation of regional precipitation analyses in NOAA 14. We discuss the findings of the current research in the following sections, along with an analysis of these regional frequency estimates relative to PMP.

5.1 Implications for Design Assessments

The ten new storms analyzed in Caldwell et al. (2011) using gridded, radar-estimated precipitation data indicated that two storms, Floyd (1999) and Fran (1996), have the potential to challenge PMP values for large area sizes, particularly along coastal reaches of NC. More recent storms like Irene (2011) and Lee (2011) show that extreme storms can occur over a short time span, similar to Hurricanes Dennis and Floyd in 1999. In addition, Irene and Floyd impacted nearly the same region in eastern NC during the past 22 years, indicating potential impacts on the tail of the frequency distribution. The impact on PMP at large area sizes could have implications for design in coastal basins, such as the Cape Fear River Basin. At area sizes above 5,000 mi^2 (12,950 km^2), it is possible that the PMP contours over eastern portions of North Carolina should be shifted northward to account for recent storms like Floyd.

Maps of the precipitation frequencies from NOAA 14 highlight the increased spatial resolution compared to HMR 51 PMP and, hence, discrimination of climatologically-favored regions of heavier/lighter precipitation. The regional frequency distributions from NOAA 14 show that the precipitation values for AEP up to 0.001 are fairly consistent between the 12 statistically-homogeneous regions in the Carolinas, but diverge significantly at return periods greater than 1-in-1000 years. In particular, region 12 in SC shows the sensitivity to the selection of distribution type (i.e., GLO). The NOAA 14 regional precipitation frequency approach and distributions can be used for risk-based estimates, but users must exercise judgment and caution in extrapolating these functions. Custom analyses for specific sites may need to be performed, rather than relying on published values.

By generating ratios of the 24-hour 100- and 1000-year precipitation values from NOAA 14 with HMR 51 PMP, we indicate the spatial variations in NOAA 14 dominate with lowest ratios across region 12, where the distributional artifact creates more frequent, higher precipitation yielding storms. The 1-in-1000 year event is likened to an approximately half of PMP storm, which is unrealistic given the limited moisture available in that area and downslope drying from the Appalachians.

Since the regional distributions were fitted by Reclamation using data from NOAA 14, the return period of HMR 51 PMP across the state can be estimated. Using the NWS COOP sites, the 24-hour, 10 mi^2 (26km^2) values of PMP were extracted at each of the NWS COOP sites for which the regional distributions were modeled. The quantile of the PMP value on the distribution was calculated and converted to an AEP. Return periods of PMP were generally greater than 1-in-100,000 years, except along the coast and in region 12, where return periods were less than 1-in-100,000. The spatial variation in AEP shows that the PMP may vary in its associated risk when using the value for design. A preliminary analysis using the same distributions to determine the amount of precipitation associated with a 1E-09 AEP is shown in Figure 5-1 as a proof of concept. If a design standard requires a specific AEP, then the mean precipitation associated with that value could be determined (after considering the limits of the dataset). Uncertainty estimates would also need to be quantified. It is important to note that the maximum 24-hour rainfall ever observed in the United States was 43 in (109 cm) during Tropical Storm Claudette in Alvin, TX, on 25-26 July 1979.

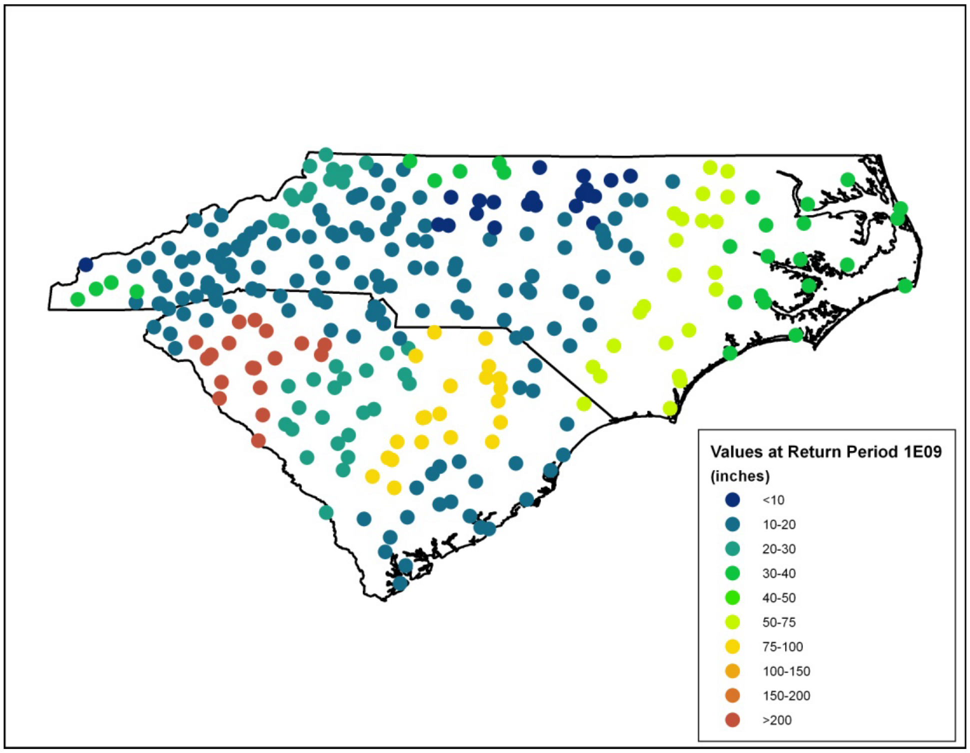

Figure 5-1 The values of 24-hour precipitation at a return period of 109 years using the current regional distributions ***Maximum values in region 12 exceed 200 inches and are unrealistic.***

Associated with the mean precipitation at each duration and frequency are upper and lower confidence limits. As was performed for PMP, the return period for a particular storm can be determined along each of the distributions. Using the 18.30" annual maximum for 1999, associated with Floyd, the mean and confidence limits were downloaded from NWS-HDSC. Since the point estimates from NWS-HDSC are site-specific, we used the downloaded text files and used linear interpolation to determine the approximate range of return periods for such an event. The results showed the potential uncertainty in the estimate translates to approximately an order of magnitude difference (240 vs. 908 years).

5.2 Limitations

The appropriate use of these data for design requires careful consideration of the limitations. First, the current estimates of maximized DAD from radar-based datasets fail to include any adjustments for envelopment, orographics or transposition, and are only maximized in-place. The radar-estimated precipitation also exhibits issues with quality. One particular example is the reliance of the radar on gauge data to serve as ground truth; the gauges can also over/underestimate the amount of precipitation falling during heavy rain events. During Hurricane Fran, the radar over-estimated values by 22 percent when compared with available gauges. As a sensitivity experiment, the DADx was recomputed using radar estimates that were 78 percent of the original values, which yielded values of DADx that approached but did not exceed PMP at any area size or duration.

To partially account for the variability associated with radar-biases and the selection of methodology for computing the IPMF, an exhaustive set of combinations of moisture variables (e.g., dewpoint or SST) were used to generate a boxplot of IPMF. The expectation is that this range will capture the variability associated with estimating PMP using the DADx. For each of the storms in Caldwell et al. (2011), the maximum IPMF was used to provide conservative estimates for design purposes. For Hurricane Floyd, the median value was also tested to determine the sensitivity of DADx calculations to the choice of IPMF. When using this lower threshold, the DADx does not exceed HMR 51 PMP at large area sizes at 24-hour durations, but falls within the +/- 10 percent errors associated with PMP as described in HMR 51.

Trends in moisture variables that go into the IPMF were also investigated preliminarily. Initial results show that there is limited trend in either dewpoint temperature or sea surface temperatures using gridded data. Over-smoothing in these datasets could be an issue; however, the significance of the trends was tested at the 90 percent confidence level to capture any subtle trends. In addition, NOAA 14 performed a similar linear trend analysis of precipitation for all the points with sufficient period of record that were included in the regional frequency analysis (Figure 5-2). Of a total of 220 sites used in the Carolinas for the analysis, only 36 showed any trend. Positive (negative) trends were found for 23 (13) of the sites. This would indicate that in general there is no observable trend that can be regionally assumed for the two states. Visual inspection may suggest that there is some tendency for increasing trends along the coast of NC and central SC, with negative trends on the eastern escarpment of the Appalachians in western NC. Remember, however, that this is only a small percentage of the total number of stations included in the analysis.

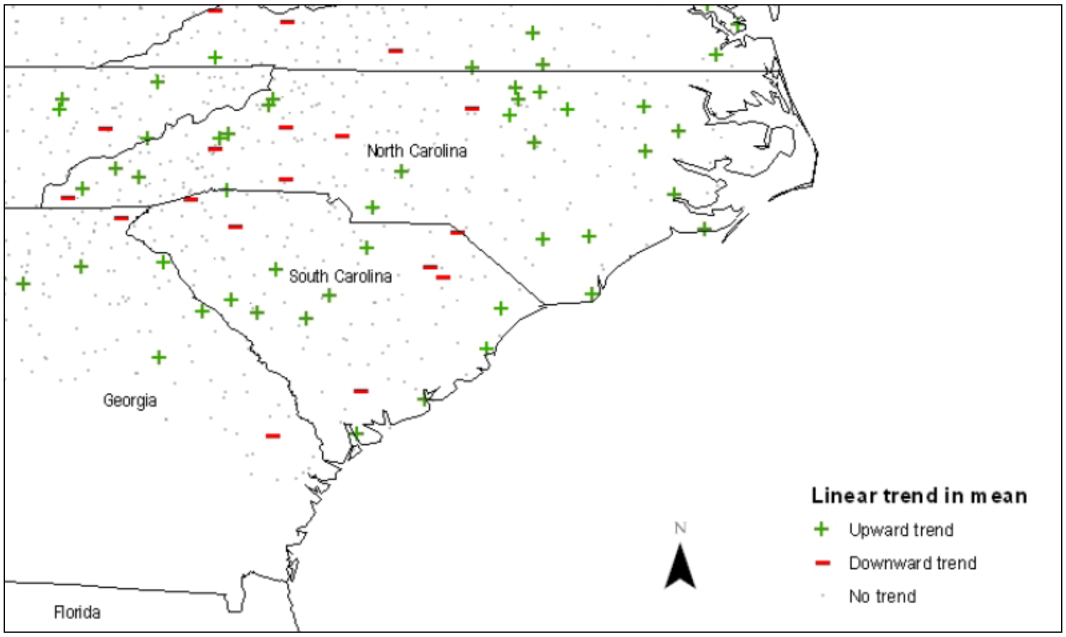

Figure 5-2 Spatial distribution of linear trend results, where "+" indicates a station with a positive trend and "-" indicates a negative trend *(Excerpted from Bonnin et al., 2006 p. 88).*

5.3 Future Work

There are opportunities to conduct additional work that could expand and improve the methods utilized and results obtained in this NC-SC pilot study. Future efforts should consider work in the following areas. A larger spatial domain, extreme storm data set, including Georgia, Tennessee, Virginia and Florida can be gathered and analyzed, focusing on radar rainfall estimates from NWS Multisensor Precipitation Estimation. Orographic effects and storm maximization can be examined using a numerical modeling framework, such as the Weather Research and Forecasting (WRF) model, and conduct place-based analysis and experiments. Transposition concepts should be critically reviewed and evaluated using numerical models. Transposition and envelopment evaluations may require a focus on tropical cyclone tracks and larger-scale synoptic effects (e.g. Coastal, Direct, Appalachians; Caldwell et al., 2011). Principal Components Analysis (PCA) can be used to identify forcings of maximum precipitation events, and how to incorporate this into maximization and transposition. An ingredients-based methodology, using probability density functions of various predictors to transpose an event and to get adjustment factors for the storm, should be investigated. Larger-scale community efforts on extreme storm data collection and synthesis are needed.

6 CONCLUSIONS

This report synthesized research on extreme storm rainfall for a North Carolina and South Carolina pilot region. The major objectives of the work were to: (1) describe potential impacts of new storms on existing PMP estimates; (2) present some sensitivities of PMP estimates; and (3) provide preliminary probability estimates of PMP. Key findings of the research are as follows, and center on the use of radar-rainfall estimates from Multisensor Precipitation Reanalysis.

1. New data analyses of ten tropical cyclones suggest HMR 51 PMP values are too low for durations > 12 hrs and area sizes > 5,000 mi^2 (12,950 km^2) along coastal Carolinas, based on analysis of Hurricanes Floyd and Fran. Other durations and area sizes are unaffected in this location. HMR 51 may need to be updated for coastal areas in Carolinas. There are unknown impacts in the Carolinas because envelopment, transposition and orographic effects are unclear due to the limited sample. These factors, if included, would tend to increase PMP estimates in some locations.

2. Storm Depth-Area Duration maximized values are somewhat sensitive to radar rainfall biases and use of maximized moisture. Using a median moisture maximization ratio, Floyd is still close to HMR 51 PMP.

3. No significant trends were found in SST and dew point temperature (Td) grids. This suggests stationary series for storm maximization.

4. There is a potential for increased temporal clustering of TC events in August-September based on recent storms in 1999, 2004, and 2011. Longer-duration rainfalls (> 72 hr) and soil moisture for runoff may be changing factors.

5. Regional precipitation frequency techniques were used to estimate PMP ratios and probabilities. PMP ratios to 1/1000 AEP 24hr rainfall ranged from 2 to 6 times. PMP 24hr, 10 mi^2 return periods ranged from 10^{-5} to > 10^{-7}. HMR 51 PMP estimates might be high in the Piedmont (26km^2) based on NOAA 14 point frequency estimates. Additional efforts are needed to address orographics and decreases in Piedmont areas.

A risk-based perspective suggests the following points. NOAA 14 extrapolations suggest PMP point values may be exceeded at 10^{-5} along coast and less frequent inland. There are problems with the use of different distributions in space and extrapolations, especially GLO in Western South Carolina. Point frequency estimate confidence intervals need to be utilized (e.g. observed events). PMP amounts are estimates and can be exceeded. Uncertainties of PMP estimates can be quantified for point values. Further work is needed for areal estimates and uncertainties. Existing regional precipitation frequency methods exist and can be used for a transition from a design maximum, PMP-focused assessment to probabilistic assessments.

From a design/maximum perspective, we suggest the following. The database behind HMR 51 is severely outdated and needs to be comprehensively updated. Use of recent gridded data sets is extremely valuable. The resolutions of recent products (NOAA 14) are superior to HMR 51 smoothed estimates. A coastal multiplier for HMR 51 PMP estimates could be considered in design concepts. An open design question is should one focus on specific locations, versus generalized or regional PMP estimates.

Future work should consider several critical aspects. These include orographics with the use of numerical models (e.g. WRF); transposition effects; and larger-scale community efforts on data collection and synthesis.

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10. SUPPLEMENTARY NOTES

E. Yegorova

11. ABSTRACT (200 words or less)

Data and analyses of ten recent extreme storms in North and South Carolina have been completed by Caldwell et al. (2011). These new storms may influence Probable Maximum Precipitation (PMP) estimates in the region. This report builds on the storm analyses to illustrate some potential impacts to design precipitation estimates and to introduce some alternative, risk-based perspectives, including precipitation frequency. The major objectives of the work were to: (1) describe potential impacts of new storms on existing PMP estimates; (2) present some sensitivities of PMP estimates; and (3) provide preliminary probability estimates of PMP.

The approach that is used is to examine in finer detail the impacts of Hurricanes Floyd and Fran on PMP estimates, based on new Depth-Area-Duration and in place storm maximization results from these storms. Brief comparisons are made to 2011 storms. The sensitivity of PMP estimates to several factors is illustrated, including examination of potential climate influences and trends in moisture and surface observations. Approximate PMP exceedance probabilities for example sites within the Carolinas Pilot Region are estimated using regional precipitation frequency analysis.

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