APPENDIX E – PMP Development Version Log

v.80

- Only 29 storms included.
- Preliminary transposition limits.

v.90

- Added the remaining storm events (58 total)
- Updated transposition limits for nearly every storm event
- Updated DAD tables for many local storms that were missing 2 through 6-hour values. SPAS 1343 (still missing 4&5)

v.91

General

- SPAS 1208 – Transpose to Zone 4
- SPAS 1218 – Transpose to Zone 4
- SPAS 1228 – Not transposed to Zone 3 (due to distance from storm center)
- SPAS 1305 – Not transposed to Zone 4
- SPAS 1428 – Not transposed to Zone 3 (due to distance from storm center)

Local

- Added the 4 and 6 hour durations to the SPAS 1343 DAD table.
- SPAS 1034 – Not transposed to Zone 3 (due to distance from storm center)
- SPAS 1343 – Transpose to Zones 1 & 2 and evaluate magnitude at shorter durations
- SPAS 1345 – Transpose to all of Zone 4

Tropical

- SPAS 1182 – adjusted transposition limits to extend farther south in Zone 3
- SPAS 1317 – adjusted transposition limits to extend farther south in Zone 3

v.92

Capped all OTF at 1.50.

v.93

General

- SPAS 1227 – Changed storm center cords slightly resulting in slightly different MTF
- SPAS 1278 – Changed storm center cords slightly resulting in slightly different MTF

Tropical

- SPAS 1312B_1 – Changed storm center cords slightly resulting in slightly different MTF
- SPAS 1312B_2 – Changed storm center cords slightly resulting in slightly different MTF

Local

- SPAS 1344 – Transpose to Zones 1 & 2
- SPAS 1345 – Do not transpose to OTF > 1.5

v.94

Local

- SPAS 1343 – Not transposed to Zones 1 & 2
- SPAS 1344 – Not transposed to Zones 1 & 2
- Removed OTF
- Introduced vertical component to MTF (no inflow barriers)

v.95a

Local (from v.92)

- SPAS 1343 – Not transposed to Zones 1 & 2
- SPAS 1344 – Transpose only to Zone 3
- SPAS 1345 – Special transposition limits defined by Bill

v.95b

Local (from v.92)

- SPAS 1343 – Not transposed to Zones 1 & 2
- SPAS 1344 – Special transposition limits defined by Bill
- SPAS 1345 – Special transposition limits defined by Bill

v.96

OTF values over southeast basin were adjusted to account for differences between NOAA Atlas 14 Volumes 2 and Volumes 9.

General

- SPAS 1195_2 – small change to DAD table (from Conowingo)
- SPAS 1305 – Update dew point climatology from 12hr to 24hr

Local

- SPAS 1344

  - Transpose only to Zone 3
  - Used revised DAD table
- SPAS 1345
  - Transpose only to Zone 4
  - Normalized OTF to a maximum of 1.00. All other grid points are a ratio to this location.
  - Used revised DAD table
- SPAS 1434 – Set MTF to 1.00 to avoid double-counting with OTF

v.96a

Local

- SPAS 1344 - Special transposition limits defined by Bill (from v.95b)

v.96b

Local

- SPAS 1344 – Zone 3 + Special transposition limits defined by Bill (from v.95b)

v.96c

Local

- SPAS 1344 –Special transposition limits defined by Bill (from v.95b) confined to far northern part of Zone 3 and 4.

v.97

Normalized SPAS 1344 OTF to a maximum of 1.00. All other grid points are a ratio to this location

v.97a

Local

- SPAS 1344 - Transposed to Zones 2, 3, and 4

v.97b

Local

- SPAS 1343 – Transposed to all zones

APPENDIX F – Storm Analysis Data

See Separate Binding

This is attached electronically to the parent ADOBE.pdf calculation file and is stored in an unalterable medium.

APPENDIX G – Storm Precipitation Analysis System Description

Introduction

The Storm Precipitation Analysis System (SPAS) is grounded on years of scientific research with a demonstrated reliability in hundreds of post-storm precipitation analyses. It has evolved into a trusted hydrometeorological tool that provides accurate 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., 2003-2012). Applied Weather Associates, LLC and METSTAT, Inc. initially developed SPAS in 2002 for use in producing Depth-Area-Duration values for Probable Maximum Precipitation (PMP) analyses. SPAS utilizes precipitation gauge data, "basemaps" and radar data (when available) to produce gridded precipitation at time intervals as short as 5 minutes, at spatial scales as fine as 1 km^2 and in a variety of customizable formats. As of the publication of this study (April 2015) SPAS had been used to analyze over 500 storm centers across all types of terrain, among highly varied meteorological settings and some occurring over 100-years ago.

SPAS output has many applications including, but not limited to: hydrologic model calibration/validation, flood event reconstruction, storm water runoff analysis, forensic cases and PMP studies. Detailed SPAS-computed precipitation data allow hydrologists to accurately model runoff from basins, particularly when the precipitation is unevenly distributed over the drainage basin or when rain gauge data are limited or not available. The increased spatial and temporal accuracy of precipitation estimates has eliminated the need for commonly made assumptions about precipitation characteristics (such as uniform precipitation over a watershed), thereby greatly improving the precision and reliability of hydrologic analyses.

To instill consistency in SPAS analyses, many of the core methods have remained consistent from the beginning. However, SPAS is constantly evolving and improving through new scientific advancements and as new data and improvements are incorporated. This write-up describes the current inner-workings of SPAS, but the reader should realize SPAS can be customized on a case-by-case basis to account for special circumstances; these adaptations are documented and included in the deliverables. The over arching goal of SPAS is to combine the strengths of rain gauge data with radar data (when available) to provide sound, reliable and accurate spatial precipitation data.

Hourly precipitation observations are generally limited to a small number of locations, with many basins lacking observational precipitation data entirely. However, Next Generation Radar (NEXRAD) data provide valuable spatial and temporal information over data-sparse basins, which have historically lacked reliability for determining precipitation rates and reliable quantitative precipitation estimates (QPE). The improved reliability in SPAS is made possible by hourly calibration of the NEXRAD radar-precipitation relationship, combined with local hourly bias adjustments to force consistency between the final result and "ground truth" precipitation measurements. If NEXRAD radar data are available (generally for storm events since the mid-1990s), precipitation accumulation at temporal scales as frequent as 5-minutes can be analyzed. If no NEXRAD data are available, then precipitation data are analyzed in hourly increments. A summary of the general SPAS processes are shown in flow chart in Figure G.1.

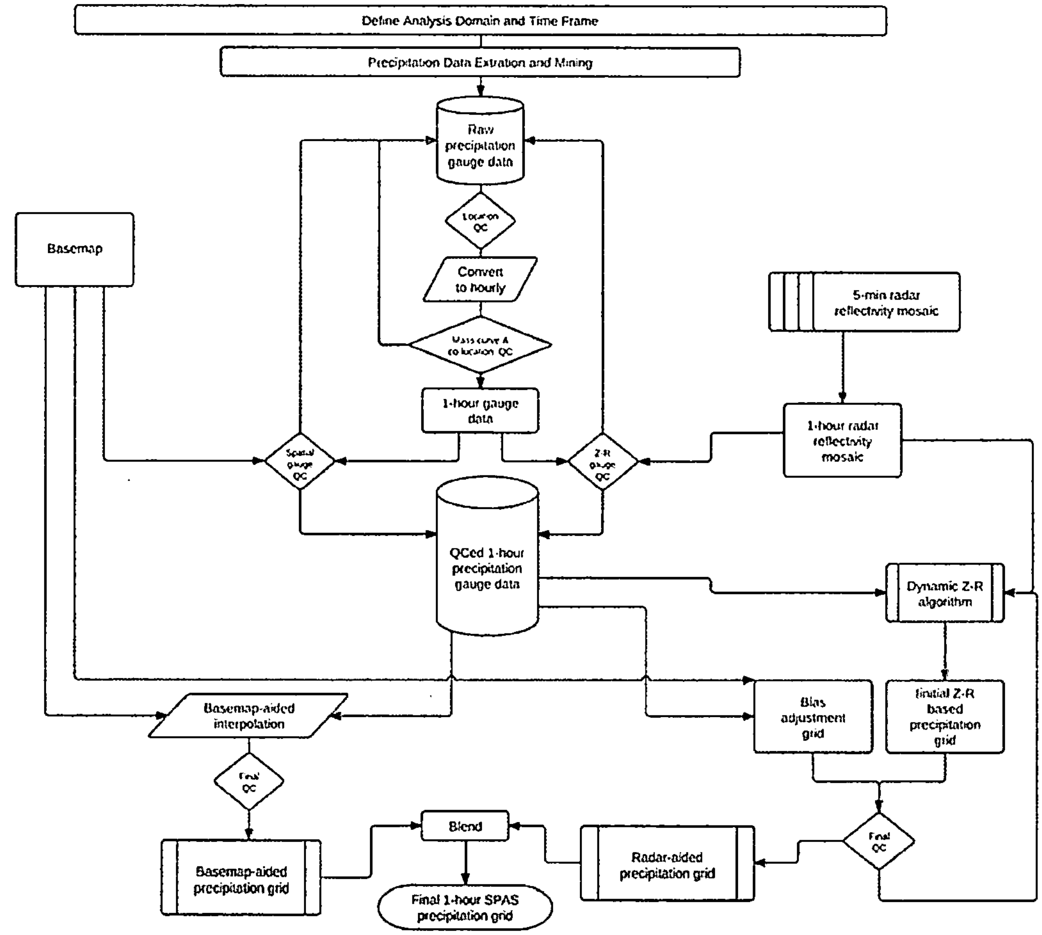


Figure G.1 SPAS flow chart

Setup

Prior to a SPAS analysis, careful definition of the storm analysis domain and time frame to be analyzed is established. Several considerations are made to ensure the domain (longitude-latitude box) and time frame are sufficient for the given application.

SPAS Analysis Domain

For PMP applications it is important to establish an analysis domain that completely encompasses a storm center, meanwhile hydrologic modeling applications are more concerned about a specific basin, watershed

or catchment. If radar data are available, then it is also important to establish an area large enough to encompass enough stations (minimum of ~30) to adequately derive reliable radar-precipitation intensity relationships (discussed later). The domain is defined by evaluating existing documentation on the storm as well as plotting and evaluating initial precipitation gauge data on a map. The analysis domain is defined to include as many hourly recording gauges as possible given their importance in timing. The domain must include enough of a buffer to accurately model the nested domain of interest. The domain is defined as a longitude-latitude (upper left and lower right corner) rectangular region.

SPAS Analysis Time Frame

Ideally, the analysis time frame, also referred to as the Storm Precipitation Period (SPP), will extend from a dry period through the target wet period then back into another dry period. This is to ensure that total storm precipitation amounts can be confidently associated with the storm in question and not contaminated by adjacent wet periods. If this is not possible, a reasonable time period is selected that is bounded by relatively lighter precipitation. The time frame of the hourly data must be sufficient to capture the full range of daily gauge observational periods for the daily observations to be disaggregated into estimated incremental hourly values (discussed later). For example, if a daily gauge takes observations at 8:00 AM, then the hourly data must be available from 8:00 AM the day prior. Given the configuration of SPAS, the minimum SPP is 72 hours and aligns midnight to midnight.

The core precipitation period (CPP) is a sub-set of the SPP and represents the time period with the most precipitation and the greatest number of reporting gauges. The CPP represents the time period of interest and where our confidence in the results is highest.

Data

The foundation of a SPAS analysis is the "ground truth" precipitation measurements. In fact, the level of effort involved in "data mining" and quality control represent over half of the total level of effort needed to conduct a complete storm analysis. SPAS operates with three primary data sets: precipitation gauge data, a "basemap" and, if available, radar data. Table G.1 conveys the variety of precipitation gauges usable by SPAS. For each gauge, the following elements are gathered, entered and archived into SPAS database:

- Station ID
- Station name
- Station type (H=hourly, D=Daily, S=Supplemental, etc.)
- Longitude in decimal degrees
- Latitude in decimal degrees
- Elevation in feet above MSL
- Observed precipitation
- Observation times
- Source
- If unofficial, the measurement equipment and/or method is also noted.

Based on the SPP and analysis domain, hourly and daily precipitation gauge data are extracted from our in-house database as well as the Meteorological Assimilation Data Ingest System (MADIS). Our in-house database contains data dating back to the late 1800s, while the MADIS system (described below) contains archived data back to 2002.

Hourly Precipitation Data

Our hourly precipitation database is largely comprised of data from NCDC TD-3240, but also precipitation data from other mesonets and meteorological networks (e.g. ALERT, Flood Control Districts, etc.) that we have collected and archived as part of previous studies. Meanwhile, MADIS provides data from a large number of networks across the U.S., including NOAA's HADS (Hydrometeorological Automated Data System), numerous mesonets, the Citizen Weather Observers Program (CWOP), departments of transportation, etc. (see http://madis.noaa.gov/mesonet_providers.html for a list of providers). Although our automatic data extraction is fast, cost-effective and efficient, it never captures all of the available precipitation data for a storm event. For this reason, a thorough "data mining" effort is undertaken to acquire all available data from sources such as U.S. Geological Survey (USGS), Remote Automated Weather Stations (RAWS), Community Collaborative Rain, Hail & Snow Network (CoCoRaHS), National Atmospheric Deposition Program (NADP), Clean Air Status and Trends Network (CASTNET), local observer networks, Climate Reference Network (CRN), Global Summary of the Day (GSD) and Soil Climate Analysis Network (SCAN). Unofficial hourly precipitation are gathered to give guidance on either timing or magnitude in areas otherwise void of precipitation data. The WeatherUnderground and MesoWest, two of the largest weather databases on the Internet, contain a considerable amount of official data, but also includes data from unofficial gauges.

Table G.1 Different precipitation gauge types used by SPAS

Precipitation Gauge Type	Description
Hourly	Hourly gauges with complete, or nearly complete, incremental hourly precipitation data.
Hourly estimated	Hourly gauges with some estimated hourly values, but otherwise reliable.
Hourly pseudo	Hourly gauges with reliable temporal precipitation data, but the magnitude is questionable in relation to co-located daily or supplemental gauge.
Daily	Daily gauge with complete data and known observation times.
Daily estimated	Daily gauges with some or all estimated data.
Supplemental	Gauges with unknown or irregular observation times, but reliable total storm precipitation data. (E.g. public reports, storms reports, "Bucket surveys", etc.)

Precipitation Gauge Type	Description
Supplemental estimated	Gauges with estimated total storm precipitation values based on other information (e.g. newspaper articles, stream flow discharge, inferences from nearby gauges, pre-existing total storm isohyetal maps, etc.)

Daily Precipitation Data

Our daily database is largely based on NCDC's TD-3206 (pre-1948) and TD-3200 (1948 through present) as well as SNOTEL data from NRCS. Since the late 1990s, the CoCoRaHS network of more than 15,000 observers in the U.S. has become a very important daily precipitation source. Other daily data are gathered from similar, but smaller gauge networks, for instance the High Spatial Density Precipitation Network in Minnesota.

As part of the daily data extraction process, the time of observation accompanies each measured precipitation value. Accurate observation times are necessary for SPAS to disaggregate the daily precipitation into estimated incremental values (discussed later). Knowing the observation time also allows SPAS to maintain precipitation amounts within given time bounds, thereby retaining known precipitation intensities. Given the importance of observation times, efforts are taken to insure the observation times are accurate. Hardcopy reports of "Climatological Data," scanned observational forms (available on-line from the NCDC) and/or gauge metadata forms have proven to be valuable and accurate resources for validating observation times. Furthermore, erroneous observation times are identified in the mass-curve quality-control procedure (discussed later) and can be corrected at that point in the process.

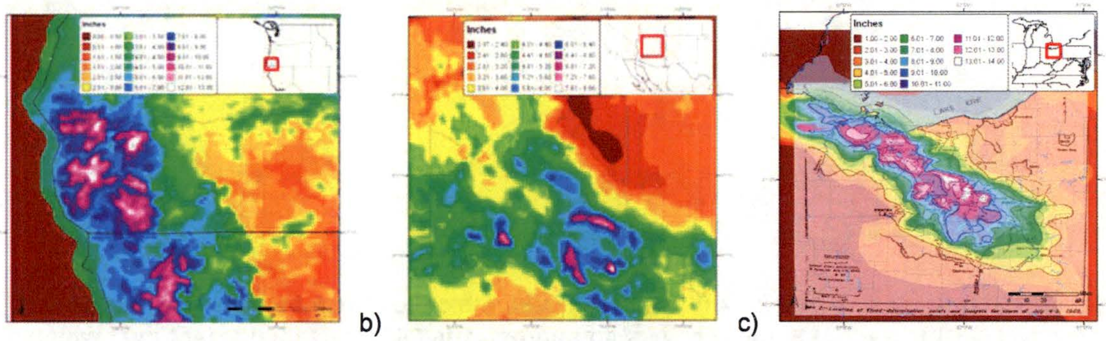
Supplemental Precipitation Gauge Data

For gauges with unknown or irregular observation times, the gauge is considered a "supplemental" gauge. A supplemental gauge can either be added to the storm database with a storm total and the associated SPP as the temporal bounds or as a gauge with the known, but irregular observation times and associated precipitation amounts. For instance, if all that is known is 3 inches fell between 0800-0900, then that information can be entered. Gauges or reports with nothing more than a storm total are often abundant, but to use them, it is important the precipitation is only from the storm period in question. Therefore, it is ideal to have the analysis time frame bounded by dry periods.

One of the most valuable sources of data, if available, is from "bucket surveys," which provide comprehensive lists of precipitation measurements collected during a post-storm field exercise. Although some bucket survey amounts are not from conventional precipitation gauges, they provide important information, especially in areas lacking data. Particularly for PMP-storm analysis applications, it is customary to accept extreme, but valid non-standard precipitation values (such as bottles and other open containers that catch rainfall) in order to capture the highest precipitation values.

Basemap

“Basemaps” are independent grids of spatially distributed weather or climate variables that are used to govern the spatial patterns of the hourly precipitation. The basemap also governs the spatial resolution of the final SPAS grids, unless radar data are available/used to govern the spatial resolution. Note that a base map is not required as the hourly precipitation patterns can be based on station characteristics and an inverse distance weighting technique (discussed later). Basemaps in complex terrain are often based on the PRISM mean monthly precipitation (Figure G.2a) or Hydrometeorological Design Studies Center precipitation frequency grids (Figure G.2b) given they resolve orographic enhancement areas and micro-climates at a spatial resolution of 30-seconds (about 800 m). Basemaps of this nature in flat terrain are not as effective given small influence terrain on precipitation distribution in these areas. Therefore, basemaps for SPAS analyses in flat terrain are often developed from pre-existing (hand-drawn) isohyetal patterns (Figure G.2c), composite radar imagery or a blend of both.



a) b) c)

Figure G.2 Sample SPAS “basemaps:” (a) A pre-existing (USGS) isohyetal pattern across flat terrain (SPAS #1209), (b) PRISM mean monthly (October) precipitation (SPAS #1192) and (c) A 100-year 24-hour precipitation grid from NOAA Atlas 14 (SPAS #1138)

Radar Data

For storms occurring since approximately the mid-1990s, weather radar data are available to supplement the SPAS analysis. A fundamental requirement for high quality radar-estimated precipitation is a high quality radar mosaic, which is a seamless collection of concurrent weather radar data from individual radar sites, however in some cases a single radar is sufficient (i.e. for a small area size storm event such as a thunderstorm). Weather radar data have been in use by meteorologists since the 1960s to estimate precipitation depths, but it was not until the early 1990s that new, more accurate NEXRAD Doppler radar (WSR88D) was placed into service across the United States. Currently, efforts are underway to convert the WSR88D radars to dual polarization (DualPol) radar. Today, NEXRAD radar coverage of the contiguous United States is comprised of 159 operational sites and there are 30 in Canada. Each U.S. radar covers an approximate 285 mile (460 km) radial extent while Canadian radars have approximately 256 km (138 nautical miles) radial extent over which their radar can detect precipitation (see Figure G.3). The primary vendor of NEXRAD weather radar data for SPAS is Weather Decision Technologies, Inc. (WDT), who accesses, mosaics, archives and quality-controls NEXRAD radar data from NOAA and Environment Canada. SPAS utilizes Level II NEXRAD radar reflectivity data in units of dBZ, available every 5-minutes in the U.S. and 10-minutes in Canada

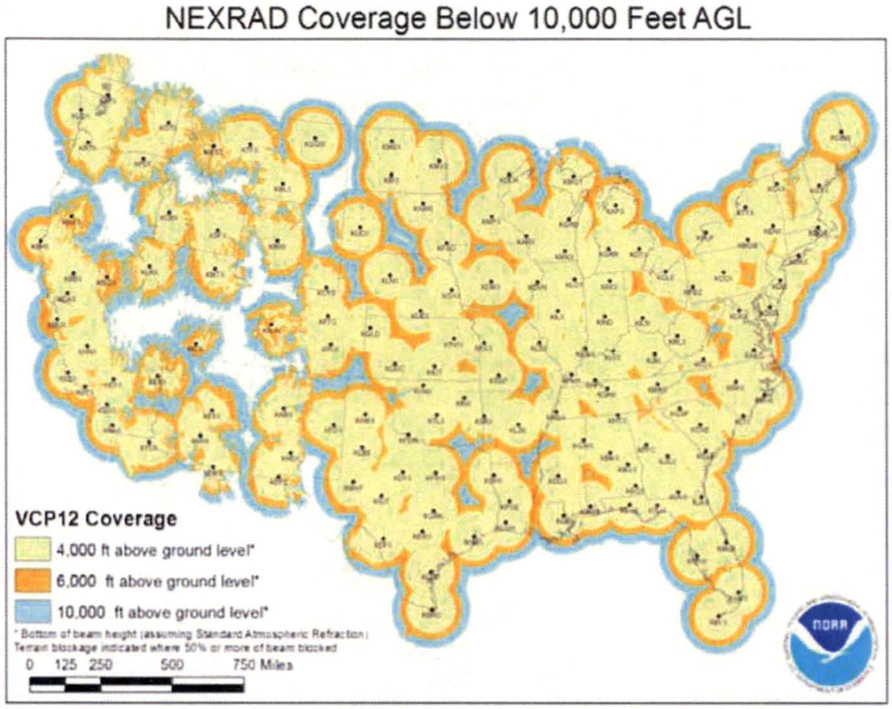


Figure G.3 U.S. radar locations and their radial extents of coverage below 10,000 feet above ground level (AGL). Each U.S. radar covers an approximate 285 mile radial extent over which the radar can detect precipitation.

The WDT and National Severe Storms Lab (NSSL) Radar Data Quality Control Algorithm (RDQC) removes non-precipitation artifacts from base Level–II radar data and remaps the data from polar coordinates to a Cartesian (latitude/longitude) grid. Non-precipitation artifacts include ground clutter, bright banding, sea clutter, anomalous propagation, sun strobes, clear air returns, chaff, biological targets, electronic interference and hardware test patterns. The RDQC algorithm uses sophisticated data processing and a Quality Control Neural Network (QCNN) to delineate the precipitation echoes caused by radar artifacts (Lakshmanan and Valente 2004). Beam blockages due to terrain are mitigated by using 30 meter digital elevation model data to compute and then discard data from a radar beam that clears the ground by less than 50 meters and incurs more than 50% power blockage. A clear-air echo removal scheme is applied to radars in clear-air mode when there is no precipitation reported from observation gauges within the vicinity of the radar. In areas of radar coverage overlap, a distance weighting scheme is applied to assign reflectivity to each grid cell, for multiple vertical levels. This scheme is applied to data from the nearest radar that is unblocked by terrain.

Once the data from individual radars have passed through the RDQC, they are merged to create a seamless mosaic for the United States and southern Canada as shown in Figure G.4. A multi-sensor quality control can be applied by post-processing the mosaic to remove any remaining "false echoes". This technique uses observations of infra-red cloud top temperatures by GOES satellite and surface temperature to create a precipitation/no-precipitation mask. Figure G.4b shows the impact of WDT's quality control measures. Upon completing all QC, WDT converts the radar data from its native polar coordinate projection (1 degree x 1.0 km) into a longitude-latitude Cartesian grid (based on the WGS84 datum), at a spatial resolution of

~1/3rd mi^2 for processing in SPAS.

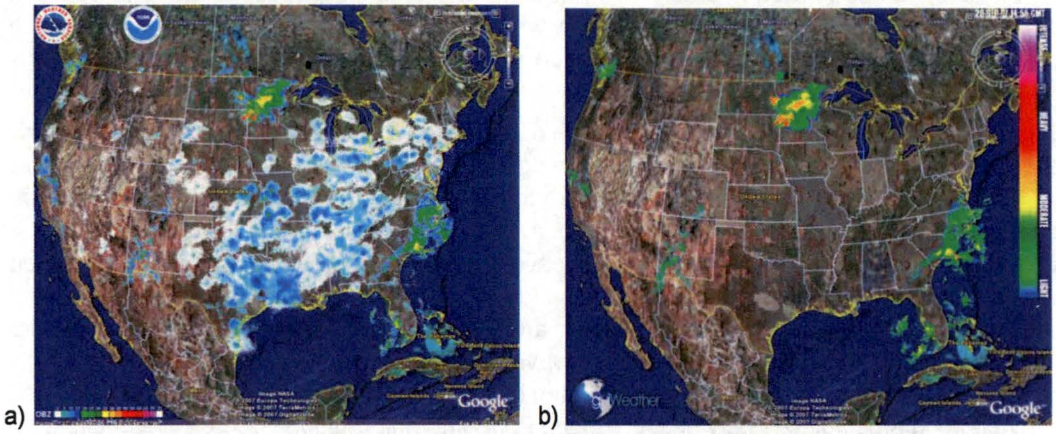


Figure G.4 (a) Level-II radar mosaic of CONUS radar with no quality control, (b) WDT quality controlled Level-II radar mosaic

SPAS conducts further QC on the radar mosaic by infilling areas contaminated by beam blockages. Beam blocked areas are objectively determined by evaluating total storm reflectivity grid which naturally amplifies areas of the SPAS analysis domain suffering from beam blockage as shown in Figure G.5.

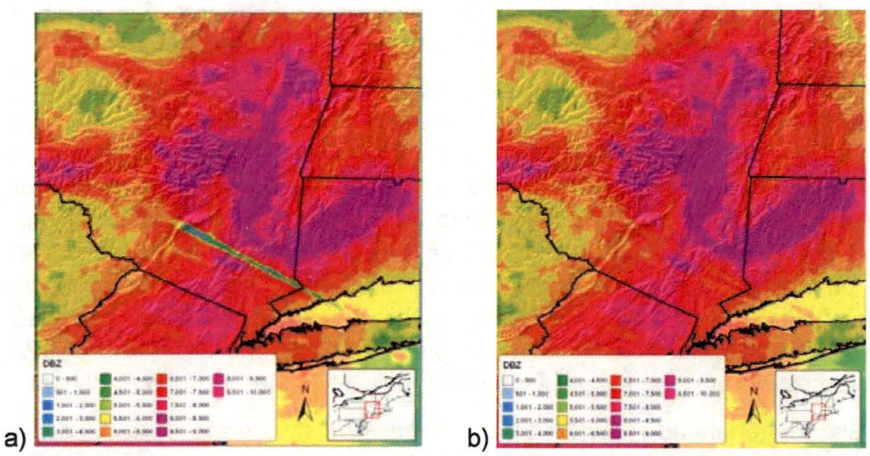


Figure G.5: Illustration of SPAS-beam blockage infilling where (a) is raw, blocked radar and (b) is filled for a 42-hour storm event

Methodology

Daily and Supplemental Precipitation to Hourly

To obtain one hour temporal resolutions and utilize all gauge data, it is necessary to disaggregate the daily and supplemental precipitation observations into estimated hourly amounts. This process has traditionally been accomplished by distributing (temporally) the precipitation at each daily/supplemental gauge in

accordance to a single nearby hourly gauge (Thiessen polygon approach). However, this may introduce biases and not correctly represent hourly precipitation at daily/supplemental gauges situated in-between hourly gauges. Instead, SPAS uses a spatial approach by which the estimated hourly precipitation at each daily and supplemental gauge is governed by a distance weighted algorithm of all nearby true hourly gauges.

To disaggregate (i.e. distribute) daily/supplemental gauge data into estimate hourly values, the true hourly gauge data are first evaluated and quality controlled using synoptic maps, nearby gauges, orographic effects, gauge history and other documentation on the storm. Any problems with the hourly data are resolved, and when possible/necessary accumulated hourly values are distributed. If an hourly value is missing, the analyst can choose to either estimate it or leave it missing for SPAS to estimate later based on nearby hourly gauges. At this point in the process, pseudo (hourly) gauges can be added to represent precipitation timing in topographically complex locations, areas with limited/no hourly data or to capture localized convention. To adequately capture the temporal variations of the precipitation, a pseudo hourly gauge is sometimes necessary. A pseudo gauge is created by distributing the precipitation at a co-located daily gauge or by creating a completely new pseudo gauge from other information such as inferences from COOP observation forms, METAR visibility data (if hourly precipitation are not already available), lightning data, satellite data, or radar data. Often radar data are the best/only choice for creating pseudo hourly gauges, but this is done cautiously given the potential differences (over-shooting of the radar beam equating to erroneous precipitation) between radar data and precipitation. In any case, the pseudo hourly gauge is flagged so SPAS only uses it for timing and not magnitude. Care is taken to ensure hourly pseudo gauges represent justifiably important physical and meteorological characteristics before being incorporated into the SPAS database. Although pseudo gauges provide a very important role, their use is kept to a minimum. The importance of insuring the reliability of every hourly gauge cannot be over emphasized. All of the final hourly gauge data, including pseudos, are included in the hourly SPAS precipitation database.

Using the hourly SPAS precipitation database, each hourly precipitation value is converted into a percentage that represents the incremental hourly precipitation divided by the total SPP precipitation. The GIS-ready x-y-z file is constructed for each hour and it includes the latitude (x), longitude(y) and the percent of precipitation (z) for a particular hour. Using the GRASS GIS, an inverse-distance-weighting squared (IDW) interpolation technique is applied to each of the hourly files. The result is a continuous grid with percentage values for the entire analysis domain, keeping the grid cells on which the hourly gauge resides faithful to the observed/actual percentage. Since the percentages typically have a high degree of spatial autocorrelation, the spatial interpolation has skill in determining the percentages between gauges, especially since the percentages are somewhat independent of the precipitation magnitude. The end result is a GIS grid for each hour that represents the percentage of the SPP precipitation that fell during that hour.

After the hourly percentage grids are generated and QC'd for the entire SPP, a program is executed that converts the daily/supplemental gauge data into incremental hourly data. The timing at each of the daily/supplemental gauges is based on (1) the daily/supplemental gauge observation time, (2) daily/supplemental precipitation amount and (3) the series of interpolated hourly percentages extracted from grids (described above).

This procedure is detailed in Figure G.6 below. In this example, a supplemental gauge reported 1.40" of precipitation during the storm event and is located equal distance from the three surrounding hourly recording gauges. The procedure steps are:

Step 1. For each hour, extract the percent of SPP from the hourly gauge-based percentage at the location of the daily/supplemental gauge. In this example, assume these values are the average of all the hourly gauges.

Step 2. Multiply the individual hourly percentages by the total storm precipitation at the daily/supplemental gauge to arrive at estimated hourly precipitation at the daily/supplemental gauge. To make the daily/supplemental accumulated precipitation data faithful to the daily/supplemental observations, it is sometimes necessary to adjust the hourly percentages so they add up to 100% and account for 100% of the daily observed precipitation.

	Hour						
Precipitation	1	2	3	4	5	6	Total
Hourly station 1	0.02	0.12	0.42	0.50	0.10	0.00	1.16
Hourly station 2	0.01	0.15	0.48	0.62	0.05	0.01	1.32
Hourly station 3	0.00	0.18	0.38	0.55	0.20	0.05	1.36
	Hour						
Percent of total storm precip.	1	2	3	4	5	6	Total
Hourly station 1	2%	10%	36%	43%	9%	0%	100%
Hourly station 2	1%	11%	36%	47%	4%	1%	100%
Hourly station 3	0%	13%	28%	40%	15%	4%	100%
Average	*1%*	*12%*	*34%*	*44%*	*9%*	*1%*	*100%*
Storm total precipitation at daily gauge				1.40			
	Hour						
Precipitation (estimated)	1	2	3	4	5	6	Total
Daily station	0.01	0.16	0.47	0.61	0.13	0.02	1.40

Figure G.6 Example of disaggregation of daily precipitation into estimated hourly precipitation based on three (3) surrounding hourly recording gauges

In cases where the hourly grids do not indicate any precipitation falling during the daily/supplemental gauge observational period, yet the daily/supplemental gauge reported precipitation, the daily/supplemental total precipitation is evenly distributed throughout the hours that make up the observational period; although this does not happen very often, this solution is consistent with NWS procedures. However, the SPAS analyst is notified of these cases in a comprehensive log file, and in most cases they are resolvable, sometimes with a pseudo hourly gauge.

Gauge Quality Control

Exhaustive quality control measures are taken throughout the SPAS analysis. Below are a few of the most significant QC measures taken.

Mass Curve Check

A mass curve-based QC-methodology is used to ensure the timing of precipitation at all gauges is consistent with nearby gauges. SPAS groups each gauge with the nearest four gauges (regardless of type) into a single file. These files are subsequently used in software for graphing and evaluation. Unusual characteristics in the mass curve are investigated and the gauge data corrected, if possible and warranted. See Figure G.7 for an example.

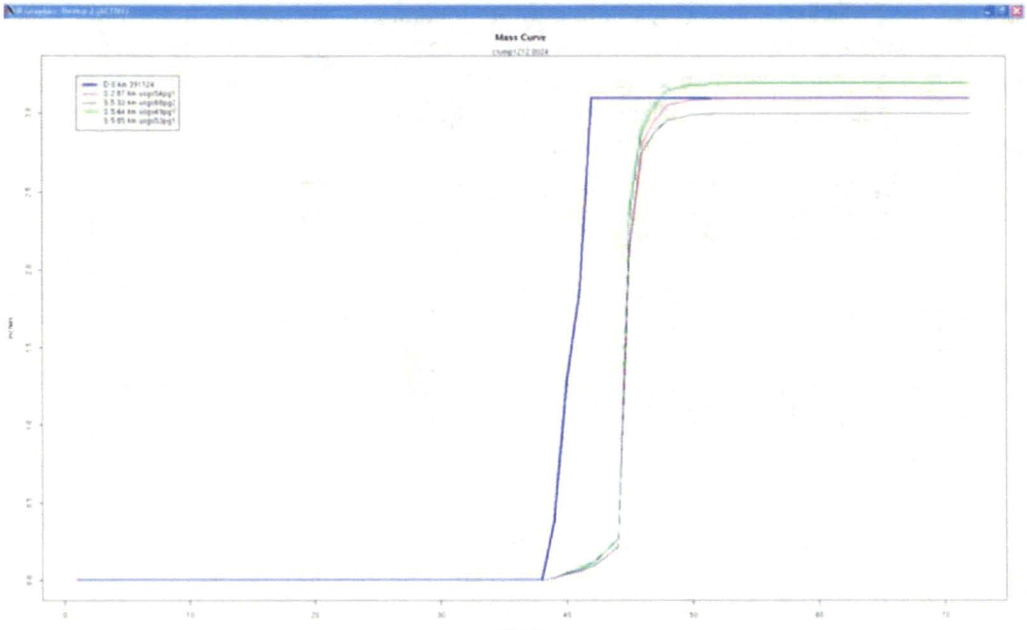


Figure G.7 Sample mass curve plot depicting a precipitation gauge with an erroneous observation time (blue line). X-axis is the SPAS index hour and the y-axis is inches. The statistics in the upper left denote gauge type, distance from target gauge (in km), and gauge ID. In this example, the center gauge (blue line) was found to have an observation error/shift of 1 day.

Gauge Mis-location Check

Although the gauge elevation is not explicitly used in SPAS, it is however used as a means of QC'ing gauge location. Gauge elevations are compared to a high-resolution 15-second digital elevation model to identify gauges with large differences, which may indicate erroneous longitude and/or latitude values.

Co-located Gauge QC

Care is also taken to establish the most accurate precipitation depths at all co-located gauges. In general, where a co-located gauge pair exists, the highest precipitation is accepted (if deemed accurate). If the hourly gauge reports higher precipitation, then the co-located daily (or supplemental) is removed from the analysis since it would not add anything to the analysis. Often daily (or supplemental) gauges report greater precipitation than a co-located hourly station since hourly tipping bucket gauges tend to suffer from gauge under-catch, particularly during extreme events, due to loss of precipitation during tips. In these cases the daily/supplemental is retained for the magnitude and the hourly used as a pseudo hourly gauge for timing.

Large discrepancies between any co-located gauges are investigated and resolved since SPAS can only utilize a single gauge magnitude at each co-located site.

Spatial Interpolation

At this point the QC'd observed hourly and disaggregated daily/supplemental hourly precipitation data are spatially interpolated into hourly precipitation grids. SPAS has three options for conducting the hourly

precipitation interpolation, depending on the terrain and availability of radar data, thereby allowing SPAS to be optimized for any particular storm type or location. Figure G.8 depicts the results of each spatial interpolation methodology based on the same precipitation gauge data.

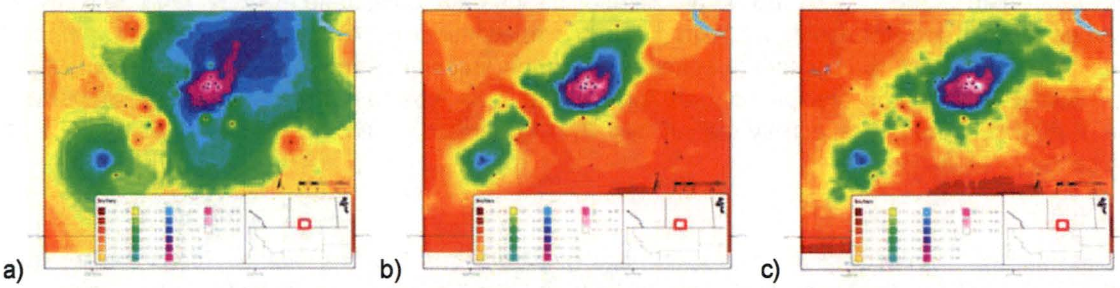


Figure G.8 Depictions of total storm precipitation based on the three SPAS interpolation methodologies for a storm (SPAS #1177, Vanguard, Canada) across flat terrain: (a) no basemap, (b) basemap-aided and (c) radar

Basic Approach

The basic approach interpolates the hourly precipitation point values to a grid using an inverse distance weighting squared GIS algorithm. This is sometimes the best choice for convective storms over flat terrain when radar data are not available, yet high gauge density instills reliable precipitation patterns. This approach is rarely used.

Basemap Approach

Another option includes use of a "basemap", also known as a climatologically-aided interpolation (Hunter 2005). As noted before, the spatial patterns of the basemap govern the interpolation between points of hourly precipitation estimates, while the actual hourly precipitation values govern the magnitude. This approach to interpolating point data across complex terrain is widely used. In fact, it was used extensively by the NWS during their storm analysis era from the 1940s through the 1970s (USACE 1973, Hansen et al., 1988, Corrigan et al., 1999).

In application, the hourly precipitation gauge values are first normalized by the corresponding grid cell value of the basemap before being interpolated. The normalization allows information and knowledge from the basemap to be transferred to the spatial distribution of the hourly precipitation. Using an IDW squared algorithm, the normalized hourly precipitation values are interpolated to a grid. The resulting grid is then multiplied by the basemap grid to produce the hourly precipitation grid. This is repeated each hour of the storm.

Radar Approach

The coupling of SPAS with NEXRAD provides the most accurate method of spatially and temporally distributing precipitation. To increase the accuracy of the results however, quality-controlled precipitation observations are used for calibrating the radar reflectivity to rain rate relationship (Z-R relationship) each hour instead of assuming a default Z-R relationship. Also, spatial variability in the Z-R relationship is accounted for through local bias corrections (described later). The radar approach involves several steps, each briefly described below. The radar approach cannot operate alone – either the basic or basemap approach must be completed before radar data can be incorporated.

Z-R Relationship

SPAS derives high quality precipitation estimates by relating quality controlled level–II NEXRAD radar reflectivity radar data with quality-controlled precipitation gauge data to calibrate the Z-R (radar reflectivity, Z, and precipitation, R) relationship. Optimizing the Z-R relationship is essential for capturing temporal changes in the Z-R. Most current radar-derived precipitation techniques rely on a constant relationship between radar reflectivity and precipitation rate for a given storm type (e.g. tropical, convective), vertical structure of reflectivity and/or reflectivity magnitudes. This non-linear relationship is described by the Z-R equation below:

$$Z = A\,R^{b} \qquad (1)$$

Where Z is the radar reflectivity (measured in units of dBZ), R is the precipitation (precipitation) rate (millimeters per hour), A is the "multiplicative coefficient" and b is the "power coefficient". Both A and b are directly related to the rain drop size distribution (DSD) and rain drop number distribution (DND) within a cloud (Martner and Dubovskiy 2005). The variability in the results of Z versus R is a direct result of differing DSD, DND and air mass characteristics (Dickens 2003). The DSD and DND are determined by complex interactions of microphysical processes that fluctuate regionally, seasonally, daily, hourly, and even within the same cloud. For these reasons, SPAS calculates an optimized Z-R relationship across the analysis domain each hour, based on observed precipitation rates and radar reflectivity (see Figure G.9).

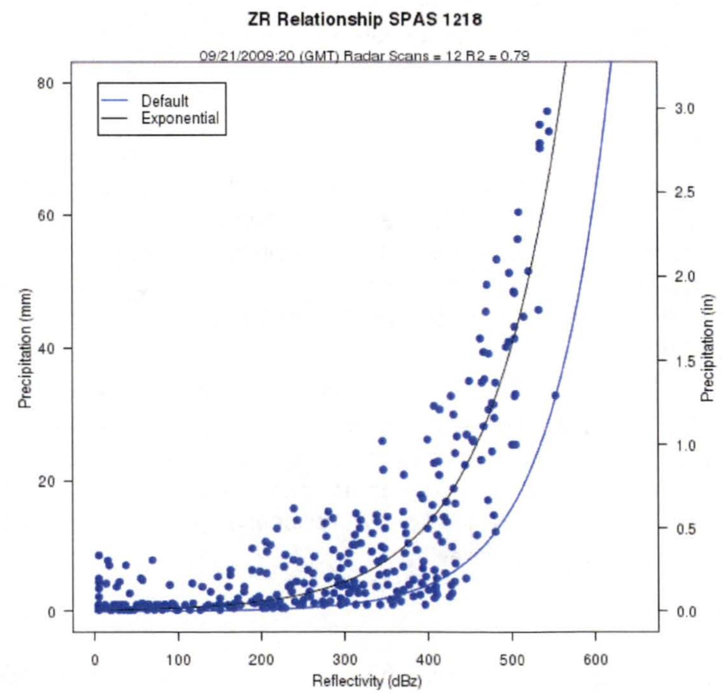


Figure G.9 Example SPAS (denoted as "Exponential") vs. default Z-R relationship (SPAS #1218, Georgia September 2009)

The National Weather Service (NWS) utilizes different default Z-R algorithms, depending on the type of precipitation event, to estimate precipitation from NEXRAD radar reflectivity data across the United States

(see Figure G.10) (Baeck and Smith 1998 and Hunter 1999). A default Z-R relationship of Z = 300R1.4 is the primary algorithm used throughout the continental U.S. However, it is widely known that this, compared to unadjusted radar-aided estimates of precipitation, suffers from deficiencies that may lead to significant over or under-estimation of precipitation.

RELATIONSHIP	Optimum for:	Also recommended for:
Marshall-Palmer ($z=200R^{1.6}$)	General stratiform precipitation	
East-Cool Stratiform ($z=130R^{2.0}$)	Winter stratiform precipitation - east of continental divide	Orographic rain - East
West-Cool Stratiform ($z=75R^{2.0}$)	Winter stratiform precipitation - west of continental divide	Orographic rain - West
WSR-88D Convective ($z=300R^{1.4}$)	Summer deep convection	Other non-tropical convection
Rosenfeld Tropical ($z=250R^{1.2}$)	Tropical convective systems	

Figure G.10 Commonly used Z-R algorithms used by the NWS

Instead of adopting a standard Z-R, SPAS utilizes a least squares fit procedure for optimizing the Z-R relationship each hour of the SPP. The process begins by determining if sufficient (minimum 12) observed hourly precipitation and radar data pairs are available to compute a reliable Z-R. If insufficient (<12) gauge pairs are available, then SPAS adopts the previous hour Z-R relationship, if available, or applies a user-defined default Z-R algorithm. If sufficient data are available, the one hour sum of NEXRAD reflectivity (Z) is related to the 1-hour precipitation at each gauge. A least-squares-fit exponential function using the data points is computed. The resulting best-fit, one hour-based Z-R is subjected to several tests to determine if the Z-R relationship and its resulting precipitation rates are within a certain tolerance based on the R-squared fit measure and difference between the derived and default Z-R precipitation results. Experience has shown the actual Z-R versus the default Z-R can be significantly different (Figure G.11). These Z-R relationships vary by storm type and location. A standard output of all SPAS analyses utilizing NEXRAD includes a file with each hour's adjusted Z-R relationship as calculated through the SPAS program.

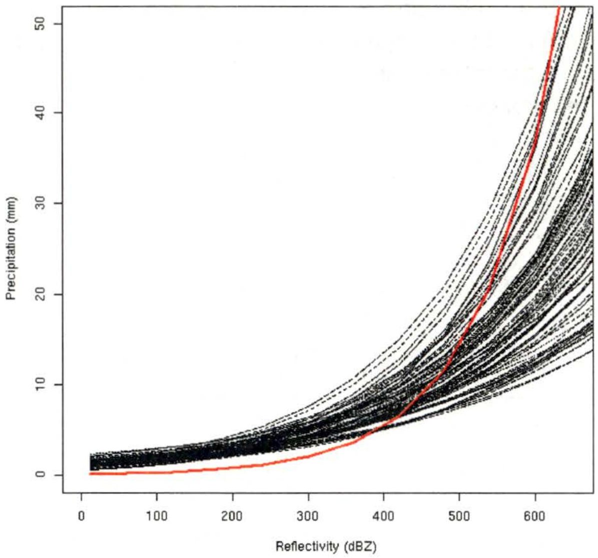


Figure G.11 Comparison of the SPAS optimized hourly Z-R relationships (black lines) versus a default Z=75R2.0 Z-R relationship (red line) for a period of 99 hours for a storm over southern California.

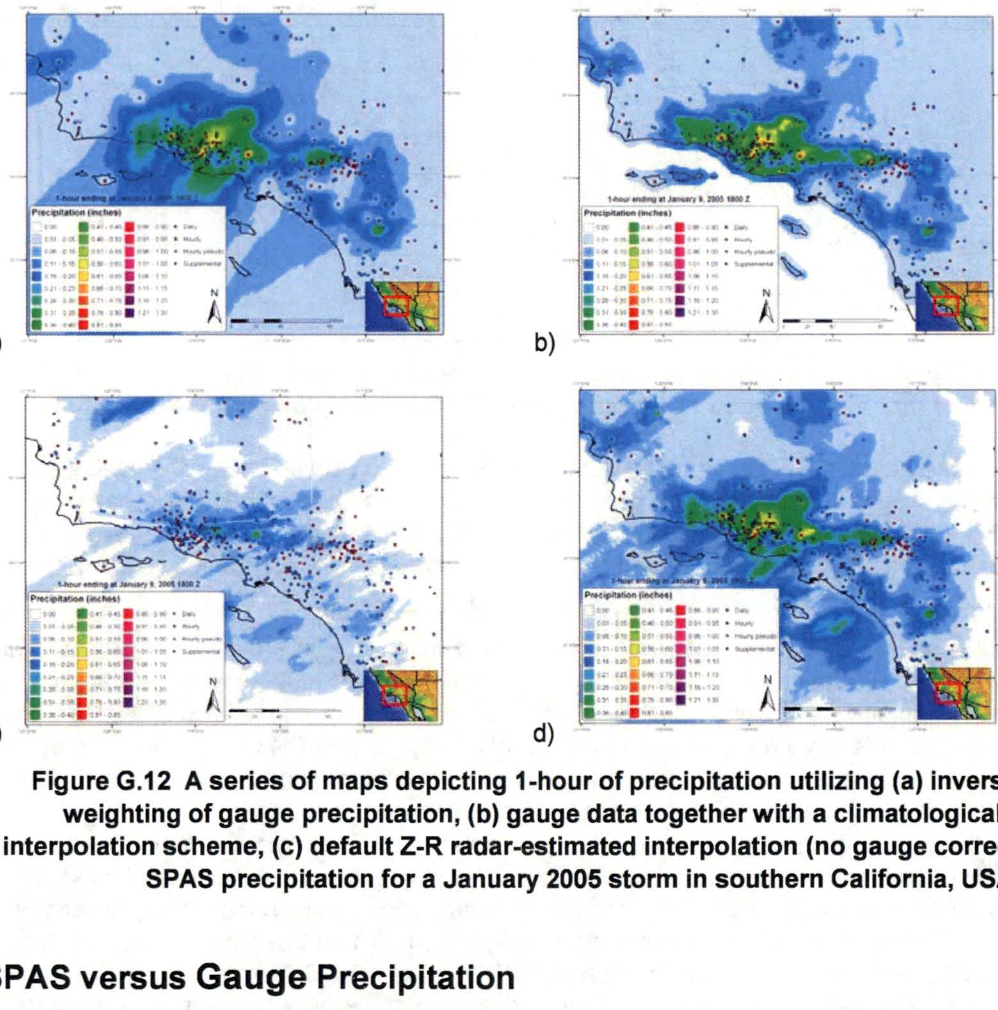
Radar-aided Hourly Precipitation Grids

Once a mathematically optimized hourly Z-R relationship is determined, it is applied to the total hourly Z grid to compute an initial precipitation rate (inches/hour) at each grid cell. To account for spatial differences in the Z-R relationship, SPAS computes residuals, the difference between the initial precipitation analysis (via the Z-R equation) and the actual "ground truth" precipitation (observed – initial analysis), at each gauge. The point residuals, also referred to as local biases, are normalized and interpolated to a residual grid using an inverse distance squared weighting algorithm. A radar-based hourly precipitation grid is created by adding the residual grid to the initial grid; this allows the precipitation at the grid cells for which gauges are "on" to be true and faithful to the gauge measurement. The pre-final radar-aided precipitation grid is subject to some final, visual QC checks to ensure the precipitation patterns are consistent with the terrain; these checks are particularly important in areas of complex terrain where even QC'd radar data can be unreliable. The next incremental improvement with SPAS program will come as the NEXRAD radar sites are upgraded to dual-polarimetric capability.

Radar- and Basemap-Aided Hourly Precipitation Grids

At this stage of the radar approach, a radar- and basemap-aided hourly precipitation grid exists for each hour. At locations with precipitation gauges, the grids are equal, however elsewhere the grids can vary for a number of reasons. For instance, the basemap-aided hourly precipitation grid may depict heavy precipitation in an area of complex terrain, blocked by the radar, whereas the radar-aided hourly precipitation grid may suggest little, if any, precipitation fell in the same area. Similarly, the radar-aided hourly precipitation grid may depict an area of heavy precipitation in flat terrain that the basemap-approach missed since the area of heavy precipitation occurred in an area without gauges. SPAS uses an algorithm to compute the hourly precipitation at each pixel given the two results. Areas that are completely blocked

from a radar signal are accounted for with the basemap-aided results (discussed earlier). Precipitation in areas with orographically effective terrain and reliable radar data are governed by a blend of the basemap- and radar-aided precipitation. Elsewhere, the radar-aided precipitation is used exclusively. This blended approach has proven effective for resolving precipitation in complex terrain, yet retaining accurate radar-aided precipitation across areas where radar data are reliable. Figure G.12 illustrates the evolution of final precipitation from radar reflectivity in an area of complex terrain in southern California.



a) b) c) d)

Figure G.12 A series of maps depicting 1-hour of precipitation utilizing (a) inverse distance weighting of gauge precipitation, (b) gauge data together with a climatologically-aided interpolation scheme, (c) default Z-R radar-estimated interpolation (no gauge correction) and (d) SPAS precipitation for a January 2005 storm in southern California, USA

SPAS versus Gauge Precipitation

Performance measures are computed and evaluated each hour to detect errors and inconsistencies in the analysis. The measures include: hourly Z-R coefficients, observed hourly maximum precipitation, maximum gridded precipitation, hourly bias, hourly mean absolute error (MAE), root mean square error (RMSE), and hourly coefficient of determination (r^2).

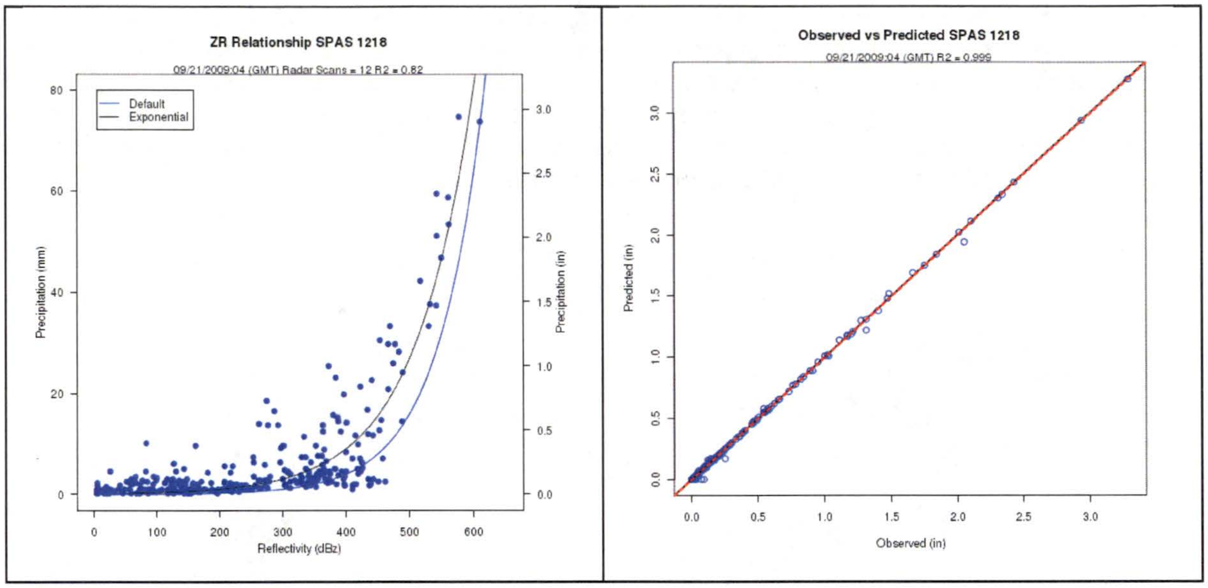


Figure G.13 Z-R plot (a), where the blue line is the SPAS derived Z-R and the black line is the default Z-R, and the (b) associated observed versus SPAS scatter plot at gauge locations.

Comparing SPAS-calculated precipitation (R_{spas}) to observed point precipitation depths at the gauge locations provides an objective measure of the consistency, accuracy and bias. Generally speaking SPAS is usually within 5% of the observed precipitation (see Figure G.13). Less-than-perfect correlations between SPAS precipitation depths and observed precipitation at gauged locations could be the result of any number of issues, including:

- **Point versus area:** A rain gauge observation represents a much smaller area than the area sampled by the radar. The area that the radar is sampling is approximately 1 km2, whereas a standard rain gauge has an opening 8 inches in diameter, hence it only samples approximately 8.0x10-9 km2. Furthermore, the radar data represents an average reflectivity (Z) over the grid cell, when in fact the reflectivity can vary across the 1 km2 grid cell. Therefore, comparing a grid cell radar derived precipitation value to a gauge (point) precipitation depth measured may vary.
- **Precipitation gauge under-catch:** Although we consider gauge data "ground truth," we recognize gauges themselves suffer from inaccuracies. Precipitation gauges, shielded and unshielded, inherently underestimate total precipitation due to local airflow, wind under-catch, wetting, and evaporation. The wind under-catch errors are usually around 5% but can be as large as 40% in high winds (Guo et al., 2001, Duchon and Essenberg 2001, Ciach 2003, Tokay et al., 2010). Tipping buckets miss a small amount of precipitation during each tip of the bucket due to the bucket travel and tip time. As precipitation intensities increase, the volumetric loss of precipitation due to tipping tends to increase. Smaller tipping buckets can have higher volumetric losses due to higher tip frequencies, but on the other hand capture higher precision timing.
- **Radar Calibration:** NEXRAD radars calibrate reflectivity every volume scan, using an internally generated test. The test determines changes in internal variables such as beam power and path loss of the receiver signal processor since the last off-line calibration. If this value becomes large, it is likely that there is a radar calibration error that will translate into less reliable precipitation estimates. The calibration test is supposed to maintain a reflectivity precision of 1

dBZ. A 1 dBZ error can result in an error of up to 17% in Rspas using the default Z-R relationship Z=300R1.4. Higher calibration errors will result in higher Rspas errors. However, by performing correlations each hour, the calibration issue is minimized in SPAS.

- **Attenuation:** Attenuation is the reduction in power of the radar beams' energy as it travels from the antenna to the target and back. It is caused by the absorption and the scattering of power from the beam by precipitation. Attenuation can result in errors in Z as large as 1 dBZ especially when the radar beam is sampling a large area of heavy precipitation. In some cases, storm precipitation is so intense (>12 inches/hour) that individual storm cells become "opaque" and the radar beam is totally attenuated. Armed with sufficient gauge data however, SPAS will overcome attenuation issues.
- **Range effects:** The curvature of the Earth and radar beam refraction result in the radar beam becoming more elevated above the surface with increasing range. With the increased elevation of the radar beam comes a decrease in Z values due to the radar beam not sampling the main precipitation portion of the cloud (i.e. "over topping" the precipitation and/or cloud altogether). Additionally, as the radar beam gets further from the radar, it naturally samples a larger and larger area, therefore amplifying point versus area differences (described above).
- **Radar Beam Occultation/Ground Clutter:** Radar occultation (beam blockage) results when the radar beam's energy intersects terrain features as depicted in Figure G.14. The result is an increase in radar reflectivity values that can result in higher than normal precipitation estimates. The WDT processing algorithms account for these issues, but SPAS uses GIS spatial interpolation functions to infill areas suffering from poor or no radar coverage.
- **Anomalous Propagation (AP):** AP is false reflectivity echoes produced by unusual rates of refraction in the atmosphere. WDT algorithms remove most of the AP and false echoes, however in extreme cases the air near the ground may be so cold and dense that a radar beam that starts out moving upward is bent all the way down to the ground. This produces erroneously strong echoes at large distances from the radar. Again, equipped with sufficient gauge data, the SPAS bias corrections will overcome AP issues.

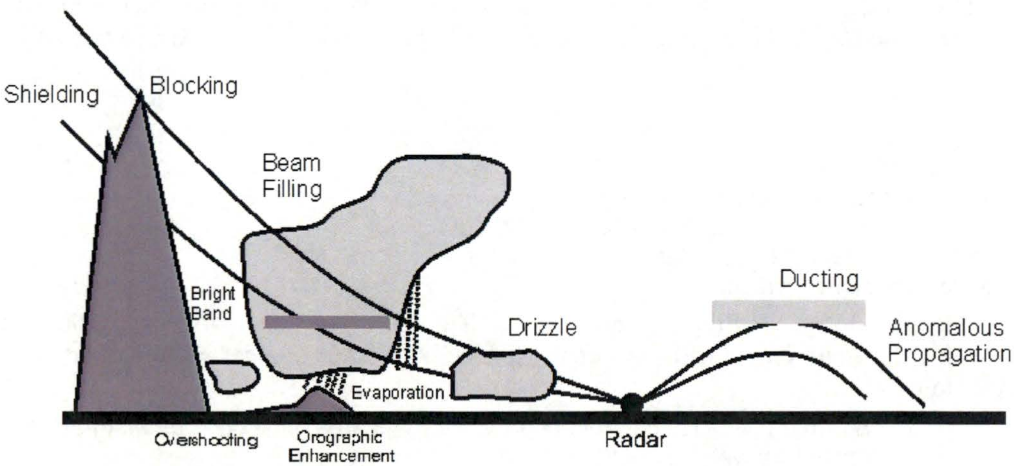


Figure G.14 Depiction of radar artifacts. (Source: Wikipedia)

SPAS is designed to overcome many of these short-comings by carefully using radar data for defining the spatial patterns and relative magnitudes of precipitation, but allowing measured precipitation values ("ground truth") at gauges to govern the magnitude. When absolutely necessary, the observed precipitation values at gauges are nudged up (or down) to force SPAS results to be consistent with observed gauge

values. Nudging gauge precipitation values helps to promote better consistency between the gauge value and the gridcell value, even though these two values sometimes should not be the same since they are sampling different area sizes. For reasons discussed in the "SPAS versus Gauge Precipitation" section, the gauge value and gridcell value can vary. Plus, SPAS is designed to toss observed individual hourly values that are grossly inconsistent with radar data, hence driving a difference between the gauge and gridcell. In general, when the gauge and gridcell value differ by more than 15% and/or 0.50 inches, and the gauge data have been validated, then it is justified to artificially increase or decrease slightly the observed gauge value to "force" SPAS to derive a gridcell value equal to the observed value. Sometimes simply shifting the gauge location to an adjacent gridcell resolves the problems. Regardless, a large gauge versus gridcell difference is a "red flag" and sometimes the result of an erroneous gauge value or a mis-located gauge, but in some cases the difference can only be resolved by altering the precipitation value.

Before results are finalized, a precipitation intensity check is conducted to ensure the spatial patterns and magnitudes of the maximum storm intensities at 1-, 6-, 12-, etc. hours are consistent with surrounding gauges and published reports. Any erroneous data are corrected and SPAS re-run. Considering all of the QA/QC checks in SPAS, it typically requires 5-15 basemap SPAS runs and, if radar data are available, another 5-15 radar-aided runs, to arrive at the final output.

Test Cases

To check the accuracy of the DAD software, three test cases were evaluated.

"Pyramidville" Storm

The first test was that of a theoretical storm with a pyramid shaped isohyetal pattern. This case was called the Pyramidville storm. It contained 361 hourly stations, each occupying a single grid cell. The configuration of the Pyramidville storm (see Figure G.15) allowed for uncomplicated and accurate calculation of the analytical DA truth independent of the DAD software. The main motivation of this case was to verify that the DAD software was properly computing the area sizes and average depths.

1. Storm center: 39°N 104°W
2. Duration: 10-hours
3. Maximum grid cell precipitation: 1.00"
4. Grid cell resolution: 0.06 sq.-miles (361 total cells)
5. Total storm size: 23.11 sq-miles
6. Distribution of precipitation:

   Hour 1: Storm drops 0.10" at center (area 0.06 sq-miles)
   Hour 2: Storm drops 0.10" over center grid cell AND over one cell width around hour 1 center
   Hours 3-10:

   1. Storm drops 0.10" per hour at previously wet area, plus one cell width around previously wet area
   2. Area analyzed at every 0.10"
   3. Analysis resolution: 15-sec (~.25 square miles)

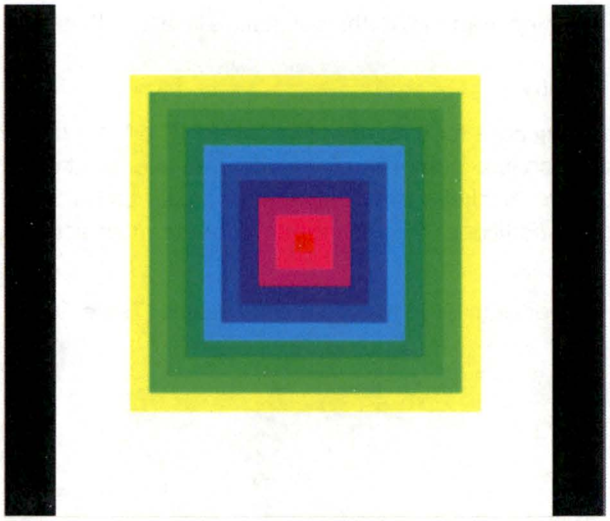


Figure G.15 "Pyramidville" Total precipitation. Center = 1.00", Outside edge = 0.10"

The analytical truth was calculated independent of the DAD software, and then compared to the DAD output. The DAD software results were equal to the truth, thus demonstrating that the DA estimates were properly calculated (Figure G.16).

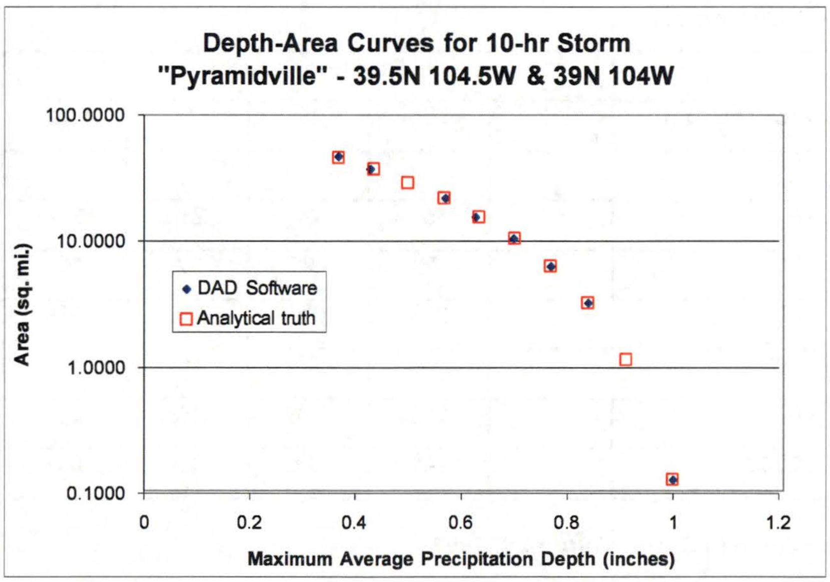


Figure G.16 10-hour DA results for "Pyramidville"; truth vs. output from DAD software

The Pyramidville storm was then changed such that the mass curve and spatial interpolation methods would be stressed. Test cases included:

- Two-centers, each center with 361 hourly stations
- A single center with 36 hourly stations, 0 daily stations
- A single center with 3 hourly stations and 33 daily stations

As expected, results began shifting from the 'truth,' but minimally and within the expected uncertainty.

Ritter, Iowa Storm, June 7, 1953

Ritter, Iowa was chosen as a test case for a number of reasons. The NWS had completed a storm analysis, with available DAD values for comparison. The storm occurred over relatively flat terrain, so orographics were not an issue. An extensive "bucket survey" provided a great number of additional observations from this event. Of the hundreds of additional reports, about 30 of the most accurate reports were included in the DAD analysis.

The DAD software results are very similar to the NWS DAD values (Table G.2).

Table G.2 The percent difference [(AWA-NWS)/NWS] between the AWA DA results and those published by the NWS for the 1953 Ritter, Iowa storm.

% Difference

	Duration (hours)				
Area (sq.mi.)		6	12	24	total
10		-15%	-7%	2%	2%
100		-7%	-6%	1%	1%
200		2%	0%	9%	9%
1000		-6%	-7%	4%	4%
5000		-13%	-8%	2%	2%
10000		-14%	-6%	0%	0%

Westfield, Massachusetts Storm, August 8, 1955

Westfield, Massachusetts was also chosen as a test case for a number of reasons. It is a probable maximum precipitation (PMP) driver for the northeastern United States. Also, the Westfield storm was analyzed by the NWS and the DAD values are available for comparison. Although this case proved to be more challenging than any of the others, the final results are very similar to those published by the NWS (Table G.3).

Table G.3 The percent difference [(AWA-NWS)/NWS] between the AWA DA results and those published by the NWS for the 1955 Westfield, Massachusetts storm

% Difference

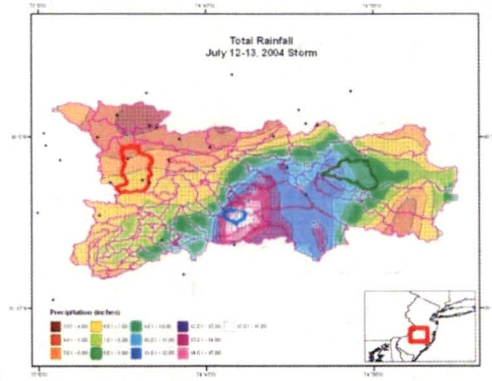
	Duration (hours)							
Area (sq. mi.)		6	12	24	36	48	60	total
10		2%	3%	0%	1%	-1%	0%	2%
100		-5%	2%	4%	-2%	-6%	-4%	-3%
200		-6%	1%	1%	-4%	-7%	-5%	-5%
1000		-4%	-2%	1%	-6%	-7%	-6%	-3%
5000		3%	2%	-3%	-3%	-5%	-5%	0%
10000		4%	9%	-5%	-4%	-7%	-5%	1%
20000		7%	12%	-6%	-3%	-4%	-3%	3%

The primary components of SPAS are: storm search, data extraction, quality control (QC), conversion of daily precipitation data into estimated hourly data, hourly and total storm precipitation grids/maps and a complete storm-centered DAD analysis.

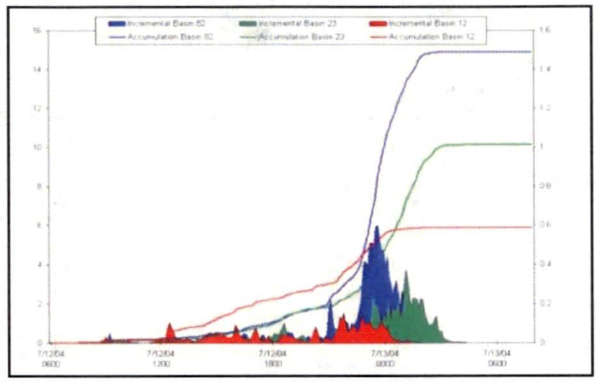
Output

Armed with accurate, high-resolution precipitation grids, a variety of customized output can be created (see Figures G.17A-D). Among the most useful outputs are sub-hourly precipitation grids for input into hydrologic models. Sub-hourly (i.e. 5-minute) precipitation grids are created by applying the appropriate optimized hourly Z-R (scaled down to be applicable for instantaneous Z) to each of the individual 5-minute radar scans; 5-minutes is often the native scan rate of the radar in the US. Once the scaled Z-R is applied to each radar scan, the resulting precipitation is summed up. The proportion of each 5-minute precipitation to the total 1-hour radar-aided precipitation is calculated. Each 5-minute proportion (%) is then applied to the quality controlled, bias corrected 1-hour total precipitation (created above) to arrive at the final 5 minute precipitation for each scan. This technique ensures the sum of 5-minute precipitation equals that of the quality controlled, bias corrected 1-hour total precipitation derived initially.

Depth-area-duration (DAD) tables/plots, shown in Figure G.17d, are computed using a highly-computational extension to SPAS. DADs provide an objective three dimensional (magnitude, area size, and duration) perspective of a storms' precipitation. SPAS DADs are computed using the procedures outlined by the NWS Technical Paper 1 (1946).



a)



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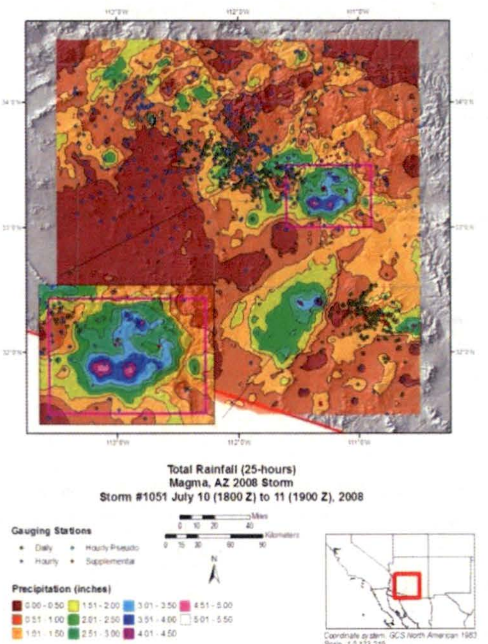
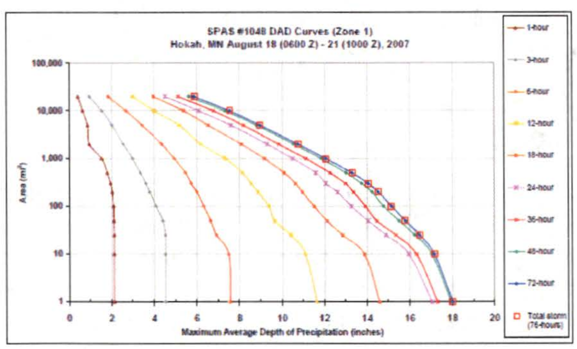


c)

Storm 1048 - Hokah, MN August 18 - August 21, 2007

MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)

Area (mi²)	Duration (hours)									
	1	3	6	12	18	24	36	48	72	Total
0.24	2.46	4.77	7.85	11.89	14.88	17.31	17.55	18.19	18.28	18.28
1	2.12	4.53	7.56	11.64	14.59	17.05	17.31	17.95	18.02	18.02
10	2.12	4.53	7.49	11.10	13.88	15.96	16.31	17.03	17.15	17.17
25	2.12	4.53	6.92	10.42	12.86	14.89	15.34	16.23	16.45	16.46
50	2.11	4.40	6.64	9.65	12.13	14.05	14.46	15.49	15.79	15.79
100	2.09	4.10	6.33	9.37	11.52	13.27	13.93	14.76	15.14	15.14
200	2.03	3.79	6.00	8.87	10.96	12.62	13.37	14.22	14.52	14.52
300	1.95	3.61	5.74	8.55	10.64	12.06	12.99	13.74	14.04	14.04
500	1.79	3.35	5.47	8.13	10.11	11.60	12.27	13.01	13.29	13.30
1,000	1.53	2.99	4.95	7.33	9.17	10.51	11.13	11.84	12.07	12.07
2,000	0.95	2.55	4.36	6.18	8.09	9.30	9.85	10.54	10.75	10.76
5,000	0.87	2.02	3.45	5.19	6.53	7.61	8.18	8.79	8.96	8.98
10,000	0.63	1.54	2.69	4.02	5.39	6.09	6.78	7.31	7.53	7.55
20,000	0.41	0.95	1.84	3.02	3.97	4.53	5.13	5.63	5.87	5.90



d)

Figure G.17 Various examples of SPAS output, including (a) total storm map and its associated (b) basin average precipitation time series, (c) total storm precipitation map, (d) depth-area-duration (DAD) table and plot

Summary

Grounded on years of scientific research with a demonstrated reliability in post-storm analyses, SPAS is a hydro-meteorological tool that provides accurate precipitation analyses for a variety of applications. SPAS has the ability to compute precise and accurate results by using sophisticated timing algorithms, "basemaps", a variety of precipitation data and most importantly NEXRAD weather radar data (if available). The approach taken by SPAS relies on hourly, daily and supplemental precipitation gauge observations to provide quantification of the precipitation amounts while relying on basemaps and NEXRAD data (if available) to provide the spatial distribution of precipitation between precipitation gauge sites. By determining the most appropriate coefficients for the Z-R equation on an hourly basis, the approach anchors the precipitation amounts to accepted precipitation gauge data while using the NEXRAD data to distribute

precipitation between precipitation gauges for each hour of the storm. Hourly Z-R coefficient computations address changes in the cloud microphysics and storm characteristics as the storm evolves. Areas suffering from limited or no radar coverage are estimated using the spatial patterns and magnitudes of the independently created basemap precipitation grids. Although largely automated, SPAS is flexible enough to allow hydro-meteorologists to make important adjustments and adapt to any storm situation.

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APPENDIX H – Supplemental Electronic Data

The following files have been supplied to TVA electronically: The files listed below, which contain both input and output data, are electronically attached to the parent Adobe.zip (FILEKEEPER # (see identification #s below)) calculation file. The listed files are therefore stored in an unalterable medium and are retrievable through the EDMS number for this calculation. Click on the "Attachments" Tab within Adobe to view the Appendix listing, to access and view the files as needed.

1. **PMP_Evaluation_Tool (Folder)** (345269)
   - Input (Folder)
     - DAD_Tables.gdb (ArcGIS File Geodatabase)
       - Contains the DAD tables for each analyzed storm
     - Storm_Adj_Factors.gdb (ArcGIS File Geodatabase)
       - General (Feature Dataset)
         - Contains the Total Adjustment Factor feature classes for each analyzed general storm
       - Local (Feature Dataset)
         - Contains the Total Adjustment Factor feature classes for each analyzed local storm
       - Tropical (Feature Dataset)
         - Contains the Total Adjustment Factor feature classes for each analyzed tropical storm
     - Non_Storm_Data.gdb (ArcGIS File Geodatabase)
       - Contains the spatial grid network feature classes
   - Script (Folder)
     - PMP_Tools.tbx (ArcGIS Toolbox)
       - Contains the following Script Tools (Python): Basin PMP Evaluation Tool

2. **SPAS Hourly Rainfall ASCII Grids (Folder)** (Proprietary**** 345223 through 345266 ****Proprietary)
   This folder contains Individual files representing each SPAS Storm Analysis gridded hourly rainfall data used in this study in ASCII format. All rainfall depths are in inches.

3. **TVA - SPAS Mass Curve Data (Folder)**(345271)
   This folder contains individual files representing each SPAS Storm Analysis mass curve at each storm center. This contains three sub-folders, one for General storm type, one for Local storm type, and one for Tropical storm type. SPAS gridded rainfall data used in this study are in ASCII format. All rainfall depths are in inches and time increments are in hours.

4. **TVA_Sample_Basins (Folder)** (345272)

5. **PMP Evaluation Tool Description and Usage Rev1.pdf** (345268)

6. **Readme.txt** (345270)

APPENDIX I – HMR Storm Separation Method Example

Applied Weather Associates, LLC (AWA) has reviewed the Storm Separation Method (SSM) as described in detail in HMR 55A and its application in HMR 57 and HMR 59. The SSM is used in hydrometeorological analysis to arrive at an approximation of the non-orographic component of precipitation from storms centered in orographic areas. The SSM was originally developed for HMR 55A (1988) as a standardized procedure to isolate and quantify orographic from non-orographic factors in record setting storms (HMR 59, Section 5.4). HMRs 57 and 59 refer to HMR 55A for details of the development of the SSM. The application of the SSM is described in HMR 57 and HMR 59 with some examples of the maps developed for each publication provided in various figures in Chapter 7 of HMR 57, and Chapter 6 of HMR 59. An attempt was made to acquire copies of the actual maps and data used in the computation of PMP for these publications. AWA visited the Hydrometeorology Design Studies Center (HDSC) on December 8-10, 2008 to review archives of maps and working papers for HMRs 55A, 57 and 59. No maps or working papers are available for the SSM applications in those documents. Therefore, the review of the SSM is based entirely on information in HMRs 55A, 57 and 59.

Introduction

The initial review discussion describes the procedure presented in HMR 55A in detail. Maps from HMR 57 were digitized and computations completed based on the discussions in HMR 57. Results from these computations are compared with the HMR 57 PMP maps. Maps in HMR 59 were also digitized but not all maps for the SSM were available. Results from the limited information available are discussed.

The following discussion is extracted from the information provided in HMR 55A for the determination of Free Atmospheric Forced Precipitation (FAFP). The information is condensed to present major discussions. The complete text is available in Sections 6 and 7 of HMR 55A.

HMR 55A Section 6. APPROACHES

1.1 Introduction

HMR 55A states that estimation of PMP in orographic regions is difficult and storm data are limited. This is the result of a low population density that restricts the number of regular observing stations and also limits the effectiveness of supplementary precipitation surveys. In addition, the complicating effects of terrain on storm structure and precipitation must be considered. In HMR 55A, several procedures were investigated, but primary reliance was placed on a procedure that separates the effect of orography from the dynamic effects of the storm.

6.4 Storm Separation Method

It was necessary to find a procedure which would enable the precipitation potential for this diverse terrain to be analyzed in a consistent fashion. The precipitation that results from atmospheric forces (convergence precipitation) involved in the major storms in the region is defined. Convergence precipitation amounts were determined for the 24-hr 10-mi^2 precipitation amounts for all major storms in the region.

These rainfall values were moisture maximized and transposed to locations where similar storms have occurred. The moisture maximized, transposed values were then analyzed to develop a generalized map of convergence PMP throughout the region.

Values of convergence rainfall were increased for orographic effects that occur over the region. The orographic intensification factor is developed from the 100-yr 24-hr precipitation-frequency amounts of NOAA Atlas 2. Since the dynamic strength of a storm varies from the most intense 1-, 2-, 3-, or 6-hr period through the end of the storm, it is not appropriate to apply the same orographic intensification factor

throughout the entire storm. To vary this intensification factor, a storm intensity factor was developed. The storm intensification factor reduced the effect of the orographic factor during the most intense rainfall period of the maximum 24 hours of the storm.

After determining the 24-hr 10-mi² PMP, 6-/24- and 72-/24-hr ratio maps were used to develop PMP values for these two other index durations for the 10-mi² area. Finally, a 1-hr 10-mi² PMP map was developed using a 1-/6-hr ratio map. These four maps provide the key estimates of general-storm PMP for the region.

6.5 Depth-Area Relations

The technique discussed in sections 6.3 and 6.4 provide 10-mi², or point, estimates of general-storm PMP for four index durations. Depth-area relations were developed utilizing data from the important storms of record in and near the study region to permit estimates for larger areas. These relations provide percentages to estimate PMP for areas as large as 5,000 mi². Different depth-area relations are required for disparate regions. Differences also exist between orographic and non-orographic portions of the study region. These differences resulted in a set of depth-area relations.

HMR 55A Section 7. STORM SEPARATION METHOD (SSM)

7.1 Introduction

It was considered necessary to find a property of observed major storm precipitation events that is only minimally affected by terrain so transposition of observed precipitation amounts would not be limited to places where the terrain characteristics are the same as those at the place where the storm occurred. The name given to this idealized property is "free atmospheric forced precipitation" (FAFP) which has been called "convergence only" precipitation in publications such as HMR No. 49. The definition of FAFP is the precipitation not caused by orographic forcing; i.e. it is precipitation caused by the dynamic, thermodynamic, and microphysical processes of the atmosphere. It is all the precipitation from a storm occurring in an area where terrain influence or forcing is negligible, termed a non-orographic area. In areas classified as orographic, it is that part of the total precipitation which remains when amounts attributable to orographic forcing have been removed. Factors involved in the production of FAFP are:

1. Convergence at middle and low tropospheric levels and often, divergence at high levels
2. Buoyancy arising from heating and instability
3. Forcing mesoscale systems, i.e., pseudo fronts, squall lines, bubble highs, etc.
4. Storm structure, especially at the thunderstorm scale involving the interaction of precipitation unloading with the storm sustaining updraft
5. Lastly, condensation efficiency involving the role of hydroscopic nuclei and the heights of the condensation and freezing levels.

It is emphasized that FAFP is an idealized property of precipitation since no experiment has yet been devised to identify in nature which raindrops were formed by orographic forcing and which by atmospheric forcing.

7.2 Glossary of Terms (partial list)

A_o: See P_a. It is the term for the effectiveness of orographic forcing used in module 3.

Bi: It is the term representing the "triggering effects" of orography. It is used in module 2. Bi is a number

between 0 and 1.0 representing the degree of FAFP implied by the relative positioning of the 1st through i-th isohyetal maxima with those terrain features (steepest slopes, prominences, converging upslope valleys) generally thought to induce or "stimulate" precipitation. A high positive correlation between terrain features and isohyetal maxima yields a low value for Bi.

BFAC: 0.95 (RCAT). It represents an upper limit for FAFP in modules 2 and 5. See also the definition for PX.

DADRF: The depth-area-duration reduction factor is the ratio of two average depths of precipitation.

DADRF: RCAT/MXVATS

DADFX: DADFX = (HIFX)(DADRF).

It is used in module 2 to represent the largest amount of non-orographic precipitation caused by the same atmospheric mechanism that produced MXVATS.

F_I: See PCTHIFX: The largest isohyetal value in the non-orographic part of the storm. The same atmospheric forces (storm mechanism) must be the cause of precipitation over the areas covered by the isohyet used to determine HIFX and MXVATS.

Im: That part of RCAT attributed solely to atmospheric processes and having the dimension of depth. Since it is postulated that FAFP cannot be directly observed in an orographic area, some finite portion of it was caused by forcing other than free atmospheric. The FAFP component of the total depth must always be derived by making one or more assumptions about how the precipitation was caused. The subscript "m" identifies the single assumption or set of assumptions used to derive the amount designated by I. For example, a subscript of 2 will refer to the assumptions used in module 2.

LOFACA: LOFACA is the lowest isohyetal value at which it first becomes clear to the analyst that the topography is influencing the distribution of precipitation depths. Confirmation of this influence is assumed to occur when good correlation is observed between the LOFACA isohyet and one or more elevation contours in the orographic part of the storm. The significance of LOFACA is that precipitation depths at and below this value are assumed to have been produced solely by atmospheric forces without any additional precipitation resulting from topographic effects; i.e., they represent the "minimum level of FAFP for the storm.

<u>LOFAC:</u> $$\mathrm{LOFAC} = \mathrm{LOFACA} + \frac{\mathrm{AI}}{2}\left(\mathrm{PB}^{\frac{(\mathrm{AI})}{2}} - 1\right).$$

It is a refinement to LOFACA based on the concept that AI may prejudice the assigning of a minimum level of FAFF.

MXVATS: The average depth of precipitation for the total storm duration for the smallest area size analyzed, provided that it is not larger than 100 sq mi.

OSL: Orographic Separation Line is a line which separates the region into two distinct regions. In one region, the non-orographic, it is assumed no more than a 5 percent change (in either increasing or decreasing the precipitation amount for any storm or series of storms) results from terrain effect. In contrast, the other region is one where the influence of terrain on the precipitation process is significant. An upper limit of 95 percent and a lower limit of no less than 5 percent is allowed. The line may exist anywhere from a few to 20 miles upwind (where the wind direction is that which is judged to prevail in typical record setting storms.

P_a (and A_a) is a ratio in which the effectiveness of an actual storm in producing precipitation is compared with a conceptualized storm of "perfect" effectiveness.

The SSM was developed because four distinct sets of precipitation were available for record-setting storms.

1. Reported Total storm precipitation, used in Module 1
2. Isohyet and depth-area-duration analyses of total storm precipitation, including Part I and Part II Summaries, used in Module 2
3. Meteorological data and analyses, used in Module 3
4. Topographic charts, used in all modules

It is noted that clearly the SSM depends on the validity of the input information.

The mechanics of the procedure used to arrive at FAFP are accomplished by completing the tasks symbolically represented in a MAIN FLOWCHART for the SSM along with its associated SSM MODULE FLOWCHARTS.

The validity of the techniques in the SSM depends on the validity of the concepts upon which they are based.

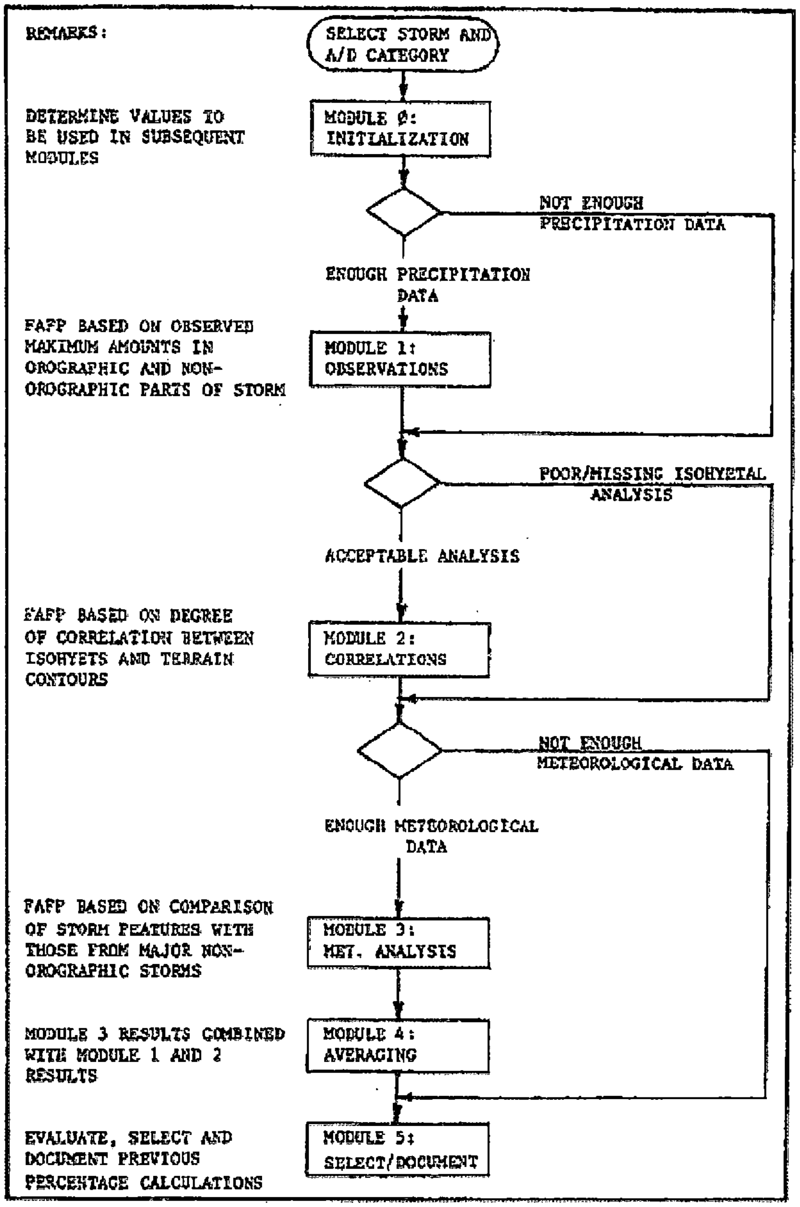


Figure 7.2.—Main flowchart for SSM.

SSM Modules from HMR 55A

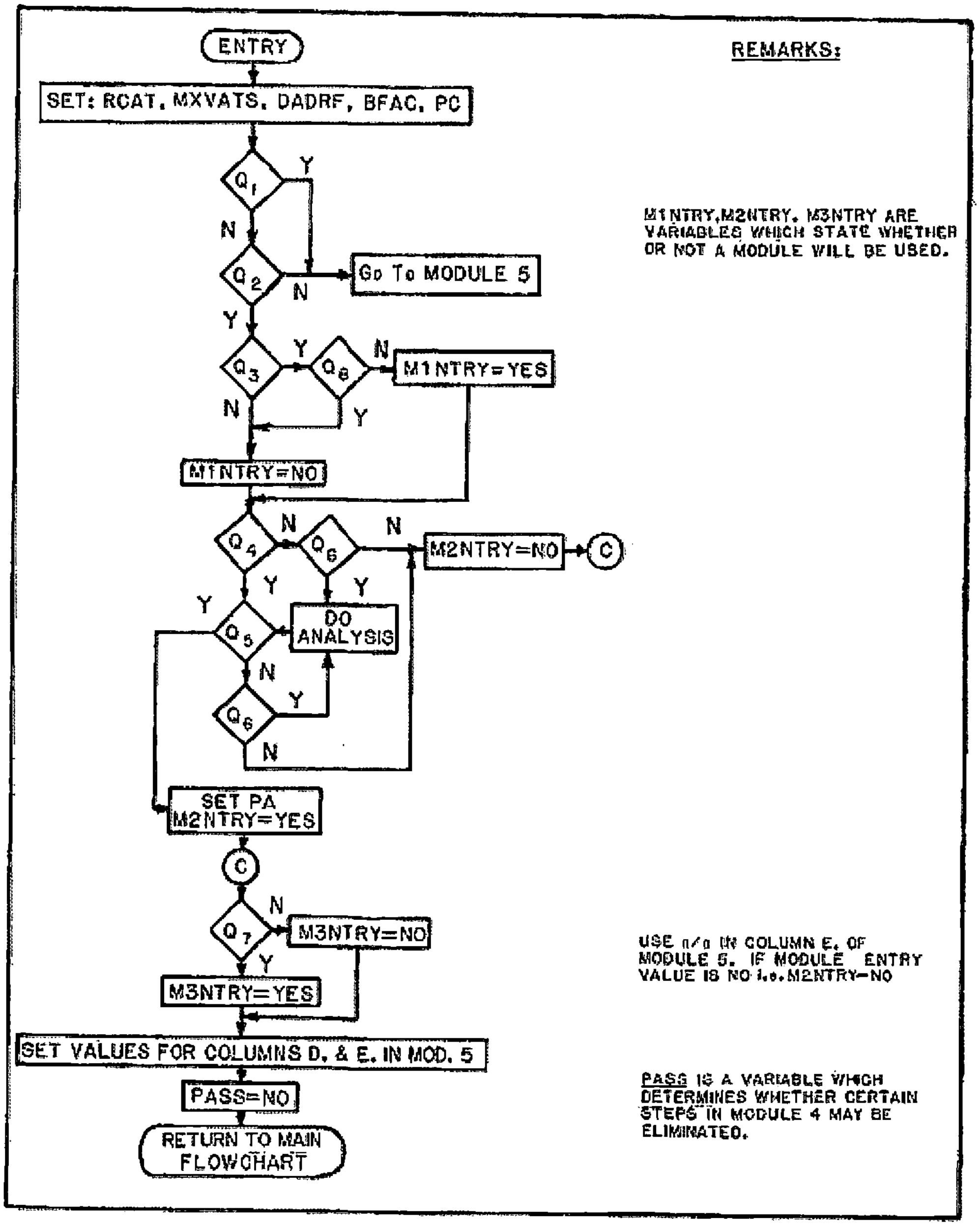


Figure 7.3.—Flowchart for module 0, SSM.

7.4.1.1 Module 0.

Module 0 is used to decide if there is adequate data available. A decision is made by the analyst if there are no data available, if the data are judged to be adequate or if the data are judged to be highly adequate. Values range from 1 for the lowest level to 9 for the highest level. The analyst assigns the value that is considered most applicable. Questions that are asked include the following:

1. Is the isohyetal analysis reliable?
2. Is there adequate data in non-orographic areas to select a reliable value for non-orographic precipitation?
3. Is the highest observed precipitation in the non-orographic part of the storm equal to zero?
4. Are the data adequate to determine a ratio of the effectiveness of the actual storm in producing precipitation to a conceptual storm of "perfect" effectiveness?

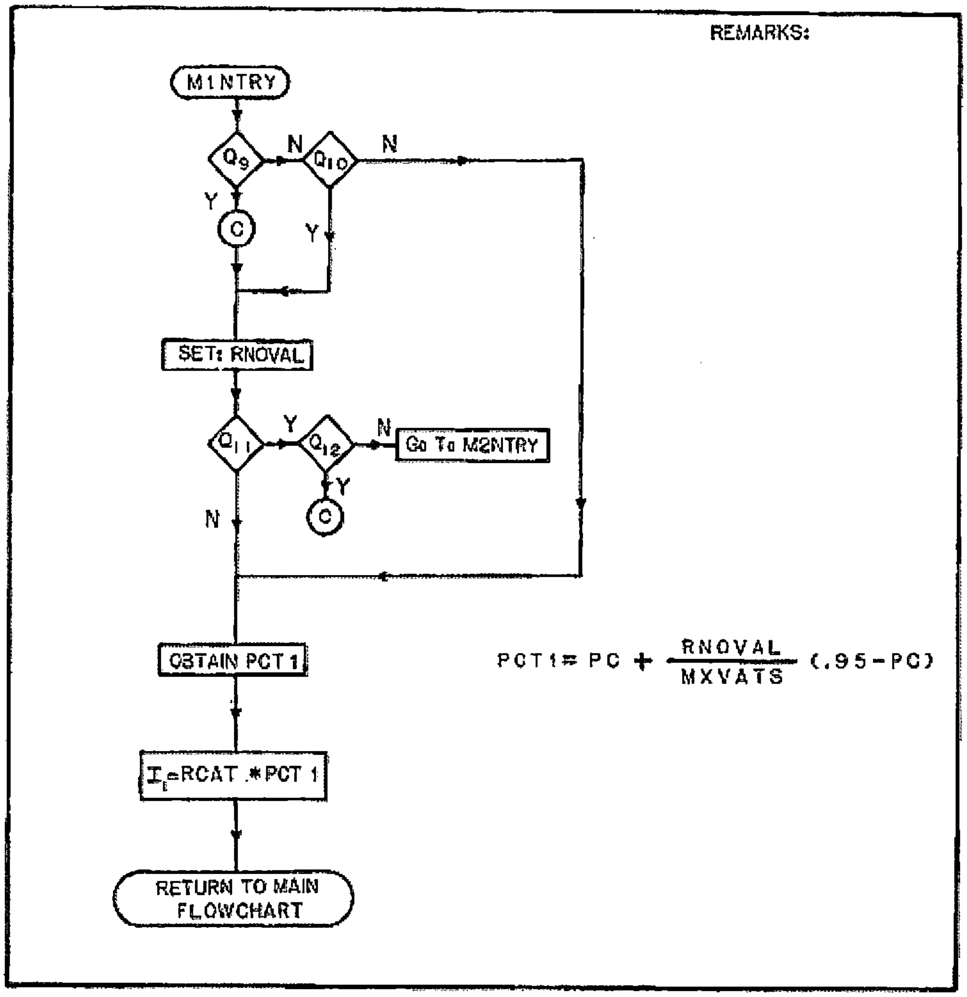


Figure 7.4.--Flowchart for module 1, SSM.

7.4.1.2 Module 1.

An analytical judgment must be made concerning the storm mechanism that resulted in the maximum precipitation over orographic regions and over non orographic regions. Questions asked include the following:

1. Is a review of the data needed?
2. Is the precipitation in the non-orographic region equal to the precipitation in the orographic region?

The reliability of the result of this module depends on the density of good precipitation observations on the date the storm occurred.

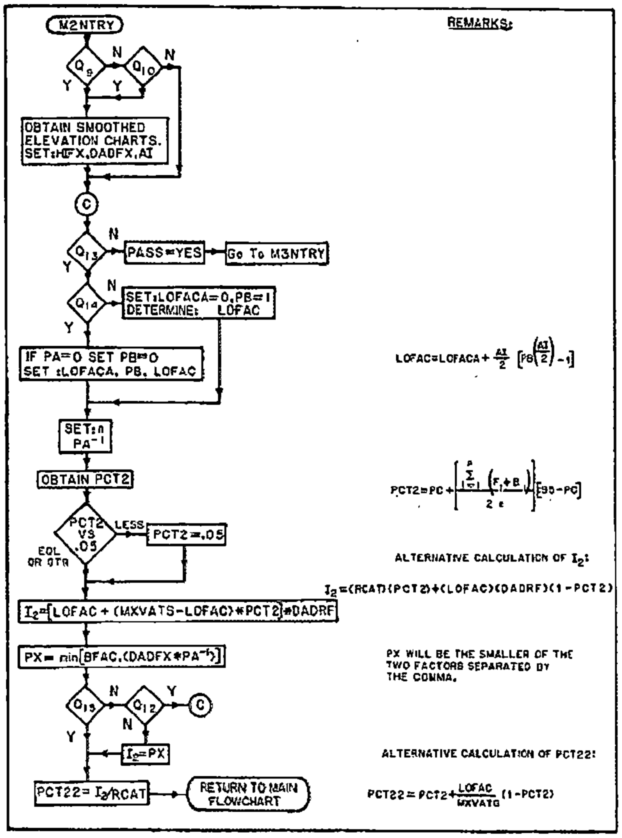


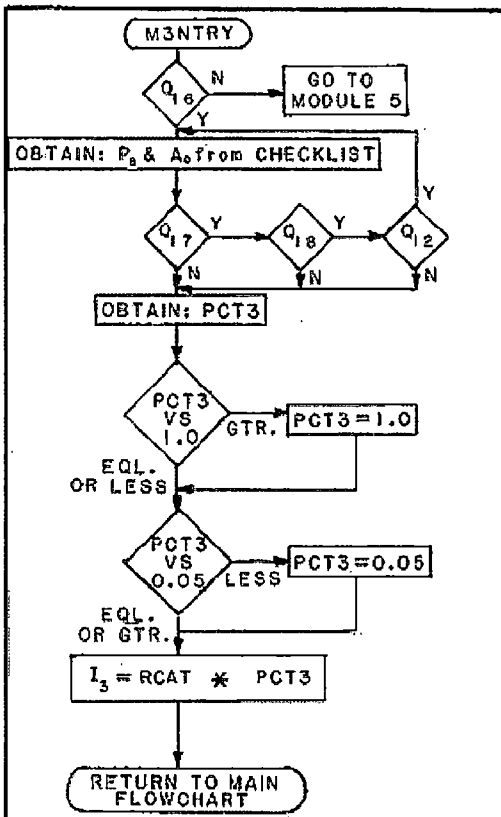
Figure 7.5.--Flowchart for module 2, SSM.

7.4.1.2 Module 2.

In this module, the average depth of precipitation is conceived of a column of water comprised of top and bottom sections. The limit to the top of the bottom section is set by the lowest isohyetal value at which it first becomes clear to the analyst that the topography is influencing the distribution of precipitation depths. The bottom section is conceived to contain only a minimum level of FAFP. The top section contains precipitation that results from orographic forcing or perhaps additional atmospheric forcing. A complex set of judgment questions are asked to evaluate each section. As in module 1, an analytical judgment must be made. Some of questions asked are as follows:

1. Is a review of the data needed?
2. Can it be determined which isohyetal maxima controls the average depth?
3. Is there a good correlation between some isohyet and the elevation contours in the orographic part of the storm?

   Is the average depth of precipitation that is FAFP less than or equal to the smaller of either the upper limit for FAFP in module 2 or the largest amount of non-orographic precipitation caused by the same atmospheric mechanism that produced the average depth of precipitation for the total storm duration for the smallest area size analyzed, provided that it is no larger than 100 square miles?



REMARKS

$$PCT3 = PC + \frac{P_a}{P_a + A_o}(.95 - PC)$$

LEGEND

PVA – Positive Vorticity Advection
MCC = Mesoscale Convective Complex
LEWP = Line Echo Wave Pattern

P_a CHECKLIST

Cat. Data	Parameter	A (√)	B .05-.95	C 1-3	D B*C
Surface	Iso.Ptn. Fronts Waves Sq.Ln. Other				
Upper Air	PVA/SW Cutoff Blocking JetStm Other				
Rawinsonde	Stability Shear Other				
Satellite	Diver. Merger MCC Other				
Radar	LEWP Merger Others				
Other					
Duration (%)					
Totals =					
P_a = Total D/Total C =					

A_o CHECKLIST

Parameter	A Phys. Val.	B 0-±.95	C 1-3	D B*C
Inflow Direct				
Inflow Speed				
Gradient of Elevation				
Stability				
Other				
Duration (%)				
Totals =				
A_o = Total D/Total C =				

Figure 7.6.—Flowchart for module 3, SSM.

7.4.1.2 Module 3.

This module uses meteorological and terrain information to evaluate an appropriate level of FAFP. This is accomplished through evaluation of the ratio in which the effectiveness of an actual storm in producing precipitation is compared with a conceptualized storm of "perfect" effectiveness. In such a conceptual model, features known by experience to be highly correlated with positive vertical motions, or an efficient storm structure, would be numerous and exist at an optimum (not always the largest or strongest) intensity level. The presence of one or more features that infer positive vertical motion, or which may contribute toward an efficient storm structure are identified. Then take as a basis for comparison an idealized storm which contains the same features or phenomena and indicate by selecting a number between 0.05 and 0.95, the degree to which the effectiveness of the selected actual storm features/phenomena approaches the effectiveness of the same features/phenomena in the idealized storm. If the quality and quantity of the information permits, the degree of convective-scale forcing may be distinguished from forcing due to larger scale mechanisms. Features may be assigned a weighted value in relationship to others. Meteorological data categories, for which there is not sufficient information from a particular storm, are disregarded in the ratio calculations.

The effectiveness of orographic forcing effects is determined. A vertical displacement parameter is determined using the component of the wind perpendicular to terrain slopes and the slope. The effectiveness is then compared with an idealized value representing 100 percent effectiveness. A stability effectiveness is assigned and combined with the vertical displacement parameter to determine a combined effect. The "model" in module 3 follows the concept that FAFP is directly proportional to the effectiveness of atmospheric forcing and inversely proportional to the effectiveness of the orographic forcing mechanisms.

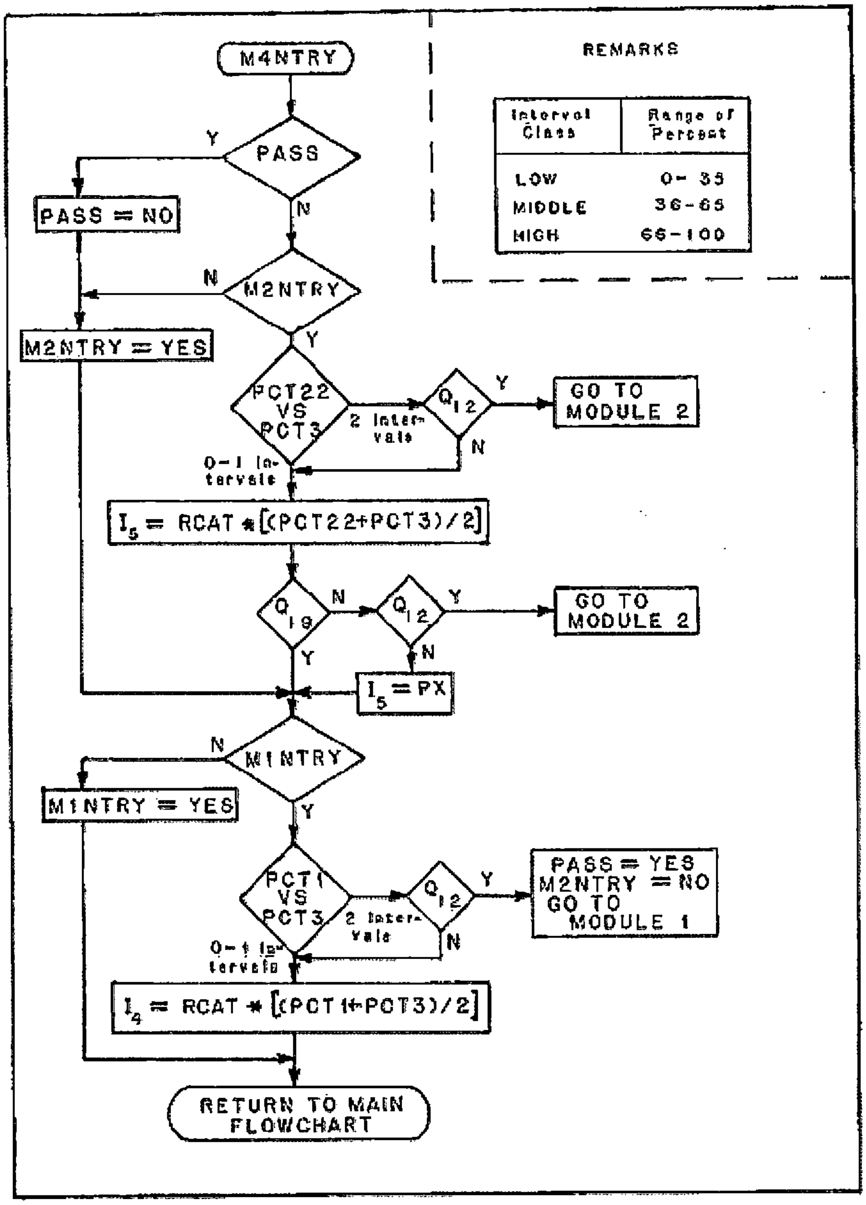


Figure 7.7.—Flowchart for module 4, SSM.

7.4.1.5 Module 4.

A basic assumption underlying the use of module 4 is that better results can be obtained by combining information; i.e., averaging the percentages obtained from the isohyetal analysis with the meteorological analysis and those obtained from analysis of the precipitation observations with the meteorological analysis. Better estimates are produced by averaging when there is little difference in the expressed preference for any one of the techniques or sources of information and, also, when the calculated percentage of FAFP from each of the modules exhibits wide differences.

Little is to be gained from use of the averaging technique over estimates produced by one of the individual analyses of modules 1, 2, or 3 when:

1. There are large differences in the expressed preference for the techniques of one module
2. The sources of information for one of the individual modules is definitely superior
3. The calculated percentages among the modules are in close agreement

DOCUMENTATION AND INDEX SELECTION

STORM ID/DATE, REMARKS:

MODULE	PARAMETER	VALUE	REMARKS	D	E	F
∅	CATEGORY RCAT BFAC MXVATS DADRF PA PC		EVALUATION SCALE: COL.D 0-9; COL.E 1-9 MODULES 1-3: COL.F: IS THE SUM OF COLS. D&E. COL.D: HOW ADEQUATE IS THE INPUT INFORMATION FOR THE REQUIREMENTS SET BY MODULE'S TECHNIQUE. COL.E: HOW LIKELY IT IS THAT THIS TECHNIQUE WILL ESTIMATE THE CORRECT INDEX VALUE BASED ON ITS ASSUMPTIONS? FOR MODULE 4 SEE SELECTION RULE. OVERALL RULE: SELECT INDEX VALUE WITH LARGEST COL. F SCORE. LARGEST SUBSCRIPT BREAKS TIES.			
1	RNOVAL PCT1 I_1					
2	AI LOFACA PB LOFAC HIFX DADFX PA^{-1} PX $\sum^{n} (F_i + B_i)$ PCT2 I_2 PCT22					
3	COLUMN: A / B / C INFLOW DIR. INFLOW SPD. GRAD. ELEV. W_o STABILITY A_o SURFACE UPPER AIR RAOB SATELLITE RADAR P_a PCT3 I_3					
4	(PCT22 + PCT3)/2 I_5 (PCT1 + PCT3)/2 I_4		RETURN TO MAIN FLOWCHART			

Figure 7.8.--Documentation form for SSM, module 5.

7.4.1.6 Module 5.

Module 5 is used for documentation. Values from the other modules are entered into the module 5 sheet. Assigning values involves subjectivity which must be the case because the "correct" value cannot be known and, hence, there is no way to know which of the various techniques used produces "correct" results most frequently. After a storm has been evaluated in each of the modules, all information is available to assign a value to the question "How likely is it that this technique will estimate the correct value based on the assumptions?" If confidence is high, assign a value of either 7, 8 or 9. If confidence is lower, assign a lower number. The scheme is designed to permit selection of one of the module results when there is a strong preference of one of them. The analyst must make a decision as to which module is to be preferred.

The final value selected for FAFP is determined by the largest value in module 5.

AWA Discussion on HMR 55A Modules

After reviewing the information provided above from Sections 6 and 7 of HMR 55A, several observations and conclusions have been made.

1. The procedures presented in HMR 55A are very detailed and following the procedures is at best very difficult since many of the parameters used are not standard meteorological parameters and their physical meaning is rarely intuitive.
2. The definition of terms in most cases includes other terms unique to this procedure and the relationship among parameters, even when a mathematical formula is provided, is not obvious when trying to associate physical characteristics to the combinations of parameters.
3. The formulas provided appear to have been subjectively derived with no obvious physical parameter associations connected through physical meteorological processes. In some cases, the process can be completed but other than a number to plug into a module, there is no meaning to the numbers that can be associated with the physical processes associated with extreme precipitation.
4. There are numerous places in the procedures where subjective evaluations are quantified with some explicit number where the number is no more than the opinion of the analyst. Then that number is used later in the procedure. In the final module, one of the critical inputs is, in the opinion of the analyst, how likely is it that the technique will estimate the correct value based on the assumptions? Examples of subjective decisions are as follows:
    1) Bi is the "triggering effect" of orography. It is a number between 0.0 and 1.0 representing the degree of FAFP implied by the relative positioning of isohyetal maxima lines with terrain features.
    2) Im is that part of the average depth of precipitation solely attributed to atmospheric processes.
    3) LOFACA is the lowest isohyetal value where it first becomes clear to the analyst that topography is influencing the distribution of rainfall depths.
    4) P_a and A_a are ratios in which the effectiveness of an actual storm in producing precipitation is compared with a conceptual storm of "perfect" effectiveness.
    5) This is a very interesting subjective decision since if the analyst knew the effectiveness of the conceptual storm of "perfect" effectiveness, then one of the major unknowns in PMP determination is no longer an unknown.
    6) The statement is made that the validity of the techniques in the SSM depends on the validity of the concepts upon which they are based. Since the concepts involve many

subjective judgments, the SSM procedure is only as valid as those subjective judgments. Unfortunately the validity of those judgments vary from analyst to analyst with no way of objectively evaluating their reliability.

7) Module 4 makes seemingly contradicting statements. A basic assumption underlying the use of module 4 is that *better results can be obtained by combining information*; i.e., averaging the percentages obtained from the isohyetal analysis with the meteorological analysis and those obtained from analysis of the precipitation observations with the meteorological analysis. *Better estimates are produced by averaging when there is little difference* in the expressed preference for any one of the techniques or sources of information and, *also*, when the calculated percentage of FAFP from each of the modules exhibits *wide differences*.

Little is to be gained from use of the averaging technique over estimates produced by one of the individual analyses of modules 1, 2, or 3 when:

- There are large differences in the expressed preference for the techniques of one module
- The sources of information for one of the individual modules is definitely superior
- The calculated percentages among the modules are in close agreement

The following discussion is extracted from the information provided in HMR 55A for the determination of the orographic factor. The information is condensed to present major discussions. The complete text is available in Section 9 of HMR 55A.

HMR 55A Section 9.2 Orographic Factor, T/C

Maps of 100-yr 24-hr precipitation from NOAA Atlas 2 were used to form a ratio of total 100-yr to convergence component 100-yr rainfall, T/C, and it was assumed that this ratio related to a ratio of similar parameters for PMP. The ratio of T/C can be used as a representative index of orographic effects.

The availability of the 100-yr 24-hr maps provides only part of the needed ratio, the total rainfall or numerator in the fraction, and it remains to determine how to obtain the convergence component, C. The rationale followed was that isopleths of the convergence component would exhibit a smooth, gradually varying geographic pattern. The gradients and general geographic variation would be somewhat similar to the FAFP component. HMR 51 has smooth PMP lines east of the 105th meridian and is assumed to be convergence only PMP, so NOAA Atlas 2 isopluvials for this region are also assumed to be convergence only.

The approach taken to determine C is to look at the 100-yr precipitation analysis for zones of least topographic effect. These zones would be tied together in some form of smooth analysis. A rough pattern of smooth contours was sketched. This provides a map of C. Using NOAA Atlas 2 and the map of C, T/C can be computed.

HMR 55A Section 9.3 Storm Intensity Factor, M

A storm intensity factor adjustment, M, was developed to relate the amount of precipitation that could be expected during the most intense precipitation period to the total amount of precipitation for a period. M varies with storm type.

The 6-hr interval was determined as the duration of the most intense precipitation period with the base period being the 24-hr duration. The storm intensity factor was defined as the ratio of rainfall in the maximum 6-hr period to the rainfall in the basic 24-hr period. M is obtained by dividing the FAFP for 6 hours by the FAFP for 24 hours.

By combining the results of the FAFP, T/C and M evaluations, then PMP can be computed using the FAFP and an orographic influence parameter, K. K is a function of the orographic factor, T/C. PMP is represented as the sum of two parts representing the core period and the remaining period. Through some mathematical combinations,

$PMP = (FAFP)\ (K) = (FAFP)(M^2 (1\text{-}T/C) + T/C)$

AWA Discussion on HMR 55A Section 9

After reviewing the information provided above from Section 9 of HMR 55A, several observations and conclusions have been made.

1. NOAA Atlas 2 is based on statistical analyses of precipitation data observed within the NOAA Atlas 2 domain. Although NOAA Atlas 2 is being updated for various regions in the United States, it is the current precipitation frequency analysis for this region and is based on evaluation of rainfall data, and hence has a basis for being objectively derived from rainfall observations.
2. C is the 100-year 24-hour convergence only component of rainfall. It is assumed that for regions where there is least orographic influence, NOAA Atlas 2 values approximate C. For regions where there is significant orographic influences, C is subjectively estimated since there are no observational data that provide only the convergence component of observed rainfall. Hence, C much like FAFP, is derived using very limited data and subjective analyses over regions where orographic influences are significant.
3. The M factor also has subjective decisions incorporated into its determination. The duration of the core rainfall period seems to be subjectively derived. For locations where a core period cannot be identified, M = 0.
4. For storms without large core precipitation periods, i.e. where M is small or 0, PMP is primarily dependent on FAFP, T and C. While T has basis for being objectively derived, FAFP and C are largely subjective determined. Hence PMP values computed using the SSM provide highly subjective PMP values.

HMR 57 SSM Application

Section 6 Storm Separation Method

The technique for developing FAFP used in HMR 55A is complex and involves the analyst tracking through a set of modules in which knowledge of observed conditions and experience are used to arrive at estimates of FAFP. The estimates are in turn weighted, based on the analyst's judgment of the amount and quality of overall information to obtain a result.

The SSM has undergone minor refinements since its development in HMR 55A. A decision about the level of FAFP for a storm may have to accommodate a fair amount of uncertainty. The questions asked in the SSM modules are formulated in such a way that analysts with different levels of experience could estimate different amounts of FAFP. Under such circumstances a consensus among analysts often leads to the best FAFP estimate for a storm, but the consensus process is not a necessary part of the SSM.

The SSM technique was considered most appropriate for the present study (HMR 57). The technique was applied directly according to original guidance, subject to modifications. A discussion is provided in HMR 57 with the comment that the discussion covers specific changes in details that may be beyond the casual reader's interest. Module 2 was not used to analyze any of the storms but the other modules were used to

determine FAFP.

A map of C was constructed using regions of relative minima in the 100-year recurrence interval map. This was used together with the 100-year recurrence interval map to compute T/C. For some locations, the T/C maps were subjectively adjusted. The M-Factor for western Washington was determined to be zero so the K factors became T/C.

AWA Discussion on HMR 57 SSM Application

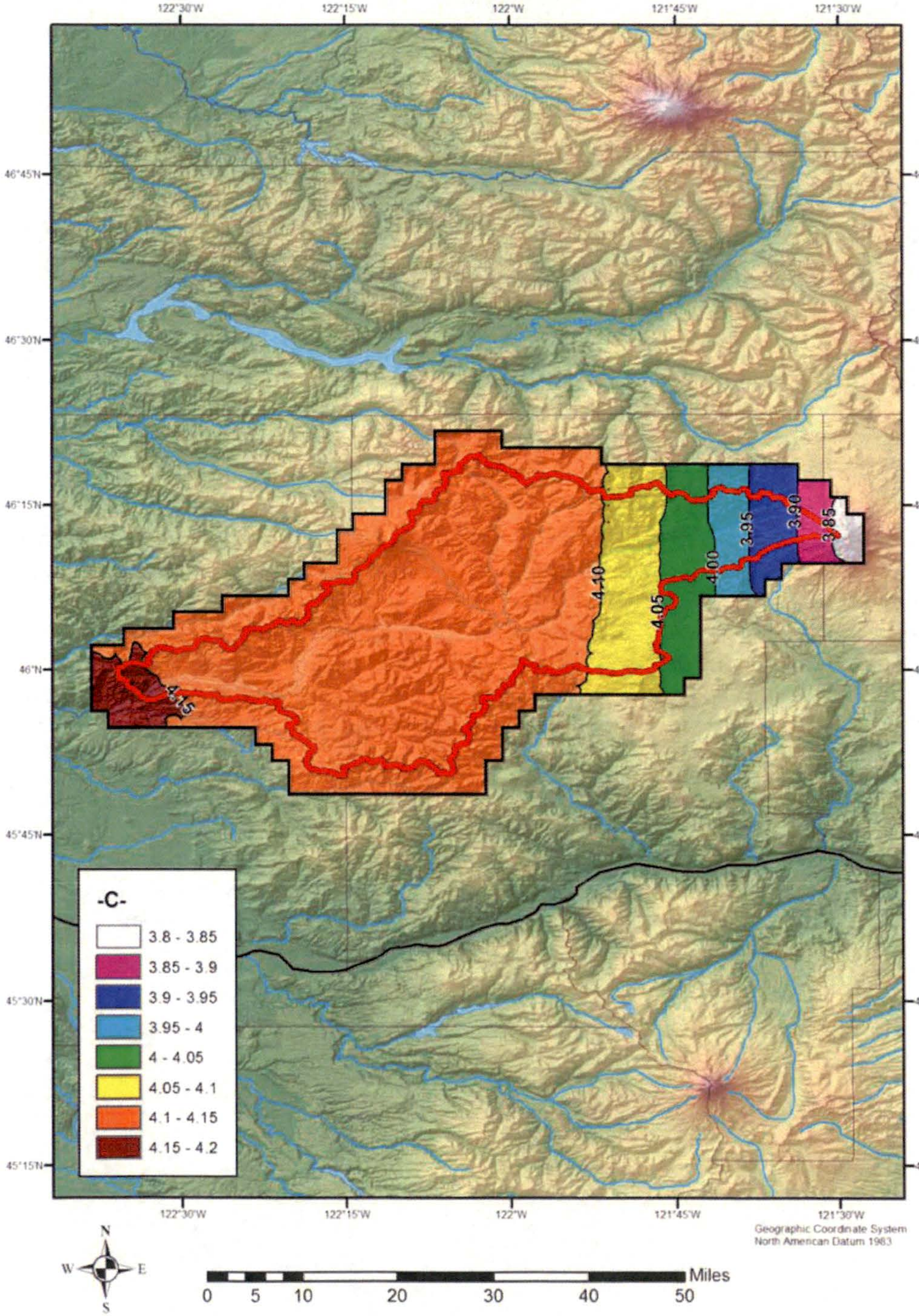
After reviewing the information provided above from Sections 6, 7 and 8 of HMR 57, several observations and conclusions have been made.

1. The discussion in Section 6 emphasizes that the SSM is complex, involves tracking through a set of modules in which knowledge of observed conditions and experience are used to arrive at estimates of FAFP, estimates are based on the analyst's judgment, and that there is a fair amount of uncertainty indicating that the authors of HMR 57 recognized major issues with the SSM. However, it was applied directly according to the original guidance in HMR 57.
2. The T/C maps were adjusted subjectively with no documentation on what adjustments were made or why.

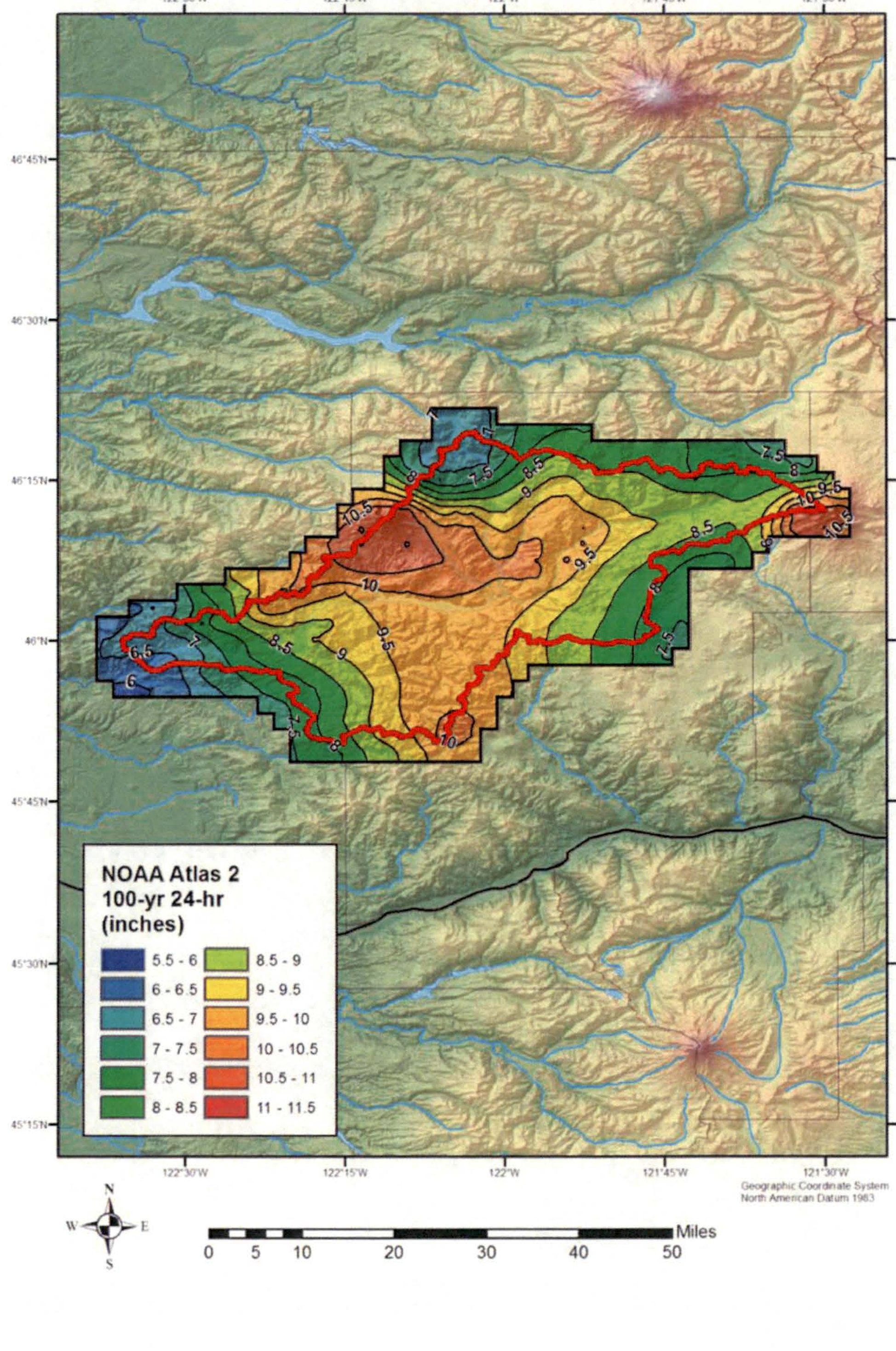
As discussed earlier, the maps used for FAFP, C and M for computation of PMP in HMR 57 are not available from the HSDC. However, low resolution example maps are published in HMR 57 for these parameters that cover western Washington. Figure 8.1 shows the C map, Figure 8.2 shows the T/C map, Figure 8.3 shows the M factor map and Figure 8.4 shows the orographic factor K map for the Lewis River basin in southern Cascades of Washington state. These maps were digitized in GIS for analysis. Using the formulas in HMR 57 Chapter 8, maps were produced from the digitized figure maps to compare with the maps shown in HMR 57. The Lewis River drainage basin in southern Washington was the domain used for the comparisons.

NOAA Atlas 2 provides the map for the 100-year 24-hour T values. Using the map of C from HMR 57 Figure 8.1, a map of T/C was computed. Since HMR 57 Figure 8.3 shows that M=0 for the Lewis River Basin, K=T/C. The computed T/C map was compared with HMR 57 Figure 8.4 (HMR 57 K). The NOAA Atlas 2 map, the HMR 57 maps for C and K, and the computed maps for K are shown below. The HMR 57 K map was compared with the computed K map and a percentage difference map is shown.

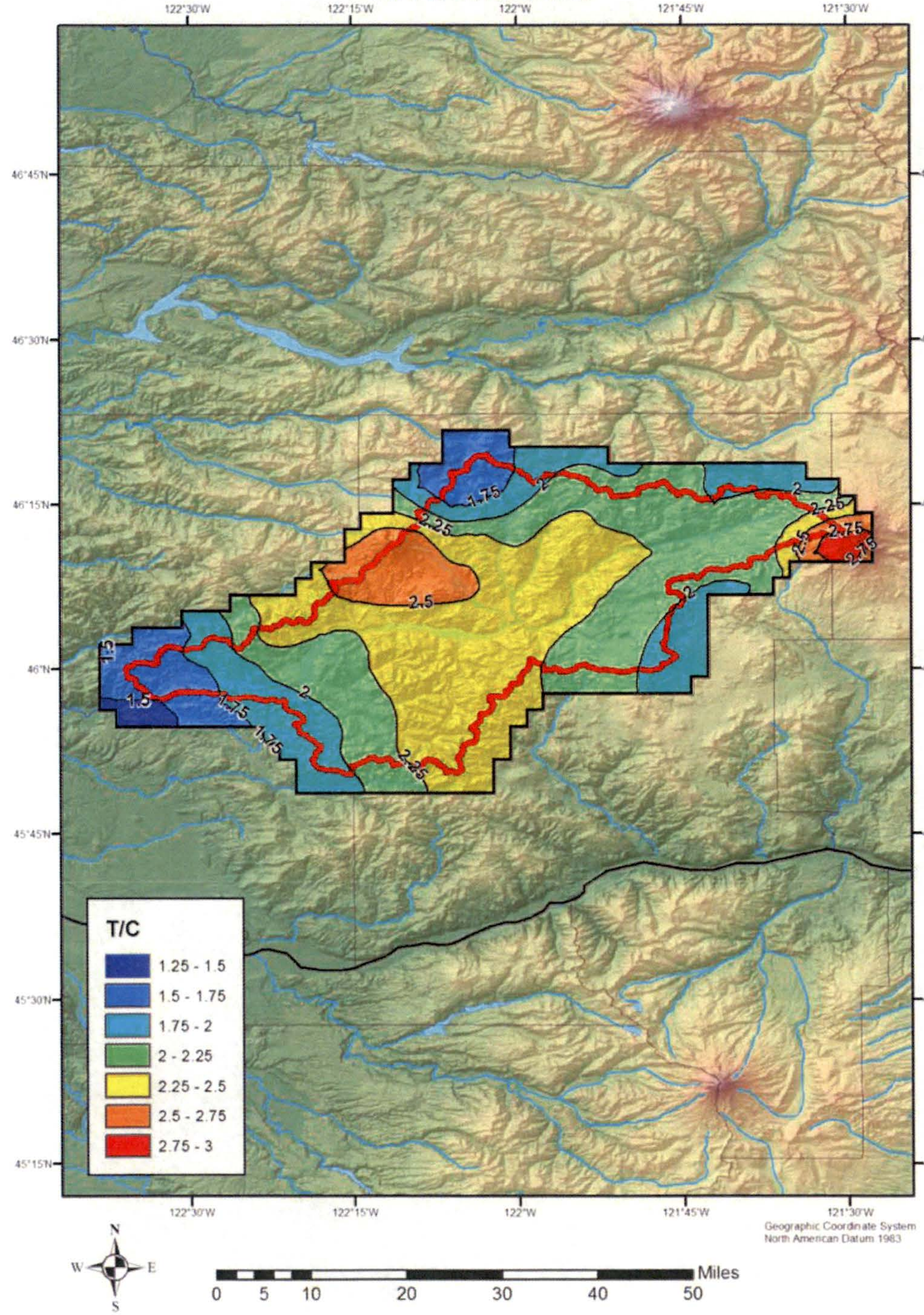
HMR-57 C (from fig 8.1)
Lewis River Basin



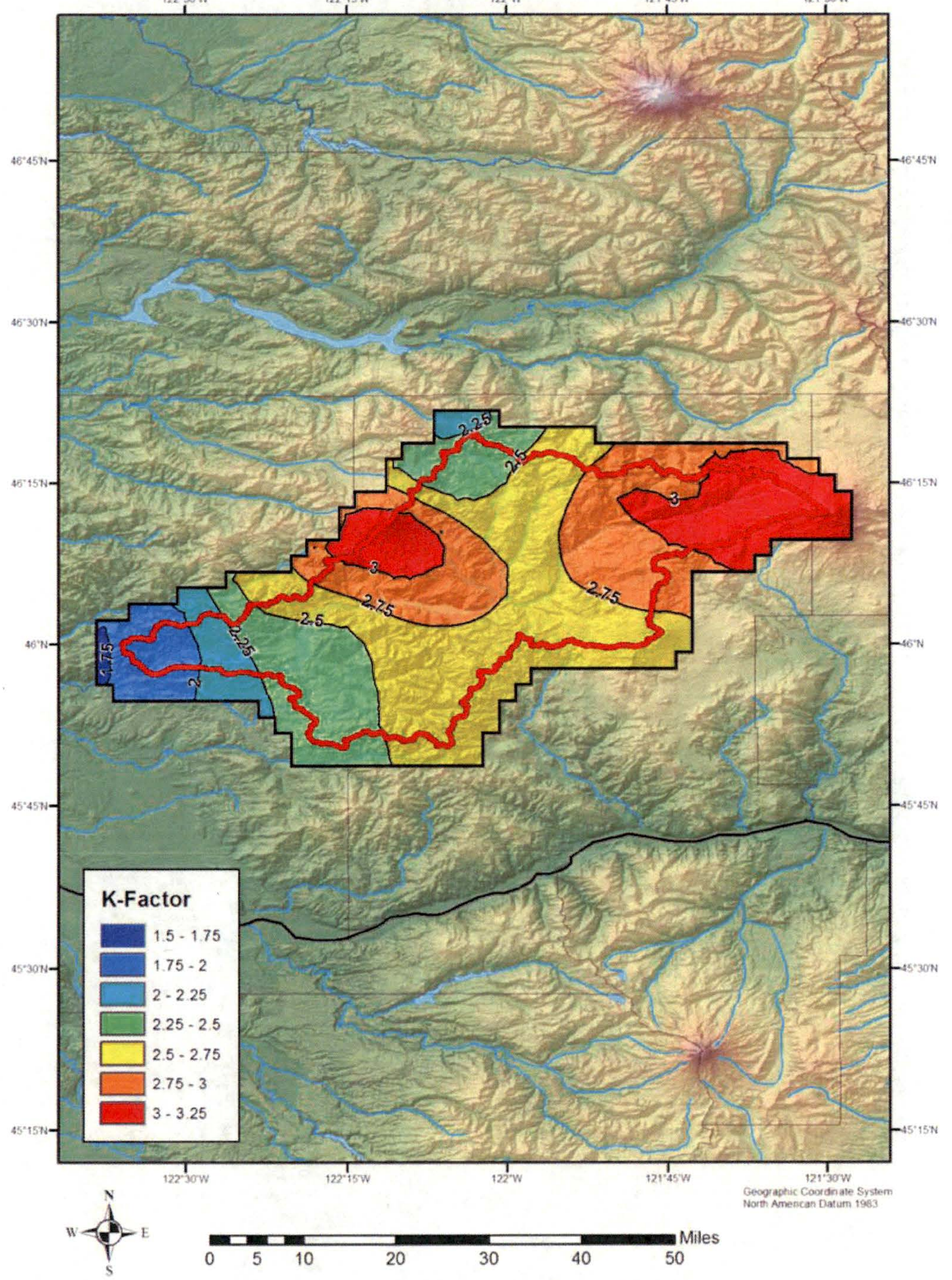
NOAA Atlas 2 100-year 24-hour Precipitation
Lewis River Basin



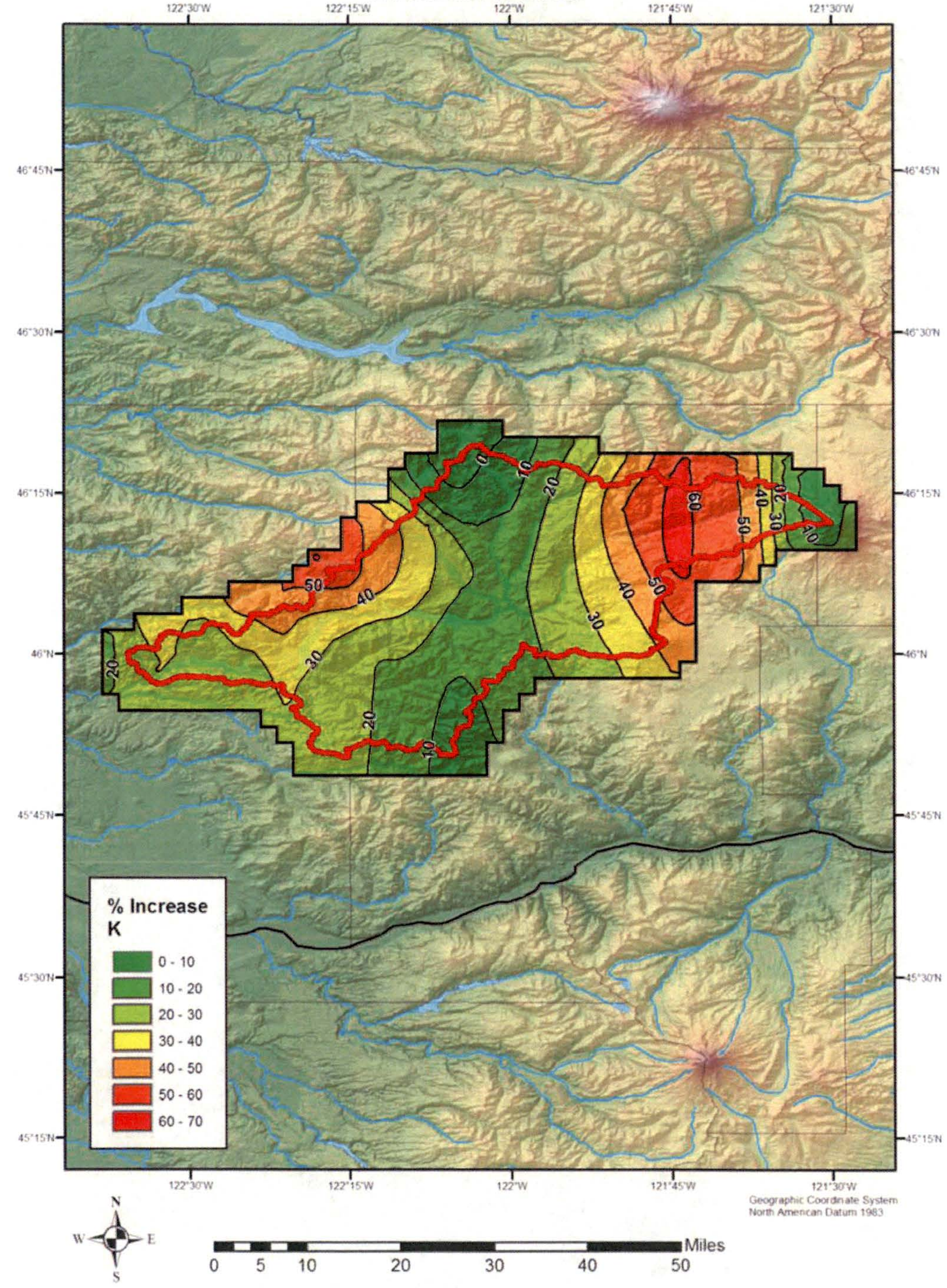
T/C - (NOAA Atlas 2 100-year 24-hour Precipitation ÷ HMR 57 C)
Lewis River Basin



HMR-57 K-Factor (from fig 8.4)
Lewis River Basin



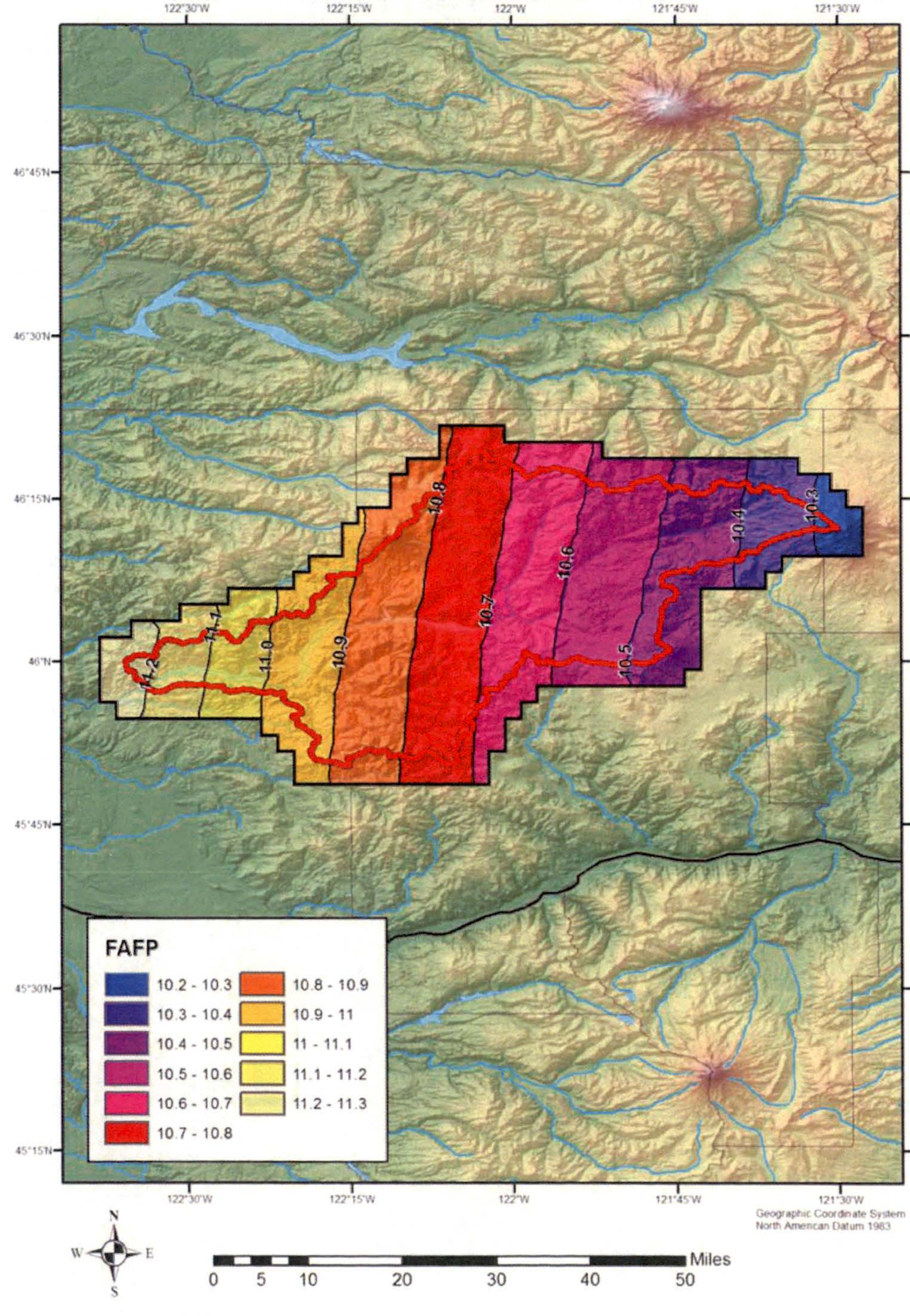
Percent Increase of HMR 57 K Values from T/C Values
Lewis River Basin



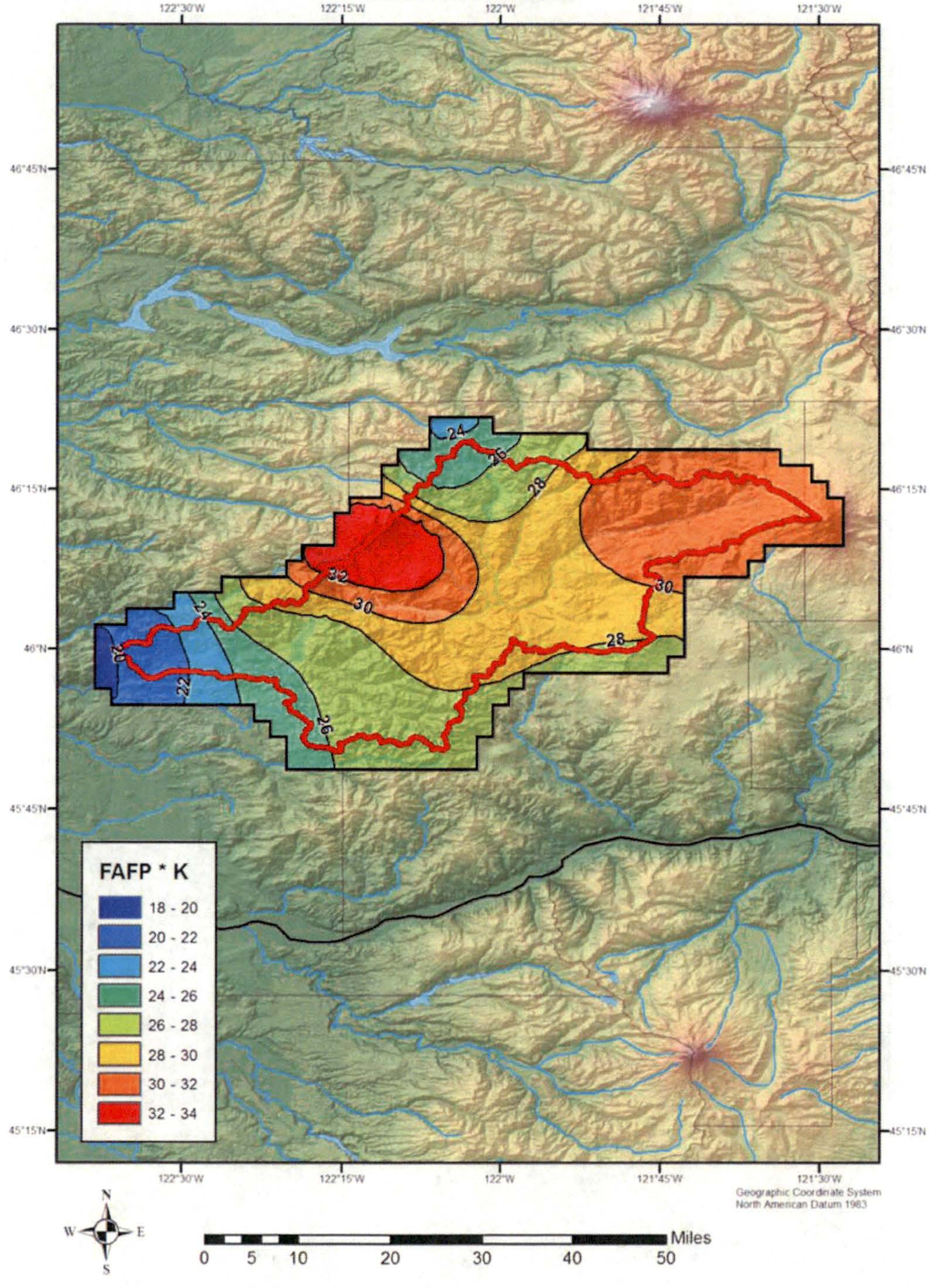
The comparison between the computed K map and the HMR 57 K map shows significant differences. Overall the computed K values are significantly smaller than the K values from HMR 57. The differences range from about 10% to over 60% with the HMR 57 values being consistently larger.

Having values for FAFP from HMR 57 Figure 7.2 and values for K from Figure 8.4, a map of PMP can be constructed using PMP = (FAFP) (K). Figures showing these values are show below along with HMR 24-hour 10-mi^2 PMP values.

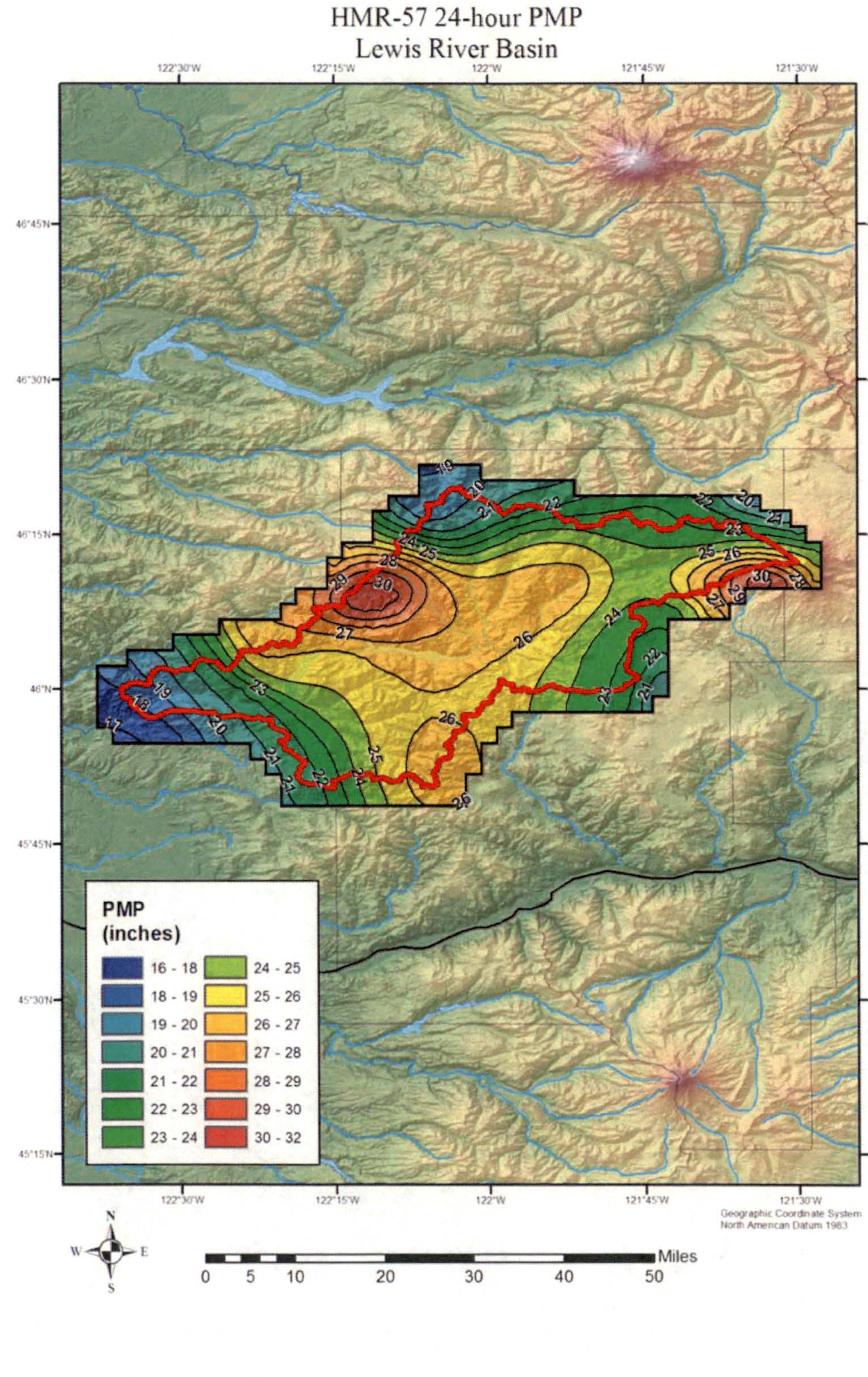
HMR-57 FAFP (from fig 7.2)
Lewis River Basin



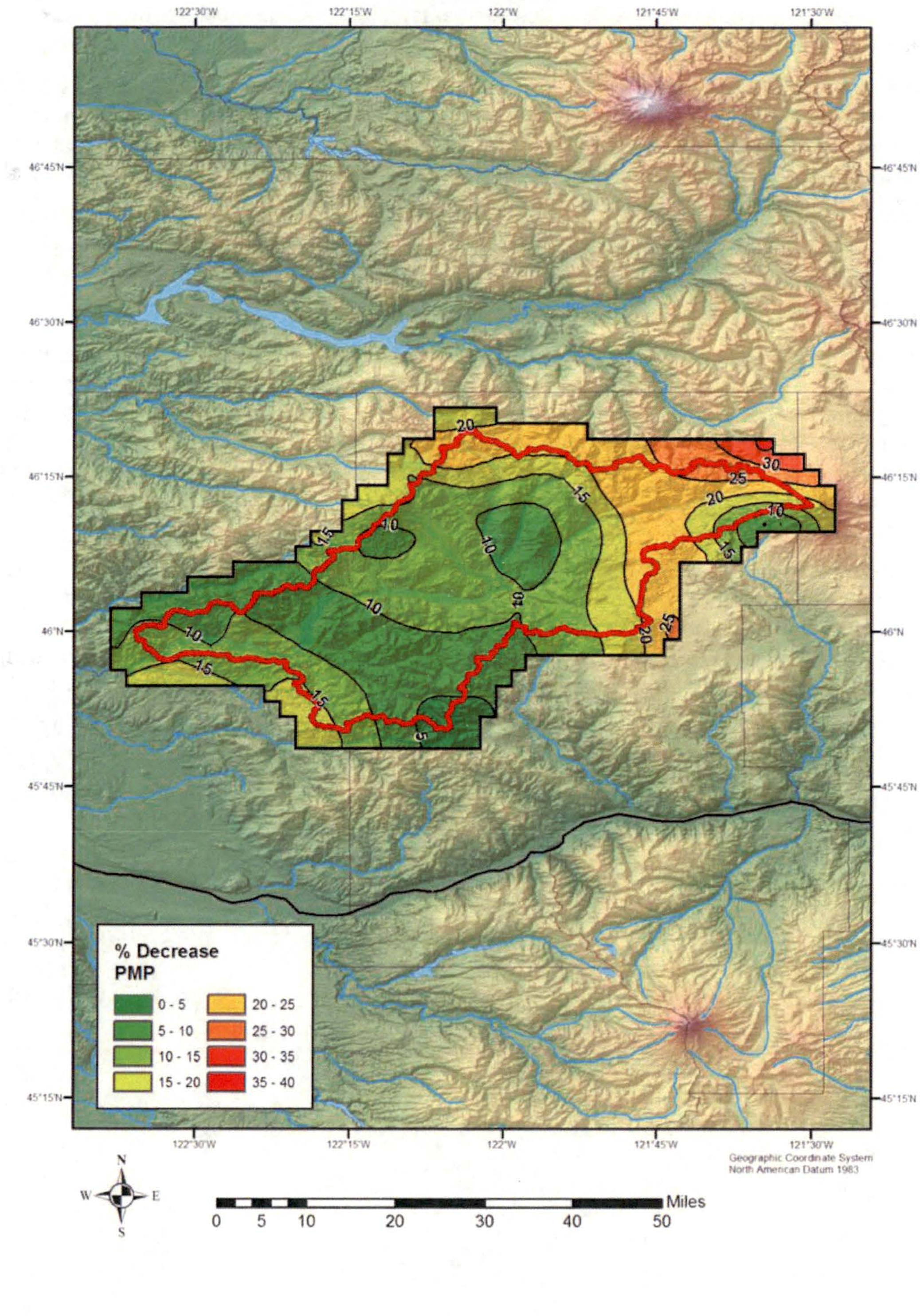
[HMR 57 FAFP] * [HMR 57 K]
Lewis River Basin



CALCULATION SHEET			
Calculation Title: Appendix I – HMR Storm Separation Method Example	Calculation No.: CDQ0000002016000041	Rev. No.: 001	Sheet: I29



Percent Decrease in HMR 57 24-hr PMP Values from HMR 57 (FAFP * K) Values
Lewis River Basin



The comparison between the computed PMP map and the HMR 57 PMP map also shows significant differences. Overall the computed PMP values are larger than the PMP values from HMR 57. The differences range from about 7% to over 25% with the HMR 57 values being consistently smaller.

The reasons for these differences are not known. It appears that after the highly subjective SSM procedure is followed, significant changes are manually made to the SSM maps and to the resulting maps of PMP produced using the SSM maps. The conclusion is made that for the Lewis River drainage basin domain, the SSM maps published in HMR 57 cannot be objectively duplicated and using the HMR 57 maps of SSM parameters, the HMR 57 PMP values cannot be objective duplicated.

HMR 59 SSM Application

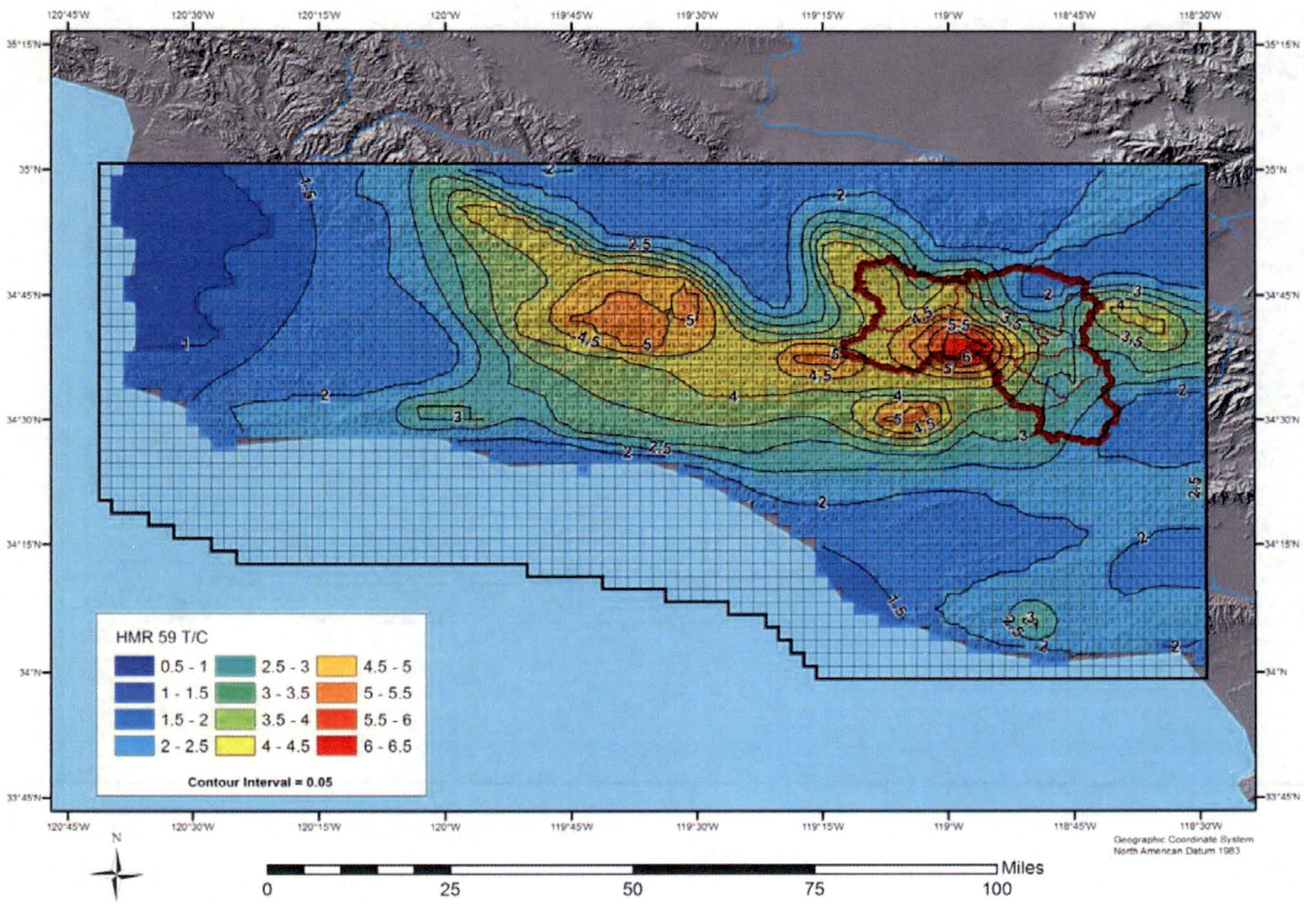
A similar exercise was completed in the HMR 59 domain in and around the Piru Creek region and the Piru Creek drainage basin in southern California was used as the domain to compare computed maps with HMR 59 maps. Again none of the HMR 59 maps used to compute PMP was available from HDSC. Example low resolution maps for T/C (Figure 6.4), M-factor (Figure 6.5), and the K factor (Figure 6.6) for southern California are included in HMR 59. Unfortunately, the example map for FAFP (Figure 6.3) was for northern California and no example map of C is included in HMR 59. Therefore comparisons of computed maps with HMR 59 maps are limited.

Using the example maps in HMR 59, maps for C and FAFP can be constructed. Unfortunately by constructing these maps, independent comparisons with HMR 59 maps is not possible. Figure 6.4 provides a map of T/C. By inverting the values on this map, a map of C/T was produced. That map is then multiplied by the NOAA Atlas 2 map (T) to produce a map of C. The M-factors for the Piru Creek drainage basin can be determined from Figure 6.5 and of course the PMP values for the Piru Creek domain are available from the HMR 59 PMP maps. Using Equation 6-5 from HMR 59,

$K = M^2 (1 - (T/C)) + T/C$ a computed map of K can be constructed.

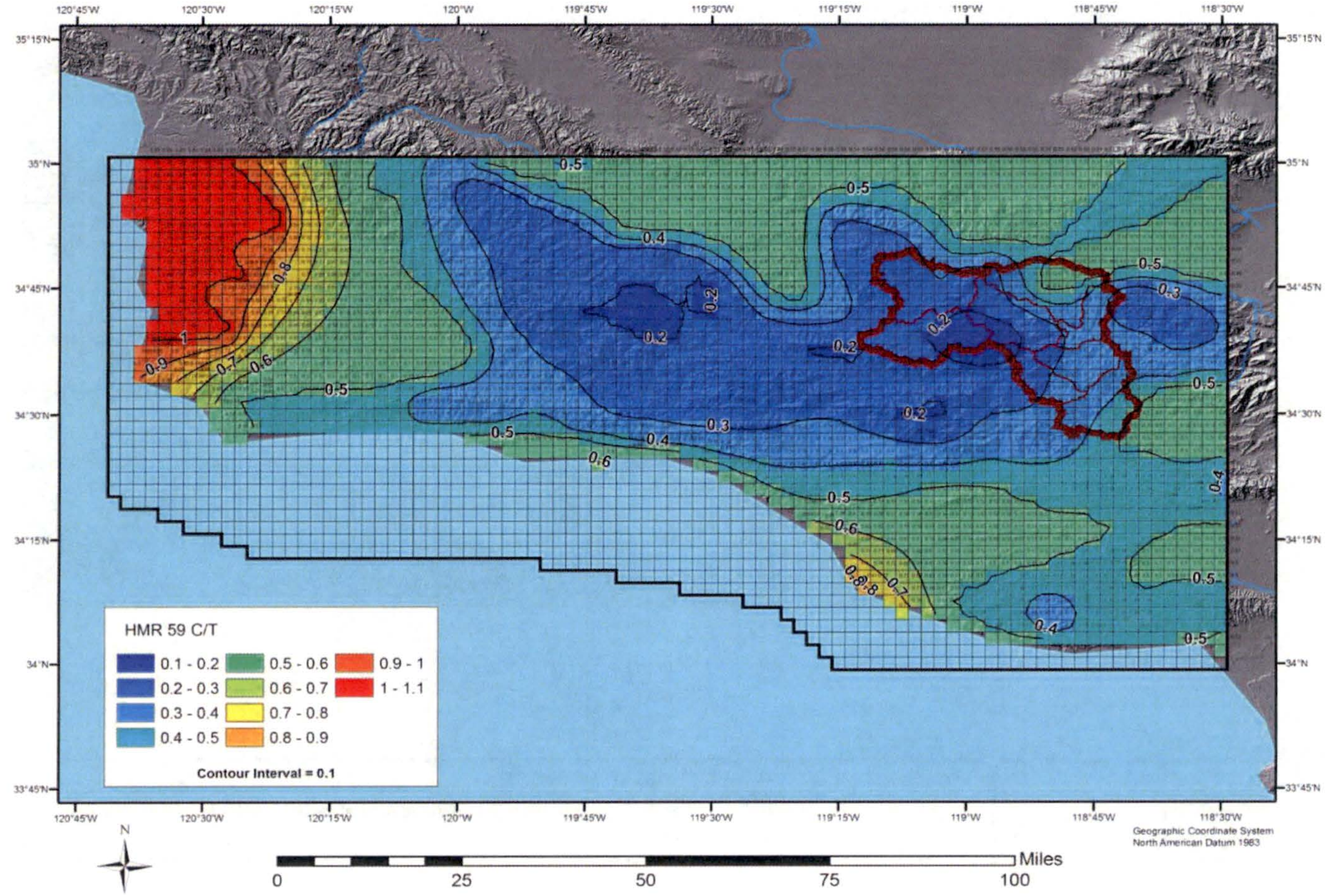
HMR 59 maps and computed maps are shown below:

HMR 59 T/C



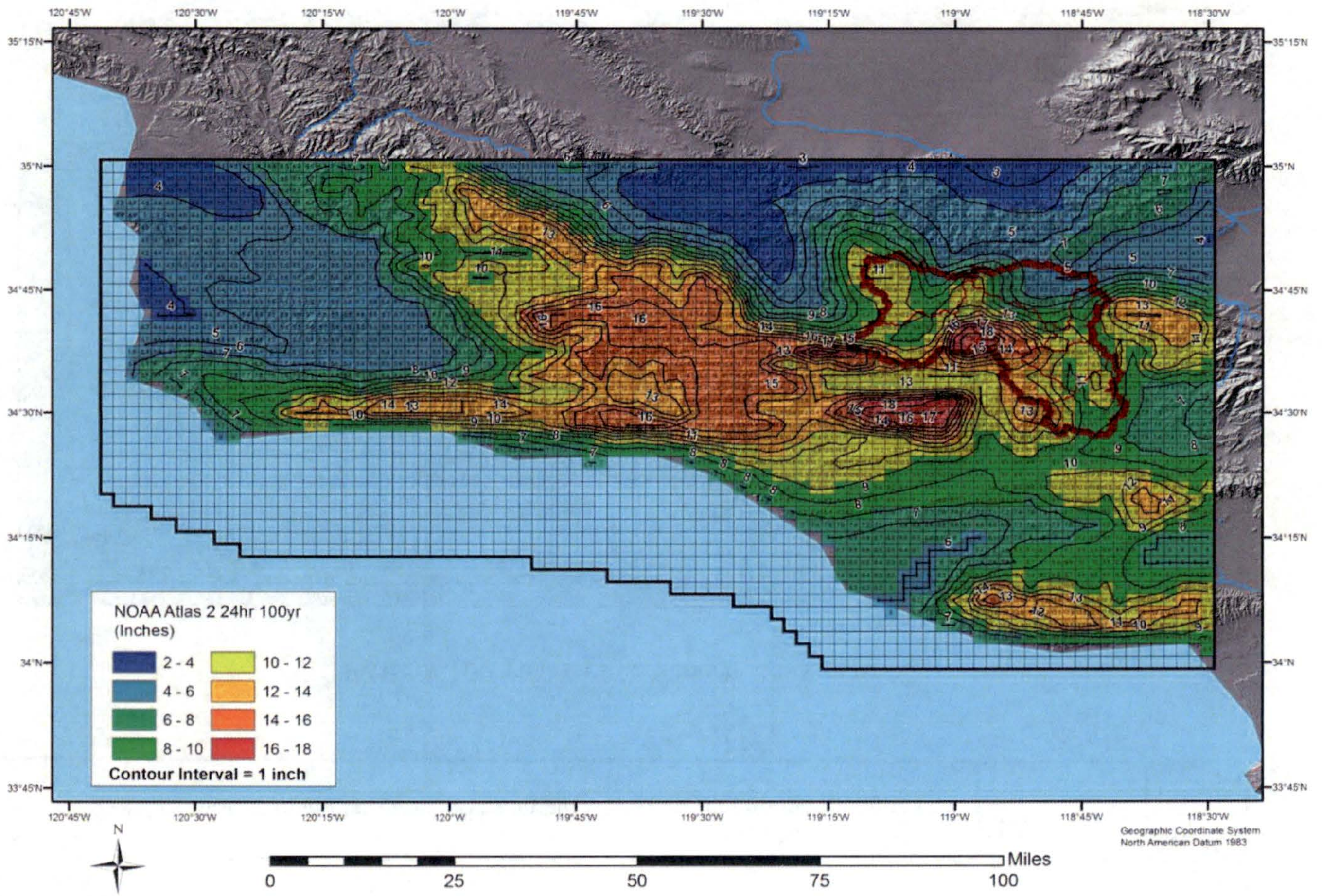
HMR 59 T/C
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
5 - 5.5
5.5 - 6
6 - 6.5
Contour Interval = 0.05
Miles
0
25
50
75
100
N
Geographic Coordinate System
North American Datum 1983

HMR 59 C/T

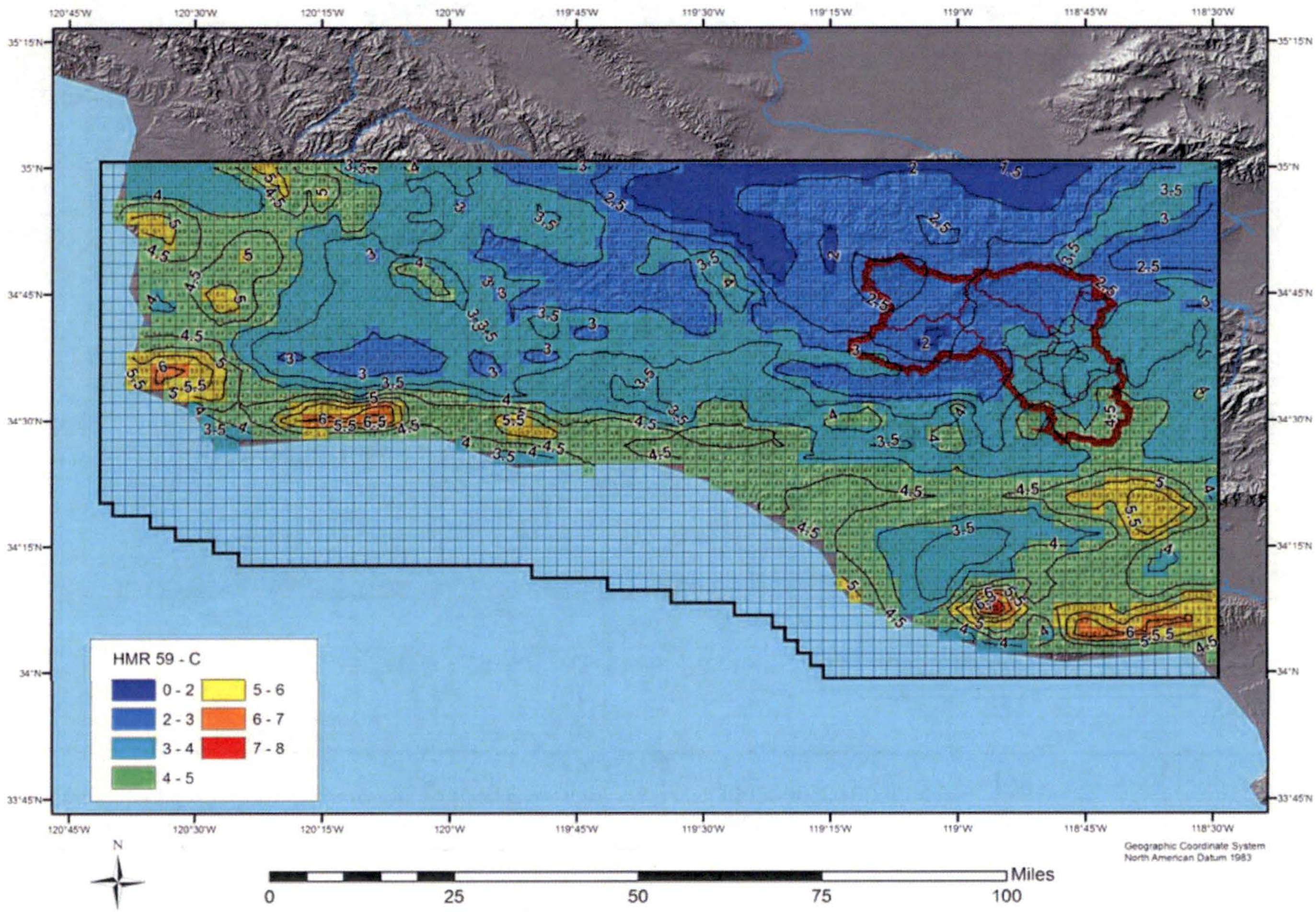


HMR 59 C/T
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
1 - 1.1
Contour Interval = 0.1
120°45'W
120°30'W
120°15'W
120°W
119°45'W
119°30'W
119°15'W
119°W
118°45'W
118°30'W
35°15'N
35°N
34°45'N
34°30'N
34°15'N
34°N
33°45'N
N
0
25
50
75
100
Miles
Geographic Coordinate System
North American Datum 1983

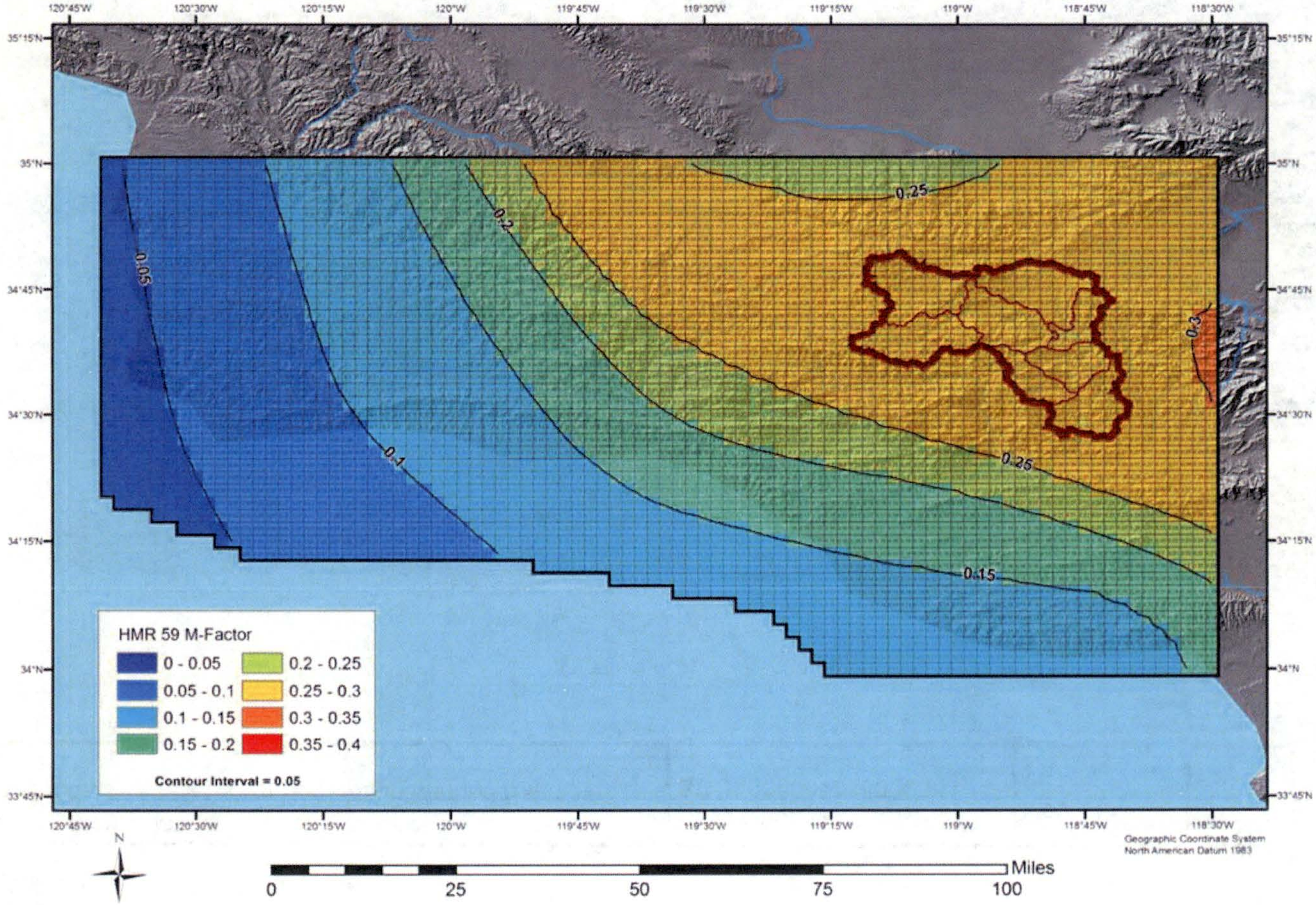
NOAA Atlas 2 - 24-hour 100-year Precipitation Frequency Estimates



HMR 59 100-year Convergence Component "C"

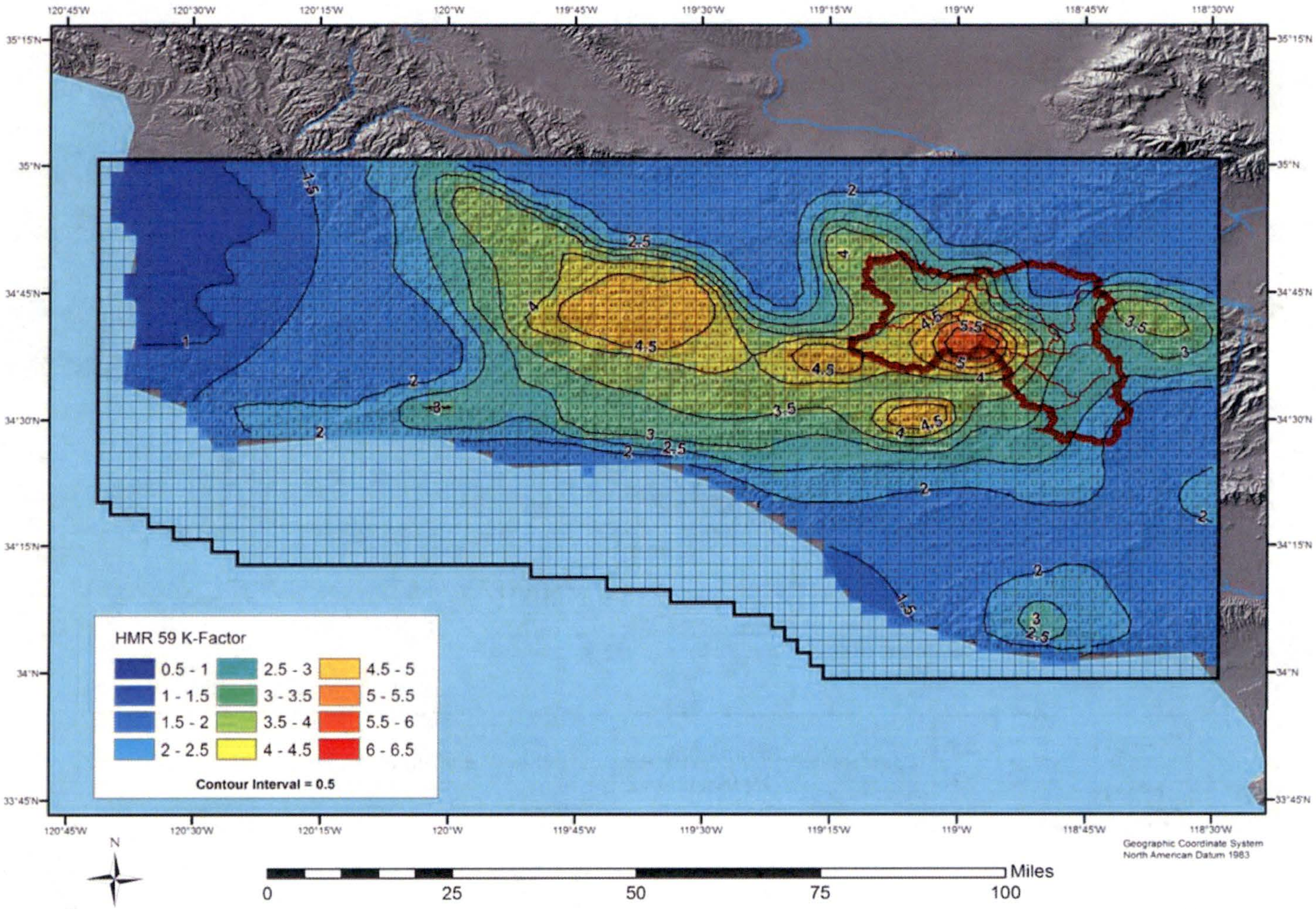


HMR 59 M-Factor



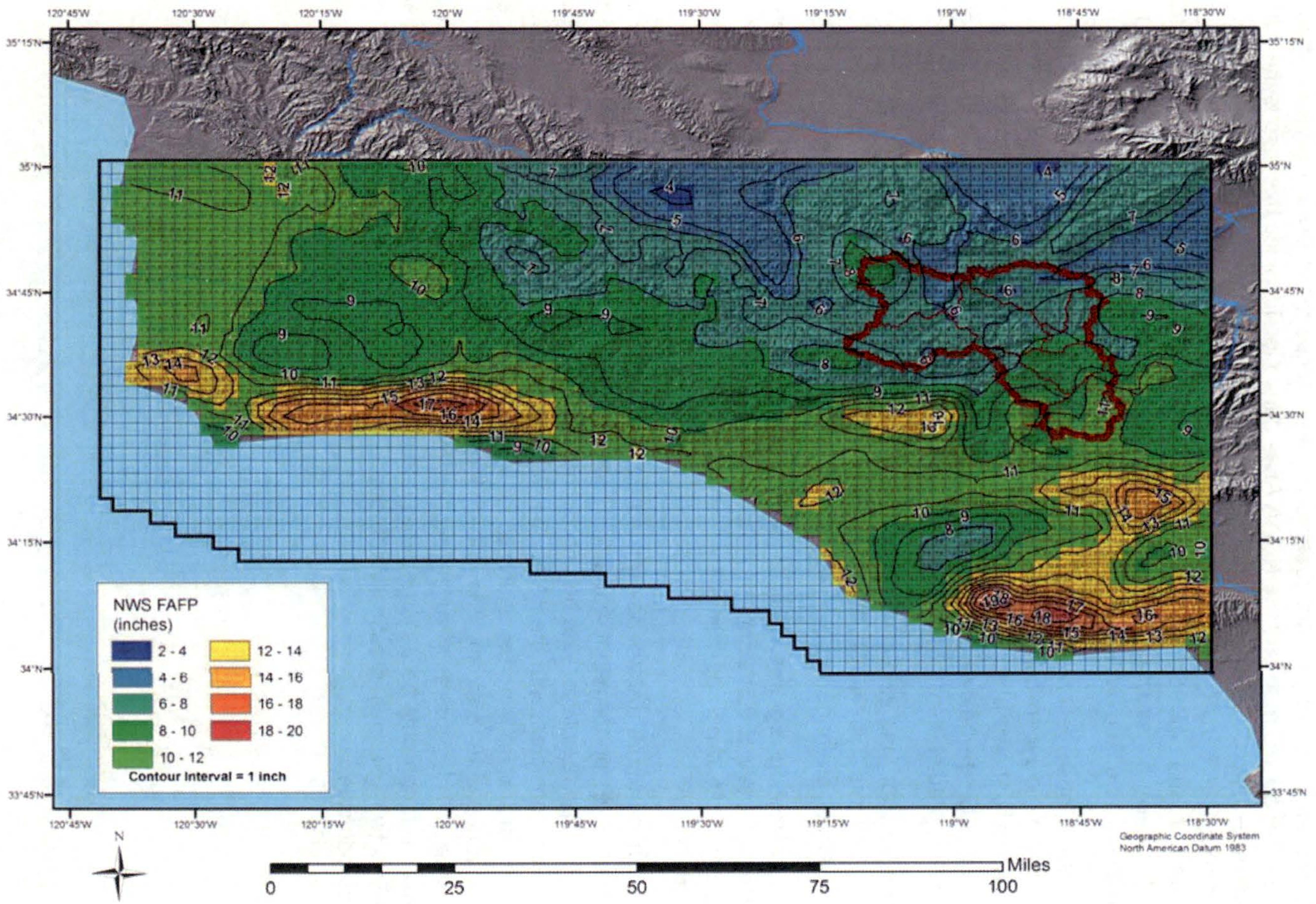
AWA Produced K-Factor

$K = M^2 (1 - (T/C)) + (T/C)$



CALCULATION SHEET			
Calculation Title: Appendix I – HMR Storm Separation Method Example	Calculation No.: CDQ0000002016000041	Rev. No.: 001	Sheet: I38

NWS FAFP = PMP ÷ K



There are several significant observations from these maps. The 100-year C map has been constructed using the HMR 59 T/C map and the NOAA Atlas 2 map for T. Since this map is the 100-year rainfall produced from storm dynamics without any influence from underlying terrain, the gradients of rainfall should be relatively smooth. The C map from HMR 57 shown previously shows a relatively smooth analysis. The constructed C map from the HMR 59 data shows areas of large gradients, especially for coastal regions. Since this map is subjectively constructed in the SSM procedure, the large gradient areas were manually introduced into the analysis for unknown reasons.

A similar observation is made for the constructed FAFP map. FAFP is the rainfall produced by a storm from atmospheric dynamics without the influence of the underlying topography. The FAFP map from HMR 57 shown previously shows a relatively smooth analysis. The large rainfall gradient areas in the FAFP map (HMR 59 Figure 6.3-see below) indicate that subjective adjustments were made to the FAFP map which introduced artificial gradients from the coast through the Central Valley and into the Sierra Nevada.

The K factor map in HMR 59 was compared to the computed K factor map using values for M, C and T from HMR 59 and from NOAA Atlas 2. The comparison resulted in good agreement for the region surrounding the Piru Creek drainage basin.

An interesting region to look at is the relatively non-orographic region between Lompoc and Santa Maria, approximately 120.5W and 34.75N. Both the HMR 59 K factor map and the computed K factor map identify values of M to be approximately 0 and K to be approximately 1. Hence for this area PMP is approximately equal to FAFP.

According to the discussions related to the SSM, the FAFP map is constructed using storm data for regions where K is approximately equal to 1, i.e. regions where orographic influences are at a minimum. This region seems appropriate for K to be approximately 1. The FAFP values in this region are between 11 inches and 12 inches, consistent with the HMR 59 PMP values of approximately 12 inches. However, the largest maximized storm rainfall from storms analyzed for the Piru Creek site-specific PMP study for this region is 4.5 inches from the January 1943 storm. It is not obvious how the largest maximized storm rainfall was increased from 4.5 inches to 11.5 inches resulting significantly larger FAFP values than those from maximized storm rainfall values. It can only be assumed that use of the various subject producers and decisions was applied. These subjective changes drastically affect the final PMP values developed for HMR 59 and of course or not reproducible.

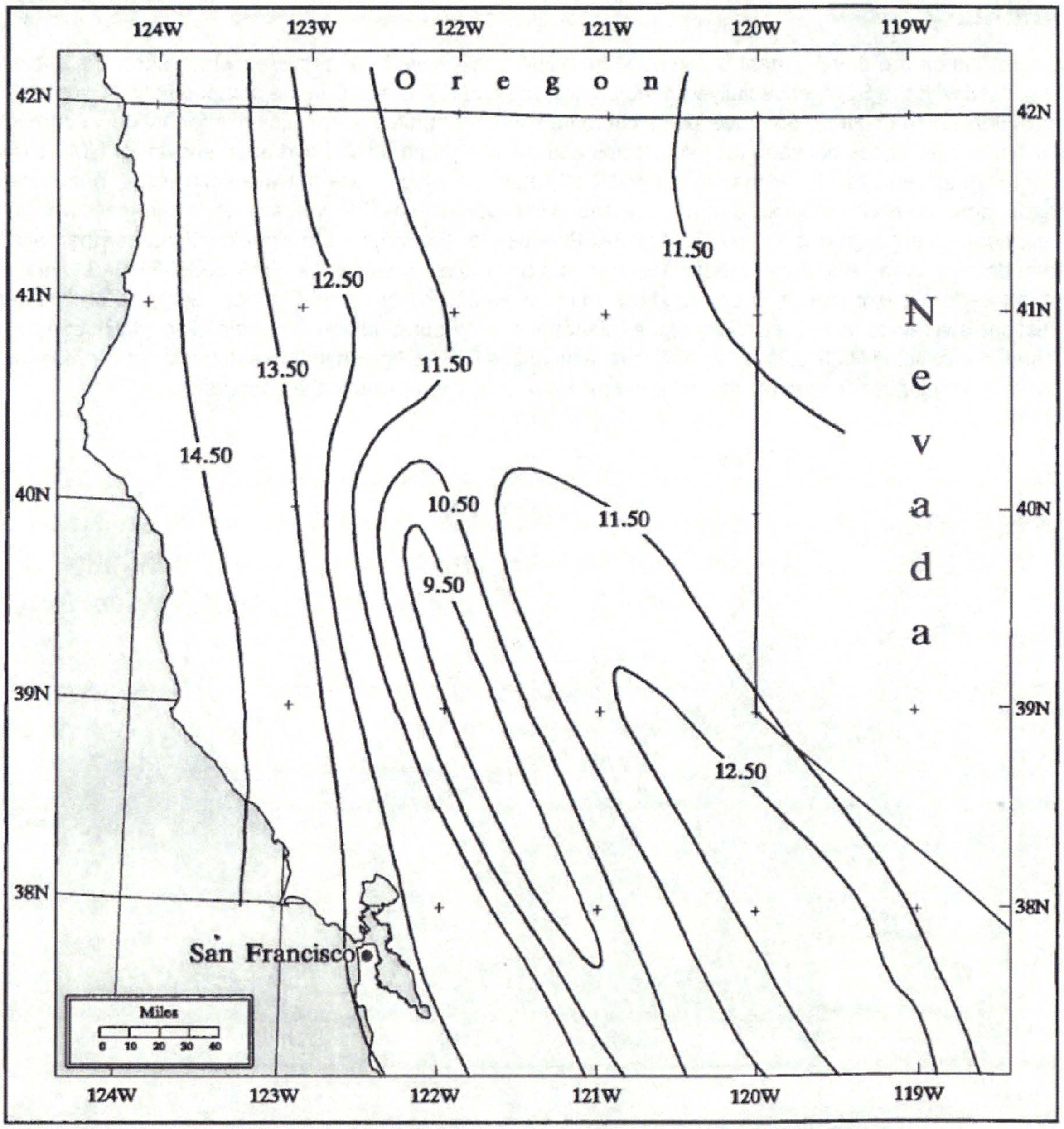


Figure 6.3. *Non-orographic PMP (FAFP) at 1000 mb (inches of rainfall).*

HMR 59 Figure 6.3 FAFP map for northern California

Summary

Discussions on the development of the SSM from HMR 55A have been provided which show the subjectivity associated with the SSM, especially with the development of FAFP and C in the computations. Example maps from HMR 57 and HMR 59 have been compared with computed maps using information in the HMRs. Significant differences between the HMR maps and the computed maps have been shown for HMR 57 in the K factor maps and the PMP maps. For HMR 59, example maps were not available for all parameters so independent comparisons could not be made. However, the FAFP values for the region where K is approximately equal to one shows that the FAFP values for that region are significantly larger than available storm data indicate. Additionally there are large rainfall gradient areas in the HMR 59 FAFP and C maps that are not generally expected and do not show up in the HMR 57 FAFP and C maps. Because of this, serious questions are raised as to the validity of the treatment of orographic influence on rainfall in HMRs 55A, 57, and 59 and the resulting PMP values. Specifically, any values for PMP given in those documents in areas that are orographically influenced should at the very least be re-evaluated to verify their accuracy.

APPENDIX J – Point OTF Evaluation for PMP Calculations – Use of Single Point vs Areal-Average Precipitation Climatology Values

The memo included in this appendix provides information on the investigations of using the grid point location with the highest total storm rainfall as the source location in the OTF calculation process. The investigation was requested by the review board to determine whether using some number of grid points would provide a better representation of the precipitation frequency values associated with the source location versus using the single highest point in the OTF calclation process. The memo below was developed as part of both this study and the concurrent Wyoming statewide PMP study. In both studies, the same questions arose in regards to the OTF calculation process.

Applied Weather Associates

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September 5, 2014

Memo for Record

To: Review Board

Subject: OTF Evaluation for PMP Calculations – Use of Single Point vs Areal-Average Precipitation Climatology values.

Background

The calculation of PMP in orographically dynamic areas necessitates accounting for the effect of surface topography and elevation on rainfall when transposing a storm. AWA quantifies this effect as the Orographic Transposition Factor (OTF). For a gridded PMP study, the OTF is calculated for each storm at each grid point over a basin domain. The OTF is a ratio of a climatological precipitation depth at a source storm location to the depth at a target grid point within the drainage basin. Typically the precipitation frequency climatology depths, such as NOAA Atlas 14, are used to determine a relationship, or correlation, between the source and target location using the 10 through 1,000-year return frequencies. It is assumed that the difference in the climatological precipitation depths between the storm source location and a transpositionable target location is primarily due to the effects of elevation and orographics. Therefore, the climatological precipitation relationship between the two locations, when expressed as a factor and applied to a storm's rainfall depth, can be used to determine the adjusted rainfall depth of a storm when transposed to a target location.

Recent approved PMP studies (e.g. Lewis River 2011, Arizona statewide PMP 2013, Susitna-Watana 2014, North Umpqua 2014) completed by AWA use a procedure for calculating the OTF for a grid point location by determining the ratio of precipitation frequency values at the SPAS total storm rainfall DAD zone center location to the grid point location. It is assumed that since the rainfall center for a given DAD zone is the location of the greatest total precipitation for an event, that the precipitation climatology data at that same location would *best* represent the orographic rainfall effect attributable to that event. In actuality, the underlying terrain over an area contributes to the orographic effect for a storm event, not only the specific discrete location of the storm center. However, it is assumed that the greater the distance from the storm center, the less representative the underlying precipitation frequency data is to most critical rainfall for that storm event, based on the spatial distribution of the storm analysis. The purpose of this evaluation is to consider the difference in OTF values resulting from applying precipitation climatology values averaged over an area at the storm location versus using the values only at the storm center point, and to discuss which approach is most feasible and appropriate.

Procedure

Ten SPAS-analyzed storm centers were assessed to compare OTF values resulting from the use of precipitation climatology values at the storm center point location versus an areal-average of multiple points surrounding the storm center. The storm centers were chosen from events in orographic regions of both the Rocky and the Appalachian Mountain Ranges (Table J.1).

Table J.1 List of storm centers evaluated

NAME	SPAS	DADZONE	STATE	LAT	LON	YEAR	MONTH	DAY	RAINFALL	TYPE
DEER CREEK DAM	1241	2	UT	41.360	-111.910	2010	10	25	4.74	General
COTTONWOOD	1265	1	UT	40.404	-111.638	1982	9	26	10.13	General
COTTONWOOD	1265	2	UT	40.379	-112.204	1982	9	26	10.02	General
COTTONWOOD	1265	3	UT	41.604	-112.013	1982	9	26	9.71	General
ALTA PASS	1299	1	NC	35.879	-81.871	1916	7	13	24.9	General
ELBA	1305	1	AL	31.363	-86.121	1929	3	12	29.73	General
SAVAGETON	1325	1	WY	43.880	-105.930	1923	9	27	17.1	General
BIG THOMPSON CANYON	1231	1	CO	40.479	-105.429	1976	7	31	12.52	Local
MORGAN	1248	1	UT	41.079	-111.654	1958	8	16	7.01	Local
JOHNSON CITY	1343	1	TN	36.304	-82.063	1924	6	13	16.14	Local

ArcGIS and Excel software was used to aid in data extraction and calculations. Figure J.1 shows the location of each analyzed storm center. Centers were deliberately chosen in highly orographic locations or where the precipitation frequency values change rapidly over short distances. These sites were chosen as potentially *worst case* scenarios where the largest difference in point-based OTF vs area-based OTF is likely to occur. Two storms, Savageton, WY and Elba, AL occurred over relatively homogeneous terrain and were included as *typical* scenarios where the point vs areal OTF difference is not likely to be significant.

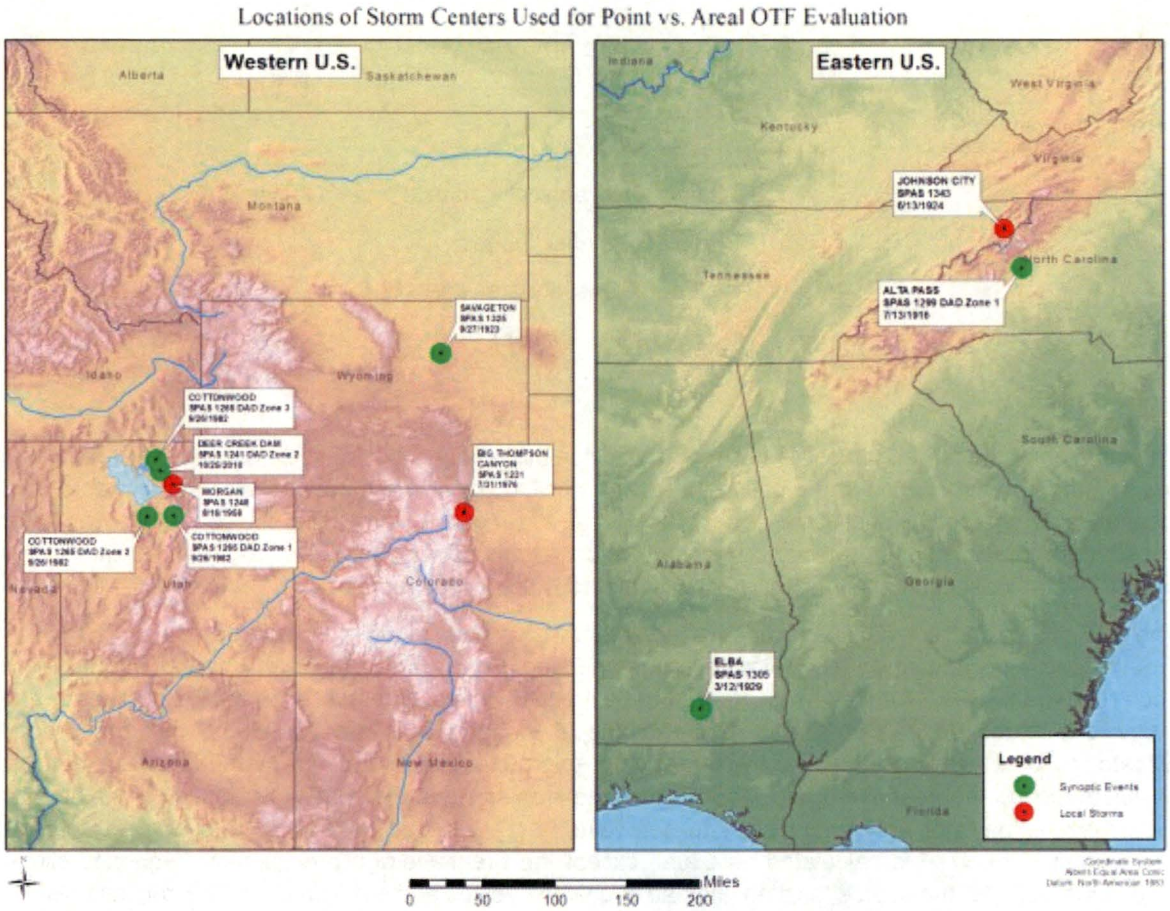

Figure J.1 Locations of analyzed storm centers.

Using ArcGIS, a grid point network was created covering the extent of each SPAS total storm raster. The grid network coincides with the spacing and orientation used for the Wyoming Statewide PMP Study for the Western U.S. storms and the TVA PMP Study for the Eastern U.S. storms. Precipitation frequency climatology depths were extracted to each grid point for the 10, 25, 50, 100, 200, 500, and 1,000-year return frequencies. The 24-hour duration data sets were used for synoptic tropical/general type storms and the 6-hour duration data sets were used for the local storm types.

To calculate the OTF, the ratio of the adjusted precipitation P_a at the target grid cell location to the in-place storm precipitation P_i.

$$OTF = \frac{P_a}{P_i}$$

The in-place storm precipitation is determined by SPAS, 6-hour for local storms, 24-hour for general storms. The adjusted rainfall is predicted from the precipitation climatology datasets using a linear regression least squares trendline between the precipitation climatology depths (10 through 1000-year) at the source and target locations:

$$P_a = mP_i + b$$

where,

P_o	=	target orographically adjusted rainfall (inches)
P_i	=	in-place rainfall (inches)
m	=	slope of least squares line
b	=	origin offset (inches)
)		

The location of the target grid cell is not important since this evaluation is only concerned with what values are used at the source location, therefore the target grid cell locations were chosen arbitrarily. The source point location is determined by finding the largest SPAS total storm grid cell and using the centroid. The relationship between the precipitation frequency climatology values at this point and the arbitrary target point is calculated as the OTF as described above, consistent with methods used in past projects.

The OTF is also calculated using a series of incremental area sizes at the storm source location; 10-, 50-, 100- 250 mi^2, etc., depending on the storm coverage and type. For a given area size, the grid points are ordered according to the SPAS total storm depth and the extracted values were averaged for the number of grid cells equivalent to the desired area size. For example, if the grid cells are each ~2.5 mi^2, the precipitation climatology data would be used for the largest four grid points as determined by the SPAS rainfall depth to calculate the 10 mi^2 areal-average. Depending on the area size and the spatial distribution of the storm, these cells may or may not be contiguous. The cell values are averaged for the 10 through 1,000 year return frequencies. The OTF is calculated as usual, except the areal-average precipitation frequency climatology values are used for the source location, instead of only the values at the maximum SPAS rainfall point.

Example Calculations

EXAMPLE 1

The July 31, 1976 storm over Big Thompson Canyon, CO (SPAS 1231) occurred along the steep and abrupt eastern slopes of the Rocky Mountains. The 6-hour precipitation climatology developed for the Wyoming PMP study was used for this event. At this location, the gradient of precipitation climatology is very high with a large degree of variability over small geographic areas, making a good candidate for a *worst-case* scenario in terms of point vs. areal OTF. Figure J.2 illustrates the SPAS total storm rainfall over the gridded network. Each cell is outlined in a color indicating which areal-average category the cells falls within.

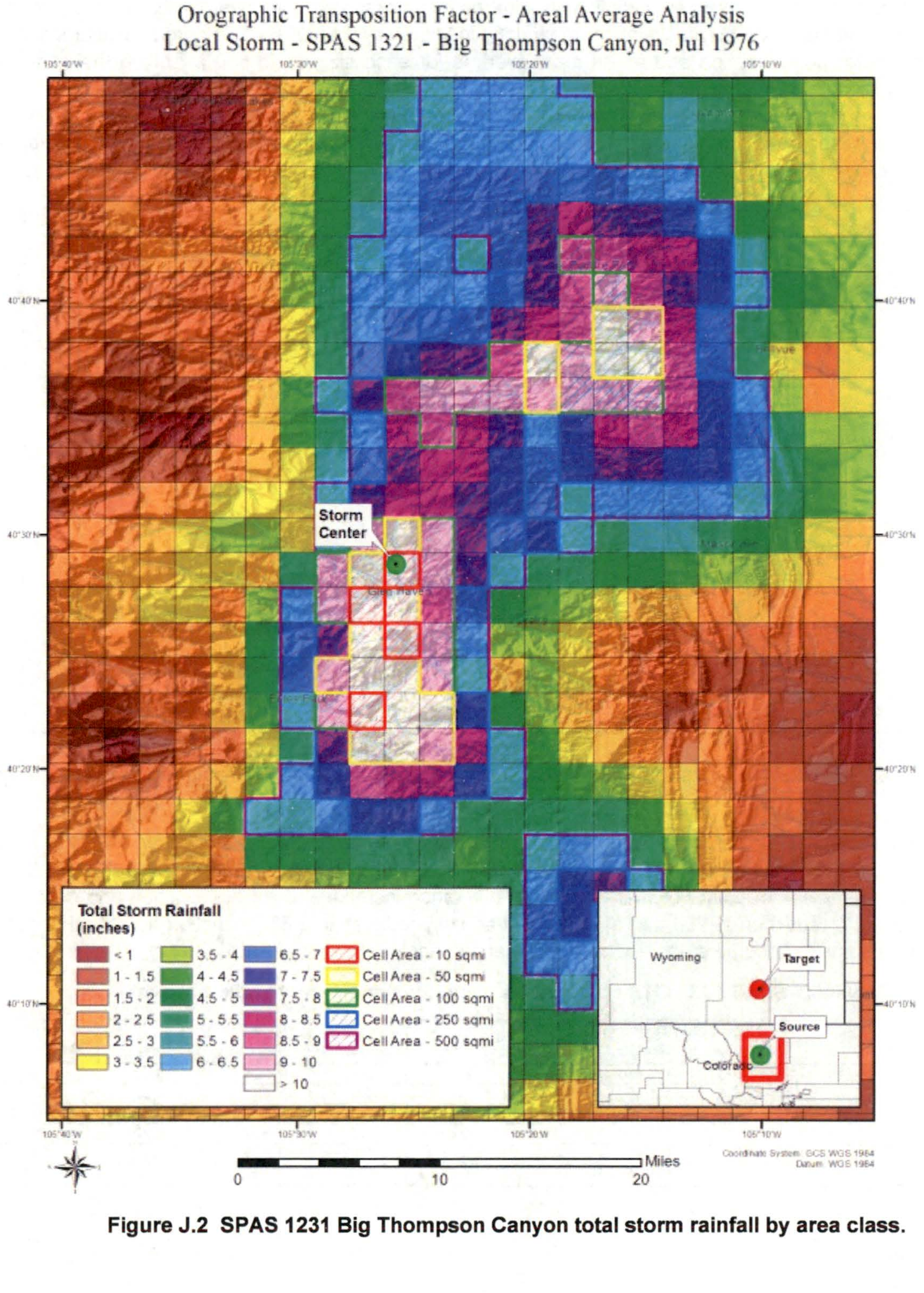

Figure J.2 SPAS 1231 Big Thompson Canyon total storm rainfall by area class.

It is expected that the OTF will vary significantly with the incorporation of data over increased area sizes due to the extreme variation of the precipitation climatology in this area. The OTF values area calculated for using the storm center point location and as an areal-average for each size up to 500 mi^2 using the relationship between the climatology values at the source and target cells. Figure I.3 shows the best fit trend lines for each of the linear regression relationships. The red line represents the storm center point and each of the other trend lines represents the various areal averages up to 500 mi^2. The graph visually illustrates the divergence of each areal-average OTF compared to the single-point OTF.

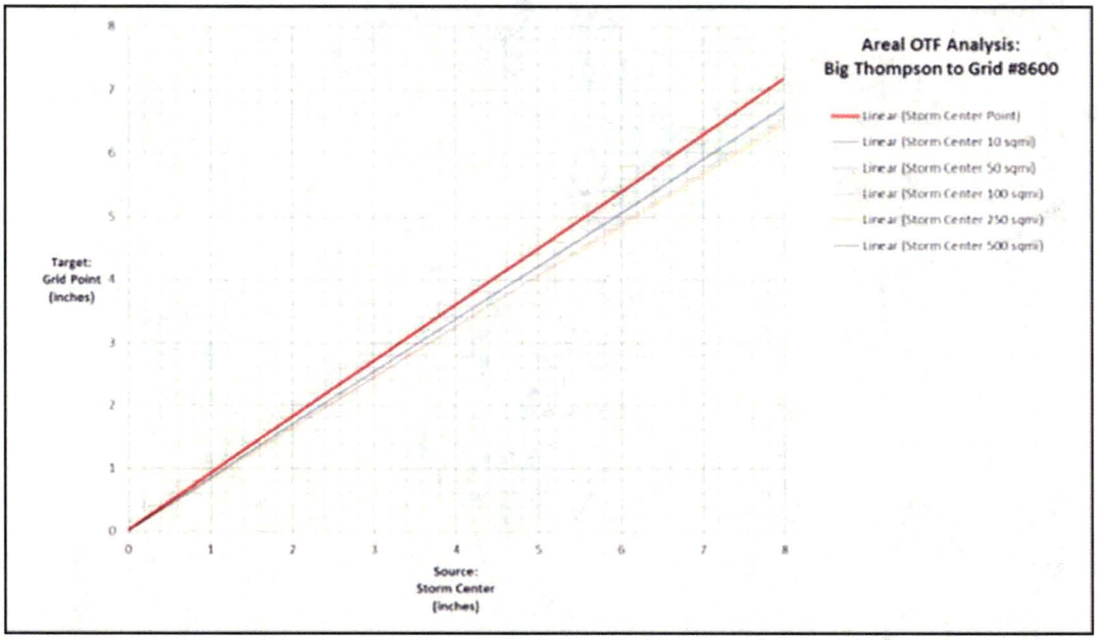

Figure J.3 Linear best fit trend lines for the SPAS 1231 point and areal precipitation climatology relationships.

Table J.2 summarizes the OTF calculated from using the storm center point and each areal-average for each area size and the percent difference of each areal OTF to the point OTF. At 10 mi^2 there is nearly no difference from using the maximum point only. At 50 mi^2 the difference increases to a 5% reduction and continues to increase to a 9% reduction at 250 mi^2, after which it actually reduces to a 6% reduction at 500 mi^2 where the climatology begins to become smoothed as a regional average.

Table J.2 SPAS 1231 OTF comparison using maximum point and areal averages.

	Target Latitude	Target Longitude	Max 6hr Rainfall	Slope	Y-intercept	Adjusted Rainfall	OTF	% Difference from Point
Point Location	**41.575**	**-105.450**	**10.12**	**0.89**	**0.03**	**9.08**	**0.90**	**0%**
10 sqmi	41.575	-105.450	10.12	0.90	0.03	9.09	**0.90**	**0%**
50 sqmi	41.575	-105.450	10.12	0.84	0.01	8.54	**0.84**	**-5%**
100 sqmi	41.575	-105.450	10.12	0.82	0.00	8.28	**0.82**	**-8%**
250 sqmi	41.575	-105.450	10.12	0.81	0.02	8.19	**0.81**	**-9%**
500 sqmi	41.575	-105.450	10.12	0.84	0.02	8.51	**0.84**	**-6%**

<u>EXAMPLE 2</u>

A similar example is shown for a synoptic storm occurring in a less orographic area. The Savageton, WY synoptic event of September 1923 (SPAS 1325) occurred on the high plains of eastern Wyoming. Although this storm covers a much larger area, the precipitation climatology values and underlying terrain are fairly homogenous in this area. Therefore it is assumed the difference between the point-based OTF and areal-OTF will be much less than what was seen in the Big Thompson Canyon comparison. Figure J.4 shows the SPAS 1325 total storm grid classified by area size.

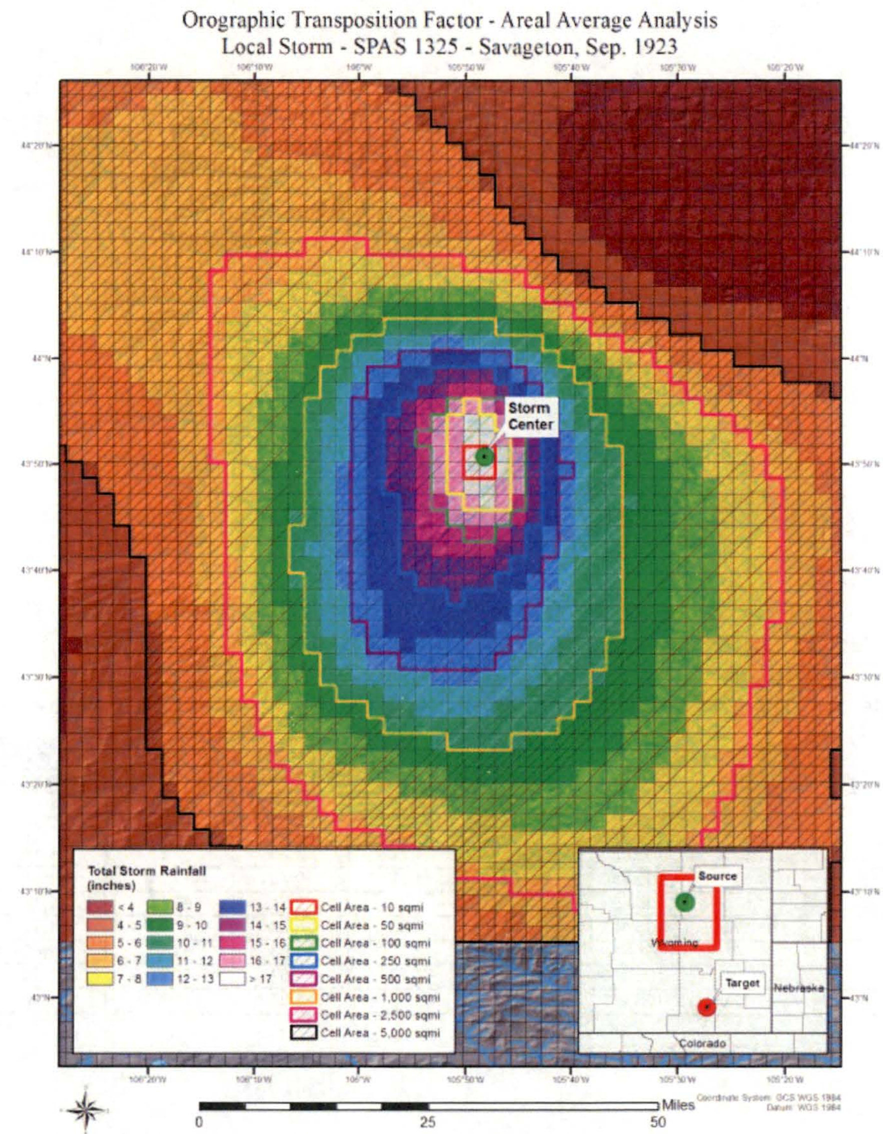

Figure J.4 SPAS 1325 Savageton, WY total storm rainfall by area class.

The best fit trend lines are shown in Figure I.5 for up to 5,000 mi^2. There is very little divergence from the point to

the various areal-average relationships, even over large areas.

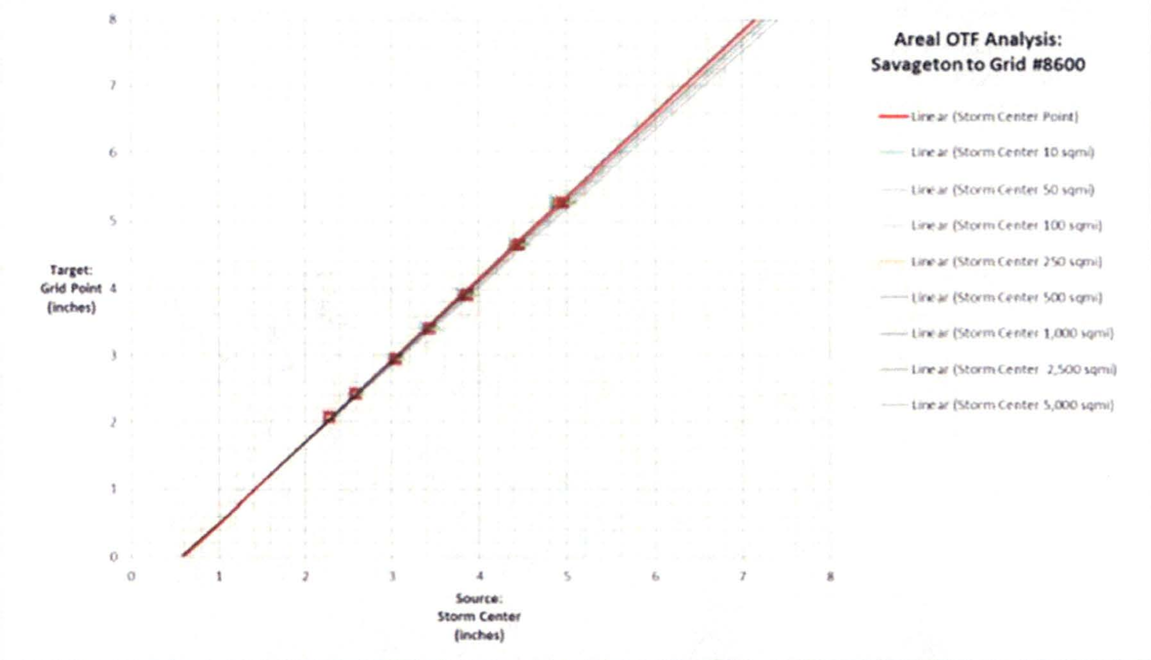

Figure J.5 Linear best fit trend lines for the SPAS 1325 point and areal precipitation climatology relationships.

Table J.3 lists the magnitude and percent differences for the point OTF and areal average OTFs. As expected, the percent difference slowly increases up to a maximum of 5% reduction at 5,000 miles.

Table J.3 SPAS 1325 OTF comparison using maximum point and areal averages.

	Target Latitude	Target Longitude	Max 6hr Rainfall	Slope	Y-intercept	Adjusted Rainfall	OTF	% Difference from Point
Point Location	**41.575**	**-105.450**	**10.32**	**1.22**	**-0.73**	**11.88**	**1.15**	**0%**
10 sqmi	41.575	-105.450	10.32	1.23	-0.73	11.91	**1.15**	**0%**
50 sqmi	41.575	-105.450	10.32	1.22	-0.73	11.88	**1.15**	**0%**
100 sqmi	41.575	-105.450	10.32	1.22	-0.73	11.89	**1.15**	**0%**
250 sqmi	41.575	-105.450	10.32	1.21	-0.72	11.80	**1.14**	**-1%**
500 sqmi	41.575	-105.450	10.32	1.20	-0.70	11.71	**1.13**	**-2%**
1,000 sqmi	41.575	-105.450	10.32	1.20	-0.68	11.65	**1.13**	**-2%**
2,500 sqmi	41.575	-105.450	10.32	1.18	-0.67	11.55	**1.12**	**-3%**
5,000 sqmi	41.575	-105.450	10.32	1.17	-0.65	11.40	**1.10**	**-5%**

Results

Tables J.4 through J.13

Table J.4 SPAS 1241 DAD Zone 2 (Deer Creek Dam, UT) general storm OTF comparison using maximum point and areal averages.

	Target Latitude	Target Longitude	Max 24hr Rainfall	Slope	Y-intercept	Adjusted Rainfall	OTF	% Difference from Point
Point Location	**41.575**	**-105.450**	**4.54**	**0.76**	**-0.79**	**2.67**	**0.59**	**0%**
10 sqmi	41.575	-105.450	4.54	0.73	-0.71	2.60	**0.57**	**-2%**
50 sqmi	41.575	-105.450	4.54	0.78	-0.69	2.86	**0.63**	**4%**
100 sqmi	41.575	-105.450	4.54	0.77	-0.63	2.87	**0.63**	**4%**
250 sqmi	41.575	-105.450	4.54	0.83	-0.56	3.22	**0.71**	**12%**
500 sqmi	41.575	-105.450	4.54	0.90	-0.52	3.58	**0.79**	**20%**
1,000 sqmi	41.575	-105.450	4.54	0.96	-0.49	3.89	**0.86**	**27%**
2,500 sqmi	41.575	-105.450	4.54	1.07	-0.47	4.40	**0.97**	**38%**

Table J.5 SPAS 1265 DAD Zone 1 (Cottonwood, UT) general storm OTF comparison using maximum point and areal averages.

	Target Latitude	Target Longitude	Max 24hr Rainfall	Slope	Y-intercept	Adjusted Rainfall	OTF	% Difference from Point
Point Location	**40.925**	**-111.050**	**6.07**	**0.73**	**-0.60**	**3.82**	**0.63**	**0%**
10 sqmi	40.925	-111.050	6.07	0.84	-0.74	4.39	**0.72**	**9%**
50 sqmi	40.925	-111.050	6.07	0.91	-0.72	4.80	**0.79**	**16%**
100 sqmi	40.925	-111.050	6.07	0.91	-0.76	4.78	**0.79**	**16%**
250 sqmi	40.925	-111.050	6.07	0.95	-0.76	4.99	**0.82**	**19%**
500 sqmi	40.925	-111.050	6.07	1.00	-0.75	5.33	**0.88**	**25%**
1,000 sqmi	40.925	-111.050	6.07	1.09	-0.77	5.86	**0.96**	**34%**

Table J.6 SPAS 1265 DAD Zone 2 (Cottonwood, UT) general storm OTF comparison using maximum point and areal averages.

	Target Latitude	Target Longitude	Max 24hr Rainfall	Slope	Y-intercept	Adjusted Rainfall	OTF	% Difference from Point
Point Location	**40.925**	**-111.050**	**4.34**	**0.93**	**-0.82**	**3.22**	**0.74**	**0%**
10 sqmi	40.925	-111.050	4.34	0.95	-0.90	3.22	**0.74**	**0%**
50 sqmi	40.925	-111.050	4.34	1.05	-0.91	3.64	**0.84**	**10%**
100 sqmi	40.925	-111.050	4.34	1.11	-0.91	3.93	**0.90**	**16%**
250 sqmi	40.925	-111.050	4.34	1.27	-0.95	4.58	**1.06**	**31%**
500 sqmi	40.925	-111.050	4.34	1.47	-1.00	5.39	**1.24**	**50%**
1,000 sqmi	40.925	-111.050	4.34	1.61	-0.97	6.00	**1.38**	**64%**

Table J.7 SPAS 1265 DAD Zone 3 (Cottonwood, UT) general storm OTF comparison using maximum point and areal averages.

	Target Latitude	Target Longitude	Max 24hr Rainfall	Slope	Y-intercept	Adjusted Rainfall	OTF	% Difference from Point
Point Location	**40.925**	**-111.050**	**4.34**	**0.93**	**-0.82**	**3.22**	**0.74**	**0%**
10 sqmi	40.925	-111.050	4.34	0.95	-0.90	3.22	**0.74**	**0%**
50 sqmi	40.925	-111.050	4.34	1.05	-0.91	3.64	**0.84**	**10%**
100 sqmi	40.925	-111.050	4.34	1.11	-0.91	3.93	**0.90**	**16%**
250 sqmi	40.925	-111.050	4.34	1.27	-0.95	4.58	**1.06**	**31%**

500 sqmi	40.925	-111.050	4.34	1.47	-1.00	5.39	**1.24**	**50%**
1,000 sqmi	40.925	-111.050	4.34	1.61	-0.97	6.00	**1.38**	**64%**

Table J.8 SPAS 1299 (Alta Pass, NC) general storm OTF comparison using maximum point and areal averages.

	Target Latitude	Target Longitude	Max 24hr Rainfall	Slope	Y-intercept	Adjusted Rainfall	OTF	% Difference from Point
Point Location	**41.575**	**-105.450**	**23.15**	**0.85**	**1.47**	**21.17**	**0.91**	**0%**
10 sqmi	41.575	-105.450	23.15	0.87	1.46	21.52	**0.93**	**2%**
50 sqmi	41.575	-105.450	23.15	0.86	1.46	21.47	**0.93**	**1%**
100 sqmi	41.575	-105.450	23.15	0.86	1.48	21.34	**0.92**	**1%**
250 sqmi	41.575	-105.450	23.15	0.86	1.46	21.26	**0.92**	**0%**
500 sqmi	41.575	-105.450	23.15	0.87	1.27	21.32	**0.92**	**1%**
1,000 sqmi	41.575	-105.450	23.15	0.88	1.16	21.47	**0.93**	**1%**
2,500 sqmi	41.575	-105.450	23.15	0.90	0.99	21.88	**0.95**	**3%**
5,000 sqmi	41.575	-105.450	23.15	0.95	0.92	22.90	**0.99**	**8%**

Table J.9 SPAS 1305 (Elba, AL) general storm OTF comparison using maximum point and areal averages.

	Target Latitude	Target Longitude	Max 24hr Rainfall	Slope	Y-intercept	Adjusted Rainfall	OTF	% Difference from Point
Point Location	**41.575**	**-105.450**	**23.15**	**0.40**	**3.58**	**12.85**	**0.56**	**0%**
10 sqmi	41.575	-105.450	23.15	0.40	3.56	12.86	**0.56**	**0%**
50 sqmi	41.575	-105.450	23.15	0.41	3.54	12.95	**0.56**	**0%**
100 sqmi	41.575	-105.450	23.15	0.41	3.55	12.96	**0.56**	**0%**
250 sqmi	41.575	-105.450	23.15	0.41	3.55	12.96	**0.56**	**0%**
500 sqmi	41.575	-105.450	23.15	0.41	3.56	12.96	**0.56**	**0%**
1,000 sqmi	41.575	-105.450	23.15	0.41	3.56	12.94	**0.56**	**0%**
2,500 sqmi	41.575	-105.450	23.15	0.41	3.46	12.98	**0.56**	**1%**
5,000 sqmi	41.575	-105.450	23.15	0.42	3.38	13.03	**0.56**	**1%**

Table J.10 SPAS 1325 (Savageton, WY) general storm OTF comparison using maximum point and areal averages.

	Target Latitude	Target Longitude	Max 6hr Rainfall	Slope	Y-intercept	Adjusted Rainfall	OTF	% Difference from Point
Point Location	**41.575**	**-105.450**	**10.32**	**1.22**	**-0.73**	**11.88**	**1.15**	**0%**
10 sqmi	41.575	-105.450	10.32	1.23	-0.73	11.91	**1.15**	**0%**
50 sqmi	41.575	-105.450	10.32	1.22	-0.73	11.88	**1.15**	**0%**
100 sqmi	41.575	-105.450	10.32	1.22	-0.73	11.89	**1.15**	**0%**
250 sqmi	41.575	-105.450	10.32	1.21	-0.72	11.80	**1.14**	**-1%**
500 sqmi	41.575	-105.450	10.32	1.20	-0.70	11.71	**1.13**	**-2%**
1,000 sqmi	41.575	-105.450	10.32	1.20	-0.68	11.65	**1.13**	**-2%**
2,500 sqmi	41.575	-105.450	10.32	1.18	-0.67	11.55	**1.12**	**-3%**
5,000 sqmi	41.575	-105.450	10.32	1.17	-0.65	11.40	**1.10**	**-5%**

Table J.11 SPAS 1231 (Big Thompson Canyon, CO) local storm OTF comparison using maximum point and areal averages.

	Target Latitude	Target Longitude	Max 6hr Rainfall	Slope	Y-intercept	Adjusted Rainfall	OTF	% Difference from Point
Point Location	**41.575**	**-105.450**	**10.12**	**0.89**	**0.03**	**9.08**	**0.90**	**0%**
10 sqmi	41.575	-105.450	10.12	0.90	0.03	9.09	**0.90**	**0%**
50 sqmi	41.575	-105.450	10.12	0.84	0.01	8.54	**0.84**	**-6%**

100 sqmi	41.575	-105.450	10.12	0.82	0.00	8.28	**0.82**	**-8%**
250 sqmi	41.575	-105.450	10.12	0.81	0.02	8.19	**0.81**	**-9%**
500 sqmi	41.575	-105.450	10.12	0.84	0.02	8.51	**0.84**	**-6%**

Table J.12 SPAS 1248 (Morgan, UT) local storm OTF comparison using maximum point and areal averages

	Target Latitude	Target Longitude	Max 6hr Rainfall	Slope	Y-intercept	Adjusted Rainfall	OTF	% Difference from Point
Storm Center Point	**41.575**	**-105.450**	**7.10**	**0.89**	**0.05**	**6.34**	**0.89**	**0%**
10 sqmi	41.575	-105.450	7.10	0.95	0.09	6.85	**0.96**	**7%**
50 sqmi	41.575	-105.450	7.10	0.95	0.09	6.85	**0.96**	**7%**
100 sqmi	41.575	-105.450	7.10	0.93	0.08	6.72	**0.95**	**5%**
250 sqmi	41.575	-105.450	7.10	0.91	0.06	6.51	**0.92**	**2%**
500 sqmi	41.575	-105.450	7.10	0.90	0.05	6.47	**0.91**	**2%**

Table J.13 - SPAS 1343 (Johnson City, TN) local storm OTF comparison using maximum point and areal averages.

	Target Latitude	Target Longitude	Max 24hr Rainfall	Slope	Y-intercept	Adjusted Rainfall	OTF	% Difference from Point
Point Location	**41.575**	**-105.450**	**14.48**	**1.61**	**-0.70**	**22.68**	**1.57**	**0%**
10 sqmi	41.575	-105.450	14.48	1.61	-0.66	22.69	**1.57**	**0%**
50 sqmi	41.575	-105.450	14.48	1.61	-0.64	22.63	**1.56**	**0%**
100 sqmi	41.575	-105.450	14.48	1.61	-0.65	22.71	**1.57**	**0%**
250 sqmi	41.575	-105.450	14.48	1.61	-0.61	22.67	**1.57**	**0%**

Discussion

In most cases evaluated, using an areal-average of precipitation climatology values results in different OTF values than using values from a single storm-center point only. The magnitude of the difference varies from storm to storm and generally increases with area size (at least to a certain point), but not always. The two non-orographic region storms, Elba, AL and Savageton, WY, both showed no significant difference between the point and areal-average OTF, as expected in topographically homogeneous areas.

The comparison for the storms over dynamic terrain becomes more complex. None of the three Eastern U.S. storms evaluated showed a significant difference between point or areal-average OTF values, despite two of these events occurring over very dynamic terrain. For the Western U.S. storms occurring over dynamic terrain the results varied somewhat. The Big Thompson Canyon, Deer Creek Dam, and Morgan storms exhibited a small to moderate percent difference between point and areal-average OTF values. The Cottonwood, UT storm centers exhibited very little change at areas less than 50 mi^2 but the percentages increased rapidly as area size got larger. This is due to the storm centers occurring at peaks or very high elevations among the Wasatch mountains where elevation, and the relating precipitation climatology drops off quite rapidly over relatively short distances. For this reason, the area sizes evaluated probably go far beyond what is representative of the peak rainfall for those storms and the point comparisons with areal averages beyond 10 or 20 mi^2 may not be particularly applicable to this evaluation, particularly for those storms.

Using areal-average precipitation climatology values may provide somewhat different OTF values than using a single point only in areas with significant topographic variation. The *most* correct approach should apply precipitation climatology values that are the most representative of the most critical precipitation for a given storm event. An areal-average approach introduces terrain beyond the storm center that undoubtedly contributed to the overall rainfall for the event. However, by using an average, the surrounding terrain is given the same "weight" as the terrain under the storm center even though it likely had a lesser contribution to the most extreme rainfall for the event. It can be assumed that farther away from the storm center, the less of an effect the underlying terrain would have on the most extreme rainfall for that event. If an areal-average was used, there would need to be a reasonable areal threshold determined that would strike a balance between too little area not providing a proper representative sample of the underlying terrain and too large of an area introducing terrain that is not applicable to the most extreme rainfall. This threshold would likely be different for every storm and, by necessity, would be highly subjective.

Recommendations

Currently the procedure employed by AWA for calculating OTF involves using only the precipitation climatology values at the storm center point location. Based on this evaluation of ten sample storms, AWA continues to recommend that the single point value be applied rather than an areal-average approach. This study evaluates many of the potentially *worst-case* scenarios, yet for small areas deemed to be the most representative to a storm's extreme rainfall, there is not a significant difference in resulting OTF values when using an aerial-average. Furthermore, applying an areal-average approach introduces subjectivity that reduces confidence and technical complexities that reduce the practicality of the OTF analysis overall.

The point-based and areal-average methods both seek to predict the effects of a very complicated relationship between terrain and rainfall using a relatively straightforward approach. Although AWA currently suggests that a point-based approach is *more* appropriate than an areal-average approach for their gridded PMP studies, any new methods, technology, or information should always be considered and applied when appropriate.

APPENDIX K – Review Board Letter

PEER REVIEW GROUP

Barry Keim Ph.D.
Mel Schaefer Ph.D. P.E.

September 25, 2015

Mr. Curt Jawdy P.E.
Tennessee Valley Authority
400 West Summit Hill Drive
Knoxville, TN 37902

Dear Mr. Jawdy:

This letter will serve to document participation by the Peer Review Group (PRG) in reviewing analyses conducted by Applied Weather Associates (AWA) for development of Generalized Estimates of Probable Maximum Precipitation (PMP) for watersheds in the Tennessee Valley.
The letter also conveys conclusions from the PRG regarding the technical merits of the PMP analyses for use in conducting hydrologic studies for Probable Maximum Floods for watersheds in the Tennessee Valley.

Peer Review Group Participation

The PRG has provided review and comment on the methods of analyses used for development of PMP Estimates for the Tennessee Valley from near the start of the study in early 2014. Three Peer Review meetings were held in Knoxville TN to provide a forum for presentations by AWA on methods and findings of analyses, and discussion and comments from the PRG. These meetings also provided the opportunity for participation and comments by representatives from the Dam Safety, River Operations, and Nuclear sections of the Tennessee Valley Authority (TVA); the Nuclear Regulatory Commission (NRC); and representatives from Barge, Waggoner, Sumner and Cannon, Inc. (BWSC). The PRG conducted separate discussions following these three meetings to compare notes and provide a comprehensive response to the issues identified during the meetings.

The first Peer Review meeting was held on March 19-20, 2014 and AWA provided preliminary findings and background information on the methods proposed for development of generalized PMP estimates for the various storm types that affect the Tennessee Valley. The PRG prepared a summary report dated April 4, 2014 that contained initial perspectives and review comments regarding the analyses completed to date and the proposed methods for the next steps.

A second meeting was held on September 17-18, 2014. This meeting served to provide information on progress-to-date as well as a workshop for addressing issues regarding the suitability of transposition of selected historical storms to the Tennessee Valley. There were several noteworthy storms where there were questions about the appropriate values of meteorological factors to be used in the

transposition computations. This included Tropical Storms and Tropical Storm Remnants with landfalls along the coast of the Gulf of Mexico, and the tropical storm of July 1916 (Alta Pass NC); Mesoscale Convective Complexes such as the July 1942 Smethport PA storm; and Local Storms such as the July 1939 Simpson KY and June 1942 Holt MO storms.

The PRG provided recommendations for locations where storms could be transposed along with suggestions for addressing issues and transposition factors associated with the extreme Smethport PA and Simpson KY storms. Meeting notes were taken by AWA and subsequently used in storm transpositions and for advancing the analyses for PMP estimates.

A third Peer Review meeting was held on February 3-4, 2015. An initial draft of the PMP report and Appendix F containing the PMP calculations for historical storms were provided prior to the meeting. This allowed the PRG and others to review detailed descriptions of the various methods and the findings of analyses. Some sections of the draft report were incomplete at the time of the meeting. Extensive discussions were held regarding the methods and findings of analysis and the resultant estimates of PMP for the various storm types. The PRG provided comments and recommendations in the form of "notes" and "track changes" in the documents for the draft PMP report and Appendix F.

AWA prepared a final draft report which addressed the review comments arising from the February 3-4, 2015 meeting. The PRG reviewed the final draft report, particularly those sections that were previously incomplete and prepared a written report dated July 21, 2015 (attached) which contained final comments and recommendations. AWA responded to those comments and made revisions which were incorporated into their final report dated August 24, 2015.

PRG Final Comments and General Conclusions

The PRG has been an active participant in review of the analyses for development of Generalized Estimates of PMP for the Tennessee Valley since early 2014. Applied Weather Associates has been responsive in providing technical materials, conducting additional analyses and addressing technical issues identified by the PRG in the process of developing PMP estimates.

The methods for PMP development included several advancements in the analysis of extreme storms that were developed since the original hydrometeorological studies were conducted by the National Weather Service in the 1960s through 1980s. This includes use of the HYSPLIT computer model for assistance in identifying the source location for atmospheric moisture in the moisture-maximization of a storm at its original location; results of regional precipitation-frequency analysis for specific storm types to establish base maps for spatial mapping of precipitation; the SPAS computer model for spatial and temporal analyses of storms and using base maps for specific storm types; and GIS methods for transposition of storms from the location where they occurred to locations of interest.

In summary, we concur that the methods employed by AWA are consistent with the current methods used for development of Generalized Probable Maximum Precipitation estimates and are suitable for use in developing estimates of Probable Maximum Floods in the Tennessee Valley.

Need for Improvements in PMP Methods

It should be noted there are several areas in the methods for PMP estimation where improvements are needed and new methods should be investigated. In particular, we encourage AWA to explore methods to incorporate a larger areal component in the transpositioning process for generalized PMP studies, such as use of a representative storm center (100, 500, 1,000-mi^2) rather than a single grid-cell. This approach would also help reduce uncertainties imparted due to the implicit transference of the depth-area-duration relationship in the current AWA procedure for transposition of a storm using a single grid-cell as representative of the storm center.

We also recommend that the computation of the Orographic Transposition Factor (OTF) be based on the findings of regional-precipitation frequency analyses conducted for specific storm types. The use of the precipitation-frequency findings from NOAA Atlas 14 for computation of the OTF has limitations in locations where the annual maxima data are from a mixed population of storm types, such as the Tennessee Valley. Use of datasets partitioned by duration helps somewhat with the problems posed by mixed populations of storm types. However, a representative OTF cannot be reliably computed where precipitation annual maxima in a dataset are produced by multiple storm types or where only a few instances of a storm type are contained in the annual maxima dataset. This latter case is common for datasets containing only a few Tropical Storms and Tropical Storm Remnants.

Additional investigations are needed regarding use of the Moisture Transposition Factor (MTF), which likely includes some double counting when combined with the OTF. Research is needed to better understand the relationship between the OTF and MTF.

Lastly, we want to thank Mr. Curt Jawdy, Mr. Mike Eiffe and the Tennessee Valley Authority for the opportunity to participate in this project.

Barry Keim

Mel Schaefer

The conclusions of the Peer Review Group are based upon analyses conducted by Applied Weather Associates. The Peer Review Group used their best professional judgment in evaluating the analyses conducted by Applied Weather Associates and in evaluating the conclusions expressed in their report. We note that the final PMP estimates are based on the historical record of the past century and longer, with the underlying assumption that this record across the eastern United States region yields insight into the behavior of PMP across the Tennessee Valley Region. As such, we do not make any warranty, express or implied, regarding use of any information or method contained in the report titled *TVA Basin Probable Maximum Precipitation Analysis*, or assume any future liability regarding use of any information or method contained therein.

REVIEW COMMENTS

Local Storm PMP Mapping

(Figure 30, Local Storm PMP, page 73) The Local Storm PMP values need to be revised in the southwestern area of the Appalachian Mountains where there is a significant discontinuity in the spatial distribution of 6-hour Local Storm PMP values. This discrepancy is due to the discontinuity in the precipitation-frequency relationships in the two versions of NOAA 14. The discontinuity of spatially mapped values are not meteorologically plausible and the discontinuity significantly detracts from the credibility of the proposed values in the southwestern area of the Appalachian Mountains. The analysis in this area must be reviewed and adjustments made to produce a coherent spatial distribution for Local Storm PMP.

AWA Resolution

Local storm PMP data has been updated to address the discontinuity in north eastern Georgia resulting from the NOAA Atlas 14 differences in the region.

Storm Transpositioning – Areal versus Point Transpositioning Methods

(page 54-57) Storm transpositions were conducted using point-to-point precipitation for the storm center (single grid-cell values). We have frequently expressed our preference for use of area-to-area transpositioning rather than point-to-point transpositioning to take advantage of a larger sample of the "storm center". We understand that point transpositions were conducted because of complexities encountered in conducting area-to-area transpositions for generalized PMP where the target location is non-specific.

AWA conducted a small pilot study examining differences in computed storm magnitudes between storm transpositions conducted using point-to-point and area-to-area methods for several storm area sizes. The findings of this pilot study should be presented as a lead-in to a broader discussion of the issues/uncertainties associated with point-to-point versus area-to-area transpositioning. Uncertainties imparted due to the implicit transference of the depth-area-duration relationship for a storm from the source to target location should also be discussed.

We encourage AWA to continue to explore methods to incorporate a larger areal component in the transpositioning process for generalized PMP studies. This could include use of a representative storm center (100 or 500-mi^2) rather than a single grid-cell as well as other approaches.

AWA Resolution

No change was made to this report. However, AWA appreciates the discussions and recommendations and will continue to pursue evaluating this process. The ultimate goal is to most accurately represent the components used for PMP development, while lowering uncertainty and unknowns as much as possible.

Storm Transpositioning – Capping of OTF at 1.5

(page 57) A clarification is needed whether the magnitude of the Orographic Transposition Factor (OTF) was capped at a value of 1.5 or if storms with a computed OTF greater than 1.5 were not used in storm transpositions.

AWA Resolution

Wording was adding to further clarify the application of the application of the 1.50 cap. Storms were not automatically eliminated from being transpositionable just because of the 1.50 OTF value, this just justified a further evaluation and the 1.50 cap was applied.

Storm Transpositioning - Mixed Population of Storm Types

(page 20) "This mixed population effect is overcome by using 6-hour duration precipitation-frequency relationships for local storms. Likewise, use of the 24-hour precipitation-frequency relationships for the general storms and tropical storms eliminates the effects of mixed populations for those storm types".

This is a significant overstatement and requires a more complete description of the implications of mixed populations. The OTF provides the mechanism for scaling storm magnitude from the location where the storm occurred (source) to the location of interest (target). The suitability of this scaling factor is dependent upon a representative sample of storms of a given type being used to compute the scaling factor. The existence of a mixed population of storm types in computing the OTF can distort this factor, particularly where a given storm type of interest is under-represented in the sample set of storms used to compute the OTF.

The issue of mixed populations was adequately addressed where storm transpositions were conducted using the findings of the precipitation-frequency study conducted specifically for the Tennessee Valley (MGS Engineering Consultants et al, 2015) for those cases where the storm source and target locations were within the TVA study area. This study utilized storm typing where separate precipitation-frequency relationships were developed for each storm type.

Conversely, the precipitation-frequency findings contained in NOAA 14 are based on all-season annual maxima data which are produced by a mixed population of storm types. The effect of mixed populations of storm types is mitigated somewhat for the case of local storms by using the precipitation-frequency findings from NOAA 14 for the 6-hour duration in transposition of local storms. This occurs because precipitation annual maxima at the 6-hour duration are typically produced by convective activity which is the storm mechanism of interest for local storms.

Uncertainties imparted from mixed populations of storm types is most pronounced for transposition of tropical storms using NOAA 14 findings because only a small percentage of tropical storms are represented in the annual maxima data series at the 24-hour duration. The effect of mixed populations is less for general storms where the majority of storms in the annual maxima data series at the 24-hour duration are produced by fall-winter and early spring synoptic-scale mid-latitude cyclones.

This section should be rewritten to better describe the uncertainties and complexities imparted to the storm transposition process by the existence of mixed populations of storm types present in the NOAA 14 precipitation-frequency relationships.

AWA Resolution

Wording was adding to further clarify why using specific durations and recurrence intervals provides a mechanism to address the mixed population effects on the precipitation frequency estimates. In addition, a new reference was added referring to the Australian Bureau of Meteorology discussion on this topic and their recognition that utilizing precipitation frequency climatologies in the same way accomplish this process and to the WMO PMP manual discussion.

Double Counting of Moisture Transposition Factor (MTF)

AWA expanded the discussion of uncertainties and possible (likely) double-counting of the Moisture Transposition Factor (MTF) with the storm/Orographic Transposition Factor (OTF). While we have some differences of opinion with their discussion, we think the topic and uncertainties have been highlighted sufficiently.

AWA Resolution

No changes required.

Reference for TVA Precipitation-Frequency Findings

A reference is needed for the 2015 TVA precipitation-frequency study. This reference will need to be cited at several locations in the report.

1. MGS Engineering Consultants, MetStat, Applied Climate Services and Riverside Technology, Regional Precipitation-Frequency Analyses for Mid-Latitude Cyclones, Mesoscale Storms with Embedded Convection, Local Storms and Tropical Storm Remnant Storm Types in the Tennessee Valley Watershed, prepared for Tennessee Valley Authority, January 2015.

AWA Resolution

Reference added as appropriate.

From: Bill Kappel [mailto:billkappel@comcast.net]
Sent: Tuesday, January 05, 2016 3:40 PM
To: Spink, Thomas E
Cc: billkappel@appliedweatherassociates.com
Subject: RE: AWA PMP Calculation for review

TVA External Message. Please use caution when opening.

No problem, response below:

- Need AWA to provide a rebuttal argument for the PRG statement "*However, a representative OTF* ***cannot be reliably computed*** *where precipitation annual maxima in a dataset are produced by multiple storm types or where only a few instances of a storm type are contained in the annual maxima dataset. This latter case is common for datasets containing only a few Tropical Storms and Tropical Storm Remnants.*"

First, the statement "cannot be reliable computed" is an overstatement. They can be computed with reliability, but like anything involving statistical analysis to derive an output, the more data you have from which to draw a conclusion (or in this case a precipitation frequency estimate) the better.

The argument is really about how representative the NOAA Atlas 14 values are at both 6-hr and 24-hr recurrence intervals and how the storms events that were used to derive those data match the PMP storm types used for TVA. It is AWA's judgment that the NOAA Atlas 14 data used for PMP development during the TVA study are reliable and provide enough data from which to derive PMP values using the OTF process. This has been demonstrated and accepted in all AWA PMP studies using the OTF process (see references in the TVA PMP report).

During the development of PMP for TVA using the OTF process, the 24-hr precip frequency data from NOAA Atlas 14 was used. The 24-hr duration was chosen specifically because it is LEAST affected by mixed populations. This is because the local storm type would NOT control the annual maximum series data used to derive the 24-hr 100-yr precipitation frequency data. Therefore, the 24-hr NOAA Atlas 14 data is most representative of the general and tropical storm types.

Also, given that NOAA Atlas 14 data included hundreds of tropical storm remnants within its data set, both from the data covering the Gulf Coast states and the data covering the Southeast and Mid Atlantic states, there are sufficient number of tropical events contained within the data set. Therefore, the statement "only a few" is not accurate in this circumstance.

This is also confirmed by the spatial continuity of the PMP values and their representative magnitudes by storm types. We do not see major discontinuities in the data that would be evident if the underlying data from NOAA Atlas 14 was not useable.

Let me know if this provides what you need for this. Bill Kappel
President/Chief Meteorologist
Applied Weather Associates PO Box 175
Monument, CO 80132 (719) 488-4311 direct (719) 964-3395 cell
www.appliedweatherassociates.com

SECTION C

Tennessee Valley Authority, 1101 Market Street, Chattanooga, Tennessee 37402

CNL-16-136

September 20, 2016

10 CFR 50.4

ATTN: Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Browns Ferry Nuclear Plant, Units 1, 2, and 3
Renewed Facility Operating License Nos. DPR-33, DPR-52, and DPR-68
NRC Docket Nos. 50-259, 50-260, and 50-296

Sequoyah Nuclear Plant, Units 1 and 2
Renewed Facility Operating License Nos. DPR-77 and DPR-79
NRC Docket Nos. 50-327 and 50-328

Watts Bar Nuclear Plant, Units 1 and 2
Facility Operating License Nos. NPF-90 and NPF-96
NRC Docket Nos. 50-390 and 50-391

Subject: Request for Review and Approval of Topical Report TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041"

Reference: Summary of April 4, 2016, Public Meeting With TVA Regarding Hydrology-Related Licensing Actions, Sequoyah Nuclear Plant, Units 1 and 2 (CAC Nos. ME9238 AND ME9239), dated May 2, 2016 (ML16117A551)

Tennessee Valley Authority (TVA) is submitting topical report TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041" for review and approval. Approval of this Topical Report is requested to support Probable Maximum Flood calculations and associated License Amendment Requests for Sequoyah Nuclear Plant, Units 1 and 2, and Watts Bar Nuclear Plant, Units 1 and 2, as discussed in the Reference. This topical report does not contain proprietary information.

This topical report describes the work performed to calculate the Probable Maximum Precipitation for any location within the overall Tennessee Valley Authority (TVA) basin and Local Intense Precipitation (LIP) at the BFN, SQN, and WBN sites. The report outlines the process, data, and methods used to analyze storms and develop the PMP values. Results and background data are provided and discussed, along with comparisons to previous PMP work in the region. Relevant background data, input calculation, and reference materials are included in various appendices.

Enclosed is one copy of topical report TVA-NPG-AWA16 and one compact disk containing a portable document format (PDF) version of this letter and the topical report.

There are no regulatory commitments associated with this submittal. Please address any questions regarding this request to Russell Thompson at 423-751-2567.

Respectfully,

J. W. Shea
Vice President, Nuclear Licensing

Enclosure: TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041"

cc (Enclosure):

NRC Regional Administrator - Region II
NRC Senior Resident Inspector - Browns Ferry Nuclear Plant
NRR Project Manager - Browns Ferry Nuclear Plant
NRC Senior Resident Inspector - Sequoyah Nuclear Plant
NRR Project Manager - Sequoyah Nuclear Plant
NRC Senior Resident Inspector - Watts Bar Nuclear Plant
NRR Project Manager - Watts Bar Nuclear Plant

SECTION D

NRR-DMPSPEm Resource

From:	Hon, Andrew
Sent:	Friday, February 23, 2018 3:20 PM
To:	Thompson, Russell R
Subject:	Request For Additional Information Related to TVA Fleet Topical Report TVA-NPG-AWA16 – EPIC: L-2016-TOP-0011)
Attachments:	TVA ssPMP TR RAIs_02222018_final.docx

By a letter dated September 20, 2016 (Agencywide Documents Access and Management System (ADAMS) Accession Number ML16264A454), the Tennessee Valley Authority (TVA) submitted the a fleet topical report (TR) TVA-NPG-AWA16 "Overall Basin probable Maximum Precipitation and Local Intense Precipitation Analysis." This TR will be used for future licensing actions for Browns Ferry Units 1,2 and 3, Sequoyah Units 1 and 2 and Watts Bar Units 1 and 2.

The U.S. Nuclear Regulatory Commission (NRC) staff is reviewing your submittal and has determined that additional information is required to complete the review. The specific information requested is attached to this email. The proposed questions were emailed in draft form and a clarification call was held on January 22, 2018. Your staff confirmed that these draft questions did not include proprietary or security-related information and agreed to provide a response April 20, 2018 to this request for additional information (RAI).

The NRC staff considers that timely responses to RAIs help ensure sufficient time is available for staff review and contribute toward the NRC's goal of efficient and effective use of staff resources. Please note that if you do not respond to this request by the agreed-upon date or provide an acceptable alternate date, we may deny your application for amendment under the provisions of Title 10 of the *Code of Federal Regulations*, Section 2.108. If circumstances result in the need to revise the agreed upon response date, please contact me at (301) 415-8480 or via e-mail Andrew.Hon@nrc.gov.

Docket Nos. 50-259, 50-260, 50-296, 50-327, 50-328, 50-390, and 50-391

Andy Hon, *PE*
Project Manager (Brunswick Nuclear Plant 1 & 2, Sequoyah Nuclear Plant 1 & 2)
Plant Licensing Branch II-2
Division of Operating Reactor Licensing
Office of Nuclear Reactor Regulation
301-415-8480
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Mail Stop O8G-9a
andrew.hon@nrc.gov

Hearing Identifier: NRR_DMPS
Email Number: 209

Mail Envelope Properties (Andrew.Hon@nrc.gov20180223151900)

Subject: Request For Additional Information Related to TVA Fleet Topical Report TVA-NPG-AWA16 – EPIC: L-2016-TOP-0011)
Sent Date: 2/23/2018 3:19:44 PM
Received Date: 2/23/2018 3:19:00 PM
From: Hon, Andrew

Created By: Andrew.Hon@nrc.gov

Recipients:
"Thompson, Russell R" <rrthompson@tva.gov>
Tracking Status: None

Post Office:

Files	**Size**	**Date & Time**
MESSAGE	2116	2/23/2018 3:19:00 PM
TVA ssPMP TR RAIs_02222018_final.docx		5815025

Options
Priority: Standard
Return Notification: No
Reply Requested: No
Sensitivity: Normal
Expiration Date:
Recipients Received:

Request for Additional Information

Issue Date: 02/22/2018

Topical Report TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ000002016000041"

Operating Company: Tennessee Valley Authority

Docket Nos. 50-259, 50-260, and 50-296, Browns Ferry Nuclear Plant, Units 1, 2, and 3
50-327 and 50-328, Sequoyah Nuclear Plant, Units 1 and 2
50-390 and 50-391, Watts Bar Nuclear Plant, Units 1 and 2

Regulatory Basis

10 CFR Part 50, Appendix A, General Design Criterion (GDC) 2, states, in part, that structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as floods without loss of capability to perform their safety functions. The design bases for these structures, systems, and components shall reflect appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated.

NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition, Section 2.4.3, "Probable Maximum Flood (PMF) On Streams and Rivers," states that to meet the requirements of GDC 2 with regards to design bases for flooding in streams and rivers, the probable maximum precipitation (PMP) on the drainage area that contributes to runoff on the stream network adjacent to the plant site should be determined. Similarly, NUREG-0800 Section 2.4.2, "Floods," states that estimates of potential local flooding on the site and drainage design should be based on estimates of local intense precipitation or local PMP.

RAI #1: Complete Storm Analysis Information for All Short List Storms

Technical Deficiency: Information in the Topical Report is incomplete; additional information is necessary for the staff to make its regulatory finding.

Request:

Provide the analysis information for all short list storms that were used for PMP calculation. The detailed storm analysis information should include:

- Storm calculation spreadsheet
- Depth-area-duration values and chart
- Storm cumulative mass curve chart
- Total storm isohyetal analysis map
- HYSPLIT moisture trajectory map
- In-place storm representative dew point (or sea surface temperature) analysis map

RAI #2: TVA Observed Hourly Dew Point Data Sheet for All Short List Storms

Technical Deficiency: Information in the Topical Report is incomplete; additional information is necessary for the staff to make its regulatory finding.

Request:

For each short list storm, provide an individual spreadsheet documenting the hourly dew point data that were used for storm representative dew point selection. If publicly-accessible dew point data were used (e.g., NCDC ISD), the unique station identifier (e.g., USAF, WBAN, and/or ICAO) and the starting/ending dew point date and hour (used for the calculation of average 6-, 12-, or 24-hour dew points) should be clearly specified. Provide detailed meteorological reasoning if the selection of storm representative dew point location deviated significantly from the HYSPLIT trajectories. If sea surface temperature is used as a surrogate of surface dew point observation, the sea surface temperature observation should be provided. Provide the relevant data or source information used to determine the storm representative dew point for short list storms for which hourly dew point data were unavailable or not used.

RAI #3: TVA Storm Adjustment Factor Feature Class Table for All Short List Storms

Technical Deficiency: Information in the Topical Report is incomplete; additional information is necessary for the staff to make its regulatory finding.

Request:

For each short list storm, provide the storm adjustment factor feature class table developed for the TVA PMP study (as documented in Figure 24 of Calculation No. CDQ000002016000041). The data layers should be in a common GIS data format that can be processed by ESRI ArcGIS, and should cover all of the information shown in Figure 24 including STORM, LON, LAT, ZONE_, ELEV, IPMF, MTF, OTF, TAF, and TRANS.

RAI #4: TVA Dew Point Climatology Data and GIS Layers

Technical Deficiency: Information in the Topical Report is incomplete; additional information is necessary for the staff to make its regulatory finding.

Request:

Provide the digital dew point climatology GIS data layers used for PMP development. The digital dew point climatology GIS data layers should be provided for the monthly 6-, 12-, and 24-hour, 100-year recurrence interval dew point maps provided in Appendix C of Calculation No. CDQ000002016000041. In addition, provide the corresponding monthly dew point climatology values at each gauge that was used to develop the maps provided in Appendix C of Calculation No. CDQ000002016000041.

RAI #5: TVA Probable Maximum Precipitation Data and GIS Layers

Technical Deficiency: Information in the Topical Report is incomplete; additional information is necessary for the staff to make its regulatory finding.

Request:

Provide the final digital PMP GIS data layers (across all durations and areas) developed for the TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis. The digital PMP GIS data layer should cover the full TVA Basin for which PMP values have been determined.

RAI #6: Reasonableness of OTF Values

Technical Deficiency: Staff's review of Orographic Transposition Factor (OTF) application examples demonstrates discrepancies between expected OTF values and OTF values used by the licensee for selected storms.

The OTF is applied after an observed precipitation event is 1) moisture maximized using the in-place maximization factor (IPMF) and 2) geographically transpositioned (on a Lat-Lon plane) using a moisture transposition factor (MTF). The MTF captures geographic differences in moisture availability through comparison of dew point climatology. While it captures spatial variation in moisture, the MTF may not adequately capture the effects of terrain, hence the need for a terrain adjustment (e.g., the OTF, Barrier Adjustment Factor, or Storm Separation Method).

Staff interprets from the licensee's descriptions in the Technical Report that the OTF is intended to capture the impact that terrain will have on rainfall depths when transpositioning a storm from the original location to a new location. Therefore, staff believes that the OTF should be independent of geographical moisture influence (which is captured through use of the MTF). Consequently, staff believes that the OTF should not be significant when moving storms between regions with similar orographic characteristics (i.e., such regions should have a calculated OTF close to 1.00).

To assess whether the OTF calculation process produces OTF values close to 1.00 in cases where the original and transpositioned storm paths have similar orographic characteristics, staff evaluated the OTF for a series of case studies using data supplied by the licensee for TVA short list storms. Table 1 includes a summary of the rationale for evaluating these case studies and the subsequent observations.

Table 1. OTF case studies evaluated by staff

Storm	Rationale	Observations
Warner, OK (Example 1)	The storm center location and TVA Zone 1 share similar orographic characteristics (e.g., both locations exhibit minimal barriers, are of similar elevation, and are located at a similar distance-to-coast).	Avg. Zone 1 OTF: 0.80
Fall River, KS (Example 2)	The storm center location and TVA Zone 1 share similar orographic characteristics (e.g., both locations exhibit minimal barriers, are of similar elevation, and are located at a similar distance-to-coast).	Avg. Zone 1 OTF: 0.75

Storm	Rationale	Observations
Smethport, PA (Example 3a)	The storm center location and TVA Zone 4 share similar orographic characteristics (e.g., both locations exhibit orographic influence and are a similar distance-to-coast). TVA Zone 4 has higher overall orographic influence than the storm center due to higher terrain elevation and complexity.	Avg. Zone 4 OTF*: 0.66
Smethport, PA (Example 3b)	The storm center location and TVA Zone 2 share similar orographic characteristics (e.g., both locations exhibit orographic influence, are of similar elevation, and are a similar distance-to-coast).	Avg. Zone 2 OTF*: 0.59

**Note: the OTF for the Smethport, PA storm was manually adjusted by the licensee to include rescaling to a maximum value of 1.00. An additional question related to the Smethport, PA storm is included in RAI #7.*

For each of the examples included in Table 1, staff believes that the orographic adjustments should be minimal and the OTF should be close to 1.00; instead, the licensee's analysis results in OTF values significantly less than 1.00 and large reductions in the adjusted rainfall depths.

Request:

Provide a justification for the departure of OTF from 1.00 when transpositioning storms across orographically similar zones (examples provided in Table 1), and discuss whether the reductions in OTF are reasonable. Provide a justification for applying the OTF to the transposition of all storms throughout the TVA Basin, given the example results provided in Table 1.

RAI #7: OTF Reduction for Smethport, PA and Simpson, KY

Technical Deficiency: OTF values for two local storms which control PMP estimates were manually rescaled to a maximum of 1.00 (i.e., all original OTF values were divided by the maximum calculated OTF, resulting in widespread reductions and a maximum value of 1.00). This rescaling greatly reduces the Local Storm PMP.

As described in Section 6.1.1.5 of the Topical Report, the OTF values for two local storms (Smethport, PA and Simpson, KY) were rescaled to a maximum of 1.00. Following discussions with the Review Board and the licensee, "*it was determined that the factors leading to extreme levels of moisture and instability combined with terrain influences*" which produced extreme rainfall at Smethport and Simpson "*were similar to what could occur over the eastern foothills and mountainous terrain in the TVA basin.*"

As a result, the licensee decided it was "*unreasonable to further adjust the events upward based on the OTF*", and "*the OTF factors for these events were normalized to a maximum of 1.00.*"

Staff's review of the data provided by the licensee suggests that the maximum original (i.e., unadjusted) OTF values for the Smethport and Simpson events are 2.15 and 2.09, respectively. In comparison, the average Zone 4 original OTF is 1.39 for Smethport and 1.35 for Simpson. After rescaling the original OTF, the average Zone 4 OTF is reduced to 0.66 for Smethport and 0.65 for Simpson – approximately a 50% reduction. These modifications to the OTF result in a significant reduction in the adjusted DAD values for these storms. In addition, since these storms control PMP estimates, the resultant PMP values are significantly reduced.

Figure 1 provides a comparison of TVA's rescaled OTF values and the original (i.e., unadjusted) OTF values for the Smethport storm. Similarly, Figure 2 provides a comparison of TVA's rescaled OTF values and the original OTF values for the Simpson storm.

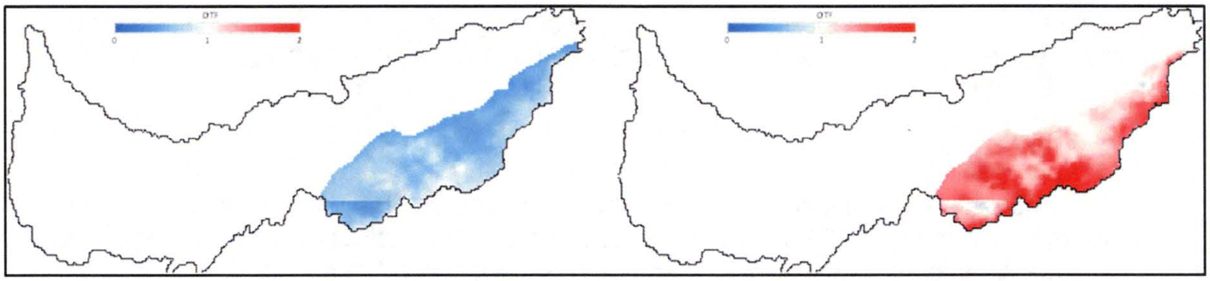


Figure 1. Comparison of Smethport OTF using TVA's rescaling approach (left) and original approach (right) for TRANS=1 grids (i.e, transpositionable zone)

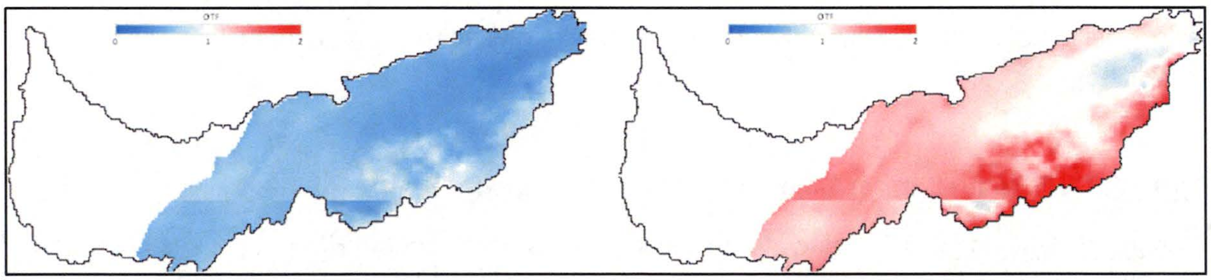


Figure 2. Comparison of Simpson OTF using TVA's rescaling approach (left) and original approach (right) for TRANS=1 grids (i.e., transpositionable zone)

<u>Request</u>:

Provide justification for adjusting the Smethport, PA and Simpson, KY OTF values to a maximum of 1.00, and for using significantly reduced OTF values throughout the transpositionable zone.

RAI #8: OTF Calculation using NWS Atlas 14

Technical Deficiency: The OTF is intended to accurately capture localized spatial variation in orography. However, the NWS Atlas 14 data used to calculate OTF are inherently regionalized, which poses a concern whether the original intention of developing an OTF was fully captured.

Section 4.5 of the Topical Report states that, in comparison to the topographic adjustments used in the TVA HMR, "*the OTF, along with hourly gridded rainfall data from SPAS analyses, is able to evaluate and quantify…variations over a much more refined scale both spatially and temporally.*" Localized refinement is achieved through use of Atlas 14 precipitation frequency (PF) data, which were developed using L-moment regional frequency analysis.

However, during the development of the PF data, Atlas 14 identified homogeneity zones (i.e., regional groups) for data pooling. Based on Section 4.2.2 of Atlas 14, Volume 2, the regional application of L-moments derives "*the shape parameters from all stations in a homogeneous region rather than from each station individually.*" From Section 4.4 of Atlas 14, Volume 2: "*effort was made during the subdivision process to mitigate discrepancies that could be caused by (1) sampling error due to small sample sizes, or (2) regionalization that does not reflect a local situation.*" Figure 3 shows the 24-h through 60-day regional groupings identified in Atlas 14, Volume 2.

Generally speaking, all precipitation data within a homogeneity zone were first locally normalized, and then pooled together for probabilistic density function fitting. Therefore, it is important to understand that the NWS Atlas 14 values do not only capture the local precipitation features. It is jointly influenced by the local mean (of annual maximum series at each gauge), regional probability density distribution, and final interpolation by PRISM.

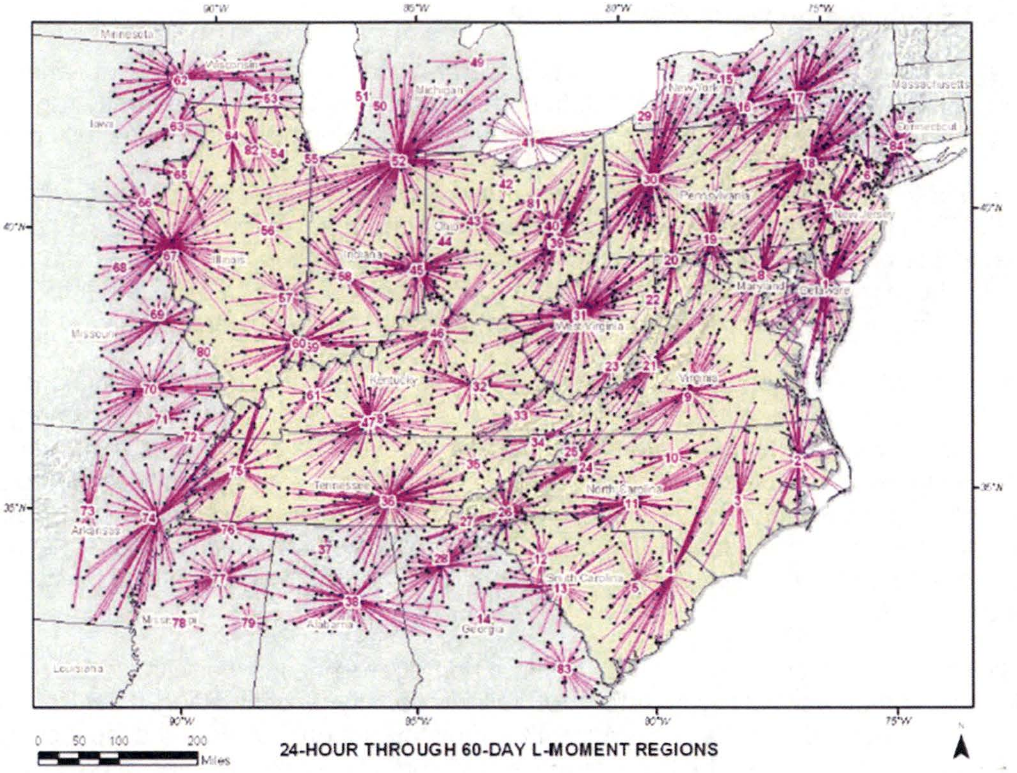


Figure 3. Regional groupings for daily data used to prepare NOAA Atlas 14 Volume 2

Section 3.1.4 of the WMO-No. 1045 Manual on Estimation of Probable Maximum Precipitation states: "*Precipitation-frequency values represent an equal probability level of rainfall. The values for the rarer recurrence intervals, for example the 50-year or 100-year recurrence interval, are associated with severe weather systems. Therefore, they are better indicators of the geographic variation of PMP than mean seasonal or annual precipitation maps.*" Thus, staff believes that the specific features of Atlas 14 are important artifacts influencing the OTF and are worth considering. Given that the Atlas 14 method scales station PF data by the mean of the annual maximum series and uses PRISM for basemap smoothing, the final rainfall estimates would induce spatial smoothing based on averages rather than rarer recurrence intervals associated with severe weather systems.

OTF Best Fit Linear Trend Method

The licensee used a 6-h precipitation frequency climatology to compute local storm OTF and a 24-h precipitation frequency climatology to compute general and tropical storm OTF. For each short list storm, the OTF calculation approach used for the TVA Topical Report used linear regression to estimate the ratio between precipitation frequency depths for the recurrence interval associated with the storm's maximum point rainfall at either 6-h or 24-h.

OTF 100-year Ratio Method

Other AWA PMP studies have calculated the OTF using the 100-y precipitation frequency ratio rather than the linear regression approach. Since longer recurrence interval estimates may be

more representative of PMP-type storms but may lack reliable estimates, AWA has used the 100-year precipitation frequency ratio to compute OTF in other studies (e.g., the PMP study for Texas). NRC staff has also conducted limited sensitivity analysis and finds that the 100-year ratio is more stable than the regression approach. For example, precipitation frequency data provide higher precipitation depths at BFN than at WBN and SQN; however, the linear regression method can result in lower OTF values at BFN than at WBN and SQN.

Request:

a) Considering Atlas 14's regional features, provide a justification regarding whether the Atlas 14 PF data represent reasonable spatial variation representative of orographic PMP effects or PMP in general.

b) Provide a justification for using the best fit linear trend method in lieu of the 100-y ratio method for determining LIP and basin-wide PMP values.

RAI #9: OTF Calculation Issues

Technical Deficiency: Potential issues with the OTF calculations in certain regions were identified by staff and require clarification.

Staff's review of the Total Adjustment Factor (TAF) Excel files provided in response to RAI #1 revealed some anomalies in how the OTF was calculated. For a select set of grid cells, the OTF was calculated using an absolute cell value in the Excel spreadsheet rather than using the OTF regression-based formula used in other cells. Visualization of the areas using the absolute cell reference value is provided in Figure 4 (for general and tropical storms) and Figure 5 (for local storms).

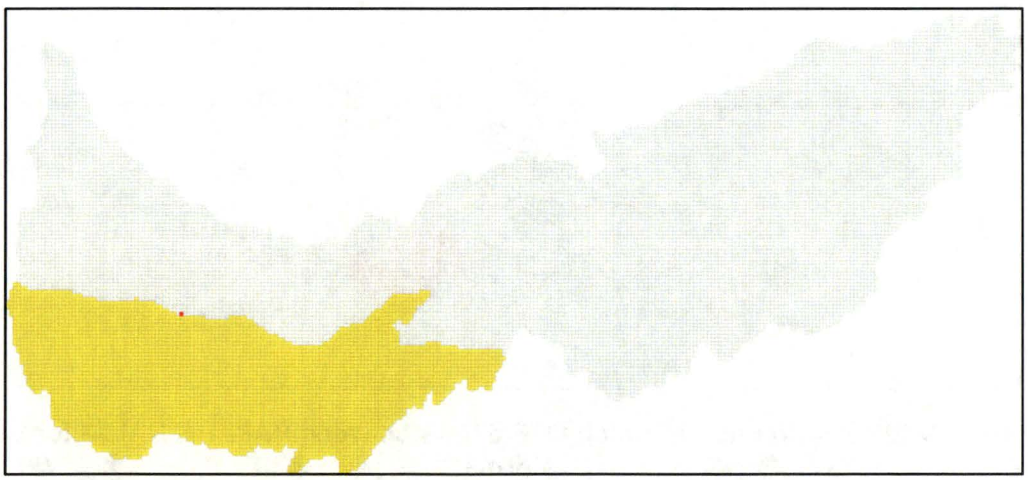


Figure 4: Grid cells for which OTF calculation used an absolute cell reference value for General & Tropical storms (the red grid cell indicates the location of the grid cell used for assigning an OTF value for all yellow colored grid cells)

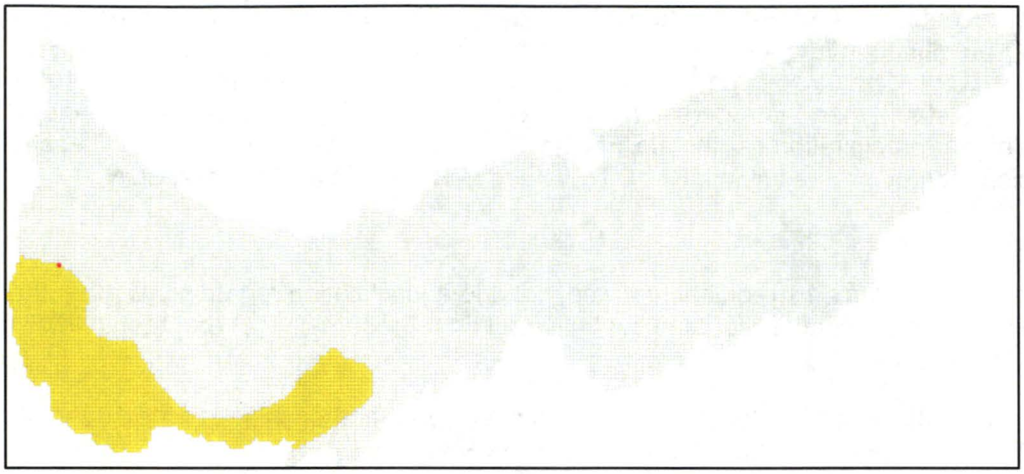


Figure 5: Grid cells (in yellow) for which OTF calculation used an absolute cell reference value for Local storms (the red grid cell indicates the location of the grid cell used for assigning an OTF value for all yellow colored grid cells)

In addition, staff compared the Excel-based OTF values from the RAI #1 response and the GIS-based OTF values from RAI #3. The comparison revealed a discrepancy in calculated OTF values for local storms which was confined to a region of the southern Appalachians. Visualization of the areas affected by this discrepancy is provided in Figure 6.

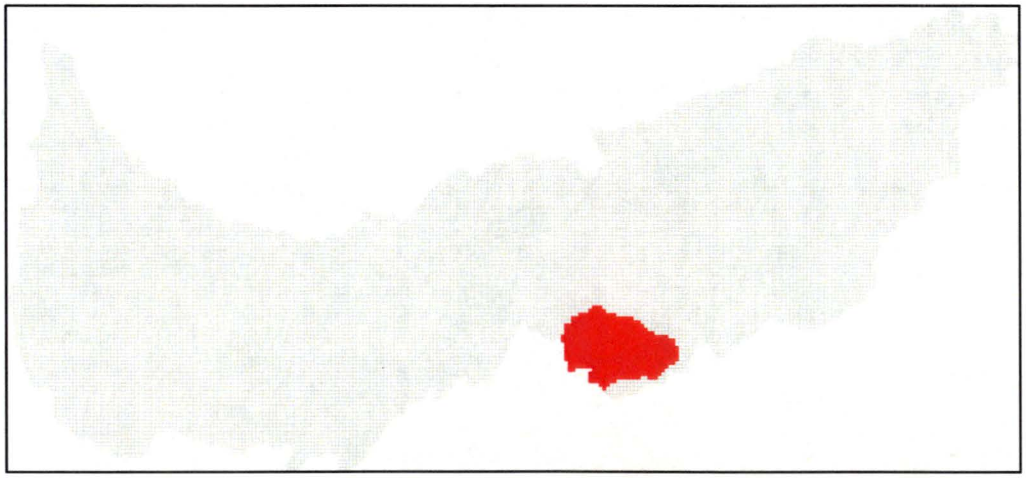


Figure 6: Grid cells (in red) for which OTF differs between RAI #1 & RAI #3 for Local storms

Request:

a) Provide an explanation for why the OTF was calculated using an absolute cell reference value for the grid cells identified in Figure 4 and Figure 5 rather than using the OTF regression-based formula used for the other cells.

b) Provide an explanation for why the OTF values provided in RAI #1 and RAI #3 differ, as illustrated in Figure 6.

RAI #10: Custom Transposition Limits

Technical Deficiency: Based on staff's review of information provided in response to RAI #1, the majority of storms included transposition limits that conform to the TVA Zone boundaries. However, at least four storms appeared to contain custom transposition limits, as listed in Table 2 that don't conform to the TVA Zone boundaries.

Table 2. Summary of storms subjected to custom transposition limits

Storm	SPAS Num	Storm Type	Transposition Limits
Elba, AL	1305	General	South of 35 deg N (exclusive of Zone 4)
Americus, GA	1317	Tropical	Based on TSR L-Cv 0.24 contour*
Larto Lake, LA	1182	Tropical	Based on TSR L-Cv 0.24 contour*
Big Rapids, MI	1206	General	North of 36.5 deg N (exclusive of Zone 4)

**Note*: *information from TAF Excel file, OTF sheet*

Request:

a) Provide a justification as to why each of the storms listed in Table 2 was subjected to custom transposition limits.

b) Provide a justification for the use of custom transposition limits for the Americus, GA and Larto Lake, LA storm using TSR L-Cv 0.24 contour. Provide the physical basis used to justify this custom approach.

RAI #11: Storm Representative Dew Point Selection: Timeframe and Location

Technical Deficiency: Staff's review of the licensee's storm representative dew point data for short list storms resulted in the identification of several storms for which questionable timeframe and/or location data may have been used when selecting the storm representative dew point. This issue can significantly impact PMP values for controlling storms

As a part of its assessment, staff reviewed the rainfall mass curves, HYSPLIT trajectories, and storm representative dew point information that the licensee provided in response to RAI #1 and RAI #2. Staff also independently evaluated this information to assess the reasonableness of the data application.

Staff's review of the above information revealed that the licensee's storm representative dew point selection used dew point data which were observed at locations far upwind of the storm center and during timeframes in which significant rainfall had already occurred. Conducting the

analysis in this way could inadequately represent the storm characteristics and (in these cases) result in PMP underestimation since the relatively higher moisture observed could not induced the observed rainfall.

Staff believes the storm representative dew point methodology regarding HYSPLIT trajectories and/or dew point timeframes may be flawed for the following storms. A comparison of the TVA and NRC storm representative dew point temperatures these storms is provided in Table 3.

1. <u>General Storm, SPAS 1206 (Big Rapids, MI)</u> – see Figure 7

    a. The licensee's dew point temperature observations correspond to a period after significant rainfall had already occurred. The representative dew point location is approximately 230 miles SW of the storm center location.

2. <u>General Storm, SPAS 1208 (Warner Park, TN)</u> – see Figure 8

    a. The licensee's dew point temperature observations correspond to a period when the most intense rainfall occurred. The representative dew point location is approximately 360 miles SSW of the storm center location.

3. <u>Tropical Storm, SPAS 1276 (Wellsville, NY)</u> – see Figure 9

    a. The licensee's dew point temperature observations correspond to a period when the most intense rainfall occurred. The representative dew point location is approximately 385 miles SSW of the storm center location.

    b. By adjusting the HYSPLIT backward trajectory timing to more closely align with the onset of rainfall, staff identified a moisture inflow direction of SE rather than SSW.

4. <u>Tropical Storm, SPAS 1317 (Americus, GA)</u> – see Figure 10

    a. By adjusting the HYSPLIT backward trajectory timing to more closely align with the onset of rainfall, staff identified a moisture inflow direction of SE-to-S rather than WSW.

5. <u>Additional storms which exhibit timeframe issues but do not control PMP</u>

    a. General Storm, SPAS 1218 (Douglasville, GA & LaFayette, GA) - Figure 11

    b. Local Storm, SPAS 1226 (College Hill, OH) - Figure 12

    c. Local Storm, SPAS 1209 (Wooster, OH) - Figure 13

    d. Tropical Storm, SPAS 1182 (Larto Lake, LA) - Figure 14

Table 3. Comparison of TVA vs NRC storm representative dew point temperature for storms with potential HYSPLIT or timing issues

Num	Storm Name	SPAS Num	Storm Type	Storm Rep. Td (deg F)		Difference (TVA-NRC)
				TVA T_d	NRC T_d	
1	Big Rapids, MI	SPAS 1206	General	70.5	68.5	+2
2	Warner Park, TN	SPAS 1208	General	75	74	+1
3	Wellsville, NY	SPAS 1276	Tropical	72.5	70.5	+2
4	Americus, GA	SPAS 1317	Tropical	76	74.5	+1.5
5a	Douglasville, GA	SPAS 1218_1	General	76	75	+1
5a	LaFayette, GA	SPAS 1218_2	General	76	75	+1
5b	College Hill, OH	SPAS 1226	Local	68.5	66.5	+2
5c	Wooster, OH	SPAS 1209	Local	76	72	+4
5d	Larto Lake, LA	SPAS 1182	Tropical	76	73	+3

Request: Provide justification for the selection of storm representative dew point values for the above storms with respect to timeframe and location selected, especially considering the timeframe of when rainfall occurs at the storm center. If corrections are warranted, provide an updated analysis as it may affect TVA's 3 NPP sites.

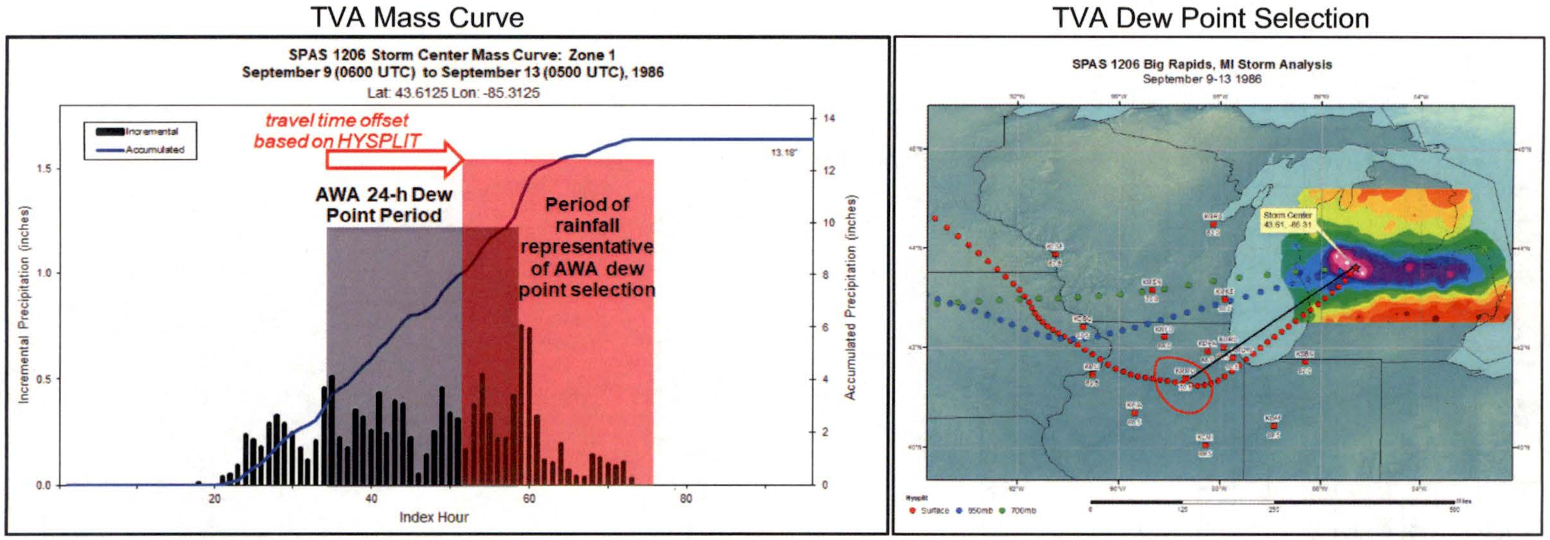


Figure 7. General Storm, SPAS 1206 (Big Rapids, MI) rainfall mass curve (left) and dew point analysis (right)

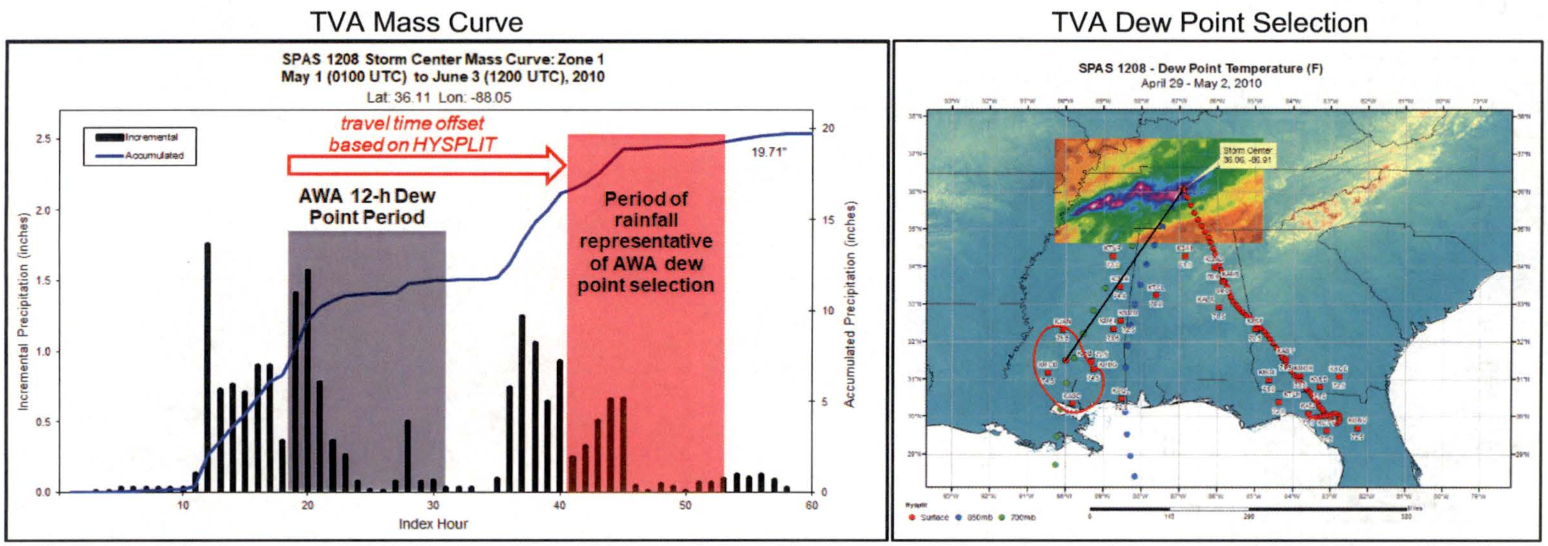


Figure 8. General Storm, SPAS 1208 (Warner Park, TN) rainfall mass curve (left) and dew point analysis (right)

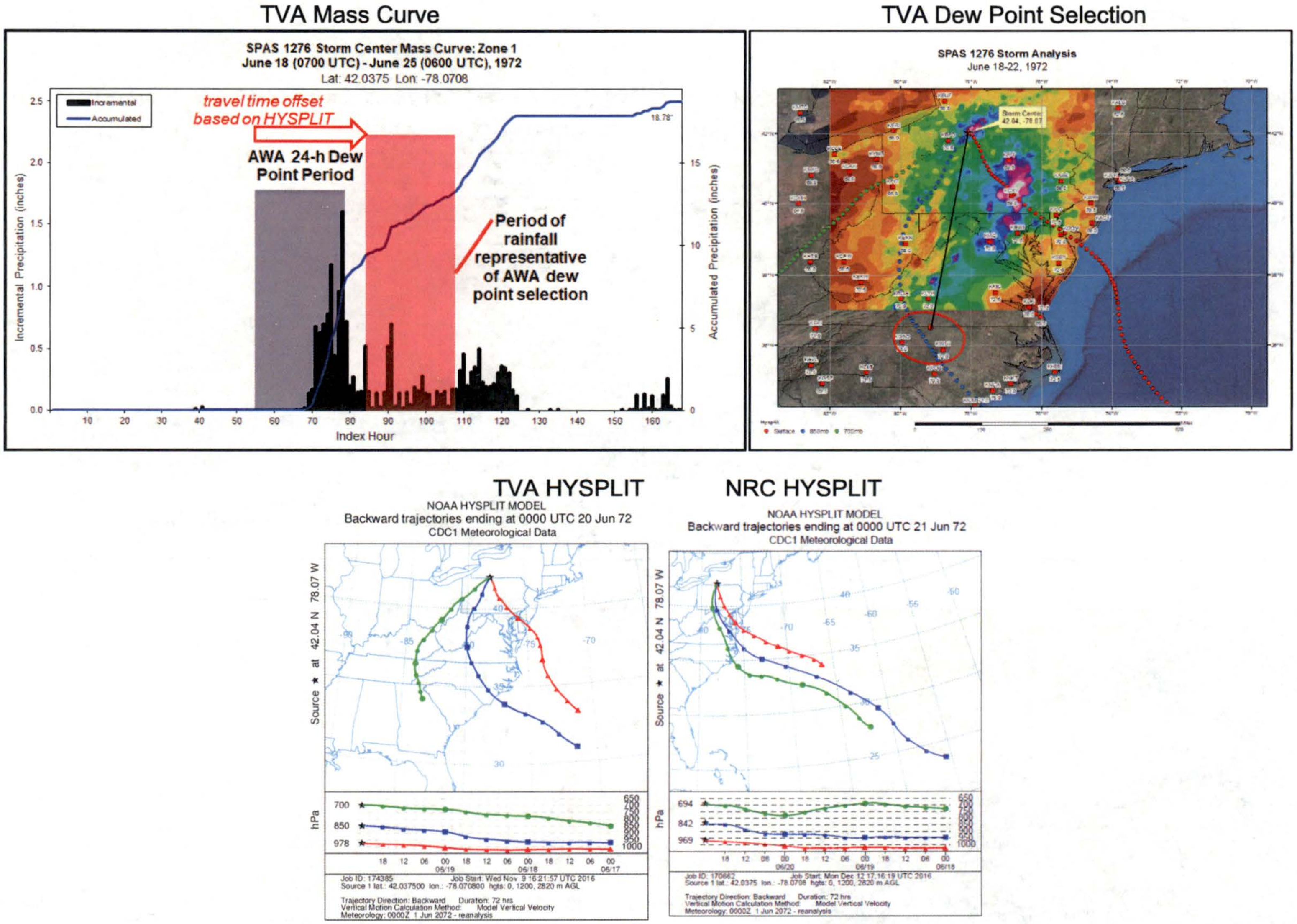


Figure 9. Tropical Storm, SPAS 1276 (Wellsville, NY) rainfall mass curve, dew point analysis, TVA HYSPLIT, and NRC HYSPLIT (from top-left to bottom-right)

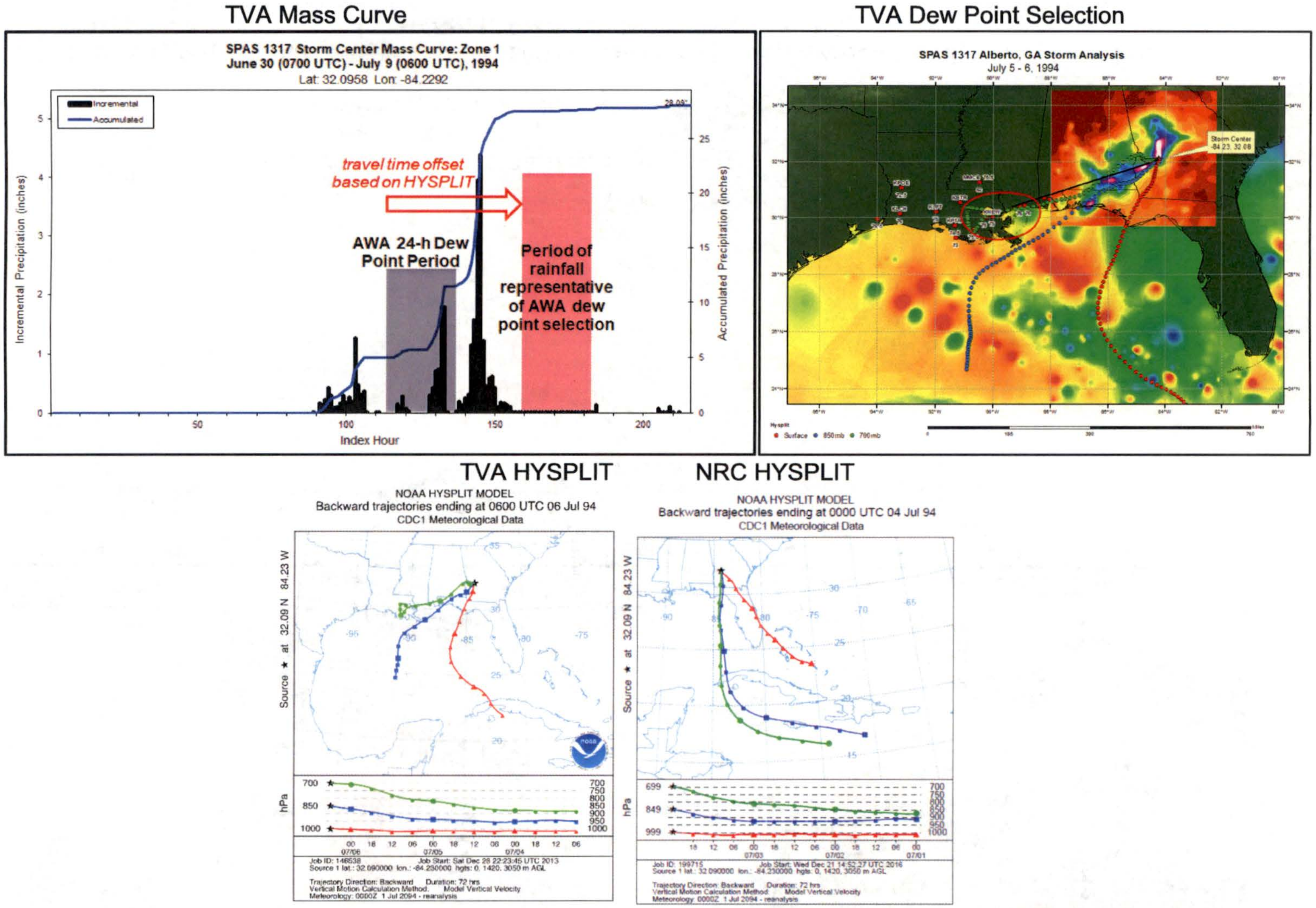
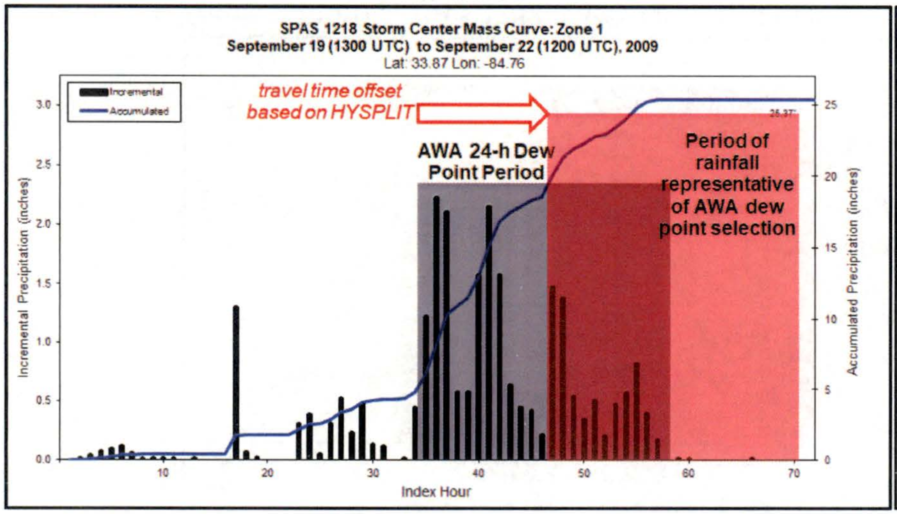


Figure 10. Tropical Storm, SPAS 1317 (Americus, GA) backwards HYSPLIT trajectory from TVA (left) and NRC (right)

TVA Mass Curve



TVA Dew Point Selection

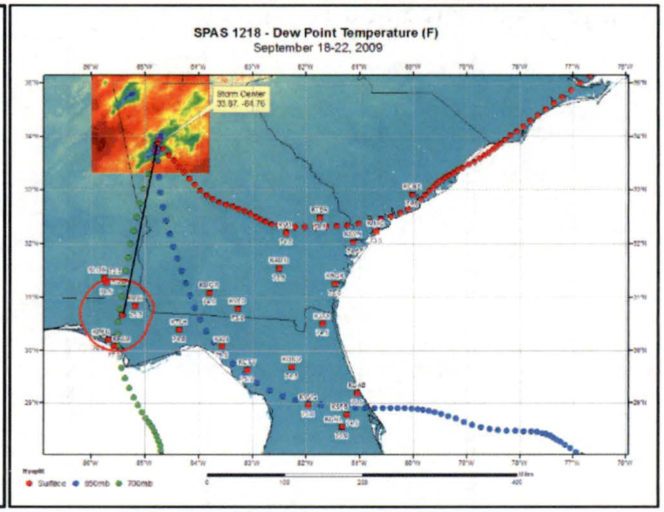
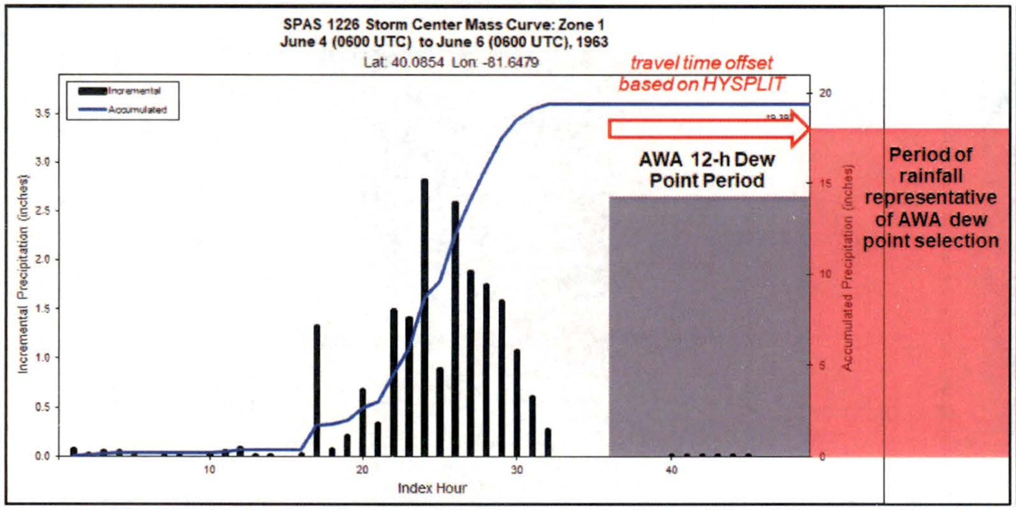


Figure 11. General Storm, SPAS 1218 (Douglasville, GA *[shown]* & LaFayette, GA) rainfall mass curve (left) and dew point analysis (right)

TVA Mass Curve



TVA Dew Point Selection

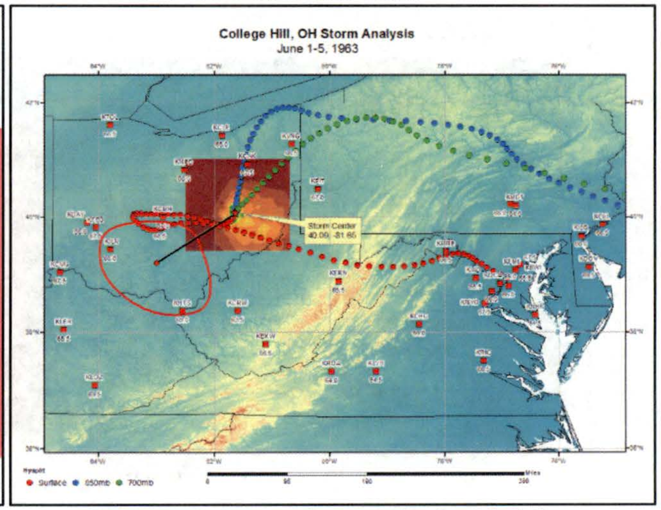
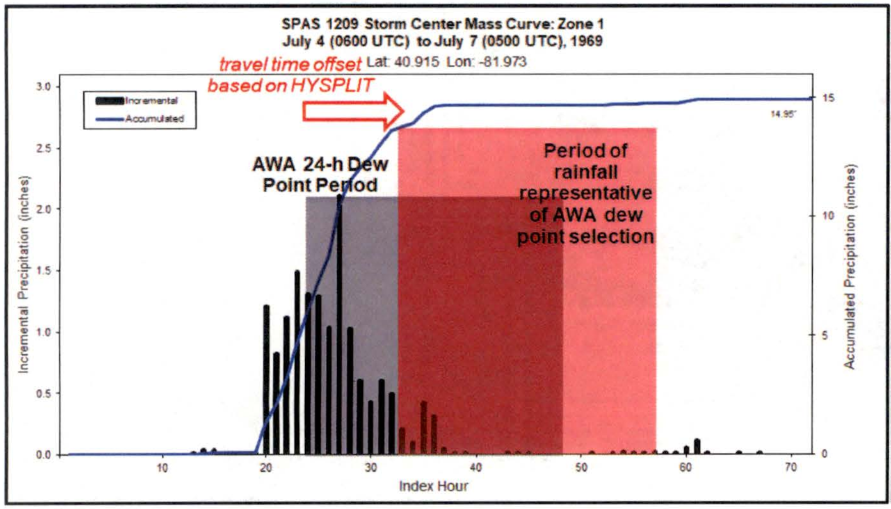


Figure 12. Local Storm, SPAS 1226 (College Hill, OH) rainfall mass curve (left) and dew point analysis (right)

TVA Mass Curve



TVA Dew Point Selection

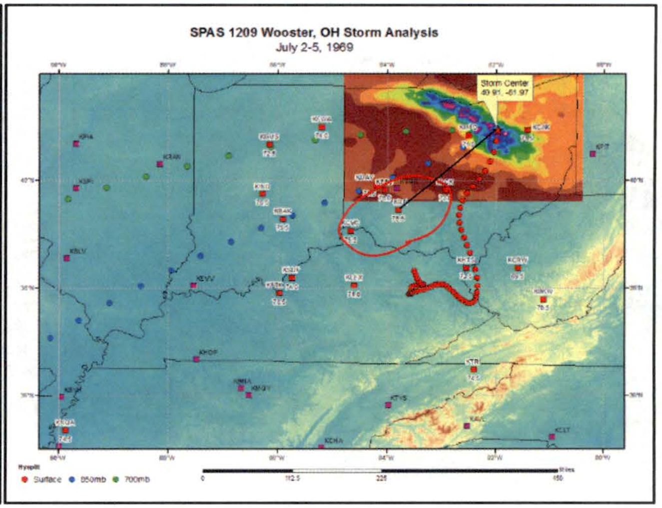
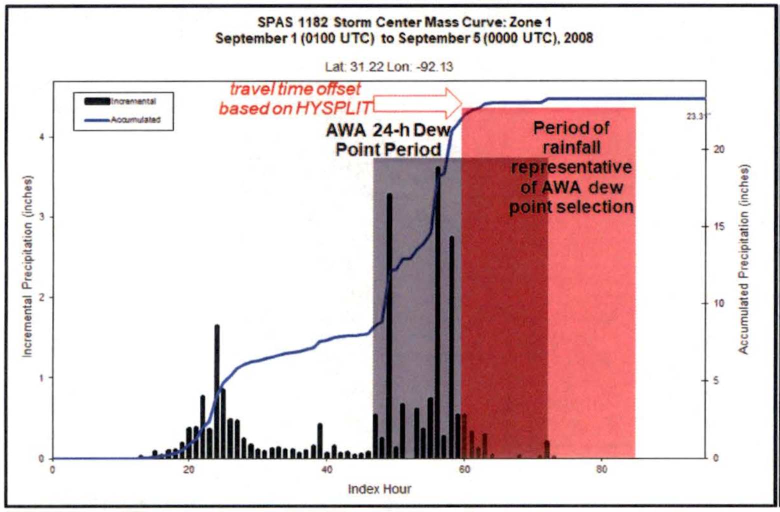


Figure 13. Local Storm, SPAS 1209 (Wooster, OH) rainfall mass curve (left) and dew point analysis (right)

TVA Mass Curve



TVA Dew Point Selection

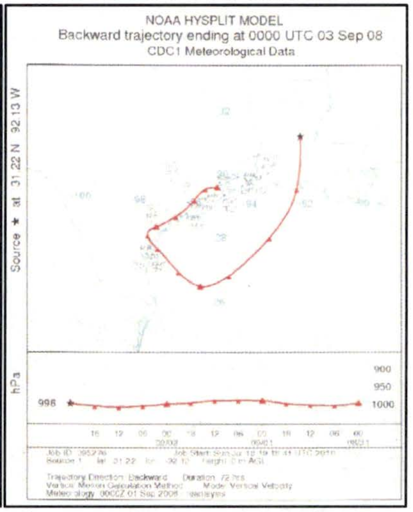


Figure 14. Tropical Storm, SPAS 1182 (Larto Lake, LA) rainfall mass curve (left) and dew point analysis (right)

RAI #12: Staff Independent Analysis of Dew Point Climatology

Technical Deficiency: Staff's independent evaluation of dew point climatology reveals that the licensee's values may be non-conservative due to potential data source and processing issues which may impact the estimated PMP values.

As a part of its assessment, staff reviewed the dew point climatology data provided by the licensee in response to RAI #1 and RAI #4; staff also independently evaluated these data to assess the reasonableness of the climatology data used.

Staff has concerns with the dew point climatology data source and processing used by TVA. While TVA used NOAA's TDL data set, NRC staff used NOAA's TD3505 data set. Both TD3505 and TDL data sets are officially released by NOAA, but the TDL data set used by TVA is basically a collection of instantaneous weather station observations whereas the TD3505 used by NRC is subjected to additional QC and processing by NOAA. Although both data sets are largely similar, there are some differences in the annual maximum series (AMS) caused by missing/erroneous values originally included in the TDL data set. This leads to different AMS and 100 y dew point estimates because of the existence and treatment of missing observations. Such differences result in systematic biases which could affect moisture maximization factors and transposition factors for all storms.

To assess the impacts of using different data (and some minor differences in processing), NRC staff conducted independent evaluation of dew point climatology for all short list storms, and it yielded a number of differences from TVA's evaluation. In general, NRC's independent evaluation resulted in higher dew point climatology values, with variation both temporally and spatially. For all else being equal, an increase in dew point climatology values will result in higher PMP estimates since historical storms would be subject to higher levels of moisture maximization.

Figure 15 shows the difference in the NRC and TVA dew point climatology values for each comparable station for all short list storms. The stations selected represent the stations which would have most influenced the dew point climatology at the transpositioned moisture source location and for which climatology values were available from both the TVA and NRC data sets. Positive values indicate that NRC's evaluation resulted in higher dew point climatology values than TVA, while negative values indicate that NRC's evaluation resulted in lower dew point climatology values than TVA. On average, the difference for General, Local, and Tropical storms is +0.69 F, +0.61 F, and +0.52 F, respectively, with an overall average station difference of +0.65 F. Individual station differences range from -1.44 F to +3.67 F.

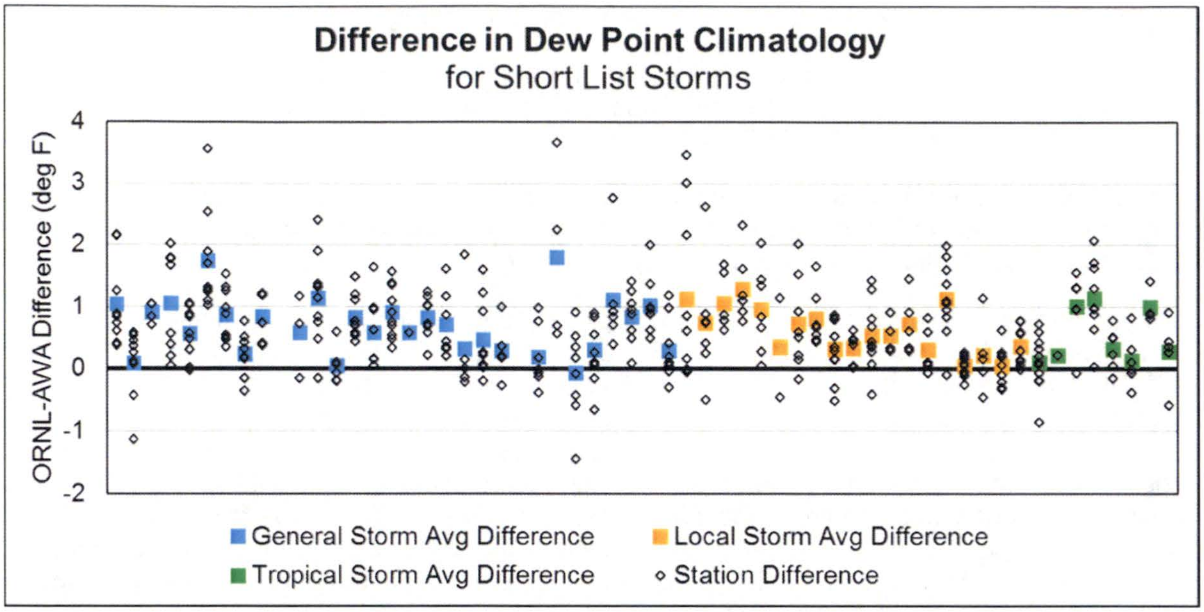


Figure 15. Difference in dew point climatology values between NRC (ORNL) evaluation and TVA(AWA) evaluation for all short list storms. Each column of data points corresponds to one short list storm. Black-outlined diamonds represent station data (one diamond corresponds to the NRC-TVA difference for a single station; for most storms, multiple stations were available for comparison) which influenced the dew point climatology at the transpositioned moisture source location and for which a direct comparison could be made. Colored squared represent the average difference in station data for each storm.

The deviations in climatology values resulting from the two analyses indicates a systematic bias in the overall values, with NRC's values typically 0.5 to 1.0 degree F higher than TVA's values.

Request:

Given the significant impacts noted above please update the dew point climatology using TD3505 dew point data and revising both the LIP and basin-wide PMP values accordingly or provide a justification for not updating it.

RAI #13: Warner Park, TN Dew Point Duration Clarification

Technical Deficiency: Staff's review of the licensee's documentation and files related to the Warner Park, TN (SPAS 1208) storm representative dew point and dew point climatology data appears to indicate inconsistent use of dew point duration.

As a part of its assessment, staff reviewed the text and digital information related to the Warner Park storm representative dew point and dew point climatology provided by the licensee. Figure 404 in the Topical Report shows that a 12-h duration was used to analyze the Warner Park storm representative dew point; however, upon further review, staff believe that a 24-h duration was used.

Figure 415 in the Topical Report shows maximum average dew point data for several stations. Comparison with the "surface_summary" worksheet in the "SPAS_1208_Obs_data.xlsx" file reveals that the data plotted in Figure 415 correspond to the 24-h maximum average dew point. Also, staff confirmed that the licensee used a 12-h duration for the Warner Park dew point climatology. Therefore, it appears that the dew point duration was used inconsistently.

Staff understand that if this is the case, then the licensee's application could be slightly overly conservative; however, since it appears that a 12-h duration was intended, only the storm representative dew point would change. The 24-h value used by the licensee is 74.8 F based on the average of 4 stations (KHBG, KASD, KJAN, and KMCB); this value was rounded to 75.0 F by the licensee. The 12-h value computed by the licensee is 75.1 F based on the average of the same 4 stations and would be rounded to 75.0 F. Therefore, it appears that changing the storm representative dew point would not change the results of the Warner Park analysis.

Request: Provide confirmation of whether this dew point duration discrepancy exists, what the intended dew point duration is, and what (if any) changes are needed.

RAI #14: Scope of NRC's Review

Regulatory Deficiency: This topical report describes the work performed to calculate the Probable Maximum Precipitation for any location within the overall TVA basin and Local Intense Precipitation (LIP) at the BFN, SQN, and WBN sites. The Summary and Conclusions section of the Topical Report states that the precipitation values in the report replace those in HMRs 41, 45, 47, and 56 (which provide PMP estimates for the Tennessee River Basin, including LIP), as well as HMRs 51 and 52 (which provide PMP estimates for the eastern half of the continental US). NRC's regulatory authority limits its approval of the precipitation values contained in the Topical Report to only those values that could potentially result in flooding at TVA's nuclear plant sites.

Request: Please clarify that the scope of the NRC's requested review is concerned with potential SSPMP impacts at the 3 TVA nuclear power plant sites and does not necessarily reflect positions with respect to the entire Tennessee River watershed except as it impacts river flooding effects and local rainfall effects at the sites.

SECTION E

Tennessee Valley Authority, 1101 Market Street, Chattanooga, Tennessee 37402

CNL-18-044

April 19, 2018

10 CFR 50.4

ATTN: Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Browns Ferry Nuclear Plant, Units 1, 2, and 3
Renewed Facility Operating License Nos. DPR-33, DPR-52, and DPR-68
NRC Docket Nos. 50-259, 50-260, and 50-296

Sequoyah Nuclear Plant, Units 1 and 2
Renewed Facility Operating License Nos. DPR-77 and DPR-79
NRC Docket Nos. 50-327 and 50-328

Watts Bar Nuclear Plant, Units 1 and 2
Facility Operating License Nos. NPF-90 and NPF-96
NRC Docket Nos. 50-390 and 50-391

Subject: Tennessee Valley Authority Response to NRC Request for Additional Information Related to Topical Report TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041"

References:

1. TVA Letter to NRC, "Request for Review and Approval of Topical Report TVA-NPG-AWA16, 'TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041'," dated September 20, 2016 (ML16264A454)

2. Electronic Mail from NRC to TVA, "Request For Additional Information Related to TVA Fleet Topical Report TVA-NPGAWA16 (EPIC: L-2016-TOP-0011)," dated February 23, 2018 (ML18057A637)

By letter dated September 20, 2016 (Reference 1), Tennessee Valley Authority (TVA) submitted topical report TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041" for review and approval. Approval of this Topical Report was requested to support Probable Maximum Flood calculations and associated with planned License Amendment Requests for Sequoyah Nuclear Plant, Units 1 and 2, and Watts Bar Nuclear Plant, Units 1 and 2, and a potential License Amendment Request for Browns Ferry Nuclear Plant, Units 1, 2, and 3.

In Reference 2, the NRC transmitted a Request for Additional Information (RAI) related to the TVA Topical Report. As described in the Reference 2 email, TVA agreed to provide responses to the RAIs by April 20, 2018. The enclosure to this letter contains TVA's response to the RAIs.

As discussed in the Enclosure, a revision of the Topical Report will be submitted to incorporate the required changes needed as a result of these RAIs.

There are no regulatory commitments associated with this submittal. Please address any questions regarding this request to Russell Thompson at 423-751-2567.

Respectfully,

J. W. Shea
Vice President, Nuclear Regulatory Affairs & Support Services

Enclosure: Response to NRC Request for Additional Information Related to Topical Report TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041"

cc (Enclosure):

NRC Regional Administrator - Region II
NRC Senior Resident Inspector - Browns Ferry Nuclear Plant
NRR Project Manager - Browns Ferry Nuclear Plant
NRC Senior Resident Inspector - Sequoyah Nuclear Plant
NRR Project Manager - Sequoyah Nuclear Plant
NRC Senior Resident Inspector - Watts Bar Nuclear Plant
NRR Project Manager - Watts Bar Nuclear Plant

Enclosure

Response to NRC Request for Additional Information Related to Topical Report TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041"

By a letter dated September 20, 2016 (Agencywide Documents Access and Management System (ADAMS) Accession Number ML16264A454), the Tennessee Valley Authority (TVA) submitted the a fleet topical report (TR) TVA-NPG-AWA16 "Overall Basin probable Maximum Precipitation and Local Intense Precipitation Analysis." This TR will be used for future licensing actions for Browns Ferry Units 1, 2 and 3, Sequoyah Units 1 and 2 and Watts Bar Units 1 and 2.

The U.S. Nuclear Regulatory Commission (NRC) staff is reviewing your submittal and has determined that additional information is required to complete the review. The specific information requested is attached to this email. The proposed questions were emailed in draft form and a clarification call was held on January 22, 2018. Your staff confirmed that these draft questions did not include proprietary or security-related information and agreed to provide a response April 20, 2018 to this request for additional information (RAI).

The NRC staff considers that timely responses to RAIs help ensure sufficient time is available for staff review and contribute toward the NRC's goal of efficient and effective use of staff resources. Please note that if you do not respond to this request by the agreed-upon date or provide an acceptable alternate date, we may deny your application for amendment under the provisions of Title 10 of the Code of Federal Regulations, Section 2.108. If circumstances result in the need to revise the agreed upon response date, please contact me at (301) 415-8480 or via e-mail Andrew.Hon@nrc.gov.

Regulatory Basis

10 CFR Part 50, Appendix A, General Design Criterion (GDC) 2, states, in part, that structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as floods without loss of capability to perform their safety functions. The design bases for these structures, systems, and components shall reflect appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated.

NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition, Section 2.4.3, "Probable Maximum Flood (PMF) On Streams and Rivers," states that to meet the requirements of GDC 2 with regards to design bases for flooding in streams and rivers, the probable maximum precipitation (PMP) on the drainage area that contributes to runoff on the stream network adjacent to the plant site should be determined. Similarly, NUREG-0800 Section 2.4.2, "Floods," states that estimates of potential local flooding on the site and drainage design should be based on estimates of local intense precipitation or local PMP.

<u>RAI #1</u>: Complete Storm Analysis Information for All Short List Storms

<u>Technical Deficiency</u>: Information in the Topical Report is incomplete; additional information is necessary for the staff to make its regulatory finding.

<u>Request:</u>

Provide the analysis information for all short list storms that were used for PMP calculation. The detailed storm analysis information should include:

- *Storm calculation spreadsheet*
- *Depth-area-duration values and chart*
- *Storm cumulative mass curve chart*
- *Total storm isohyetal analysis map*
- *HYSPLIT moisture trajectory map*
- *In-place storm representative dew point (or sea surface temperature) analysis map*

TVA Response:

The detailed storm analysis information requested above for the short list storms used in the PMP Calculation CDQ000002016000041 is provided in Attachment 1 - Folder RAI1. The information is located in the Storm Precipitation Analysis System (SPAS) folder for each storm.

Note, no Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model output is available for storms that occurred prior to 1948. Also, for the SPAS 1299 Zone 1 (Alta Pass, NC-July 1916) storm, the storm representative dew point analysis data provided in Tennessee Valley Authority Floods and Flood Control document, Figure 47 (Tennessee Valley Authority, Technical Report 26, 1961) are utilized and included within the RAI1 folder.

<u>RAI #2</u>: TVA Observed Hourly Dew Point Data Sheet for All Short List Storms

<u>Technical Deficiency</u>: Information in the Topical Report is incomplete; additional information is necessary for the staff to make its regulatory finding.

<u>Request:</u>

For each short list storm, provide an individual spreadsheet documenting the hourly dew point data that were used for storm representative dew point selection. If publicly-accessible dew point data were used (e.g., NCDC ISD), the unique station identifier (e.g., USAF, WBAN, and/or ICAO) and the starting/ending dew point date and hour (used for the calculation of average 6-, 12-, or 24-hour dew points) should be clearly specified. Provide detailed meteorological reasoning if the selection of storm representative dew point location deviated significantly from the HYSPLIT trajectories. If sea surface temperature is used as a surrogate of surface dew point observation, the sea surface temperature observation should be provided. Provide the relevant data or source information used to determine the storm representative dew point for short list storms for which hourly dew point data were unavailable or not used.

TVA Response:

Individual spreadsheets containing the hourly dew point or sea surface temperature (SST) data used in the selection of the storm representative dew point for short list storms used in PMP Calculation CDQ000002016000041 are provided in Attachment 1 - Folder RAI2. The publicly-accessible dew point station identifier information and a table cross-referencing the starting/ending dew point timeframe for each duration investigated (i.e., 6-, 12-, and 24-hours) are provided within each spreadsheet.

In each of the storms evaluated, the region used as the storm representative dew point or SST location is within the general region suggested by HYSPLIT, if available. Therefore, no significant deviations from HYSPLIT occurred. As a result, detailed meteorological reasoning is not provided. In situations where SSTs were used as a surrogate for dew point observations, that data is provided in daily format with the data source identified.

Note, many previous United States Army Corps of Engineers (USACE) / National Weather Service (NWS) storm representative values can be found in hydrometeorological report (HMR) 25A (storms prior to 1948), HMR 51, HMR 52, HMR 53, TVA Technical Report 26, and/or the USACE Storm Studies documentation. These sources are identified when they were used to derive storm representative dew point information where updated hourly and/or SST data was not available.

RAI #3: TVA Storm Adjustment Factor Feature Class Table for All Short List Storms

Technical Deficiency: Information in the Topical Report is incomplete; additional information is necessary for the staff to make its regulatory finding.

Request:

For each short list storm, provide the storm adjustment factor feature class table developed for the TVA PMP study (as documented in Figure 24 of Calculation CDQ000002016000041). The data layers should be in a common GIS data format that can be processed by ESRI ArcGIS, and should cover all of the information shown in Figure 24 including STORM, LON, LAT, ZONE_, ELEV, IPMF, MTF, OTF, TAF, and TRANS.

TVA Response:

Geographic Information System (GIS) database files with all the storm adjustment factor feature classes developed for the TVA PMP study are provided in Attachment 1 - Folder RAI3. The data layers are in a common GIS data format that can be processed by ESRI ArcGIS and cover all of the information requested including STORM, LON, LAT, ZONE_, ELEV, IPMF, MTF, OTF, TAF, and TRANS.

RAI #4: TVA Dew Point Climatology Data and GIS Layers

Technical Deficiency: Information in the Topical Report is incomplete; additional information is necessary for the staff to make its regulatory finding.

Request:

Provide the digital dew point climatology GIS data layers used for PMP development. The digital dew point climatology GIS data layers should be provided for the monthly 6-, 12-, and 24-hour, 100-year recurrence interval dew point maps provided in Appendix C of Calculation CDQ000002016000041. In addition, provide the corresponding monthly dew point climatology values at each gauge that was used to develop the maps provided in Appendix C of Calculation CDQ000002016000041.

TVA Response:

The GIS data used for the digital dew point climatology GIS data layers applied in the TVA PMP development are provided in Attachment 1 - Folder RAI4. The digital dew point climatology GIS data layers provide the monthly 6-, 12-, and 24-hour, 100-year recurrence interval dew point maps shown in Appendix C of Calculation CDQ000002016000041. The data also includes the monthly dew point climatology values at each gauge used to develop the maps provided in Appendix C of Calculation CDQ000002016000041.

After further review and discussion with the NRC staff in regard to the most appropriate dew point climatology database, TVA has agreed to conservatively revise the dew point climatology applied in Calculation No. CDQ000002016000041 and to utilize the National Center for Environmental Information (NCEI) TD3505 hourly dew point database. This will extend the period of record and provide additional dew point observational data for use in developing updated dew point climatology. The updated climatology will replace the previously used GIS layers. The updated storm adjustments will be processed and applied to each storm used for the TVA PMP development. Updates to this data set are anticipated to affect Sections 5.1.1, 6.1.1, 6.5.1, 6.8.1, 6.8.4, and Appendix C of Calculation No. CDQ000002016000041 and will be submitted as Revision 1 to Topical Report TVA-NPG-AWA16 (TVA Calculation CDQ000002016000041).

RAI #5: TVA Probable Maximum Precipitation Data and GIS Layers

Technical Deficiency: Information in the Topical Report is incomplete; additional information is necessary for the staff to make its regulatory finding.

Request:

Provide the final digital PMP GIS data layers (across all durations and areas) developed for the TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis. The digital PMP GIS data layer should cover the full TVA Basin for which PMP values have been determined.

TVA Response:

Attachment 1 - Folder RAI5 contains 3 folders, one for each storm type (i.e., general, local, and tropical) used in the TVA PMP calculation for the domain at a spatial resolution of 90 arc-seconds or .025 x .025 decimal degrees. GIS raster files are included for the entire domain and all durations.

After further review and discussion with the NRC staff in regard to the most appropriate dew point climatology database and storm representative dew points for some storms, TVA has agreed to conservatively revise Calculation No. CDQ000002016000041 as further discussed in the TVA responses to RAIs #11 and #12. Those changes are anticipated to affect Section 2.5, Section 5.1, Section 5.7 and Appendices A, C and F of Calculation No. CDQ000002016000041 and will be submitted as Revision 1 to Topical Report TVA-NPG-AWA16 (TVA Calculation No.CDQ000002016000041).

RAI #6: Reasonableness of OTF Values

Technical Deficiency: Staff's review of Orographic Transposition Factor (OTF) application examples demonstrates discrepancies between expected OTF values and OTF values used by the licensee for selected storms.

The OTF is applied after an observed precipitation event is 1) moisture maximized using the in-place maximization factor (IPMF) and 2) geographically transpositioned (on a Lat-Lon plane) using a moisture transposition factor (MTF). The MTF captures geographic differences in moisture availability through comparison of dew point climatology. While it captures spatial variation in moisture, the MTF may not adequately capture the effects of terrain, hence the need for a terrain adjustment (e.g., the OTF, Barrier Adjustment Factor, or Storm Separation Method).

Staff interprets from the licensee's descriptions in the Technical Report that the OTF is intended to capture the impact that terrain will have on rainfall depths when transpositioning a storm from the original location to a new location. Therefore, staff believes that the OTF should be independent of geographical moisture influence (which is captured through use of the MTF). Consequently, staff believes that the OTF should not be significant when moving storms between regions with similar orographic characteristics (i.e., such regions should have a calculated OTF close to 1.00).

To assess whether the OTF calculation process produces OTF values close to 1.00 in cases where the original and transpositioned storm paths have similar orographic characteristics, staff evaluated the OTF for a series of case studies using data supplied by the licensee for TVA short

list storms. NRC Table 1 includes a summary of the rationale for evaluating these case studies and the subsequent observations.

NRC Table 1. OTF case studies evaluated by staff

Storm	Rationale	Observations
Warner, OK (Example 1)	The storm center location and TVA Zone 1 share similar orographic characteristics (e.g., both locations exhibit minimal barriers, are of similar elevation, and are located at a similar distance-to-coast).	Avg. Zone 1 OTF: 0.80
Fall River, KS (Example 2)	The storm center location and TVA Zone 1 share similar orographic characteristics (e.g., both locations exhibit minimal barriers, are of similar elevation, and are located at a similar distance-to-coast).	Avg. Zone 1 OTF: 0.75
Smethport, PA (Example 3a)	The storm center location and TVA Zone 4 share similar orographic characteristics (e.g., both locations exhibit orographic influence and are a similar distance-to-coast). TVA Zone 4 has higher overall orographic influence than the storm center due to higher terrain elevation and complexity.	Avg. Zone 4 OTF*: 0.66
Smethport, PA (Example 3b)	The storm center location and TVA Zone 2 share similar orographic characteristics (e.g., both locations exhibit orographic influence, are of similar elevation, and are a similar distance-to-coast).	Avg. Zone 2 OTF*: 0.59

**Note: the OTF for the Smethport, PA storm was manually adjusted by the licensee to include rescaling to a maximum value of 1.00. An additional question related to the Smethport, PA storm is included in RAI #7.*

For each of the examples included in NRC Table 1, staff believes that the orographic adjustments should be minimal and the OTF should be close to 1.00; instead, the licensee's analysis results in OTF values significantly less than 1.00 and large reductions in the adjusted rainfall depths.

Request:

Provide a justification for the departure of OTF from 1.00 when transpositioning storms across orographically similar zones (examples provided in NRC Table 1), and discuss whether the reductions in OTF are reasonable. Provide a justification for applying the OTF to the transposition of all storms throughout the TVA Basin, given the example results provided in NRC Table 1.

TVA Response:

Orographic Transposition Factor (OTF) Background
The OTF adjustment process is being used to not only capture the difference in terrain effects between two locations but also to capture all processes that result in precipitation reaching the ground at one location versus another location. The OTF is a mathematical representation of the ratio of the precipitation frequency climatology at one location versus another location. The precipitation frequency climatology is derived from actual observed precipitation events. The largest of these storm events each year is then used to define the Annual Maximum Series (AMS) at a given station. These actual precipitation events and their observed precipitation are a result of all precipitation producing processes that occurred during a given storm event. In HMR terms, the resulting observed precipitation represents both the convergence-only component and the orographic component.

The gridded precipitation frequency climatology was produced using gridded mean annual maxima (MAM) grids developed with the Parameter-elevation Regressions on Independent Slopes Model (PRISM). PRISM utilizes geographic information such as elevation, slope, aspect, distance from coast, and terrain weighting for weighting station data at each grid location. Therefore, the use of the precipitation frequency climatology grids is reflective of all precipitation producing processes. The use of the gridded precipitation climatology represents an optimal combination of factors, including representing extreme precipitation events equivalent to the level of rainfall utilized in TVA's storm selection process, and providing the most robust statistics given the period of record used in the development of the precipitation frequency climatologies. Differences in these values between regions of similar topography reflects the variances in other precipitation producing processes, such as access to moisture, seasonality, general synoptic conditions that produce rainfall, and other meteorological parameters, as well as variances in statistical interpolation. The variability between similar topographic regions provided in NRC Table 1 reflects these differences.

National Oceanic and Atmospheric Administration (NOAA) Atlas 14 precipitation frequency climatology is the best available data set to utilize in quantifying the differences in precipitation processes between two locations within the same transposition region. It provides a reproducible and explicitly quantifiable data set. The limitations of the data are known. The processes used to develop the data are known and have been reviewed and accepted. The assumptions involved in applying the data are known and can be quantified. This includes use in highly orographic and non-orographic regions. Non-TVA examples of this process include use in the entire region covered by the Virginia statewide PMP study (Kappel, et al., 2015), the Texas statewide PMP study (Kappel, et al., 2016), and the entire region covered by the Colorado-New Mexico Regional PMP (in progress). Many of the regions are similar to less orographic regions of TVA zones 1-3 and to the regions discussed in NRC Table 1.

The review process of previous and ongoing AWA PMP studies includes representation from the National Weather Service, Corps of Engineers, Bureau of Reclamation, Federal Energy Regulatory Commission, Natural Resource Conservation Service and United States Geological Society, as well as meteorologists on faculty at major universities, private industry meteorologists, and state dam safety regulators. The review boards of these studies have concurred that the OTF process as utilized for TVA is reasonable and acceptable for PMP calculation purposes.

Similarly, the Storm Separation Method (SSM) applied in HMRs 55A, 57, and 59 utilized the 100 year 24-hour precipitation frequency climatology from NOAA Atlas 2 in a similar fashion

to TVA's application. Like TVA, these HMRs applied the process to all locations including non-orographic regions of those studies (e.g., HMR 59 Figure 6.4).

Specific examples of the use of NOAA Atlas 2 precipitation frequency data to all regions for use in calculating the HMR orographic factor (K factor) include the following:

- HMR 59 Section 6.6.1 states: "The K-factor is derived from two relationships: 1) The first involves the one-percent chance (100-year return period) precipitation amount in proximate areas of large and small topographic variation. This relationship is represented by T/C where T is the 100-year, 24-hour return-frequency precipitation."
- HMR 57 applied the NOAA Atlas 2 100-year, 24-hour precipitation to address orographics and determined it was important to maintain a close spatial correlation of maximum index values of total PMP and maximum values of 100-year, 24-hour precipitation (HMR 57 - pg 88).
- In HMR 57, a T/C (total 100 yr precipitation/100 yr convergence component) value less than 1 resulted in some areas. In the Snake River plain, where physiographic features could likely account for the low T/C values, the values were accepted. Values as low as 0.84 to the lee of the Olympic Mountains of Washington where the mountains were believed to disrupt the resupply of boundary-layer moisture were also accepted (HMR 57 - pg 76).
- HMR 56 Section 2.2.3 states: "Topography is known to play an important role in rainfall in the Tennessee River watershed."
- HMR 56 Sections 3.5.2 and 3.5.3 discuss the application of the terrain stimulation effect in smooth and intermediate regions and an additional broad scale orographic factor in the mountainous eastern region. These are some of the additional factors NOAA Atlas 14 climatologies captured as part of the OTF process. The most important aspect is defining appropriate and reasonable transposition limits to place storms within similar regions when considering topographical and meteorological interactions. The assumption is the NOAA Atlas 14 climatologies capture the effects of terrain, upwind barriers, access to moisture, preferred moisture inflow directions, seasonal variation of synoptic meteorological environments, etc. These factors are explicitly captured because the NOAA Atlas 14 climatologies are built from observed precipitation events, which inherently included these factors.
- HMR 56 Figures 67 and 68 show topographically significant terrain throughout TVA zone 1, 2, and 3.

These discussions and examples demonstrate that the OTF represents more than the difference in topographic effects between two locations. The OTF represents the difference in all precipitation processes between two locations, such as access to moisture, seasonality, and synoptic conditions, in addition to topographic effects.

General Orographic Discussion

The orographic component of the topographic effects refers to the influence that terrain has on precipitation production and accumulation, both in-place and upwind/downwind. Orographic effects include many processes; some of the important ones include the following:

- Terrain can help release atmospheric instability by initiating lift (releasing conditional instability through forced ascent), providing extra lift to already rising motions, or producing the opposite effects through descending air. Lifting processes can be triggered by a rise in terrain or upstream blocking terrain (causing downstream convergence). These forced ascent processes result in rising motions, cooling of the air mass, increased saturation, and enhanced precipitation. Forced descent has the opposite effect, attenuating the precipitation producing processes by warming and drying the atmosphere, resulting in a more stable atmosphere and less precipitation.
- Higher terrain receives more of the precipitation than adjacent lower elevations because there is a better chance the precipitation will reach the ground at higher elevations or experience less evaporation before reaching the ground than adjacent lower elevations.
- Orographic effects depend on many factors such as slope, aspect, angle of interaction, width of barrier, height of barrier, moisture advection duration, moisture depth in the atmosphere, atmospheric profile (e.g., the amount of instability), wind speed/direction, the size of the storm, and the combination of these and other factors through space and time.
- For any given storm event, the barrier and upwind topography are constant with changing atmospheric parameters.

There are many orographic processes and interactions related to terrain interactions that are not well understood or quantified. Therefore, observed data (precipitation accumulations) are used as a proxy, where it is assumed that the observed precipitation represents all the precipitation processes associated with a storm event. Given this, it is logical that observed precipitation at a given location represents a combination of all factors that produced the precipitation, including what would have occurred without any terrain influence and what actually occurred because of the terrain influence (if any). The best proxy would be to have thousands of observed events of the storm type being analyzed at any given location and then be able to compare those storm events to a similar number of storm events at another location where the topography and meteorology between the two locations is the same. However, that extensive data set of observed storm events does not exist. Therefore, judgments are made regarding regions that are considered as having the same meteorology and topography and then utilize statistical analyses provided in NOAA Atlas 14 as the comparable data set.

As part of the OTF process, the following is assumed:

- NOAA Atlas 14 precipitation frequency climatology represents all precipitation producing factors that have occurred at a location. This is based on the fact that the NOAA Atlas 14 data is derived from AMS values at individual stations that were the result of an actual storm event. That actual storm event included both the amount of precipitation that would have occurred without topography and the amount of precipitation that occurred because of topography (if any).
- Comparing the precipitation frequency climatology at one point to another will produce a ratio that shows how much more or less efficient the precipitation producing processes are between the two locations.

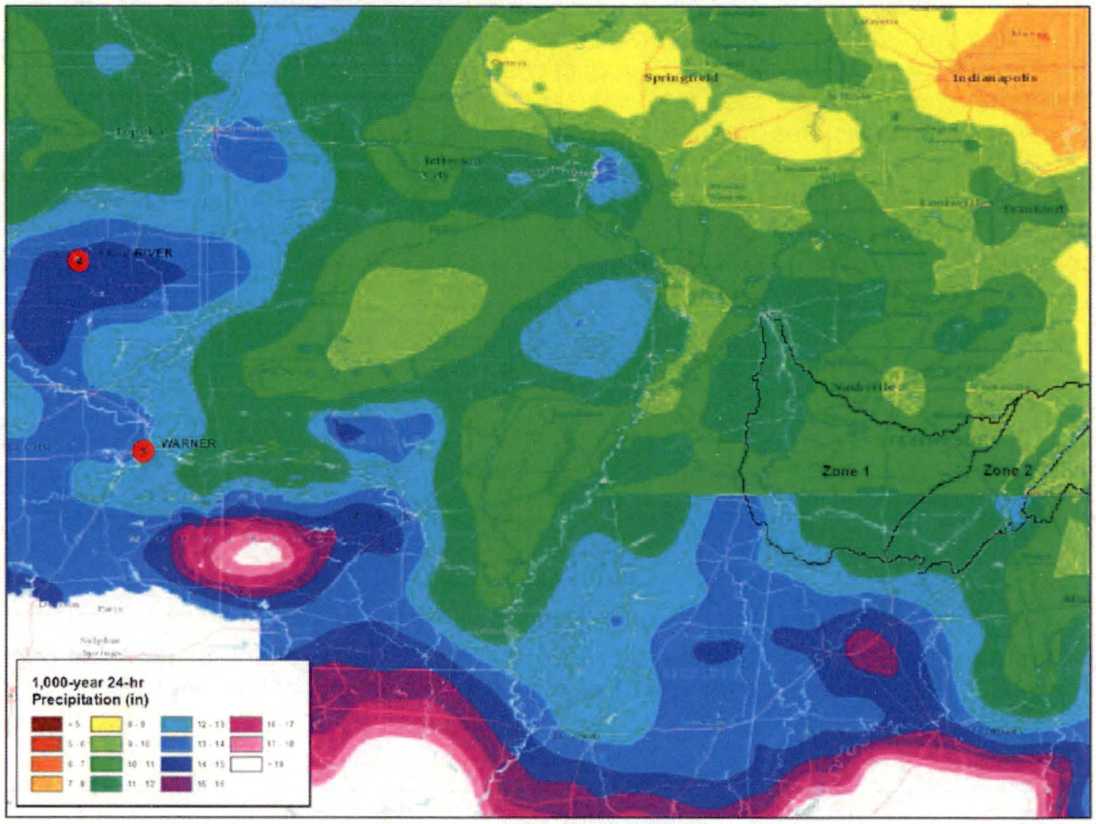
If there is no orographic influence at either location being compared or between the two locations, then the differences should be a function of (1) storm precipitation producing processes in the absence of topography (thermodynamic and dynamic), (2) how much more or less moisture is available from a climatological perspective, and (3) elevation differences at the location or intervening barriers.

Discussion Related to Departure of OTF from 1.00 in Orographically Similar Zones
It would be reasonable to expect a near constant 1.00 over orographically similar zones if the OTF only represented the orographic effect. However, as discussed previously, there are other atmospheric components inherent in the precipitation frequency outputs that are carried through into the OTF. Example 1 and 2 in NRC Table 1 address the OTF reduction exhibited in storms transposed from eastern Kansas and Oklahoma to TVA transposition zone 1, a region of similar orographic characteristics and elevation. The average OTFs are 0.80 and 0.75, respectively. TVA Figure 1 illustrates the spatial pattern of the NOAA Atlas 14 1,000-year 24-hour rainfall over the region.

The climatological precipitation over TVA transposition zone 1 is significantly lower than the storm centers west of the Mississippi River. The meteorological reason for the variation is primarily because the Warner, OK and Fall River, KS storm centers receive their moisture directly from the Gulf of Mexico at a location where air masses originating from the High Plains to the west interact preferably with the low-level jet that is common in the region. These factors combine in this region to produce more efficient thermodynamic contrast, higher instability, and more frequent high-intensity rainfall. In contrast, the frequency of occurrence of the low-level jet is much lower over TVA transposition zone 1 and zone 2 and the thermodynamic contrast in the TVA region is therefore not as extreme from a climatological perspective. Similar types of storms can occur over the Ohio River/Tennessee River Valleys, but are less common and less intense, especially from a frequency of occurrence perspective. The horizontal (reduced to sea level) climatological difference in moisture availability is addressed with the moisture transposition factor (MTF) by comparing the moisture levels associated with the 100-year recurrence interval dew point values. These values are only slightly lower over the TVA location than the storm center locations. The more significant reduction exhibited by the OTF reflects individual storm precipitation producing processes inherent in the precipitation climatology, as opposed to the climatological maximum moisture differences used in the MTF.

Examples 3 and 4 in NRC Table 1 exhibit special cases as described in the TVA PMP report. This issue is discussed in depth in the response to RAI #7 below.

As noted in the above discussions, the OTF captures all the precipitation producing processes, including the effect of topography (orographic effect), if any. The use of this process is relevant in both orographic and non-orographic regions. Therefore, the use of the OTF process is applicable for all locations within the TVA domain and for all storms used in the TVA PMP analysis (except as noted in the RAI #7 response).



TVA Figure 1 - Fall River, KS and Warner, OK storm centers over NOAA Atlas 14 1,000-year 24-hour precipitation

<u>RAI #7</u>: OTF Reduction for Smethport, PA and Simpson, KY

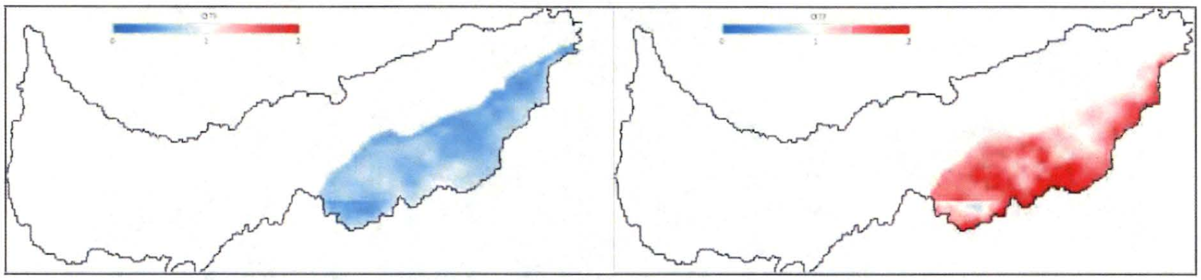
<u>Technical Deficiency</u>: OTF values for two local storms which control PMP estimates were manually rescaled to a maximum of 1.00 (i.e., all original OTF values were divided by the maximum calculated OTF, resulting in widespread reductions and a maximum value of 1.00). This rescaling greatly reduces the Local Storm PMP.

As described in Section 6.1.1.5 of the Topical Report, the OTF values for two local storms (Smethport, PA and Simpson, KY) were rescaled to a maximum of 1.00. Following discussions with the Review Board and the licensee, "it was determined that the factors leading to extreme levels of moisture and instability combined with terrain influences" which produced extreme rainfall at Smethport and Simpson "were similar to what could occur over the eastern foothills and mountainous terrain in the TVA basin."

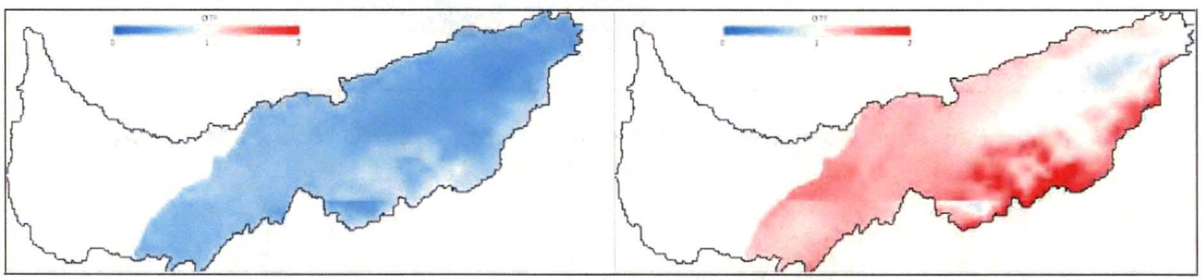
As a result, the licensee decided it was "unreasonable to further adjust the events upward based on the OTF", and "the OTF factors for these events were normalized to a maximum of 1.00."

Staff's review of the data provided by the licensee suggests that the maximum original (i.e., unadjusted) OTF values for the Smethport and Simpson events are 2.15 and 2.09, respectively. In comparison, the average Zone 4 original OTF is 1.39 for Smethport and 1.35 for Simpson. After rescaling the original OTF, the average Zone 4 OTF is reduced to 0.66 for Smethport and 0.65 for Simpson – approximately a 50% reduction. These modifications to the OTF result in a significant reduction in the adjusted DAD values for these storms. In addition, since these storms control PMP estimates, the resultant PMP values are significantly reduced.

NRC Figure 1 provides a comparison of TVA's rescaled OTF values and the original (i.e., unadjusted) OTF values for the Smethport storm. Similarly, NRC Figure 2 provides a comparison of TVA's rescaled OTF values and the original OTF values for the Simpson storm.



NRC Figure 1. Comparison of Smethport OTF using TVA's rescaling approach (left) and original approach (right) for TRANS=1 grids (i.e., transpositionable zone)



NRC Figure 2. Comparison of Simpson OTF using TVA's rescaling approach (left) and original approach (right) for TRANS=1 grids (i.e., transpositionable zone)

Request:

Provide justification for adjusting the Smethport, PA and Simpson, KY OTF values to a maximum of 1.00, and for using significantly reduced OTF values throughout the transpositionable zone.

TVA Response:

OTF Re-scaling Background Discussion

The OTF re-scaling is to preserve the spatial distribution of the adjusted rainfall for these storms over the transposed areas without unreasonably inflating the rainfall beyond the maximized in-place depths. These storm's point rainfall depths were at, or near, the world record curve for their respective critical durations. The intent of the original OTF cap of 1.0 (instead of 1.5) was to prevent exceedance of the world record depths (TVA Figure 2) after storm transposition. The cap of 1.50 was applied to these storms initially, but the resulting precipitation was far greater than the world record rainfall amounts. The intent of the normalization process was to preserve the maximum orographic adjustment for the location(s) with the most orographic impact (with a value of 1.0) while decreasing the values elsewhere so that the spatial pattern of the 100-year Atlas 14 6-hour precipitation climatology (TVA Figure 7) was maintained. Further, rainfall amounts associated with both of these events were highly questionable, because no hourly rainfall accumulation data were recorded at or near the storm center locations. Therefore, hourly incremental rainfall data provided were not based on observed data and instead were derived from surrounding stations with significantly lower total precipitation amounts or inferred from depth-duration curves. This results in having low confidence in the incremental hourly rainfall amounts. In fact, the Simpson, KY July 1939 storm is not used in HMR 51 (no working papers or notes are available as to why this storm was left out of that document). Given these considerations, extensive discussions with the TVA Review Board and AWA evaluations took place regarding the use of both storms.

Although it is possible that the Smethport, PA storm is not transpositionable to any part of the TVA basin, no conclusive data existed to eliminate the storm. However, several data adjustments suggested this possibility. This included anomalously high OTF values and high MTF values. In these types of situations where there is no clear argument for inclusion or exclusion, the TVA choice is made to include the storm. In doing so, adjustment factors and fit with other adjusted storms must be considered, similar to the discussions in HMR 51 Section 3.2.2 and Section 3.2.4. Use of the storm and the storm adjustment values as calculated, resulted in unreasonably high rainfall depths when transposing the storm from north central Pennsylvania to the TVA basin. An MTF value greater than 1.00 results from the fact that the target grid locations in the TVA basin are closer to the moisture source region than the area associated with the storm center in north central Pennsylvania. More significantly, much of the target region has greater precipitation frequency depths due to more frequent extreme rainfalls and enhanced orographic influence. This results in calculated total adjustment factors at the target grid locations that are greatly inflated where the OTF values can exceed 2.00.

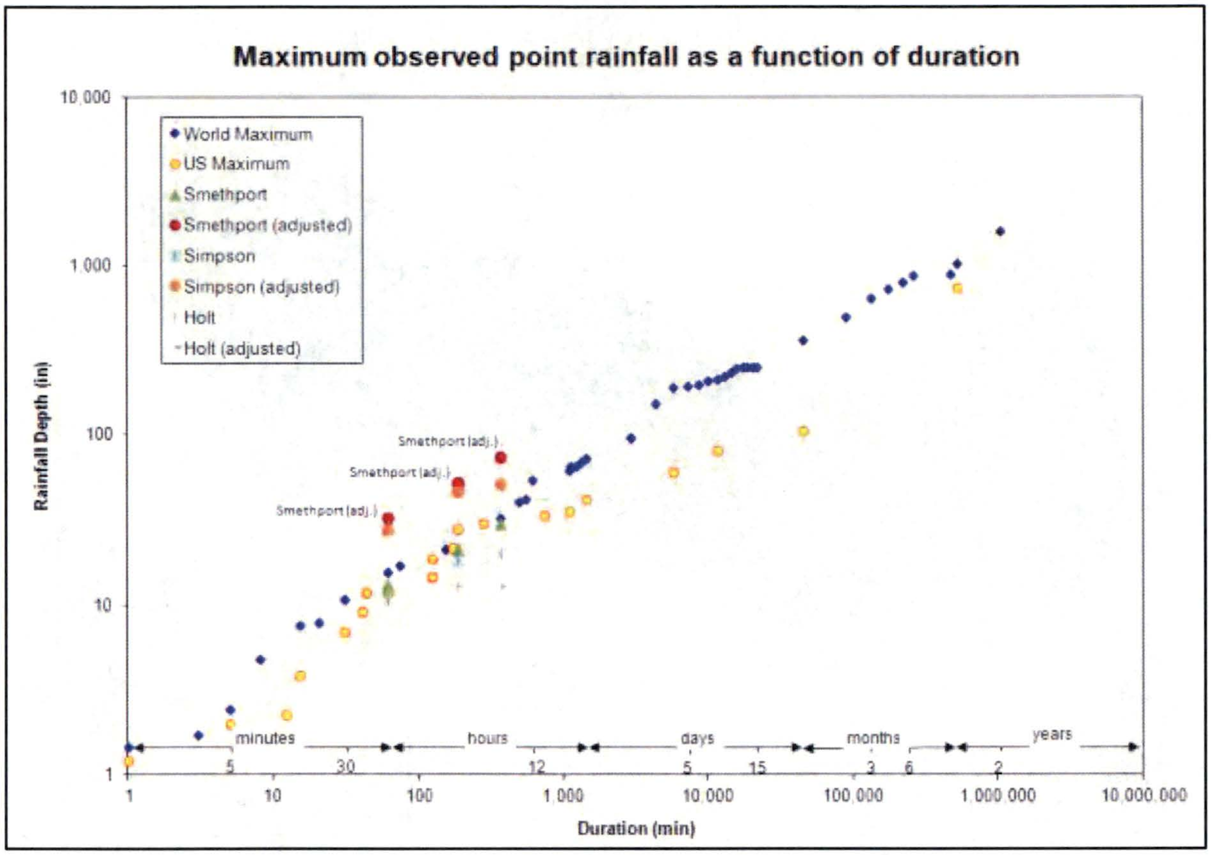
Generally, when OTF values are > 1.50, the storm transposition limits are re-evaluated. This is because OTF values greater than 1.50 or less than 0.50 are an indication that the storm may not be transposable to that location since the physical characteristics may be too different from the source location. However, the storm must still be transposed to these locations. In these cases, the practice is to cap all OTF values at a maximum of 1.50. The Smethport event was a world record at its critical durations. Increasing rainfall by an areal-average MTF of 1.12 and applying an OTF in the traditional manner (much of the target cells would be capped at 1.50) would result in an adjusted rainfall over TVA transposition zone 4 that was much too high and not physically possible. In addition, the 1.50 OTF cap would result in constant spatial fields of PMP depth because almost the entire region is greater than the 1.50 OTF. TVA Figure 2 illustrates the adjusted rainfall depths in relation to the world record rainfall depth-duration curve. In summary, typical application of the OTF and MTF to the Smethport, PA storm over transposition zone 4 created unreasonably high rainfall depths without an appropriate spatial distribution. The Simpson, KY storm transposition resulted in a similar problem, although not to the magnitude of Smethport.

The two most reasonable approaches to these problems were to either remove the storms from the database as not transposable (this was evaluated and discussed internally and in review board meetings) or to adjust the transposition factors so that the resulting rainfall levels were at a more reasonable level. In reality, the transposition limits for these storms should be very limited, but the project decision was to keep the storms and adjust the OTF. This is a more conservative application.

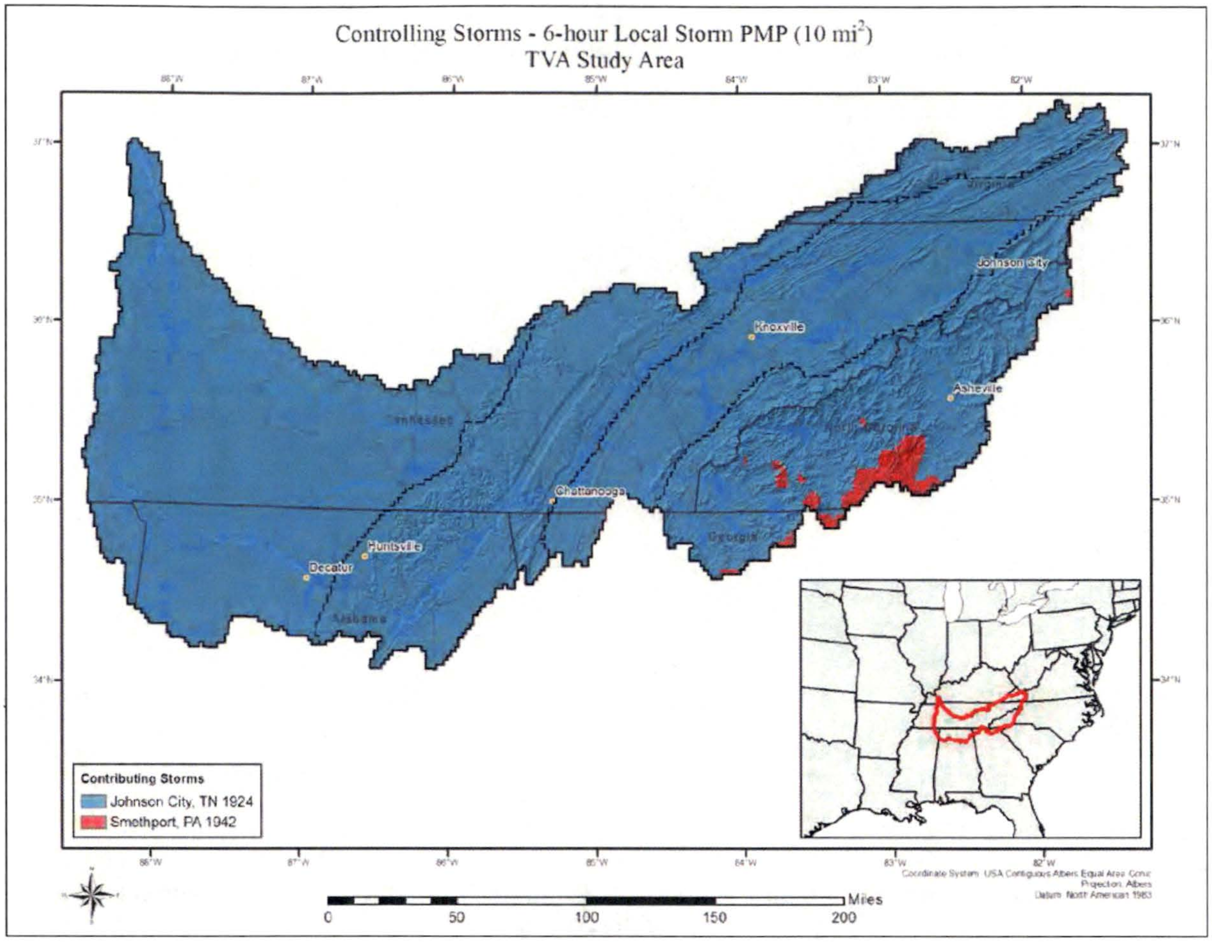
For these storms, the OTF is useful to determine the spatial distribution of gridded PMP over orographic target regions, but cannot be used to provide reasonable adjusted rainfall magnitudes. Thus, it was determined that the OTF should not further increase rainfall beyond the in-place depth. The OTF was re-scaled to a maximum of 1.00, rather than capped at 1.00, to allow the spatial distribution of the precipitation climatology to transfer through the OTF. As a result, the areal-average total adjustment factor (TAF) for Smethport, PA was 0.74, with a maximum of 1.13. For the Simpson, KY event, the areal-average TAF was 0.72, with a maximum of 1.21. Limiting the adjustment for these storms to an increase of 13% and 21%, respectively, was determined to be a reasonable constraint, keeping the adjusted depths to a minimum above the world record curve.

The adjusted transposed rainfall for Smethport was very similar to the transposed rainfall depths for the Johnson City, TN event, a storm that also occurred over the target region (TVA Figures 3 and 4). This storm provided additional confirmation that the Smethport constraints were reasonable. The maximum 6-hour 10-square mile rainfall is 29.3", which is in line with the world point maximum-recorded rainfall curve. Again, assuming the world-record rainfall curve demonstrates a physical upper limit to rainfall accumulation over time, this suggests the adjusted rainfall is reasonable, if not conservative. Furthermore, the ratio of 24-hour 10-square mile PMP to the 100-year 24-hour Atlas 14 precipitation depth was 3.4 for transposition zone 3 and 3.1 for transposition zone 4. These ratios are consistent with previous AWA and HMR PMP studies for orographic regions and provide further evidence that the constraints are reasonable.

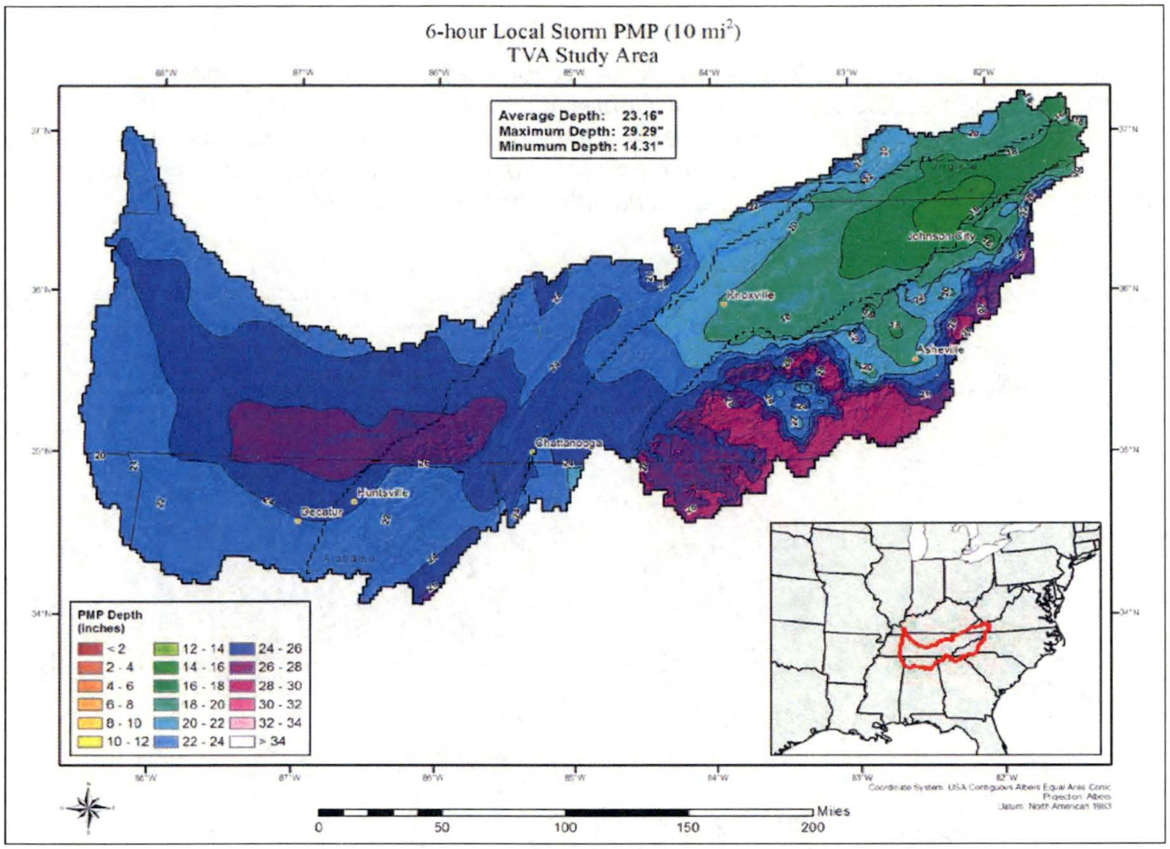
However, after further review and discussion with the NRC staff in regard to this question, TVA has agreed to add further conservatism and revise the OTF determination methodology used in LIP calculations. This methodology change ensures the OTF used in transpositioning local storms to the SQN, BFN and WBN plant sites is not less than 1.0. Note, this change only affects the Simpson, KY storm because the Smethport, PA storm was not transpositioned to the plant sites. Updates to this data set will affect Sections 6.1.1.5 and 6.4.4 of Calculation No. CDQ000002016000041 and will be submitted as Revision 1 to Topical Report TVA-NPG-AWA16 (TVA Calculation CDQ000002016000041).



TVA Figure 2. Smethport, PA and Simpson, KY adjusted rainfall plotted on the world record depth-duration curve



TVA Figure 3. Controlling storms for the 6-hour 10-sqmi PMP. Smethport, PA controls a portion over southern Zone 4



TVA Figure 4. 6-hour 10-square mile PMP resulting from the Johnson City, TN and Smethport, PA adjusted rainfall

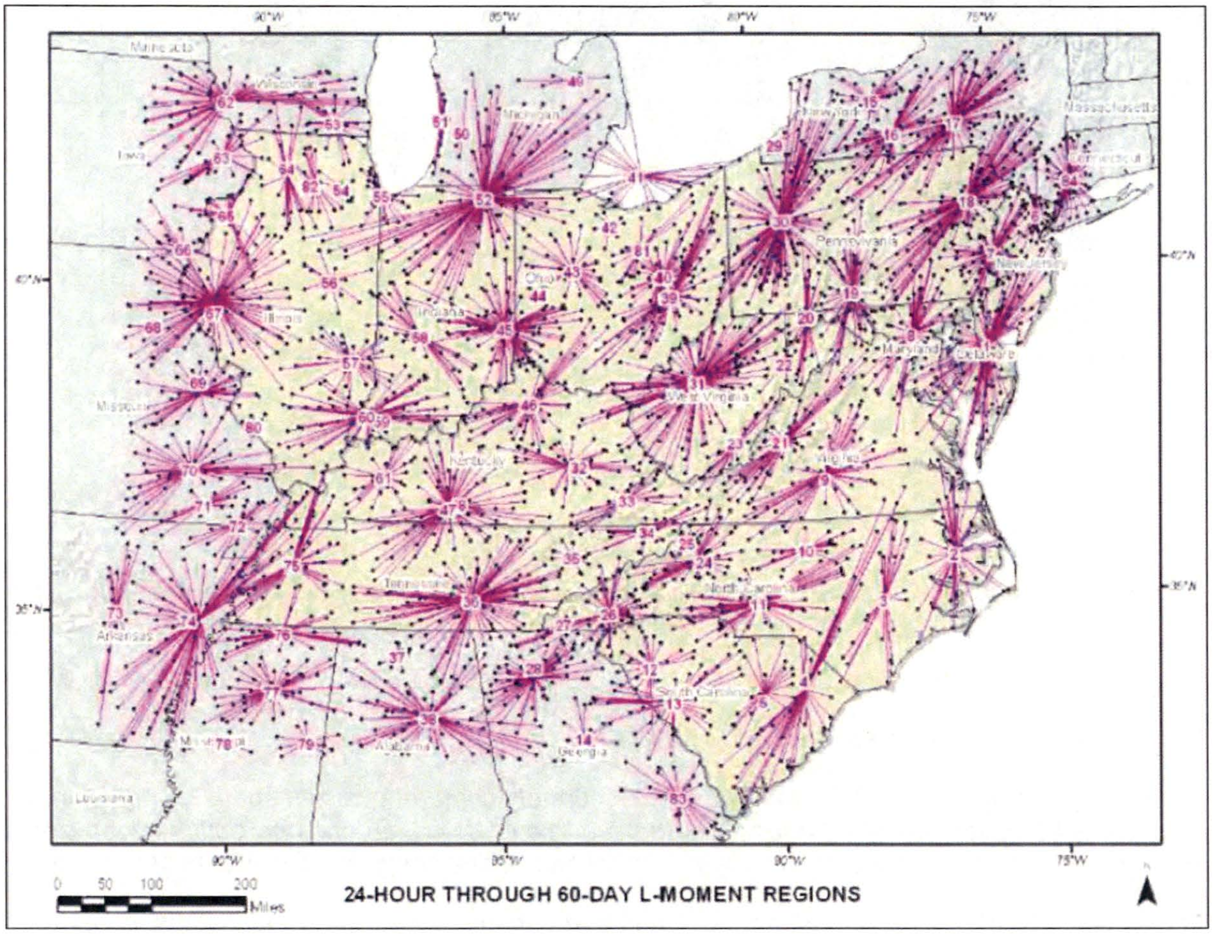
<u>RAI #8</u>: OTF Calculation using NWS Atlas 14

<u>Technical Deficiency</u>: The OTF is intended to accurately capture localized spatial variation in orography. However, the NWS Atlas 14 data used to calculate OTF are inherently regionalized, which poses a concern whether the original intention of developing an OTF was fully captured.

Section 4.5 of the Topical Report states that, in comparison to the topographic adjustments used in the TVA HMR, "the OTF, along with hourly gridded rainfall data from SPAS analyses, is able to evaluate and quantify…variations over a much more refined scale both spatially and temporally." Localized refinement is achieved through use of Atlas 14 precipitation frequency (PF) data, which were developed using L-moment regional frequency analysis.

However, during the development of the PF data, Atlas 14 identified homogeneity zones (i.e., regional groups) for data pooling. Based on Section 4.2.2 of Atlas 14, Volume 2, the regional application of L-moments derives "the shape parameters from all stations in a homogeneous region rather than from each station individually." From Section 4.4 of Atlas 14, Volume 2: "effort was made during the subdivision process to mitigate discrepancies that could be caused by (1) sampling error due to small sample sizes, or (2) regionalization that does not reflect a local situation." NRC Figure 3 shows the 24-h through 60-day regional groupings identified in Atlas 14, Volume 2.

Generally speaking, all precipitation data within a homogeneity zone were first locally normalized, and then pooled together for probabilistic density function fitting. Therefore, it is important to understand that the NWS Atlas 14 values do not only capture the local precipitation features. It is jointly influenced by the local mean (of annual maximum series at each gauge), regional probability density distribution, and final interpolation by PRISM.



NRC Figure 3. Regional groupings for daily data used to prepare NOAA Atlas 14 Volume 2

Section 3.1.4 of the WMO-No. 1045 Manual on Estimation of Probable Maximum Precipitation states: "Precipitation-frequency values represent an equal probability level of rainfall. The values for the rarer recurrence intervals, for example the 50-year or 100-year recurrence interval, are associated with severe weather systems. Therefore, they are better indicators of the geographic variation of PMP than mean seasonal or annual precipitation maps." Thus, staff believes that the specific features of Atlas 14 are important artifacts influencing the OTF and are worth considering. Given that the Atlas 14 method scales station PF data by the mean of the annual maximum series and uses PRISM for base map smoothing, the final rainfall estimates would induce spatial smoothing based on averages rather than rarer recurrence intervals associated with severe weather systems.

OTF Best Fit Linear Trend Method

The licensee used a 6-h precipitation frequency climatology to compute local storm OTF and a 24-h precipitation frequency climatology to compute general and tropical storm OTF. For each short list storm, the OTF calculation approach used for the TVA Topical Report used linear regression to estimate the ratio between precipitation frequency depths for the recurrence interval associated with the storm's maximum point rainfall at either 6-h or 24-h.

OTF 100-year Ratio Method

Other AWA PMP studies have calculated the OTF using the 100-y precipitation frequency ratio rather than the linear regression approach. Since longer recurrence interval estimates may be more representative of PMP-type storms but may lack reliable estimates, AWA has used the 100-year precipitation frequency ratio to compute OTF in other studies (e.g., the PMP study for Texas). NRC staff has also conducted limited sensitivity analysis and finds that the 100-year ratio is more stable than the regression approach. For example, precipitation frequency data provide higher precipitation depths at BFN than at WBN and SQN; however, the linear regression method can result in lower OTF values at BFN than at WBN and SQN.

Request:

a) *Considering Atlas 14's regional features, provide a justification regarding whether the Atlas 14 PF data represent reasonable spatial variation representative of orographic PMP effects or PMP in general.*

b) *Provide a justification for using the best fit linear trend method in lieu of the 100-y ratio method for determining LIP and basin-wide PMP values.*

TVA Response - 8(a):

NOAA Atlas 14 is based on several layers, decisions and assumptions that result in the final PF estimates ultimately used for OTF calculations. A high level of review on regional PF analysis is provided to ensure all aspects of the NOAA Atlas 14 PF estimates are completely understood. A regional frequency analysis approach utilizes L-moments, decreases the uncertainty of rainfall frequency estimates for more rare events and dampens the influence of outlier precipitation amounts from extreme storms as compared to site-specific station analysis. The basis of a regional frequency analysis is that data from sites within a homogeneous region can be pooled to improve the reliability of the magnitude-frequency estimates for all sites (especially the upper tail of the distribution). A homogeneous region may be a geographic area delineated by meteorological climatologies or may be a collection of sites having similar characteristics pertinent to the phenomenon being investigated.

The definition of a homogeneous region is the condition that all sites can be described by one probability distribution having common distribution parameters after the site data are rescaled by their at-site mean. Thus, all sites within a homogeneous region have a common regional magnitude-frequency curve, termed a regional growth curve, that becomes site-specific after scaling by the at-site mean of the data. Quantile estimates at a site are estimated by:

$$Q_i(F)=u_i q(F) \qquad \text{Equation 1}$$

where $Q_i(F)$ is the at-site inverse Cumulative Distribution Function (CDF), u_i is the estimate of the at-site mean, and q(F) is the regional growth curve, regional inverse CDF.

NOAA performed measurements of heterogeneity and station discordancy tests (Hosking and Wallis, 1997) to ensure all sites meet the criteria of a "homogenous region", meaning one probability distribution having common distribution parameters after the site data are rescaled by their at-site mean. Regionalization is captured through the regional growth curve for the specified homogenous region, which is then localized by the at-site scaling factor "MAM". Note, that NOAA HDSC group utilized different regionalization approaches for the various Atlas 14 volumes.

The PRISM group utilized the PRISM model to derive MAM grids based on the MAM of station data. The PRISM group used similar methods to derive 30-year climatologies when creating the MAM grids; predictor variables are listed in TVA Table 1 (NOAA Atlas Table 2). The resulting MAM PRISM grids served as the basis for deriving precipitation frequency estimates at different recurrence intervals using a spatial interpolation procedure called the Cascade, Residual Add- Back (CRAB) derivation procedure. The level of smoothing applied in orographic areas in NOAA Atlas 2 was "LIGHT" as described below. Additional text and TVA Figure 5 from NOAA Atlas 14 are below and provide details on the amount of smoothing applied to the final PF estimates.

TVA Table 1. PRISM predictors used to derive MAM grids (From NOAA Atlas 14 v2)

Table 2. Values of relevant PRISM parameters for modeling of 1- and 24-hour index flood statistics for the ORB (Ohio River Basin). See Daly et al. (2002) for details on PRISM parameters.

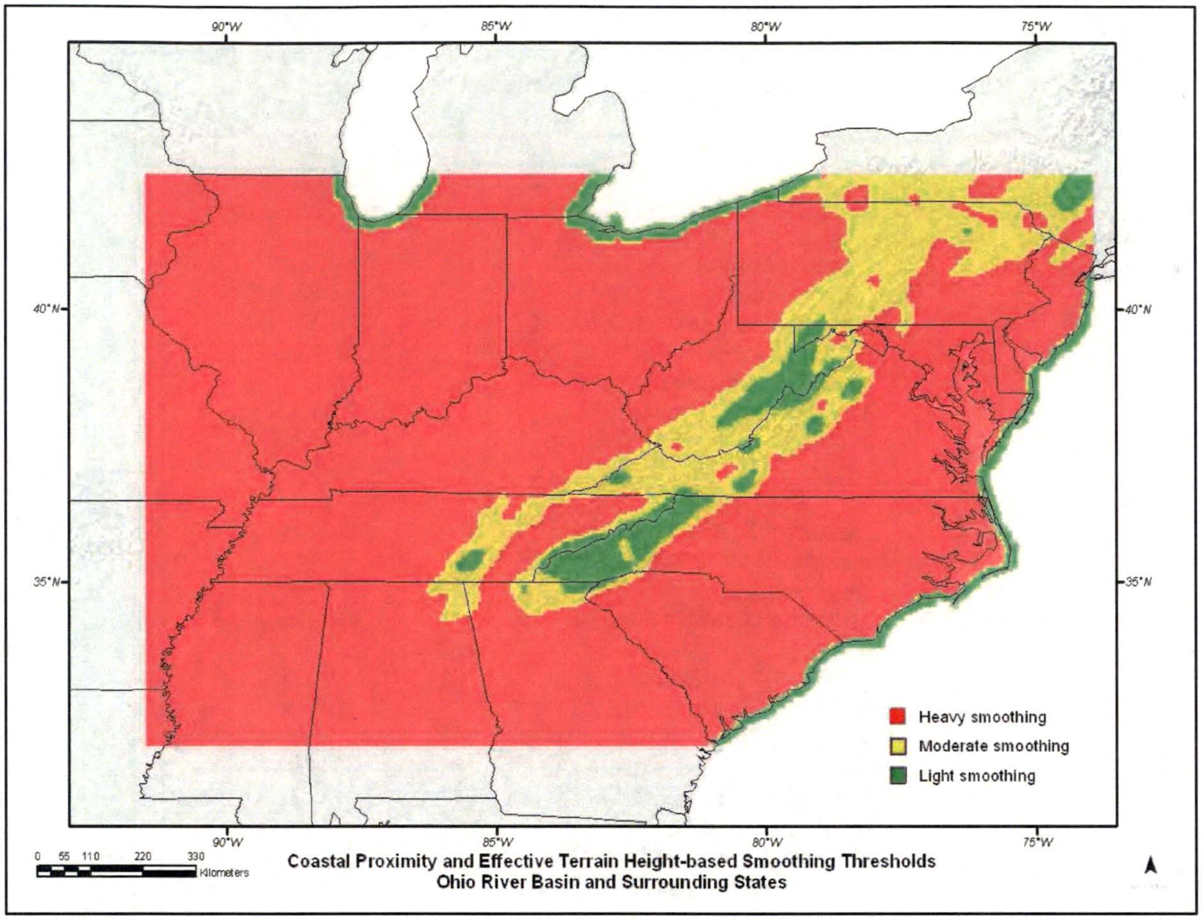
Name	Description	1-hour/24-hour Values
Regression Function		
R	Radius of influence	60/70 km*
s_f	Minimum number of on-facet stations desired in regression	2/12 stations*
s_t	Minimum number of total stations desired in regression	20/20 stations*
β_{1m}	Minimum valid regression slope	0.6/1.2⁺
β_{1x}	Maximum valid regression slope	30.0/30.0⁺
β_{1d}	Default valid regression slope	3.5/5.9⁺
Distance Weighting		
A	Distance weighting exponent	2.0/2.0
F_d	Importance factor for distance weighting	0.5/0.5
D_m	Minimum allowable distance	50/50 km
MAP Weighting**		
B	MAP weighting exponent	1.0/1.0
F_z	Importance factor for MAP weighting	0.5/0.5
Δz_m	Minimum station-grid cell MAP difference below which MAP weighting is maximum	50/50%
Δz_x	Maximum station-grid cell MAP difference above which MAP weight is zero	500/500%
Facet Weighting		
C	Facet weighting exponent	0.5/0.5 ‡
g_m	Minimum inter-cell elevation gradient, below which a cell is flat	1/1 m/cell
λ_x	Maximum DEM filtering wavelength for topographic facet determination	80/80 km
Coastal Proximity Weighting		
v	Coastal proximity weighting exponent	1.0/1.0‡

* Optimized with cross-validation statistics (see Table 4).

⁺ Slopes are expressed in units that are normalized by the average observed value of the precipitation in the regression data set for the target cell. Units here are 1/[sqrt(MAP(mm))*1000].

** Normally referred to as elevation weighting

‡ Maximum value; actual value varied dynamically by the model.



TVA Figure 5. A map of areas receiving different degrees of spatial smoothing based on PRISM's effective terrain height and coastal proximity grids from (NOAA Atlas 14 v2 Figure 4.8.4)

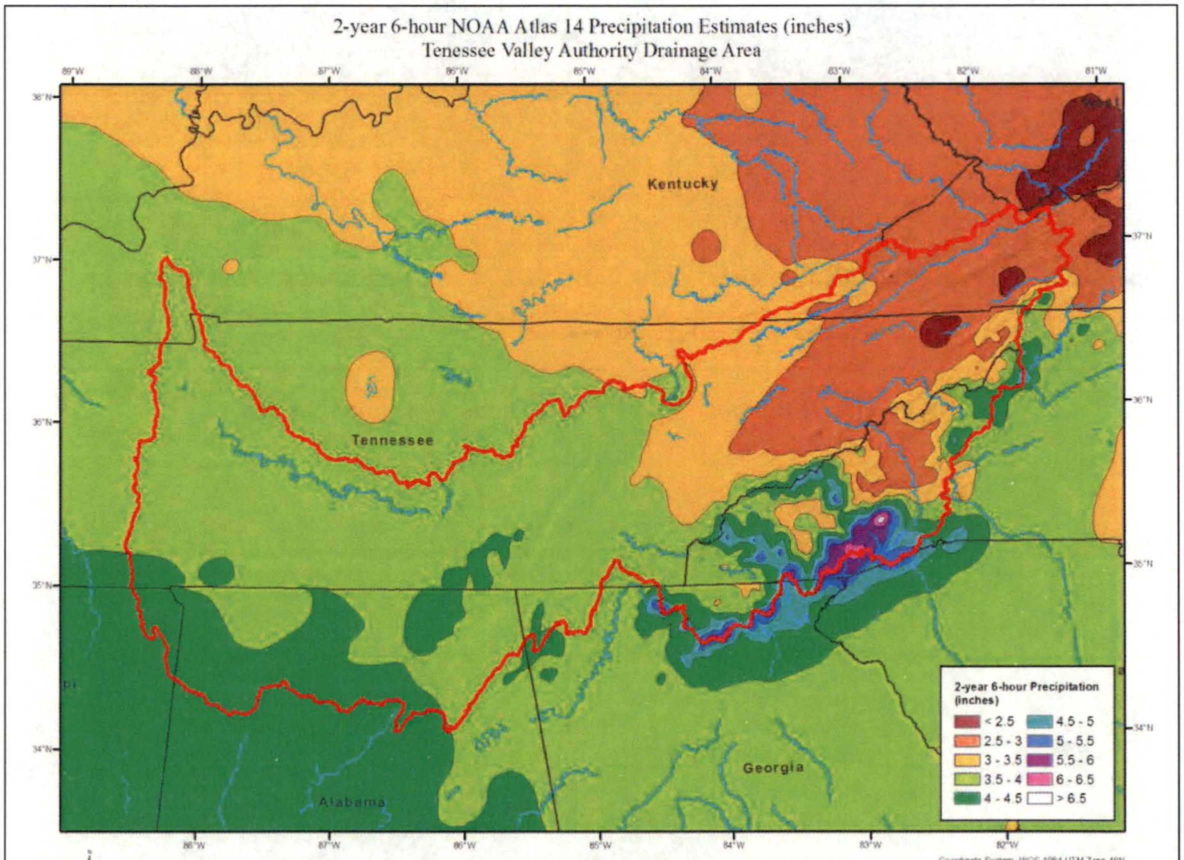
1. HEAVY: Flat areas were determined if effective terrain height is less than 100 m (328 ft), and then a 17x17 grid cell (approximately 15 miles by 15 miles), center-weighted filter was used at the longer durations and a 25x25 grid cell (approximately 25 miles by 25 miles) filter at the shorter (<24-hour) durations. The shorter durations were subjected to greater smoothing because the lower station density was prone to cause unnatural variability.

2. MODERATE: Moderately complex terrain areas were determined if effective terrain height was greater than 100 meters (328 feet) and less than 200 meters (656 feet), and then a 11x11 grid cell (approximately 5.5 miles x 5.5 miles), center weighted filter was used for all durations.

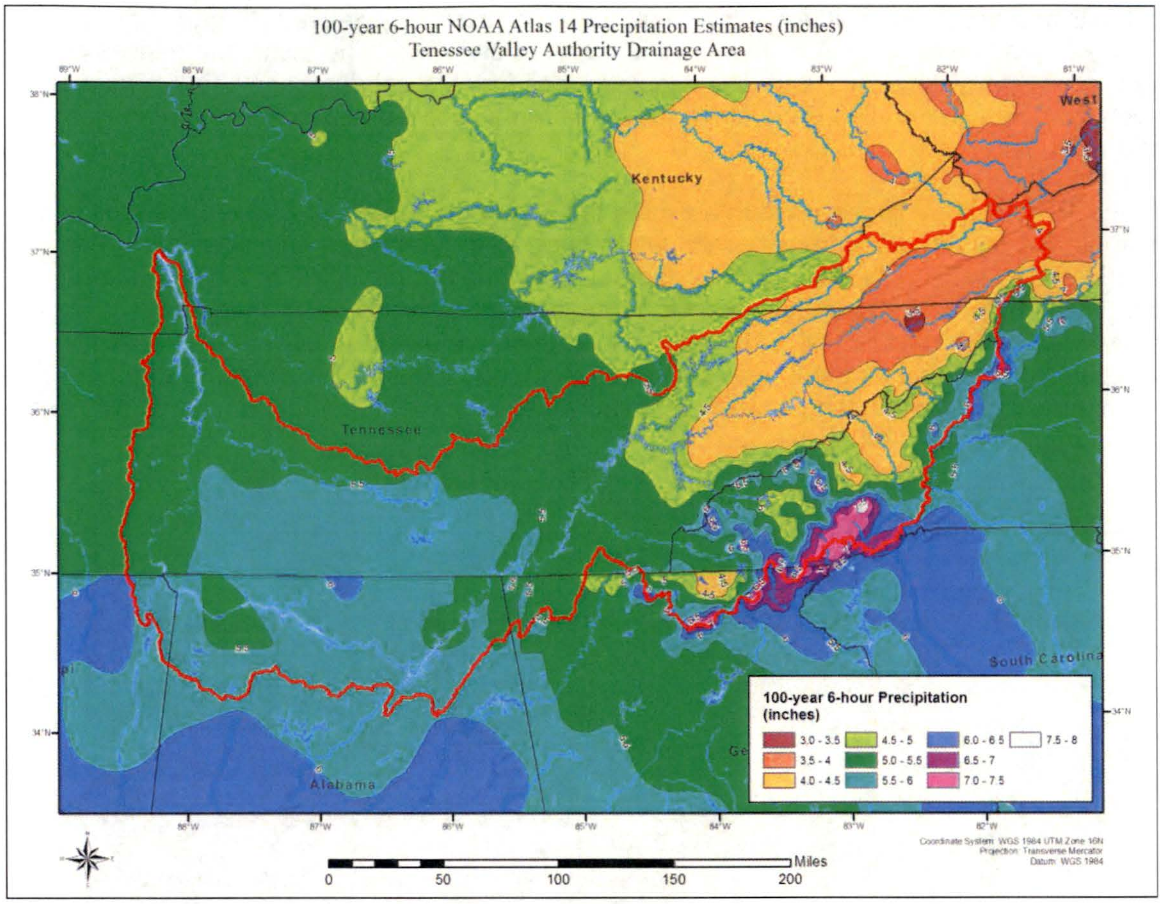
3. LIGHT: Complex terrain areas and coastlines were determined if effective terrain height was greater than 200 meters (656 feet) or if the coastal proximity grid (a grid of values indicating distance from coast) was <=5, and then no filter was used at this stage. However, light smoothing was conducted during the next stage.

The CRAB process used in NOAA Atlas 14 v2 uses the previously derived PF grid to derive the next PF grid in a cascading fashion. From NOAA Atlas 14 v2, "The technique derives grids along the frequency dimension with quantile estimates for different durations being separately interpolated. Hence, duration-dependent spatial patterns evolve independently of other durations."

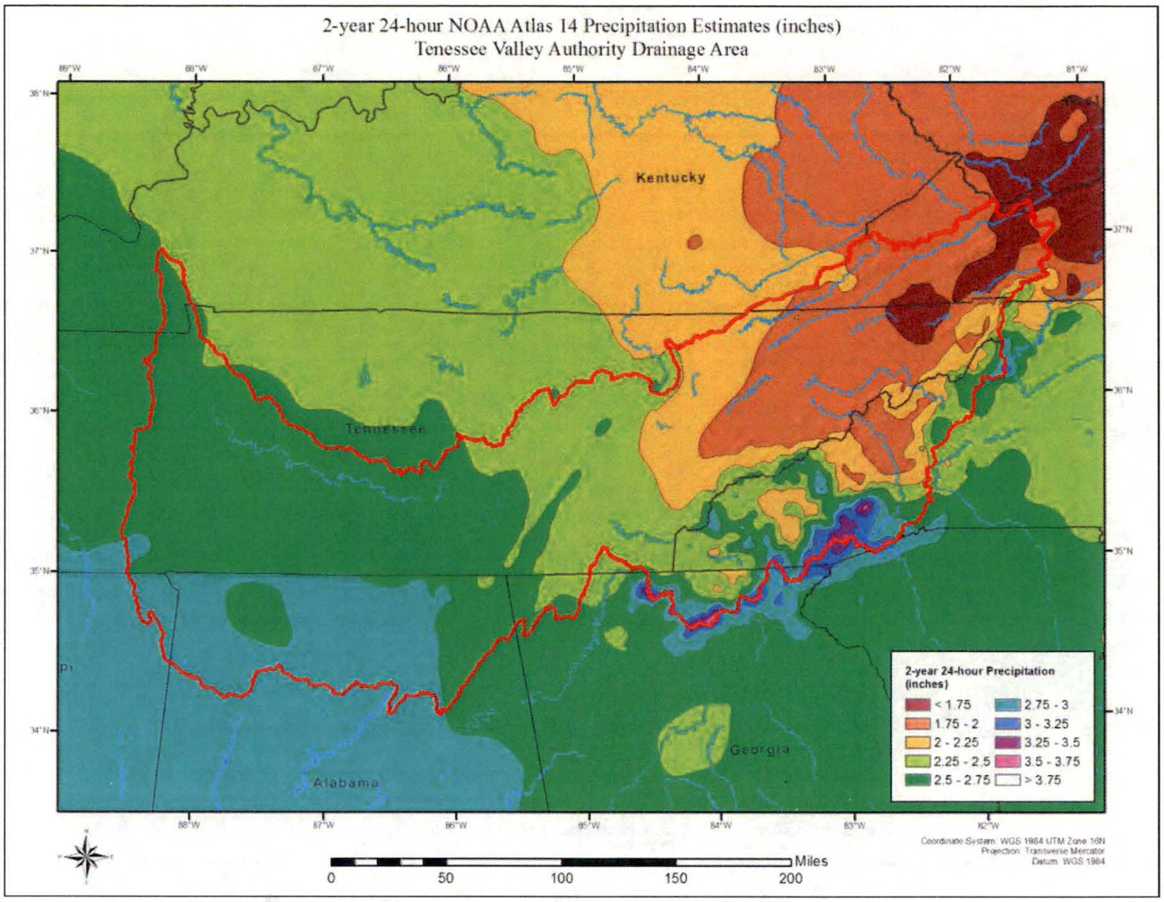
The initial PRISM MAM grid is used to estimate the 2 year grid, the final 2 year grids are used to estimate the 5 year grid, and this continues through all frequencies. A comparison of the 2-year PF (analogous to the MAM grid) to the 100 year grid are provided for the 6 hour and 24 hour (TVA Figures 6 through 9). For each frequency and duration, the grids were normalized to the highest PF value; the normalized grids are used to illustrate the variability in the spatial distribution for the 2-year and 100-year frequencies (TVA Figures 10 through 13). These figures illustrate that the variability of a more frequent event (2 year) is not that different from a more rare event (100 year).



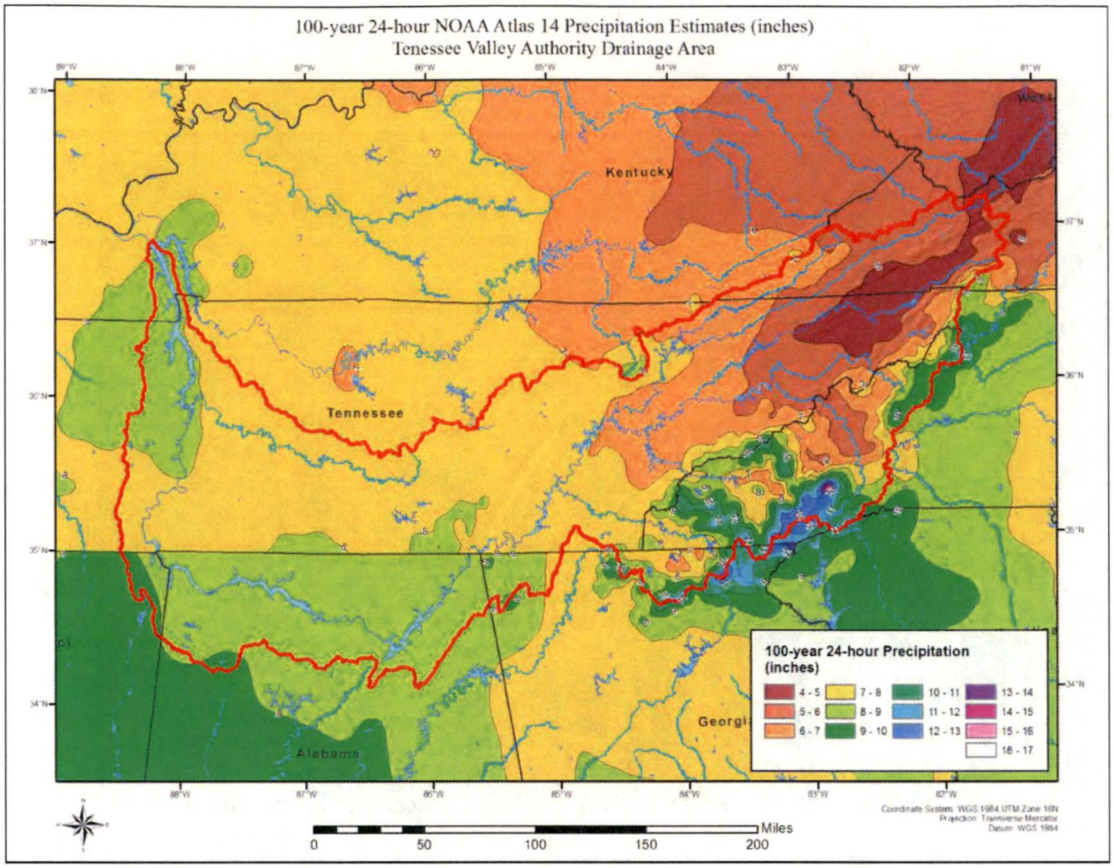
TVA Figure 6. 2-year 6-hour NOAA Atlas 14 spatial pattern



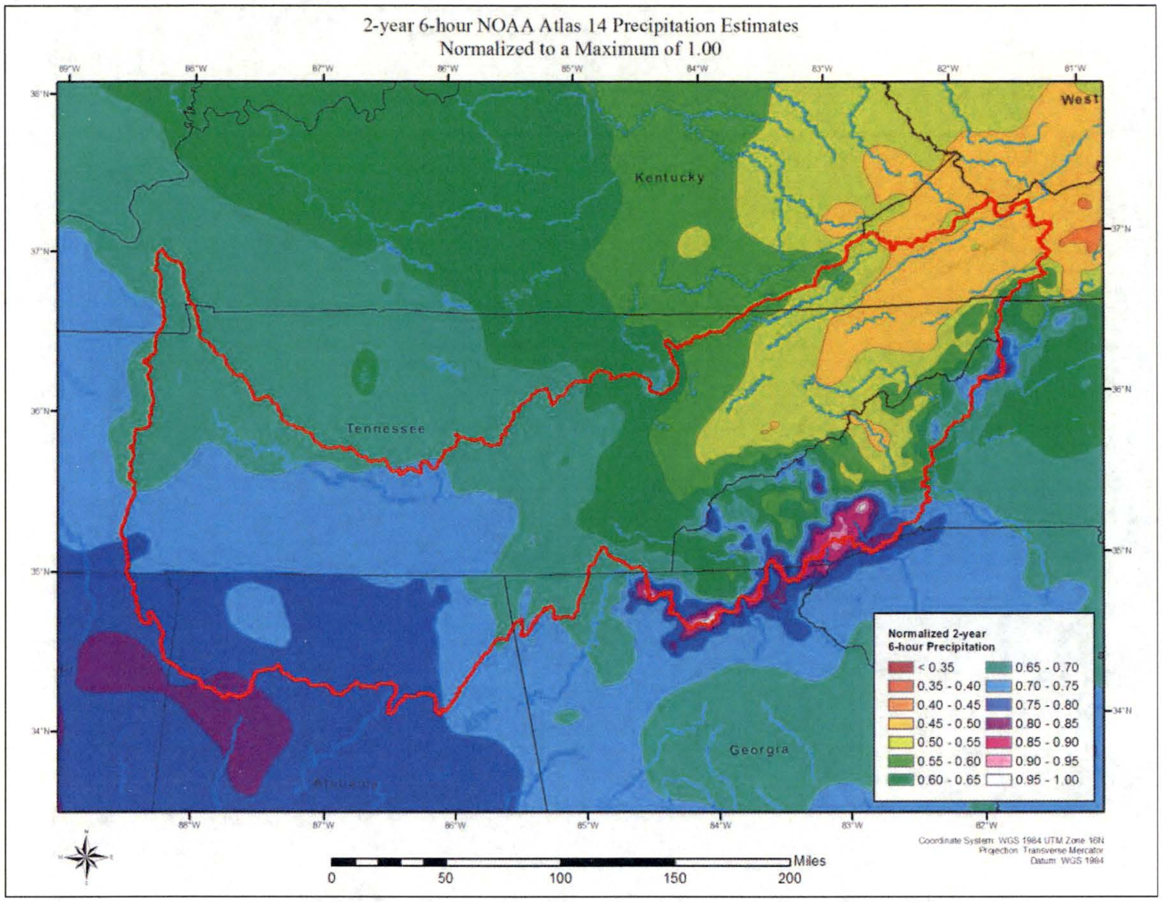
TVA Figure 7. 100-year 6-hour NOAA Atlas 14 spatial pattern



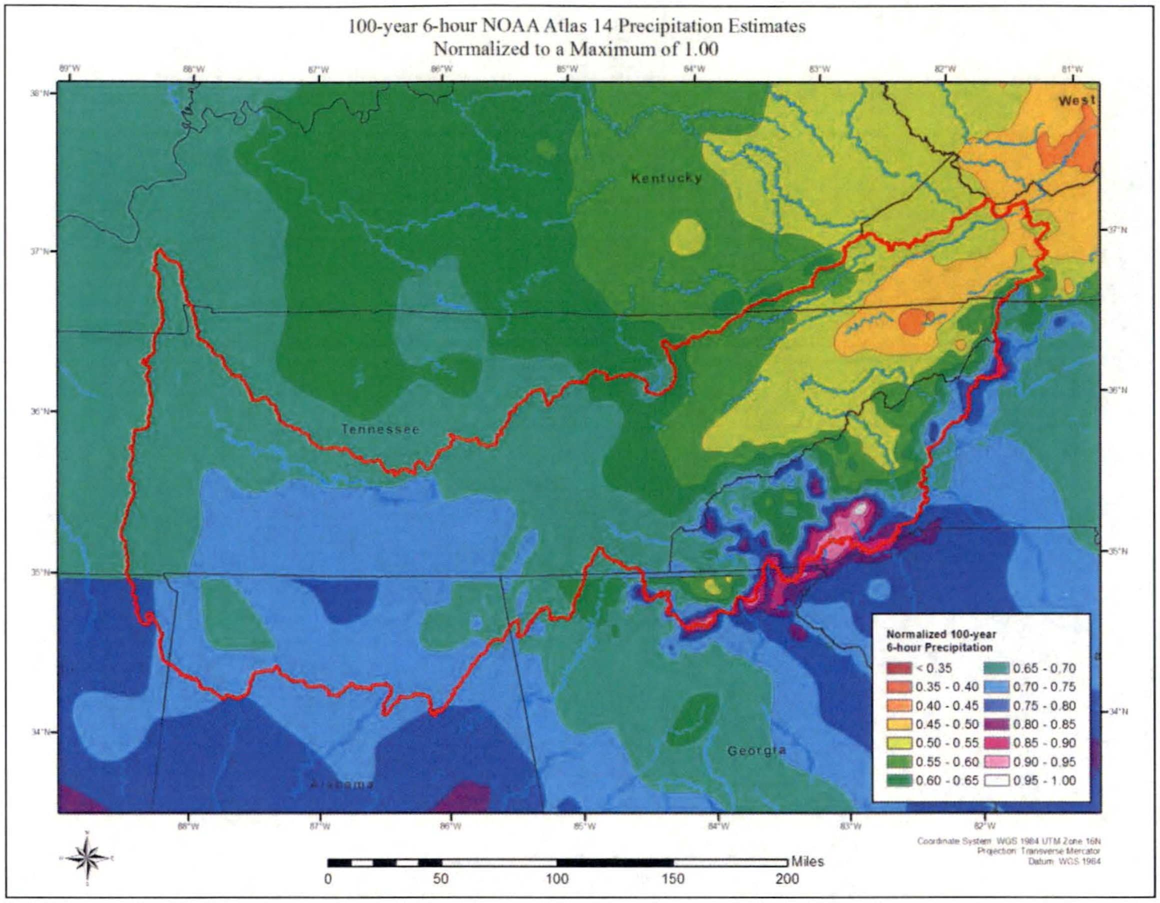
TVA Figure 8. 2-year 24-hour NOAA Atlas 14 spatial pattern



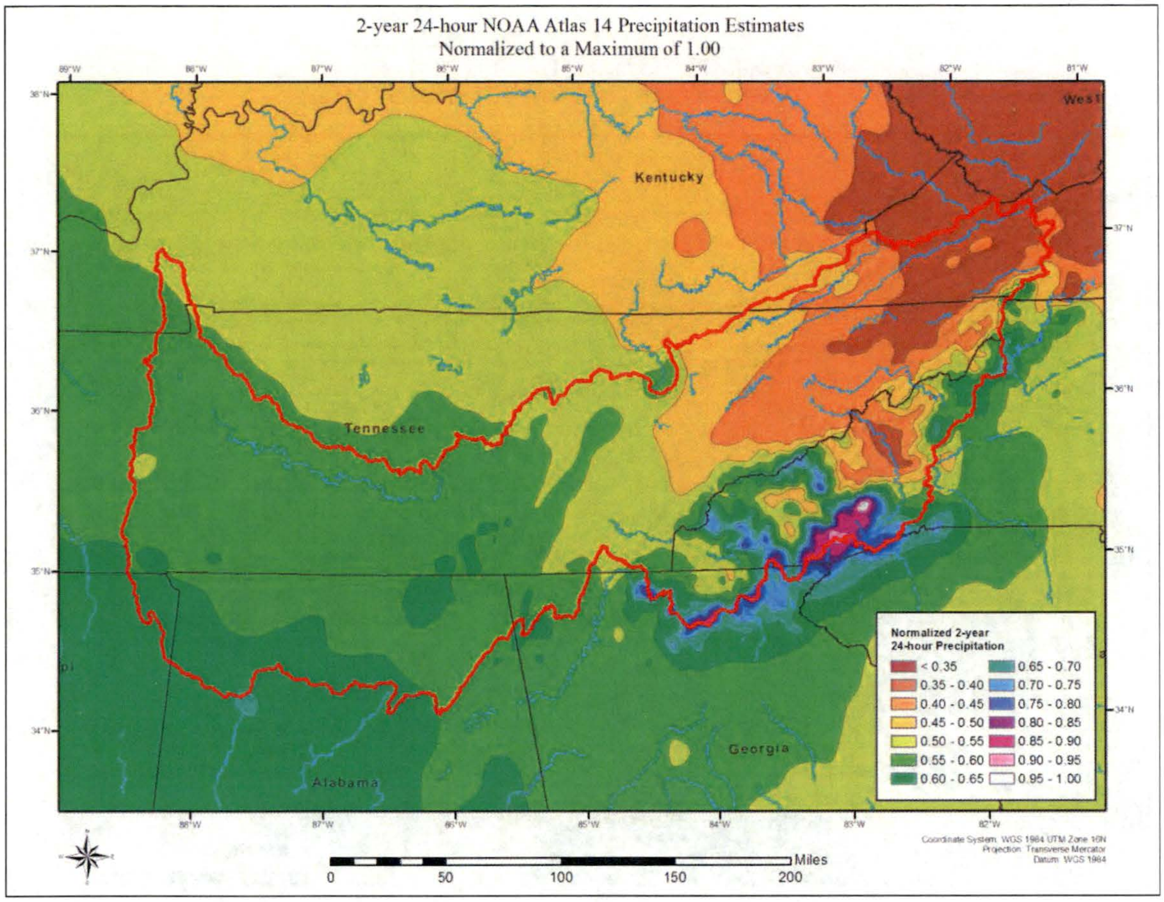
TVA Figure 9. 100-year 24-hour NOAA Atlas 14 spatial pattern



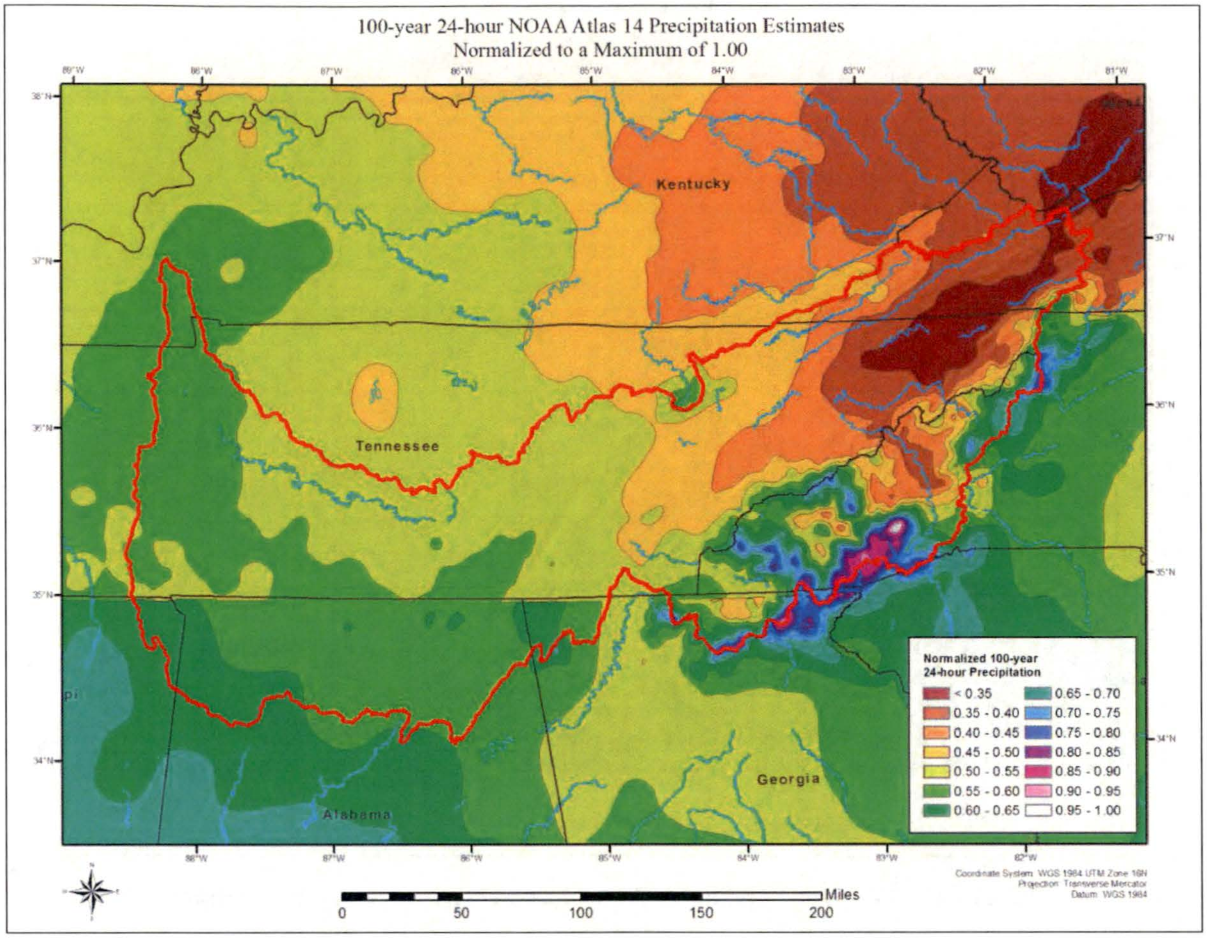
TVA Figure 10. 2-year 6-hour NOAA Atlas 14 Normalized spatial pattern



TVA Figure 11. 100-year 6-hour NOAA Atlas 14 Normalized spatial pattern



TVA Figure 12. 2-year 24-hour NOAA Atlas 14 Normalized spatial pattern



TVA Figure 13. 100-year 24-hour NOAA Atlas 14 Normalized spatial pattern

In summary, the NOAA Atlas 14 PF data provide reasonable spatial variation representative of orographic PMP because:

1. A regional approach decreases the uncertainty of rainfall frequency estimates for more rare events (upper end of distribution tail), trading space for time.
2. At-site mean or MAM is used to capture local rainfall influence, while utilizing regional distribution to attain better estimates at more rare frequencies.
3. PRISM MAM development, spatial interpolation, and smoothing provide realistic representation of spatial precipitation patterns. MAM grid is based on Mean Annual Precipitation (MAP) and other climate parameters.
4. The concern of "spatial smoothing of averages rather than rarer events" is not an issue as NOAA Atlas 14 states "duration-dependent spatial patterns evolve independently of other durations" which is evident by looking at TVA Figures 6 through 9.
5. As compared to NOAA Technical Papers 40 and 49, the regional approach (vs. site- specific) and spatial interpolation methods (PRISM and CRAB method vs. iso-contours), the NOAA Atlas 14 datasets provide a more realistic representation of orographic precipitation and the spatial distribution.

TVA Response - 8(b):

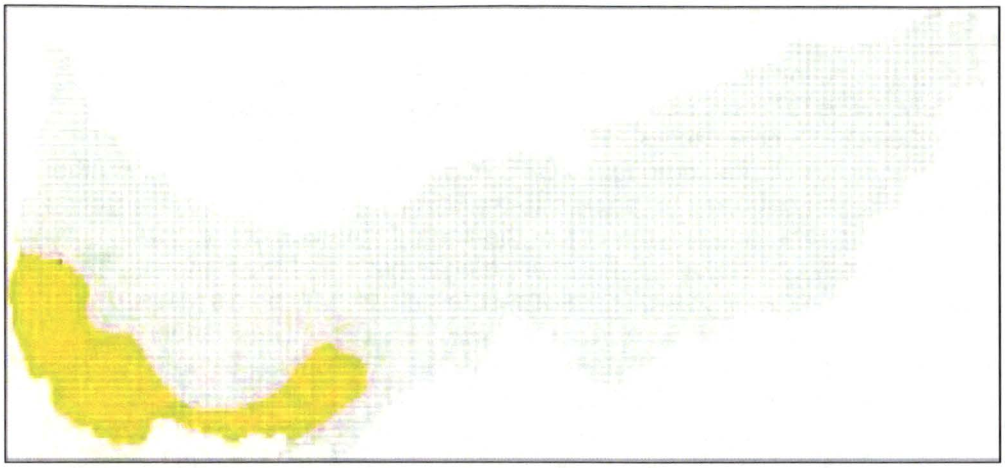
After further review and discussion with the NRC staff in regard to this question, TVA has agreed to conservatively revise OTF determination methodology used in Calculation No. CDQ000002016000041 LIP calculations. For this aspect, TVA will utilize the 6-hour 100-year precipitation frequency climatology from NOAA Atlas 14 to adjust storms during the transposition process. This approach will be applied to the storms moved to the SQN, BFN and WBN plant sites. This update replaces the use of the linear fit method of the NOAA Atlas 14 precipitation frequency climatology. This change does not affect the Simpson, KY storm or the Smethport, PA storm as those OTF values were held to 1.00 as discussed in response to RAI #7. Updates to this data set will affect Sections 6.4 of Calculation No. CDQ000002016000041 and will be submitted as Revision 1 to Topical Report TVA-NPG-AWA16 (TVA Calculation CDQ000002016000041). Note, that TVA also performed sensitivity of using the 100-year only data versus the linear fit method in all other regions of the TVA basin. Differences between using the 100-year only values and the best fit linear trend are minimal for the TVA basin and within the margin of error associated with the uncertainty in the overall PMP development. Therefore, implementation as currently applied is acceptable with the exception noted above.

RAI #9: OTF Calculation Issues

Technical Deficiency: Potential issues with the OTF calculations in certain regions were identified by staff and require clarification.

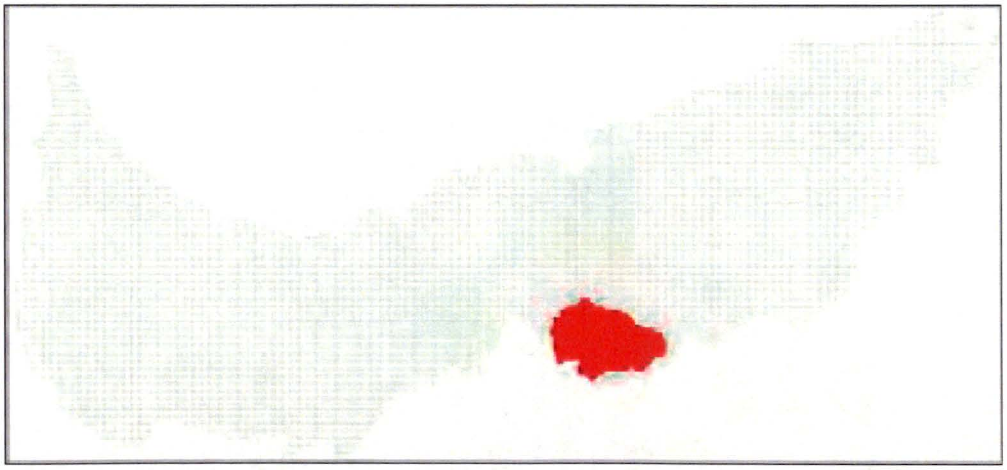
Staff's review of the Total Adjustment Factor (TAF) Excel files provided in response to RAI #1 revealed some anomalies in how the OTF was calculated. For a select set of grid cells, the OTF was calculated using an absolute cell value in the Excel spreadsheet rather than using the OTF regression-based formula used in other cells. Visualization of the areas using the absolute cell reference value is provided in NRC Figure 4 (for general and tropical storms) and NRC Figure 5 (for local storms).

NRC Figure 4: Grid cells for which OTF calculation used an absolute cell reference value for General & Tropical storms (the red grid cell indicates the location of the grid cell used for assigning an OTF value for all yellow colored grid cells)



NRC Figure 5: Grid cells (in yellow) for which OTF calculation used an absolute cell reference value for Local storms (the red grid cell indicates the location of the grid cell used for assigning an OTF value for all yellow colored grid cells)

In addition, staff compared the Excel-based OTF values from the RAI #1 response and the GIS-based OTF values from RAI #3. The comparison revealed a discrepancy in calculated OTF values for local storms which was confined to a region of the southern Appalachians. Visualization of the areas affected by this discrepancy is provided in NRC Figure 6 .



NRC Figure 6: Grid cells (in red) for which OTF differs between RAI #1 & RAI #3 for Local storms

Request:

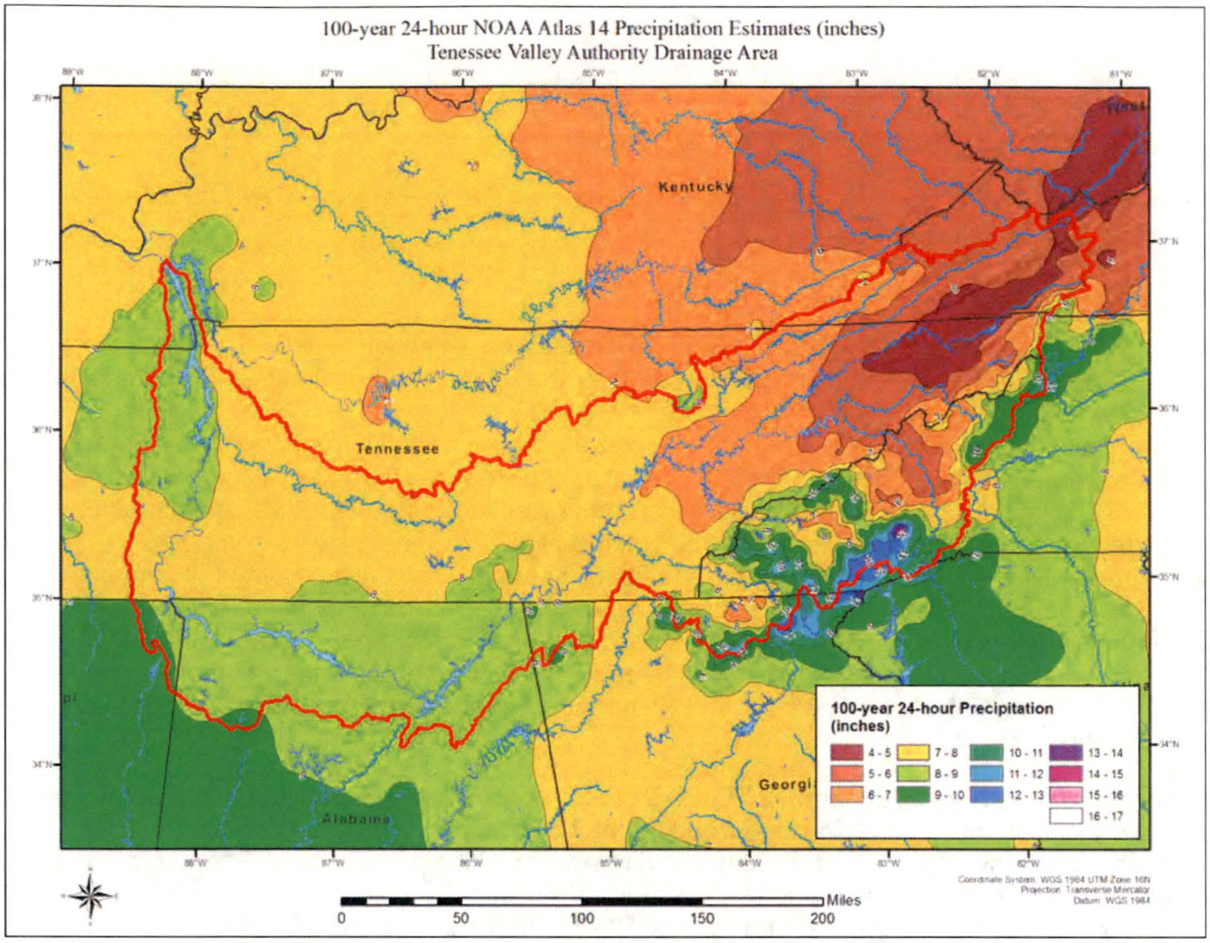
a) *Provide an explanation for why the OTF was calculated using an absolute cell reference value for the grid cells identified in NRC Figure 4 and NRC Figure 5 rather than using the OTF regression-based formula used for the other cells.*

b) *Provide an explanation for why the OTF values provided in RAI #1 and RAI #3 differ, as illustrated in NRC Figure 6.*

TVA Response - 9(a):

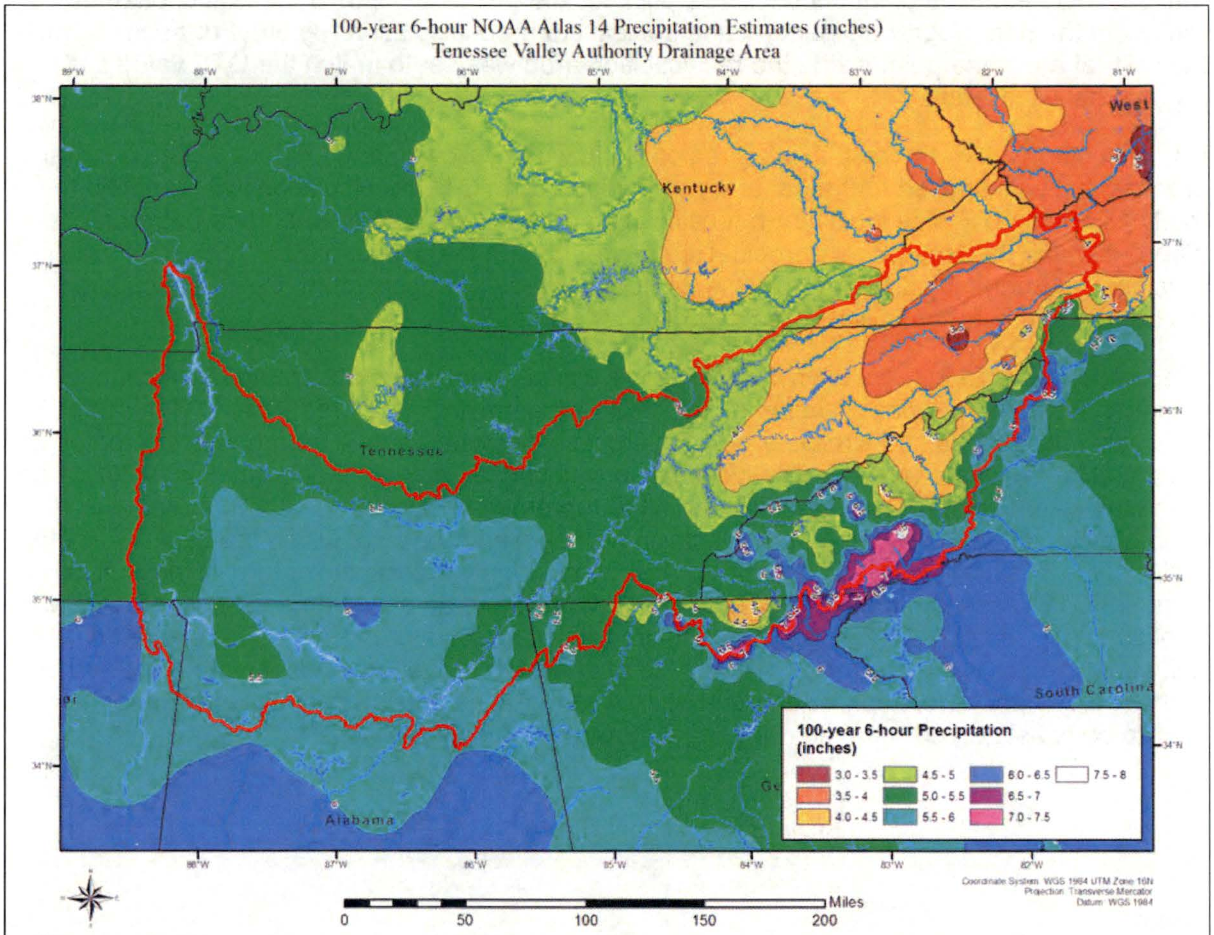
The primary reason for applying a constant OTF based on an absolute cell reference rather than using the OTF regression-based formula over the regions highlighted in TVA Figures 14 and 15 was to address a significant discontinuity in OTF values for 35° N latitude. This discontinuity is a direct result of boundary discrepancies between NOAA Atlas 14 Volume 2, which covers the project area north of 35° latitude, and Volume 9, which covers the area south of 35° latitude. The boundary issues are briefly acknowledged in Atlas 14 Volume 9: "Precipitation frequency estimates for each volume of NOAA Atlas 14 were computed independently using all available data at the time. Some discrepancies between volumes at project boundaries are inevitable and they will generally be more pronounced for rarer frequencies" (Perica, et al., 2013, pg. 4). A secondary reason for applying the constant OTF was to smooth out "bubbles" that occurred over the non-orographic western portion of the project area, primarily south of 35° N, that do not necessarily reflect orography, terrain features, or elevation.

General storm and tropical storm PMP utilize the 24-hour Atlas 14 precipitation frequency grids for OTF calculations. At the 24-hour duration, the boundary issue is most prevalent over northeast Mississippi/northwest Alabama and northeast Alabama/northwest Georgia, as shown in TVA Figure 14. For general and tropical storm PMP, the discontinuity is less of a concern than local storm PMP as general and tropical PMP tends to control the PMF for larger basins. The discontinuity tends to dissolve through the basin average over very large basins.



TVA Figure 14. 24-hour 100-year precipitation illustrating discontinuity between volumes for 35° N

Local storm PMP utilizes the 6-hour Atlas 14 precipitation frequency grids for OTF calculations. At the 6-hour duration, the boundary issue exists along the 35° N state boundaries similarly to the 24-hour duration. Furthermore, there is also a significant discontinuity over the Tennessee/North Carolina/Central Georgia state border. The depth of rainfall over the Hiwassee River drainage basin south of 35°N (Atlas 14 Volume 9) is significantly less than north of 35°N (Volume 2), as shown in TVA Figure 15.



TVA Figure 15. 6-hour 100-year precipitation illustrating discontinuity between volumes for 35° N

The western portion of the project area is non-orographic and predominantly lacking terrain features that could influence rainfall. Ideally there would be very little variation in the precipitation frequency estimates used to determine the OTF in this region. To correct for the significant variation occurring on either side of 35°N, a decision was made to recalculate the OTF over the 35°N region using a constant OTF from a representative point chosen in western Tennessee. This process was employed to remove the most significant portion of the OTF discontinuity resulting from the Atlas 14 boundary issues. Secondarily, the recalculation would smooth out any variations in the OTF over this non-orographic region that might occur from variations in the underlying Atlas 14 datasets.

There are two areas of subjectivity involved in the recalculation process; defining the region to be recalculated to a constant OTF, and selecting an absolute cell reference as a representative location from which to take the OTF to assign to the recalculation area rather than using normal OTF regression-based formula. For general and tropical storm PMP, the recalculated region is shown in yellow in NRC Figure 4. The region was manually delineated in a manner that encompassed the problem area and followed the isopleth of the OTF spatial pattern consistent with the representative point chosen. The point location of 35.2° N, 87.3° W was chosen to represent the non-orographic general and tropical storm recalculation region. For each storm, the OTF at each grid point inside the recalculation area was set to match the OTF value at the representative location.

For local storm PMP, the recalculated region is shown in yellow in NRC Figure 5. The general process that was applied to the general and tropical storm OTF recalculations was applied to the local storm OTF. The local storm recalculation area covers a somewhat different area and different shape than the general/tropical storm area due to the spatial pattern of the 6-hour precipitation frequency differing from the 24-hour patterns. For local storm OTF recalculation, the point of representation is located at 35.475° N, -88.175° W.

In addition, the area in red shown in NRC Figure 6 was reevaluated due to the significant disparity between the Atlas 14 volumes over the Hiwassee drainage area. The OTF for this area was recalculated in a similar way to the process described above for the western region of the project area where a representative location was chosen and each grid point within the area of interest (AOI) was assigned the OTF from the representative location. For this area, the absolute cell reference representative location was chosen as a point within the basin near the outlet of the basin at 35.15° N, -84.45° W. Due to the highly orographic nature of the AOI, a constant OTF reassignment alone is not sufficient; therefore an elevation adjustment factor was applied to the constant OTF to estimate the orographic effect over the AOI. The elevation adjustment factor was determined as the ratio of elevation at the target location to the elevation at the representative location, which is 1,624'. A sixth root is applied to sufficiently mute the ratio to be consistent with the surrounding OTF values outside the AOI.

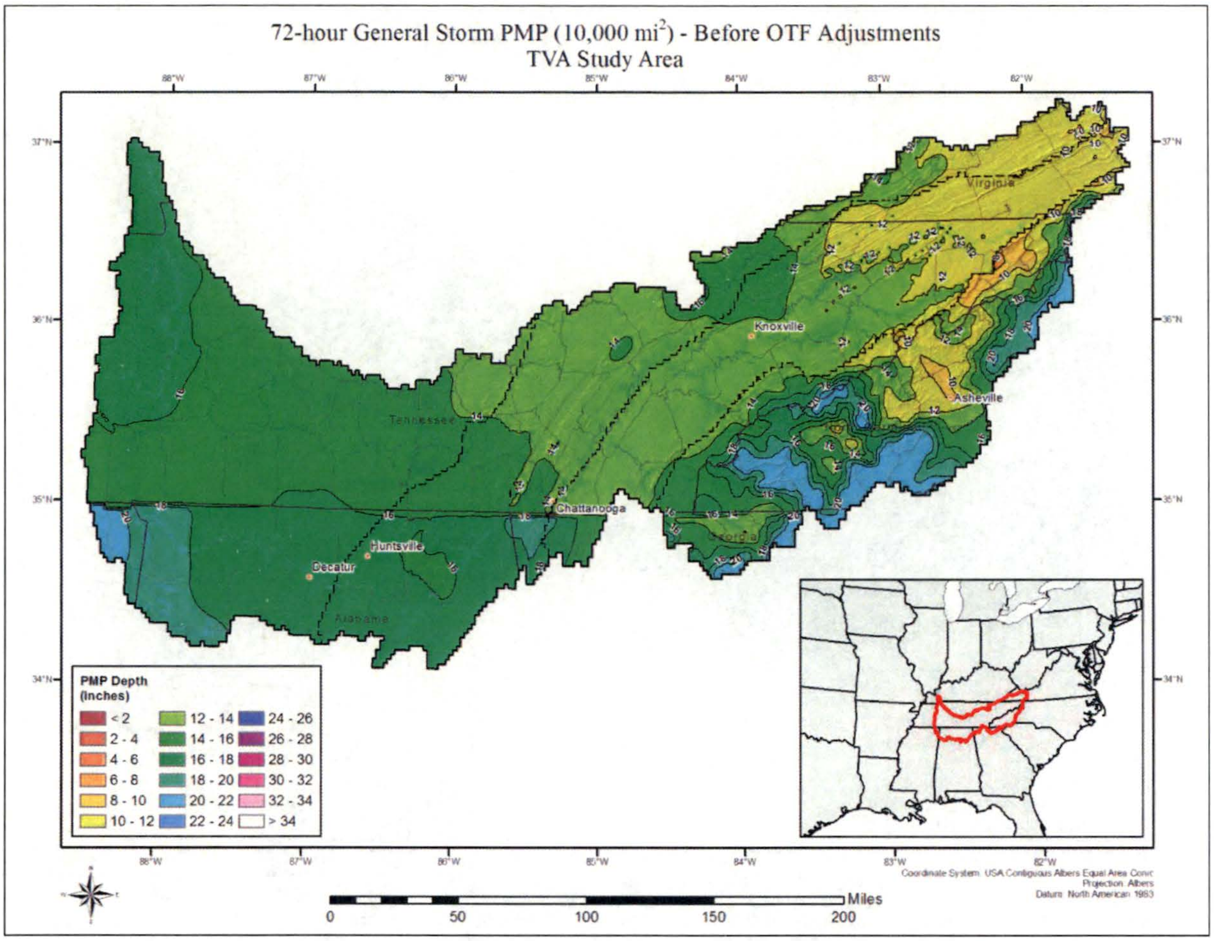
$$\text{ElevationAdjustmentFactor} = \sqrt[6]{\frac{h_{\text{target}}}{h_{\text{rep.}}}}$$

where,

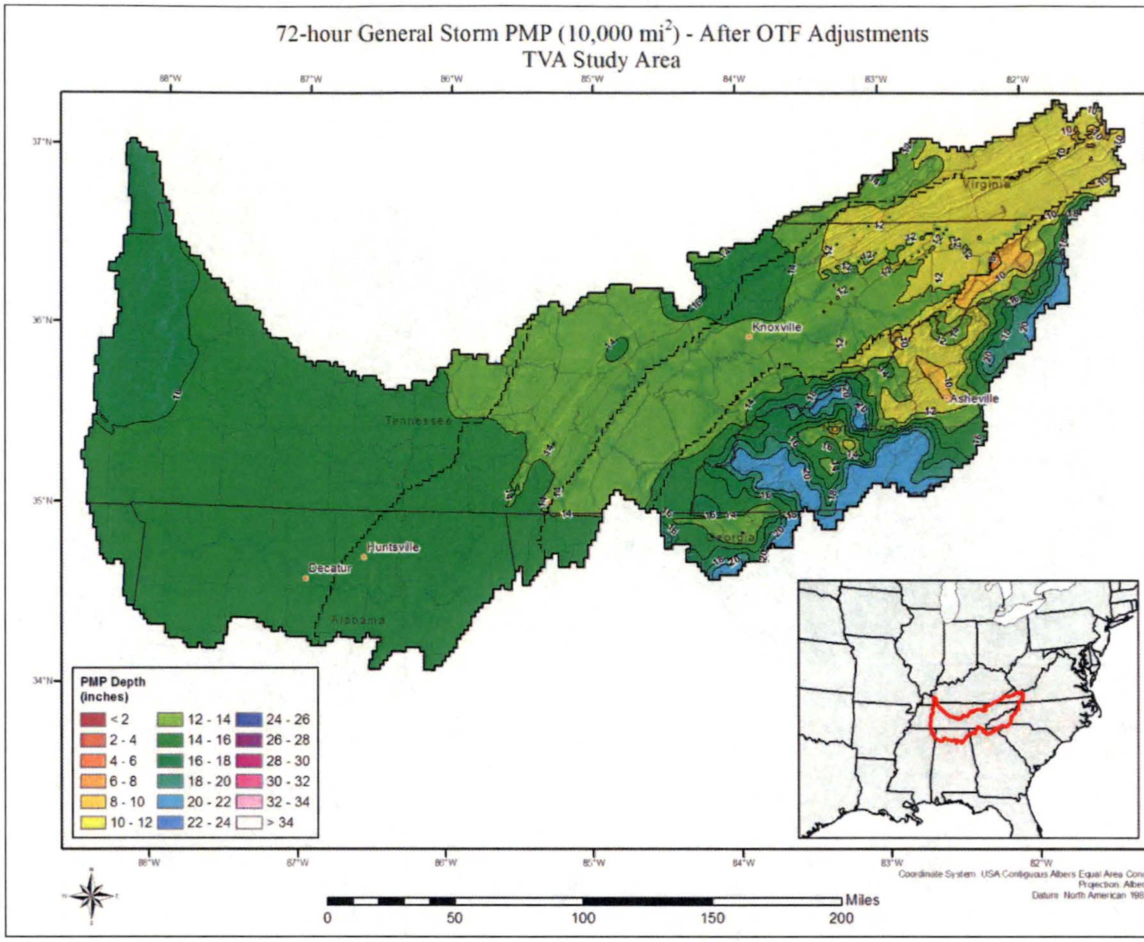
h_{target} = elevation at the target location

$h_{rep.}$ = elevation at the representative location (1,624')

An example map of general storm PMP before the constant OTF adjustments over the western portion of the project area is provided in TVA Figure 16. TVA Figure 17 shows the same PMP map after the general/tropical storm OTF adjustments are implemented.

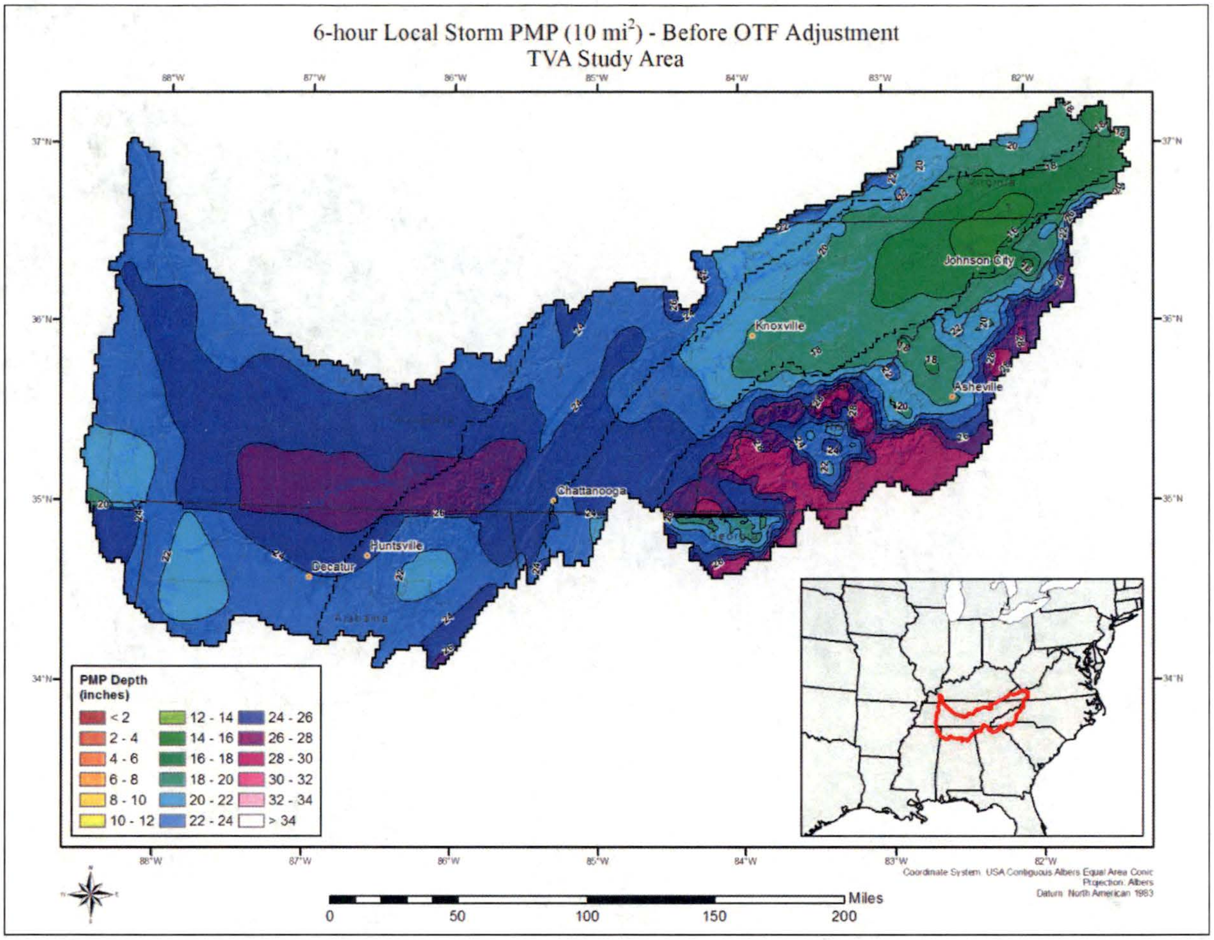


TVA Figure 16. Example of general storm PMP before constant OTF adjustment

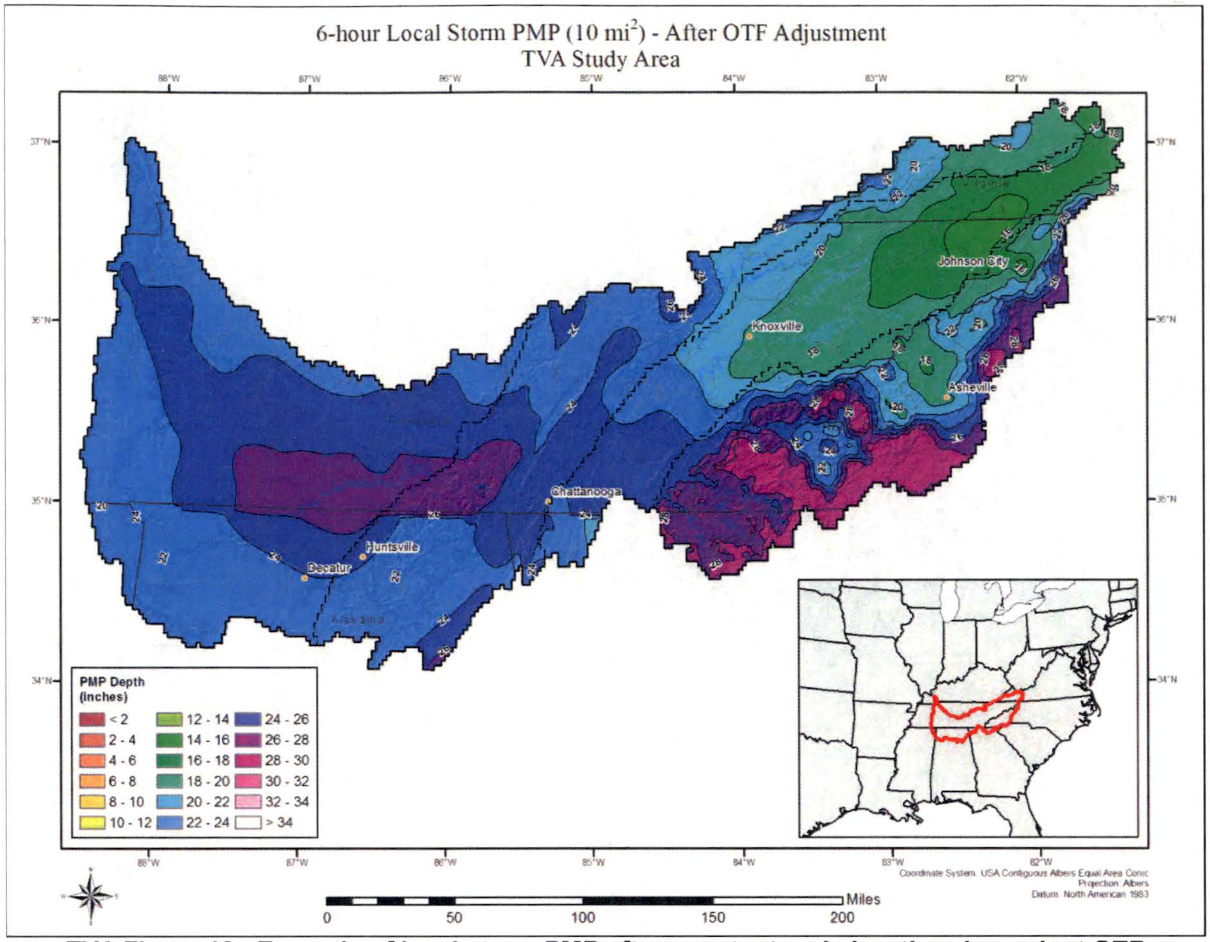


TVA Figure 17. Example of general storm PMP after constant OTF adjustment

An example map of local storm PMP before the constant OTF adjustments over the western portion of the project area and the elevation-based OTF adjustments over northern Georgia is provided in TVA Figure 18. TVA Figure 19 shows the same PMP map after the local storm OTF adjustments are implemented.



TVA Figure 18. Example of local storm PMP before constant and elevation-dependent OTF adjustments



TVA Figure 19. Example of local storm PMP after constant and elevation-dependent OTF adjustments

TVA Response - 9(b):

(Note: NRC 9(b) question references RAI #1 and RAI #3. These RAI references actually refer to informal information provided in response to NRC's audit Information Need #1 and #3, respectively.)

TVA inadvertently provided an older version of the local storm OTF values for Information Need #1. The Total Adjustment Factor spreadsheets provided for Information Need #1 included the constant OTF adjustments made over the western portion of the project area, but did not yet include the elevation-based adjustments that were applied over the Hiwassee drainage as described above. The GIS files provided in Information Need #3 were the final version of the local storm OTF and included all adjustments and therefore were different than the values provided for Information Need #1 for the grid points highlighted in NRC Figure 6.

RAI #10: Custom Transposition Limits

Technical Deficiency: Based on staff's review of information provided in response to RAI #1, the majority of storms included transposition limits that conform to the TVA Zone boundaries. However, at least four storms appeared to contain custom transposition limits, as listed in NRC Table 2 that don't conform to the TVA Zone boundaries.

NRC Table 2. Summary of storms subjected to custom transposition limits

Storm	SPAS No.	Storm Type	Transposition Limits
Elba, AL	1305	General	South of 35 deg N (exclusive of Zone 4)
Americus, GA	1317	Tropical	Based on TSR L-Cv 0.24 contour*
Larto Lake, LA	1182	Tropical	Based on TSR L-Cv 0.24 contour*
Big Rapids, MI	1206	General	North of 36.5 deg N (exclusive of Zone 4)

**Note: information from TAF Excel file, OTF sheet*

Request:

a) *Provide a justification as to why each of the storms listed in NRC Table 2 was subjected to custom transposition limits.*

b) *Provide a justification for the use of custom transposition limits for the Americus, GA and Larto Lake, LA storm using TSR L-Cv 0.24 contour. Provide the physical basis used to justify this custom approach.*

TVA Response - 10(a):

(Note: The NRC question references RAI #1. This RAI reference actually refers to informal information provided in response to NRC's audit Information Need #1.)

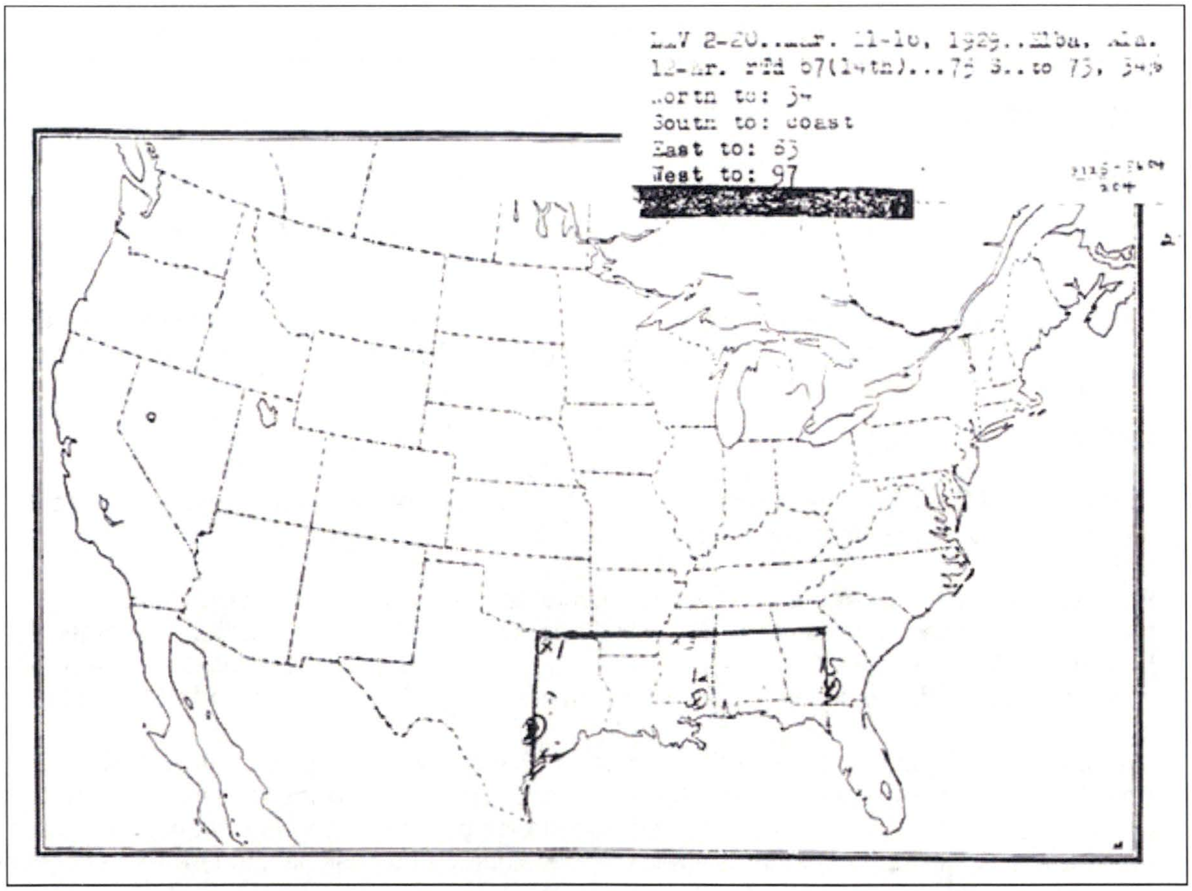
Each storm on the final storm short list was evaluated for explicit transposition limits. TVA transposition Zones (1-4) were used as initial reference for all storms. Further refinements between and within zones took place only as required based on unique individual storm characteristics and/or maintaining spatial continuity of adjustment factors and PMP depths.

Discussions took place between AWA and other TVA study participants during the Review Board meetings to evaluate specific storm transposition limits. Extensive discussions regarding transposition limits and specifically refined boundaries or constraints were required because of the meteorological judgment that is applied in developing and assigning the transposition limits for a given storm.

Specific to the four storms listed in the request, the following response is provided:

- The Elba, AL storm was limited to areas south of 35°N latitude based on the synoptic meteorology associated with the storm, including direct access to Gulf of Mexico moisture without any intervening topography, the combination of synoptic meteorological factors that led to the storm versus what could occur over the TVA basin, and previous transposition limits applied by the NWS (TVA Figure 20). The synoptic meteorology associated with this event was directly related to the moisture

and thermal environment associated with the interaction of the front moving through the region and the relatively warm waters of the Gulf of Mexico. This combination would not occur further north during this season of occurrence. Note that the NWS transposition limits map explicitly shows that the storm is only transpositionable to 34°N latitude. It is assumed the NWS considered the synoptic meteorological environment to be a limiting factor of not moving the storm further north. For final application, TVA applied a more conservative transposition limit to this storm (to 35°N latitude) to account for the judgment involved in the process, to allow consideration of general topographic similarities to regions around 35°N latitude, and to produce more spatially consistent PMP depths between where this storm was transposed and where it wasn't transposed. For this storm, it was determined that the combination of available moisture and storm dynamics could not occur further north during the March timeframe without changing the storm dynamics significantly.



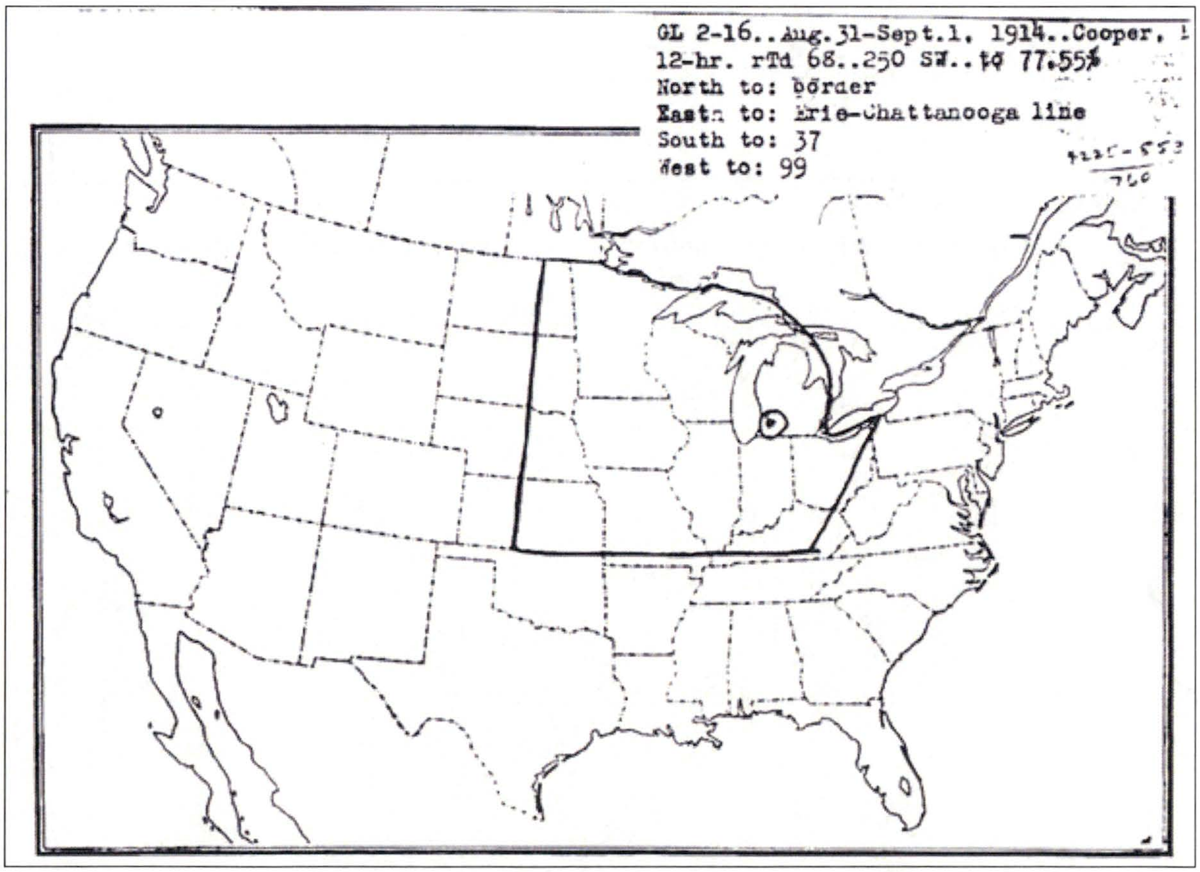
TVA Figure 20. NWS transposition map for the Elba, AL March 1929 storm

- The Americus, GA and Larto Lake, LA storms were both tropical events. As mentioned previously, each storm's individual synoptic meteorological environment, interaction of moisture source and topography, and previous transposition limits were investigated in relation to the overall TVA basin. This demonstrated that these two storms should not be transpositioned any further north than currently applied. This is because direct land falling tropical systems do not affect most of the TVA basin without significant degradation and changes to the structure. This results from interactions with topography and distance from the moisture source.

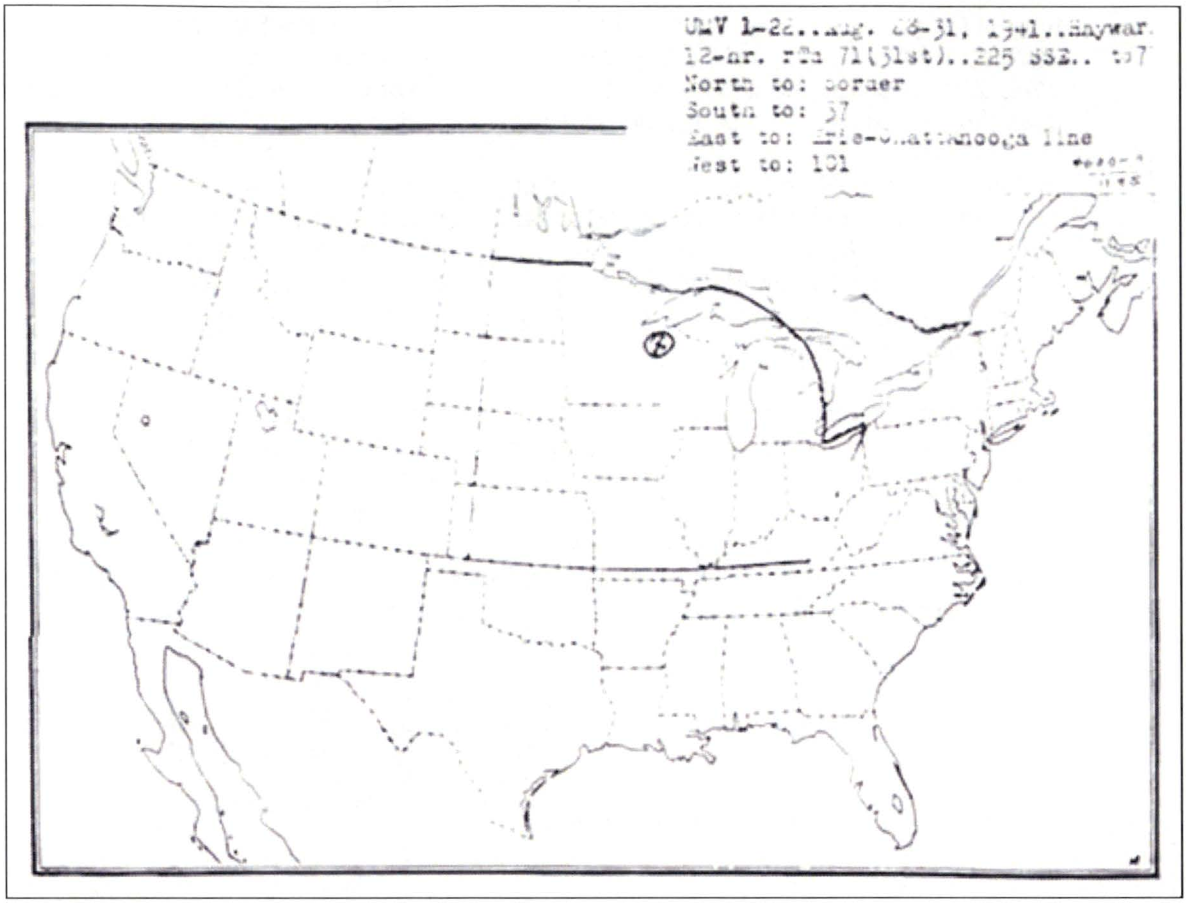
- For the Big Rapids storm, similar AWA discussions with the TVA Review Board and PMP study team took place regarding moisture source, topographic interactions and time of the year when the storm occurred. Explicit limits on the Big Rapids storm were applied because it was a controlling event and therefore required further evaluation to ensure spatial continuity in the PMP depths between the regions where it was used and the regions that bordered that area.

  In this case, a PMP-type general storm occurring in September that included the required storm dynamics related to significant thermodynamic contrast would not be able to occur in the same fashion further south. In this case, the southern limit was judged to be 36.5° N latitude. This southern limit also considered the latitudinal extent of the storm and constraints following HMR guidance of applying a 5-6° latitude constraint (HMR 57, page 69).

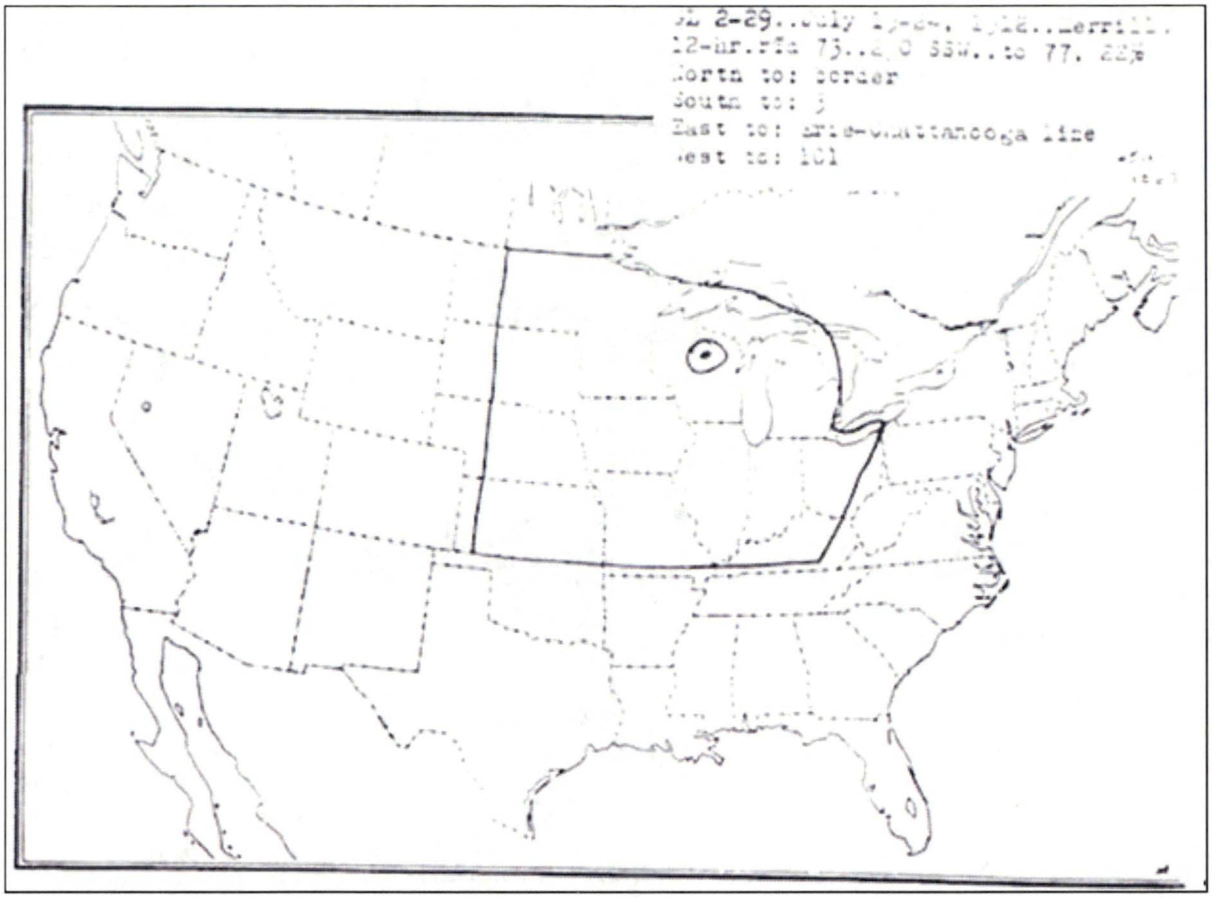
  Analog storm events with explicit NWS transposition limits maps were consulted as well as an analog data source to corroborate the transposition limits applied. Storms of similar type and season in the NWS transposition library of storms in Michigan and Wisconsin were not transpositioned south of 37° N latitude. TVA Figures 21-23 explicitly show NWS transposition limits maps and show that none were used further south than 37N latitude. Given these considerations, the application of this storm to 36.5° N latitude was a conservative application compared to prior NWS guidance.



TVA Figure 21. NWS transposition map for the Cooper, MI September 1914 storm



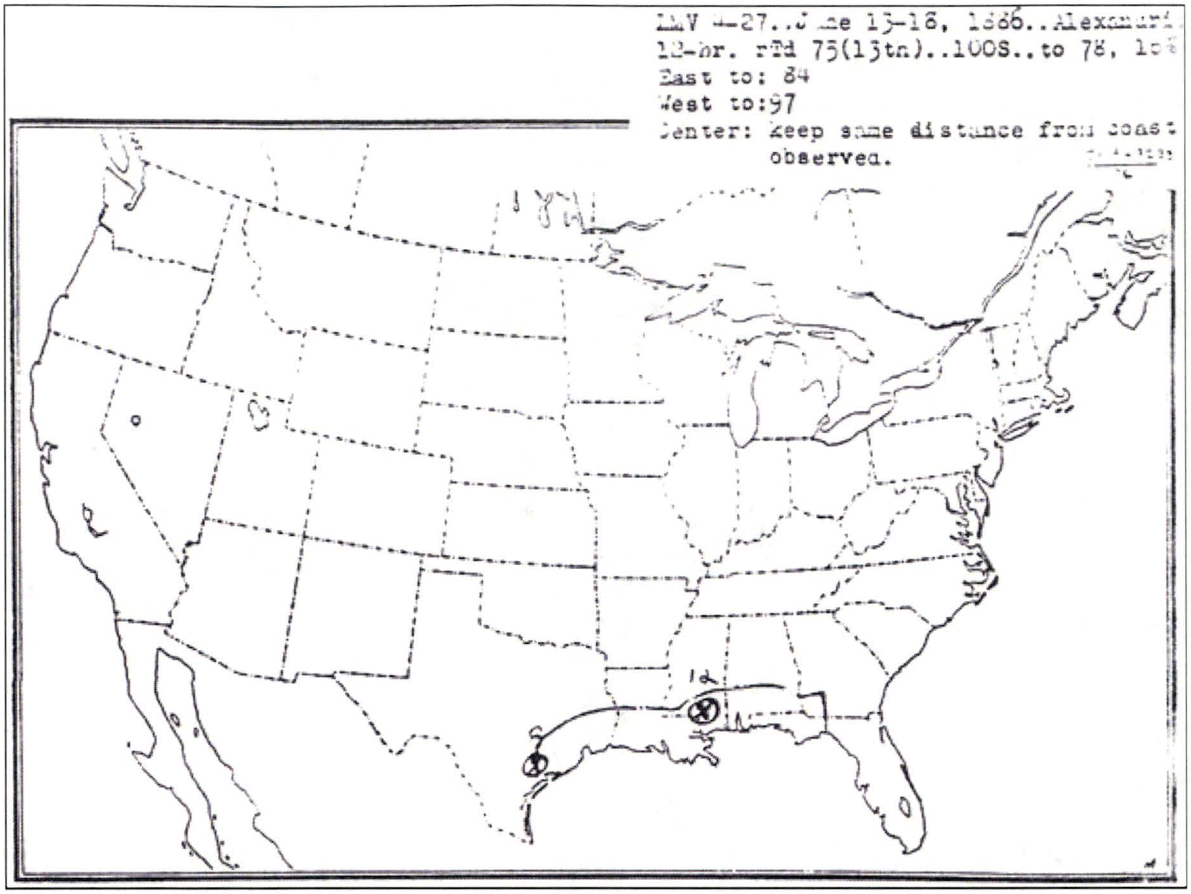
TVA Figure 22. NWS transposition map for the Hayward, WI August 1941 storm



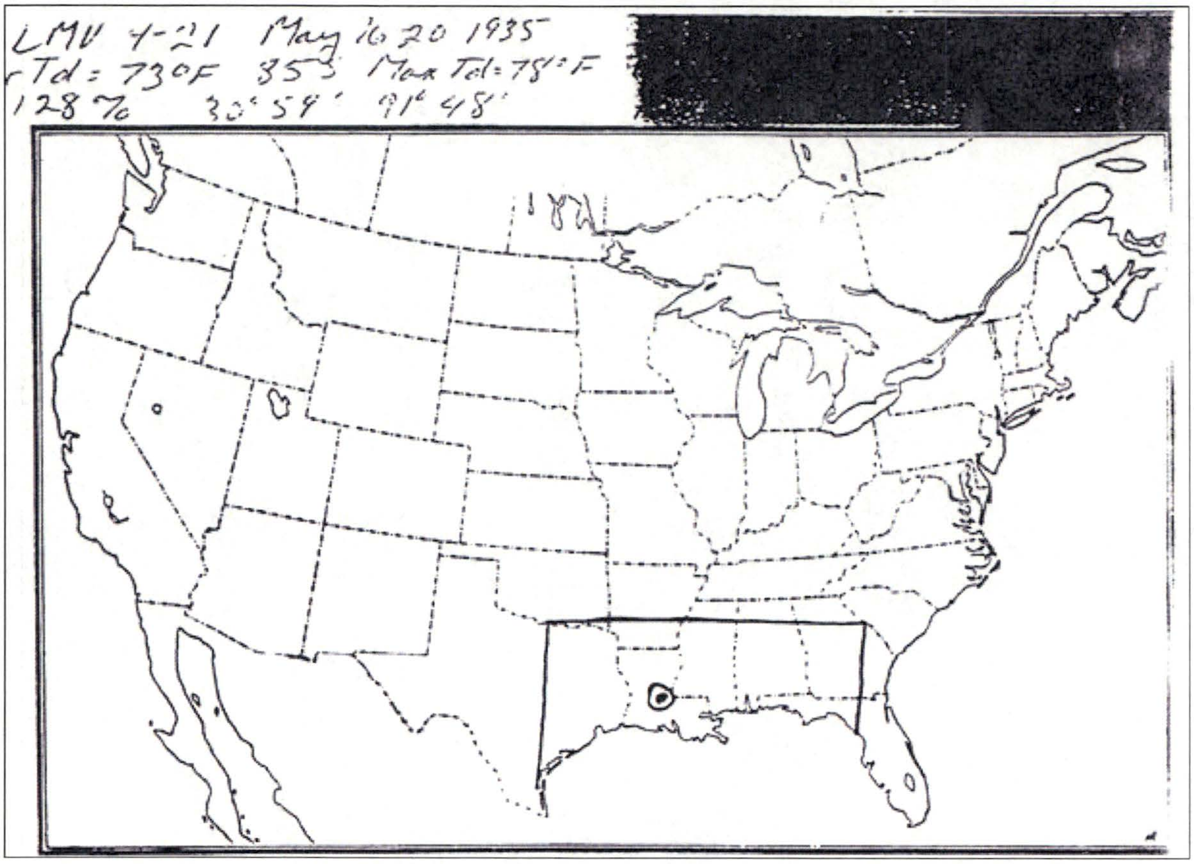
TVA Figure 23. NWS transposition map for the Merrill, WI July 1912 storm

TVA Response - 10(b):

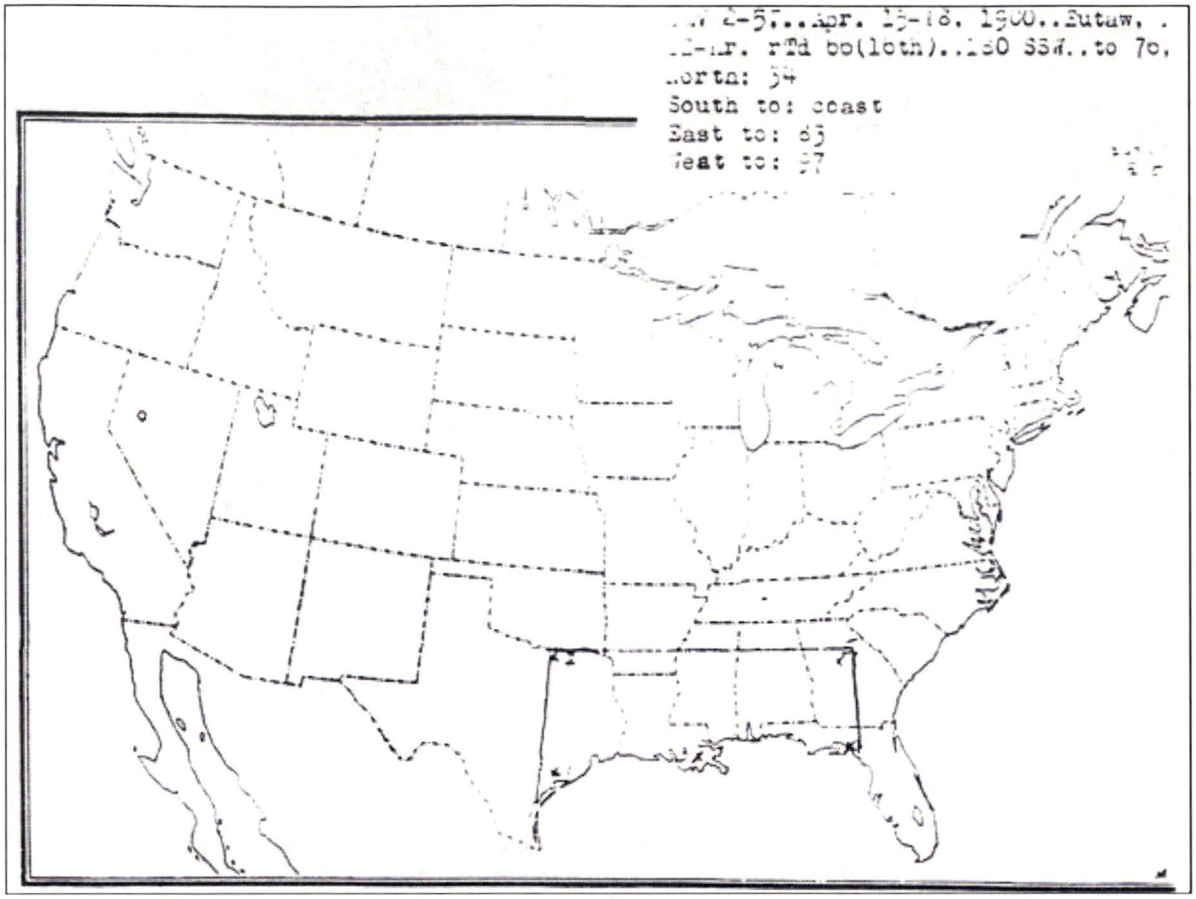
TVA Figures 24-29 display the transposition limits applied to storms by the NWS, which occurred in similar regions as Larto Lake, LA and Americus, GA events. Each of these figures clearly demonstrates that the NWS did not consider storms in these regions transpositionable to the Tennessee Valley and specifically to the interior regions of the Tennessee River basin. In fact, the custom limits applied by TVA (TVA Figures 30 and 31)are significantly more conservative than the NWS transposition limits. TVA allowed these storms to affect the southern portions of the TVA region to ensure appropriate spatial continuity in PMP values between these regions and to account for the uncertainty of where the exact boundary would occur. However, the rainfall that occurred with the storms would not occur in the same meteorological and topographical setting existing over the interior TVA regions. Note, this does not mean that remnant tropical moisture doesn't produce rainfall in that region. Instead the magnitude of those rainfall events is significantly reduced because of the different interactions of topography and meteorology, thereby violating the definition of transpositionability. This requires that remnant tropical storms that occurred in similar meteorological and topographical settings be used in that region. This excludes the Larto Lake, LA and Americus, GA storms from consideration.



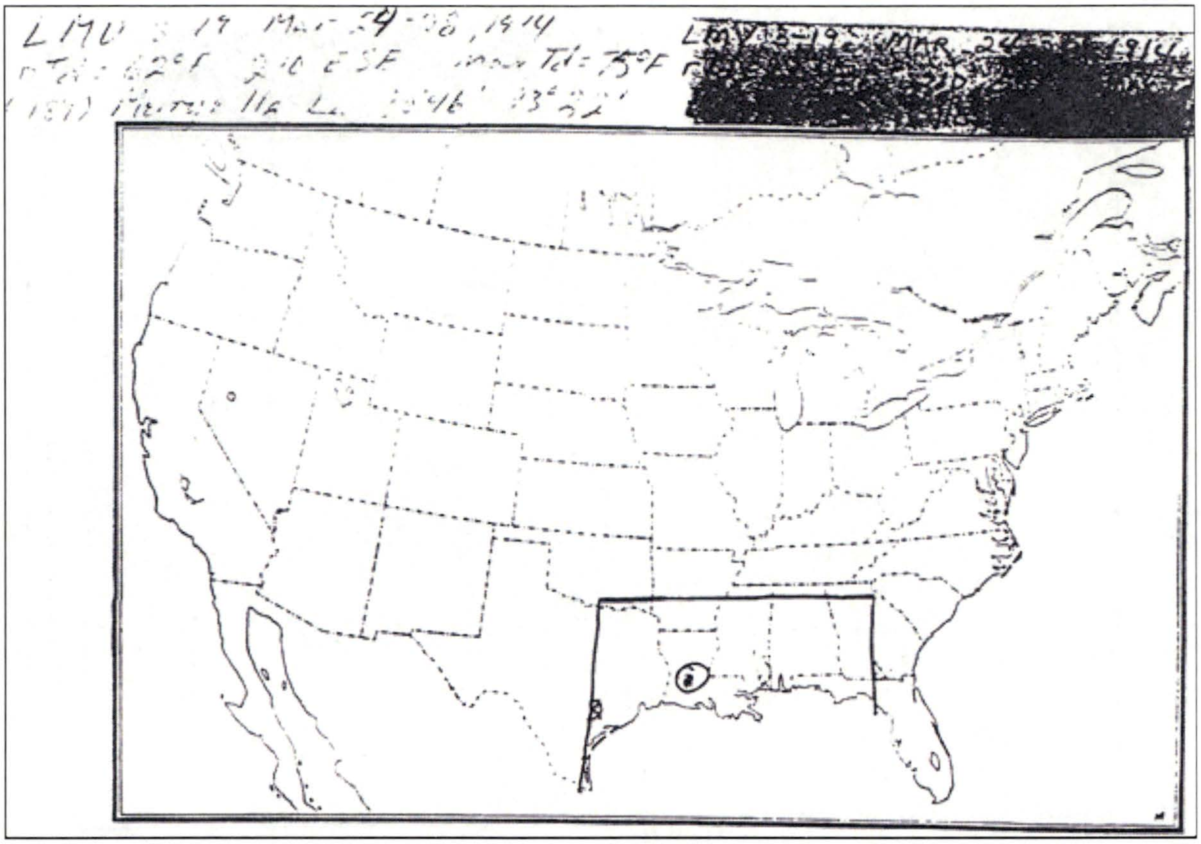
TVA Figure 24. NWS transposition map for the Alexandria, LA June 1886 storm



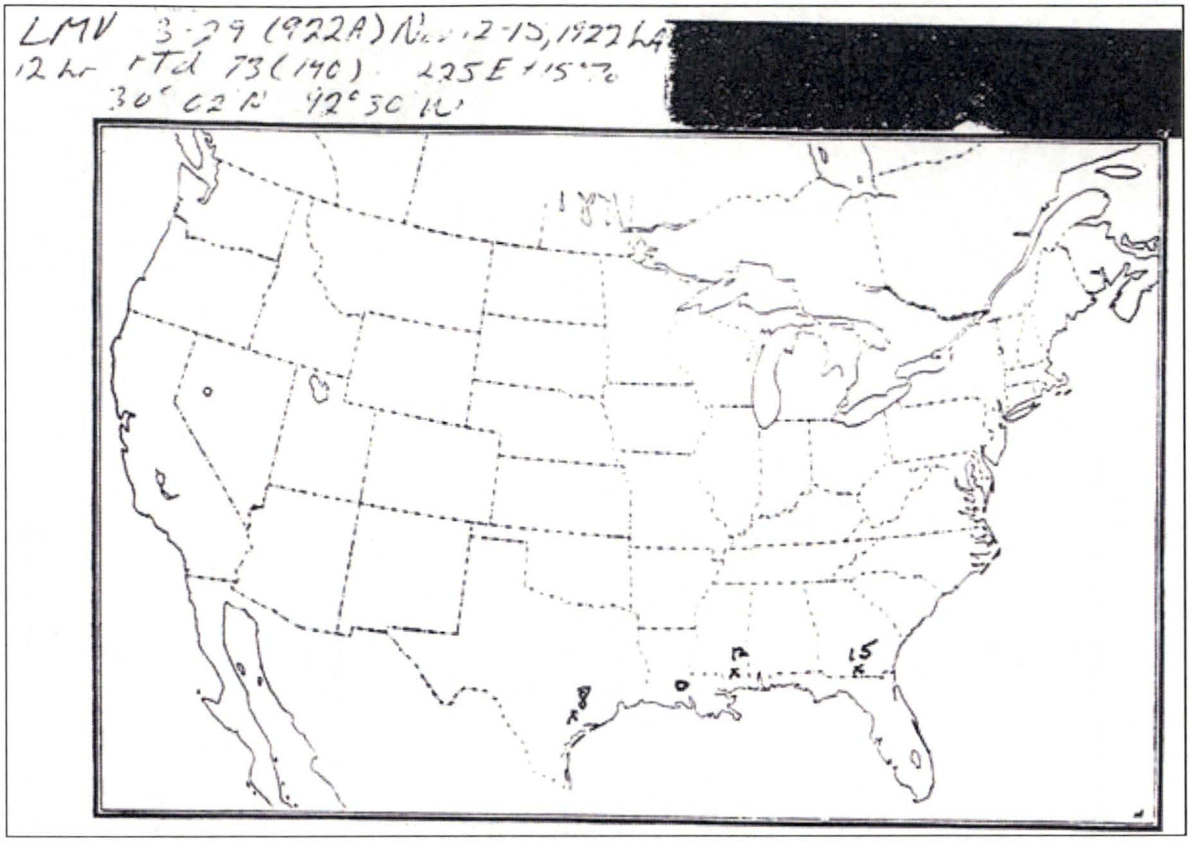
TVA Figure 25. NWS transposition map for the Simmesport, LA May 1935 storm



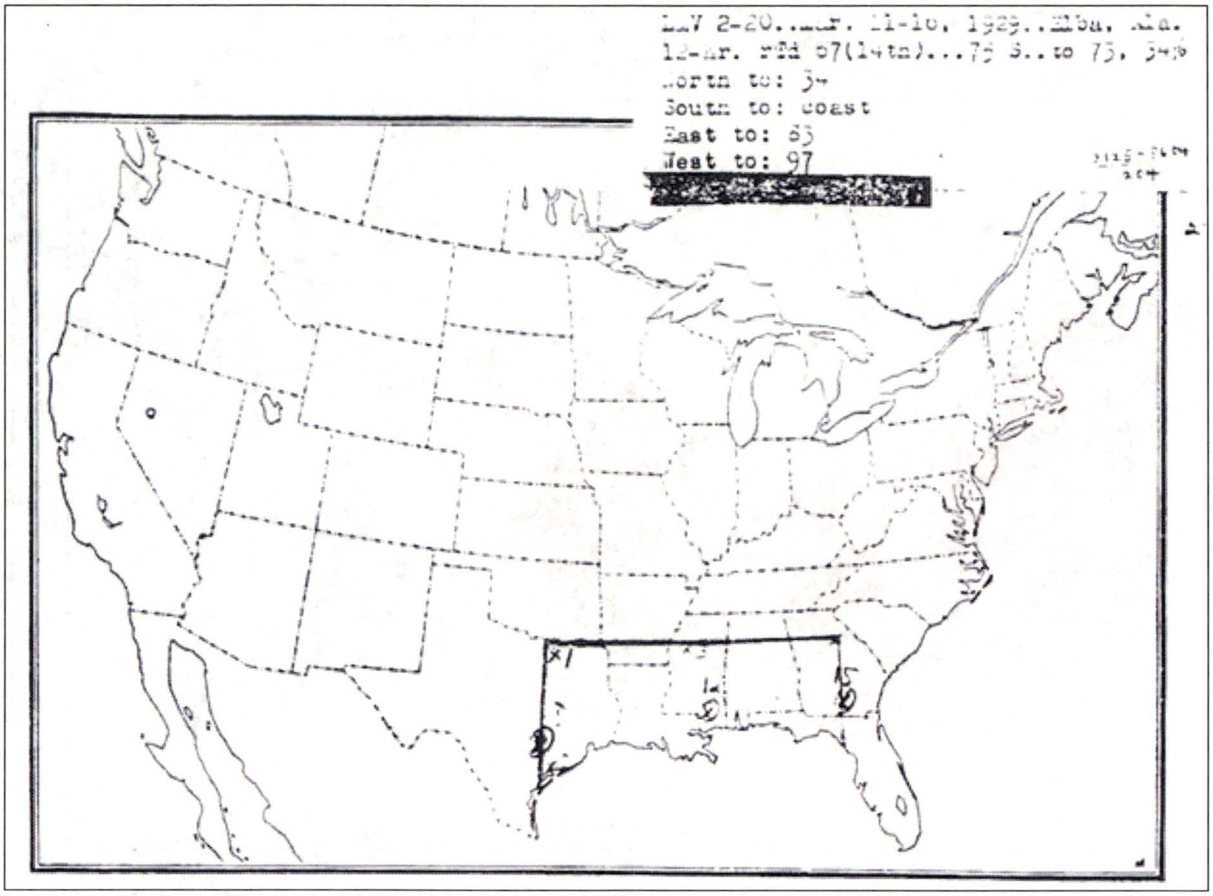
TVA Figure 26. NWS transposition map for the Eutaw, LA April 1900 storm



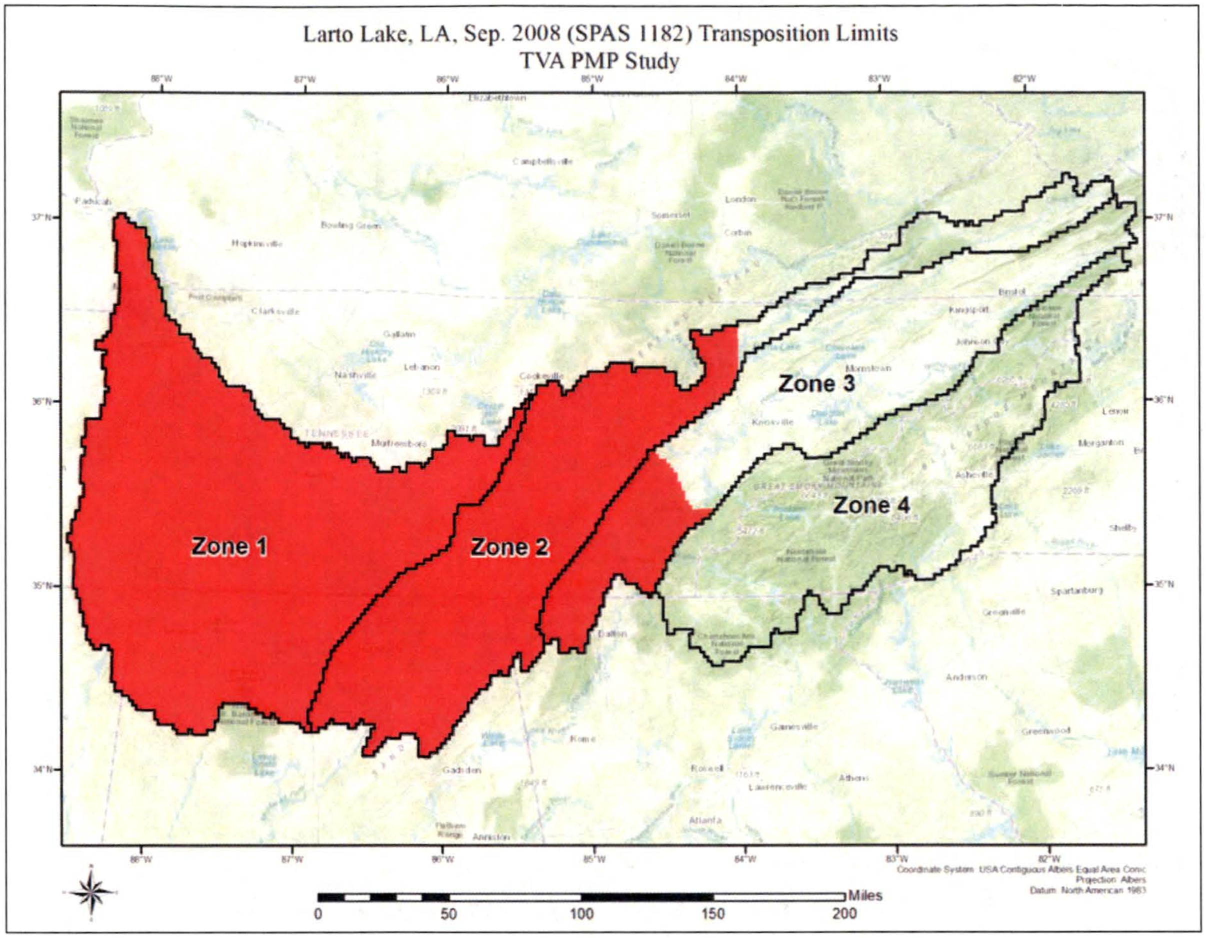
TVA Figure 27. NWS transposition map for the Merryville, LA March 1914 storm



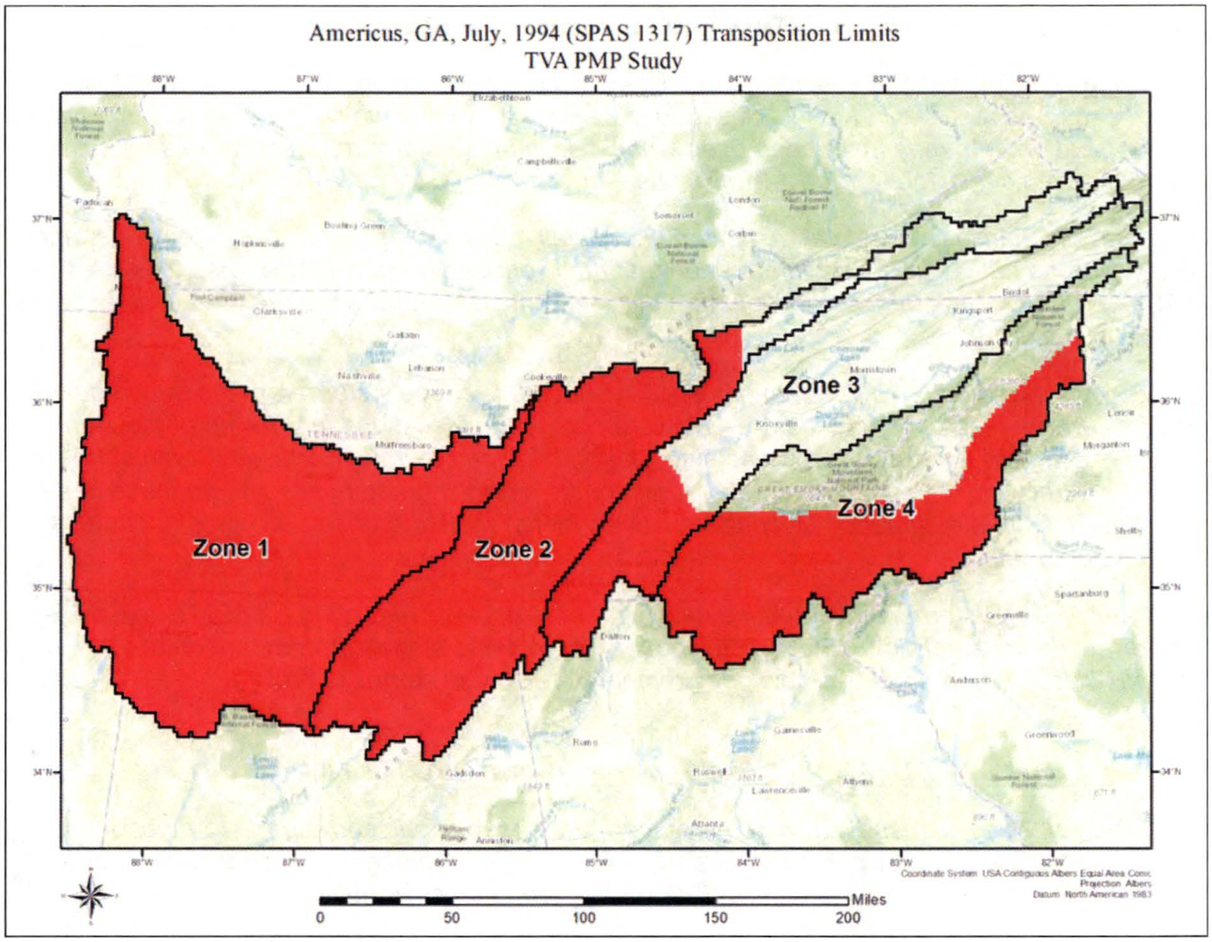
TVA Figure 28. NWS transposition map for the Lakeside, LA November 1922 storm



TVA Figure 29. NWS transposition map for the Elba, AL March 1929 storm



TVA Figure 30. TVA transposition map for the Larto Lake, LA September 2008 storm



TVA Figure 31. TVA transposition map for the Americus, GA July 1994 storm

After further review and discussion with the NRC staff in regard to this question, TVA has agreed to remove reference to use of the TSR L-Cv 0.24 contour as one of the reasons for defining the updated transposition limits of these two storms. Instead, discussions specifically related to the differences of the meteorological and topographical environments are used to define and justify the transposition limits. These updates to this data set will affect Section 5.3 of Calculation No. CDQ0000002016000041 and will be submitted as Revision 1 to Topical Report TVA-NPG-AWA16 (TVA Calculation CDQ0000002016000041).

<u>RAI #11</u>: Storm Representative Dew Point Selection: Timeframe and Location

<u>Technical Deficiency</u>: Staff's review of the licensee's storm representative dew point data for short list storms resulted in the identification of several storms for which questionable timeframe and/or location data may have been used when selecting the storm representative dew point. This issue can significantly impact PMP values for controlling storms

As a part of its assessment, staff reviewed the rainfall mass curves, HYSPLIT trajectories, and storm representative dew point information that the licensee provided in response to RAI #1 and RAI #2. Staff also independently evaluated this information to assess the reasonableness of the data application.

Staff's review of the above information revealed that the licensee's storm representative dew point selection used dew point data which were observed at locations far upwind of the storm center and during timeframes in which significant rainfall had already occurred. Conducting the analysis in this way could inadequately represent the storm characteristics and (in these cases) result in PMP underestimation since the relatively higher moisture observed could not induced the observed rainfall.

Staff believes the storm representative dew point methodology regarding HYSPLIT trajectories and/or dew point timeframes may be flawed for the following storms. A comparison of the TVA and NRC storm representative dew point temperatures these storms is provided in NRC Table 3.

1. *<u>General Storm, SPAS 1206 (Big Rapids, MI)</u> – see NRC Figure 7*

    a. *The licensee's dew point temperature observations correspond to a period after significant rainfall had already occurred. The representative dew point location is approximately 230 miles SW of the storm center location.*

2. *<u>General Storm, SPAS 1208 (Warner Park, TN)</u> – see NRC Figure 8*

    a. *The licensee's dew point temperature observations correspond to a period when the most intense rainfall occurred. The representative dew point location is approximately 360 miles SSW of the storm center location.*

3. *<u>Tropical Storm, SPAS 1276 (Wellsville, NY)</u> – see NRC Figure 9*

    a. *The licensee's dew point temperature observations correspond to a period when the most intense rainfall occurred. The representative dew point location is approximately 385 miles SSW of the storm center location.*

    b. *By adjusting the HYSPLIT backward trajectory timing to more closely align with the onset of rainfall, staff identified a moisture inflow direction of SE rather than SSW.*

4. *<u>Tropical Storm, SPAS 1317 (Americus, GA)</u> – see NRC Figure 10*

    a. *By adjusting the HYSPLIT backward trajectory timing to more closely align with the onset of rainfall, staff identified a moisture inflow direction of SE-to-S rather than WSW.*

5. Additional storms which exhibit timeframe issues but do not control PMP

   a. *General Storm, SPAS 1218 (Douglasville, GA & LaFayette, GA) - see NRC Figure 11*

   b. *Local Storm, SPAS 1226 (College Hill, OH) - see NRC Figure 12*

   c. *Local Storm, SPAS 1209 (Wooster, OH) - see NRC Figure 13*

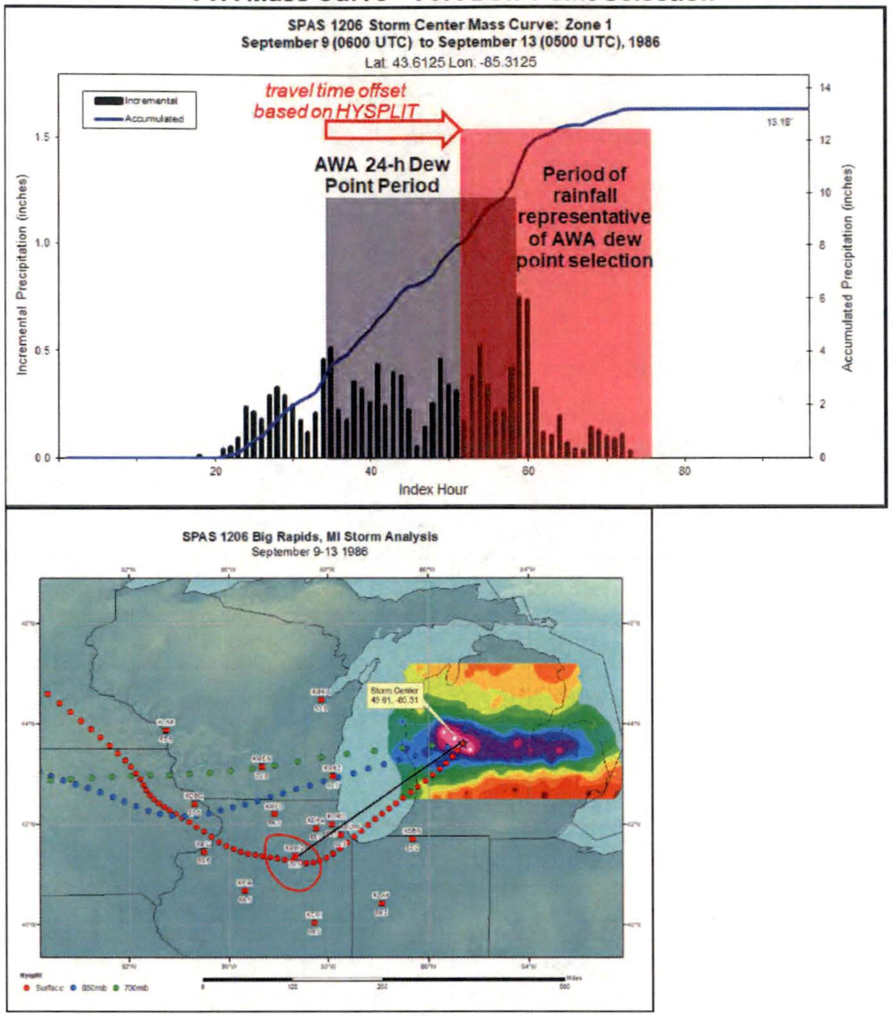
   d. *Tropical Storm, SPAS 1182 (Larto Lake, LA) - see NRC Figure 14*

NRC Table 3. Comparison of TVA vs NRC storm representative dew point temperature for storms with potential HYSPLIT or timing issues

Number	Storm Name	SPAS Number	Storm Type	Storm Rep. Td (deg F)		Difference (TVA-NRC)
				TVA T_d	NRC T_d	
1	Big Rapids, MI	SPAS 1206	General	70.5	68.5	+2
2	Warner Park, TN	SPAS 1208	General	75	74	+1
3	Wellsville, NY	SPAS 1276	Tropical	72.5	70.5	+2
4	Americus, GA	SPAS 1317	Tropical	76	74.5	+1.5
5a	Douglasville, GA	SPAS 1218_1	General	76	75	+1
5a	LaFayette, GA	SPAS 1218_2	General	76	75	+1
5b	College Hill, OH	SPAS 1226	Local	68.5	66.5	+2
5c	Wooster, OH	SPAS 1209	Local	76	72	+4
5d	Larto Lake, LA	SPAS 1182	Tropical	76	73	+3

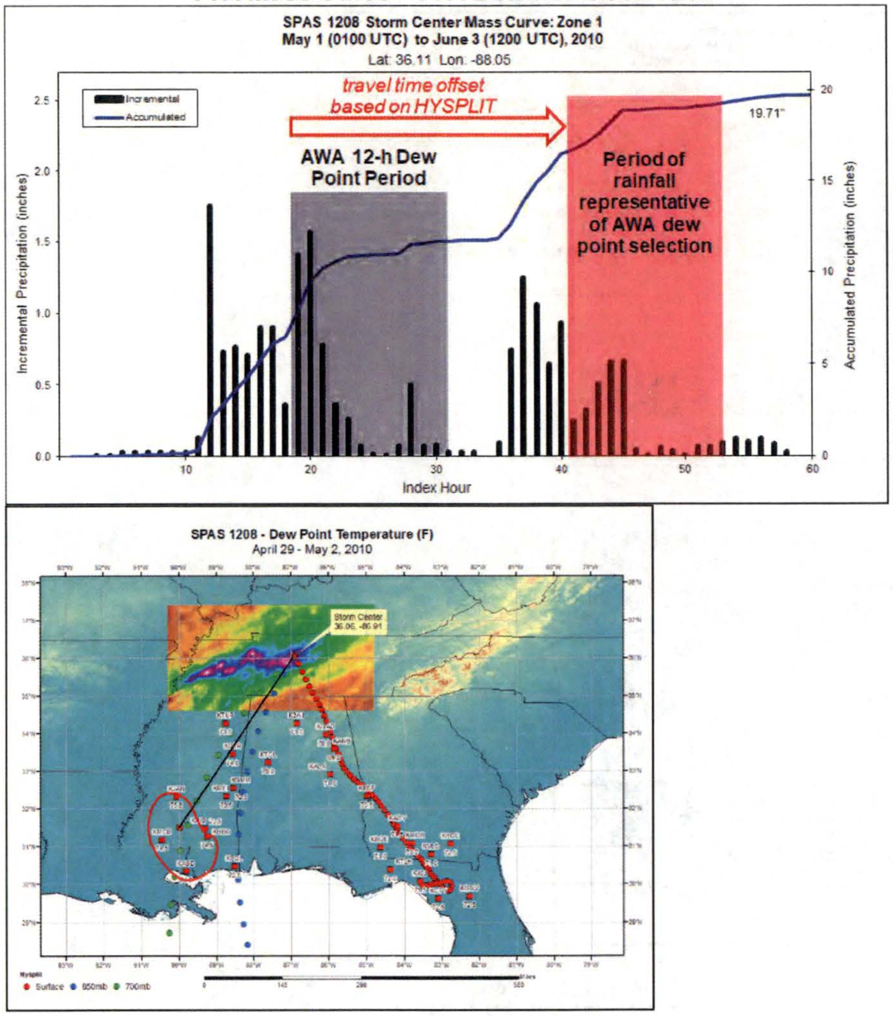
Request: Provide justification for the selection of storm representative dew point values for the above storms with respect to timeframe and location selected, especially considering the timeframe of when rainfall occurs at the storm center. If corrections are warranted, provide an updated analysis as it may affect TVA's 3 NPP sites.

TVA Mass Curve - TVA Dew Point Selection



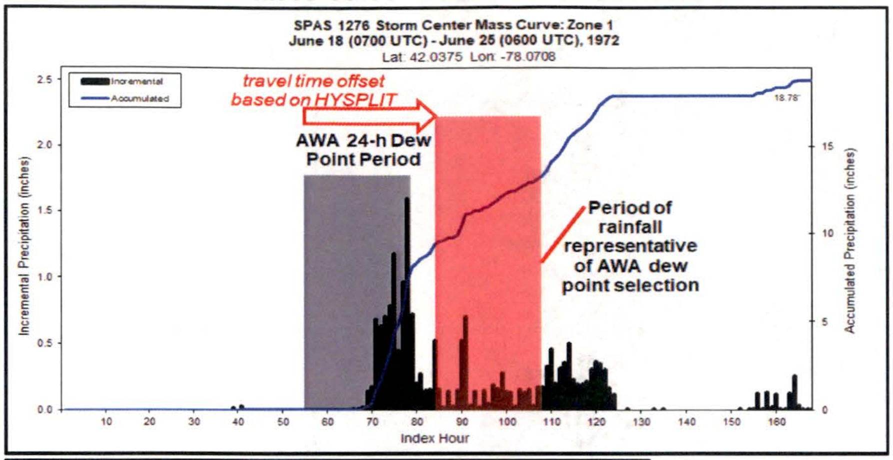
NRC Figure 7. General Storm, SPAS 1206 (Big Rapids, MI) rainfall mass curve (top) and dew point analysis (bottom)

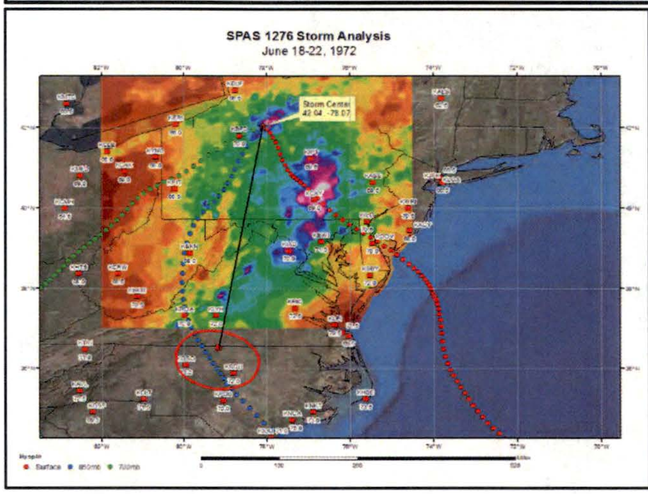
TVA Mass Curve - TVA Dew Point Selection



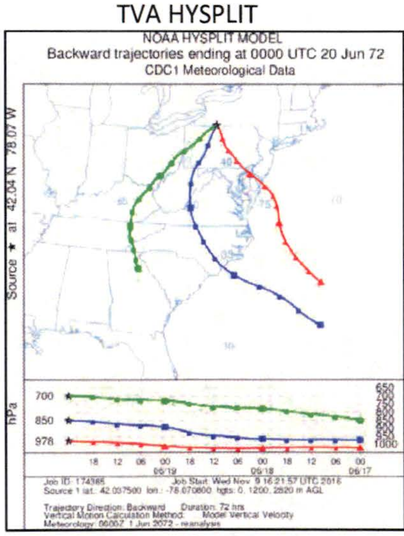
NRC Figure 8. General Storm, SPAS 1208 (Warner Park, TN) rainfall mass curve (top) and dew point analysis (bottom)

TVA Mass Curve - TVA Dew Point Selection

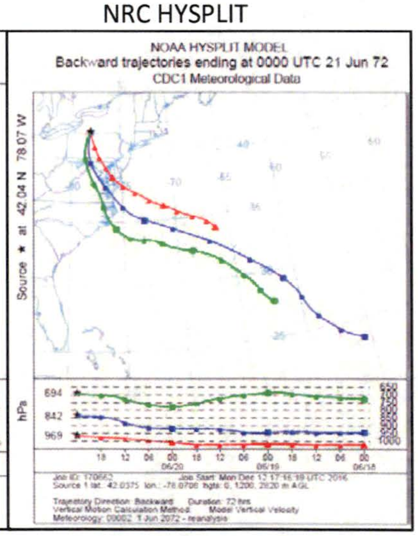




TVA HYSPLIT

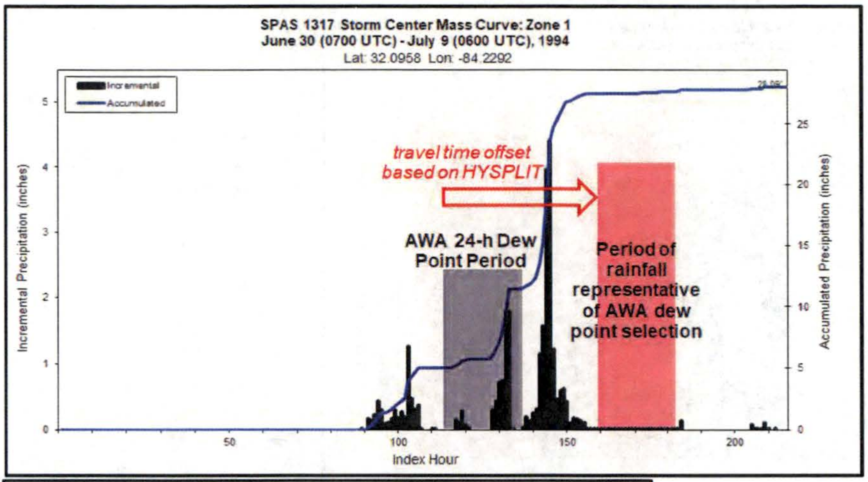


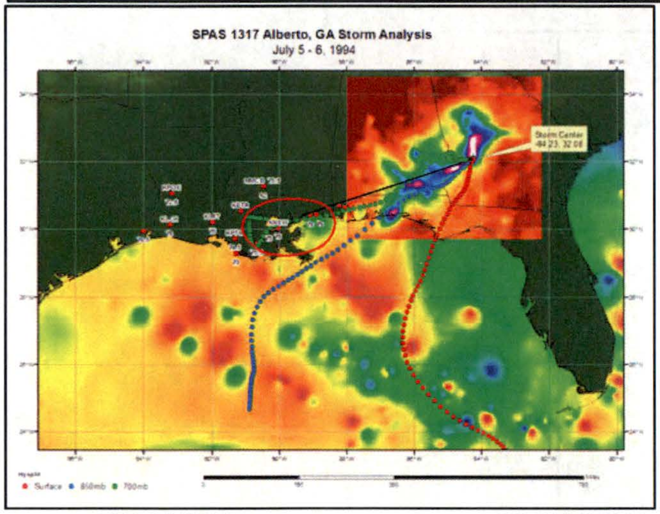
NRC HYSPLIT



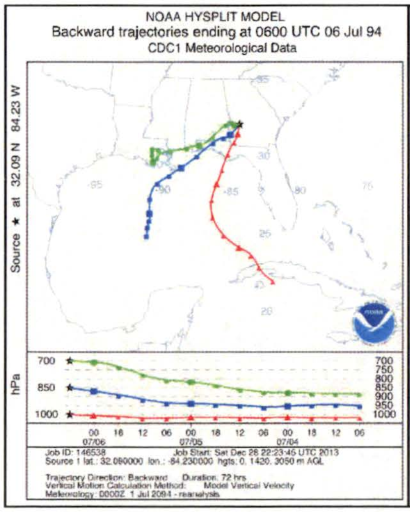
NRC Figure 9. Tropical Storm, SPAS 1276 (Wellsville, NY) rainfall mass curve, dew point analysis, TVA HYSPLIT, and NRC HYSPLIT (from top, middle and bottom)

TVA Mass Curve - TVA Dew Point Selection

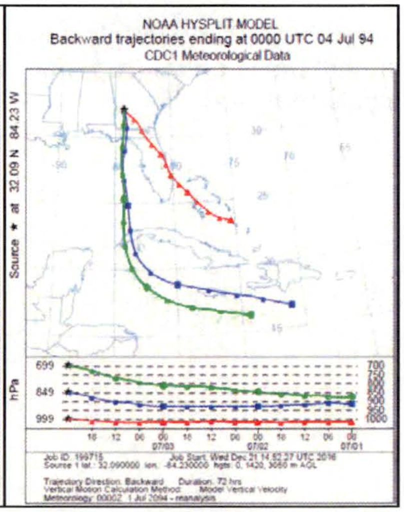




TVA HYSPLIT

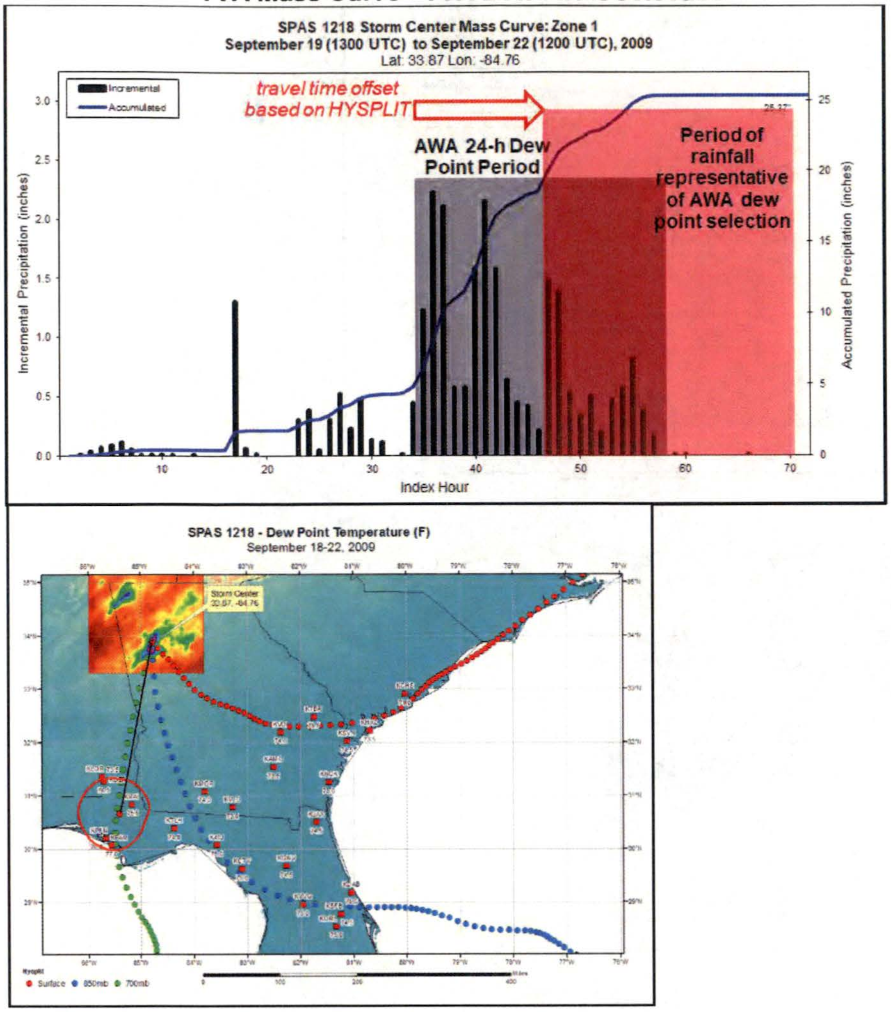


NRC HYSPLIT



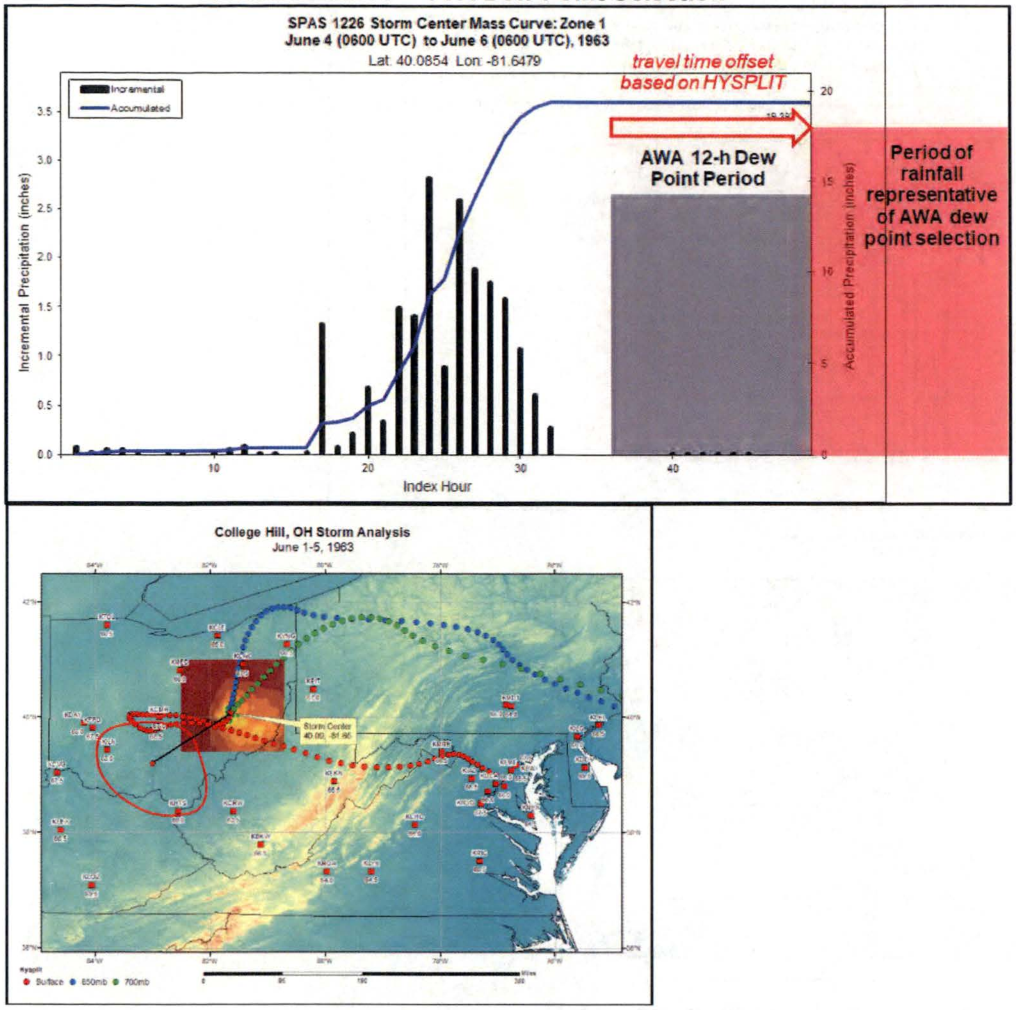
NRC Figure 10. Tropical Storm, SPAS 1317 (Americus, GA) backwards HYSPLIT trajectory from TVA (left) and NRC (right)

TVA Mass Curve - TVA Dew Point Selection



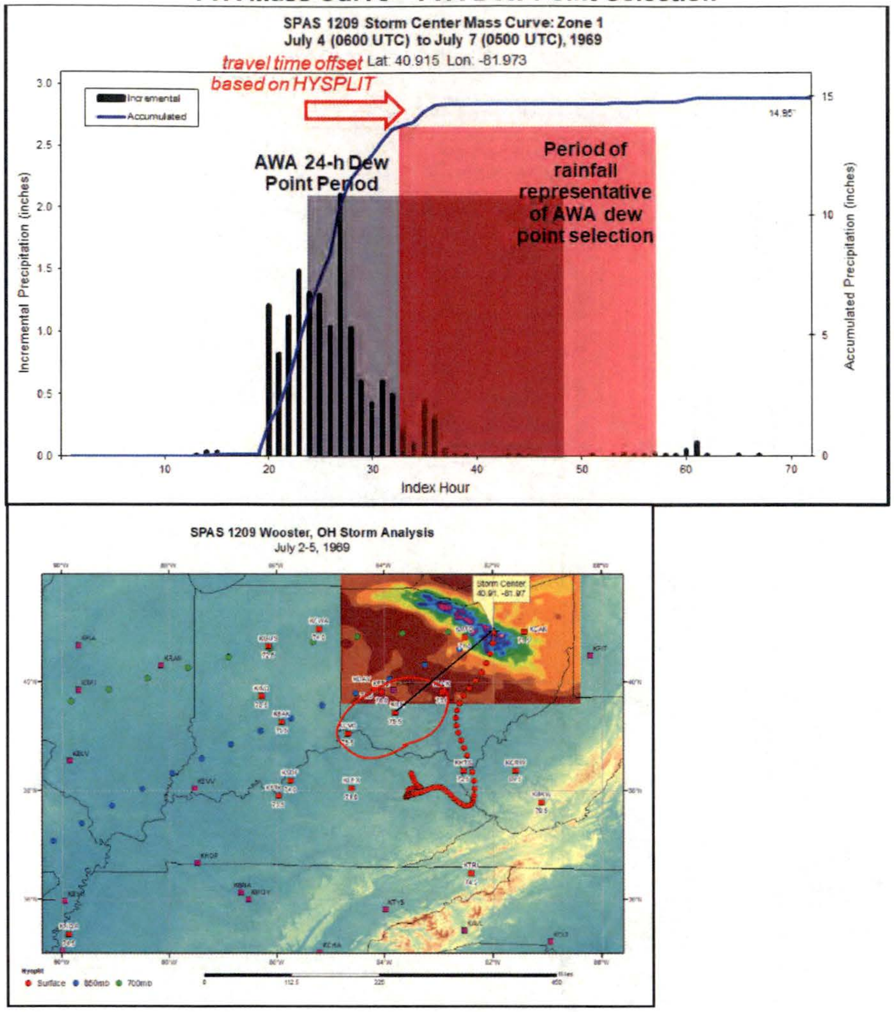
NRC Figure 11. General Storm, SPAS 1218 (Douglasville, GA [shown] & LaFayette, GA) rainfall mass curve (top) and dew point analysis (bottom)

TVA Mass Curve - TVA Dew Point Selection

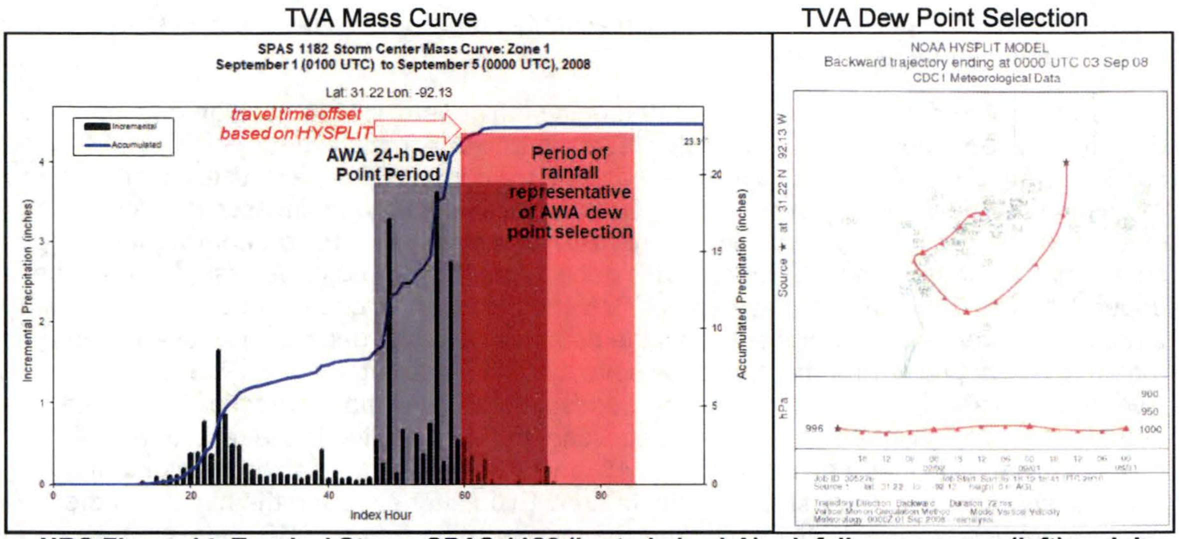


NRC Figure 12. Local Storm, SPAS 1226 (College Hill, OH) rainfall mass curve (top) and dew point analysis (bottom)

TVA Mass Curve - TVA Dew Point Selection



NRC Figure 13. Local Storm, SPAS 1209 (Wooster, OH) rainfall mass curve (top) and dew point analysis (bottom)



NRC Figure 14. Tropical Storm, SPAS 1182 (Larto Lake, LA) rainfall mass curve (left) and dew point analysis (right)

TVA Response:

In each of the four cases (NRC Table 3, Storms 1 through 4) noted as potentially controlling the PMP, the air mass evaluated as represented by the TVA storm representative dew point selection was inclusive of the overall air mass advection into the overall storm domain. Although, the exact timing of the 12- or 24-hour period chosen occurs during a later portion of the overall rainfall period at the storm center, it is still representative of the overall air mass that was part of the rainfall event across the entire region. This is the intent of the storm maximization process to represent the overall air mass resulting in the observed event. The final process requires the analyst to calculate a specific value at a specific location at a specific point in time. However, in actuality, the moisture advection and storm development processes change in space, time, and magnitude.

One of the more important considerations relative to the intent of the in-place maximization process is that moisture associated with these events is at higher than normal levels. Therefore, the region chosen as the moisture source region and the eventual storm representative dew point should also represent values that are higher than normal. In some cases, data available to analyze and select a value were inadequate and require judgments not fitting the standard processes. For example, there may be a lack of surface dew point observations in a general region where the air mass source region would be expected to originate in either space or time. Further, the storms that are being maximized are extreme rainfall events. In such cases, judgments must be applied to allow for selection of storm representative dew point values that can be used in the maximization process and represent a high level of atmospheric moisture.

Storm No. 1: Big Rapids, MI

The storm representative dew point selected by TVA does represent a later portion of the storm, which is acceptable, and within the standard process of storm representative dew point selection. This process allows for selection of a 24-hour average value even though the overall storm period may be significantly longer than 24-hours. The value selected by TVA represents a period when the heaviest rainfall occurred during the storm and is

representative of the overall air mass, which advected moisture into the overall storm environment over several days.

TVA investigated daily weather maps to determine the general location of high and low pressure centers and fronts immediately preceding and during the event. This analysis confirmed the general air mass source region as shown by HYSPLIT and used for the storm representative dew point location. Hourly surface observations were investigated for stations in a large region surrounding the general air mass source region from west through south-southwest as shown. Stations in this general region showed values ranging from the upper 60°'s to 70°F as 24-hour averages. TVA checked various surface observations to find a region that was most appropriate given the data available, the general moisture inflow region, the synoptic environment, and the severity of the resulting rainfall. These investigations showed that a region to the west/southwest was most synoptically relevant and that high values in that region were necessary to have resulted in the record rainfall that occurred. This storm controls PMP at 48- and 72-hours for area sizes greater than 5,000-sqaure miles in many studies in the region. Even after choosing the highest of the available values (70°F at KMMO), the in-place maximization factor (IPMF) was still 1.40. The KMMO wind speed and wind direction in relation to moisture inflow timing at the storm also support the general air mass source and timing as identified in HYSPLIT and daily surface weather maps.

This is an example where the available surface dew point data and the general process used to derive a storm representative value isn't necessarily representative of the overall environment. This can occur when there is an intervening frontal boundary and the most critical moisture is along an elevated boundary above the surface and not best reflected by the surface dew point values. However, the data available is still limited and the standard process and choosing the KMMO values was determined the best solution for this storm.

Storm No. 2: Warner Park, TN

This storm was associated with a large moist air mass flowing from a general south to north direction off the Gulf of Mexico, with a deep moisture tap well into the southern Caribbean. This feed of moisture lasted for several days and is one of the reasons the timing utilized by TVA is appropriate for this IPMF analysis.

Recent research has termed these types of events as the "Mayan Express", with similar characteristics to an Atmospheric River event (Higgins, et al. 2011). From https://www.climate.gov/news-features/event-tracker/maya-express-behind-gulf-coast-soaking, (Di Liberto 2016), "Four-day rainfall totals near two feet caused devastating flooding in parts of Louisiana, Texas, and Mississippi in mid-March 2016. To blame was a seemingly never-ending stream of moisture straight out of the tropics." The surface analysis completed by TVA reflects these synoptic characteristics and shows a very uniform air mass in time and space over much of the regions from Louisiana to north Florida. TVA investigated several regions with dew point observations and chose the area over southern Mississippi because it exhibited high dew points over a large area with consistent values that were within the air mass advection region. Again, this type of rainfall would only be associated with extremely moist air masses, which were reflected by the 74-76°F 12-hour average values over a large region of Louisiana, Mississippi and Alabama. This analysis shows that the timeframe and location used by TVA is appropriate given the overall rainfall accumulation period and the continued moisture advection over time through the region and into the Warner Park storm center location.

Storm No. 3: Wellsville, NY

The air mass associated with this storm covered a large region of the eastern United States from the Gulf of Mexico through New England over a several day period. This was shown by the synoptic analysis of the storm after landfall as it traveled through the region producing several rainfall centers over a period of several days. As has been explicitly demonstrated, the Wellsville, NY center received moisture that was advected over the Piedmont region of the Carolinas and Virginia, which included very moist air supplied by the Gulf Stream off of the Atlantic. Again, this air mass was present for several days and the values chosen by TVA represent the overall air mass over the several day period. The surface dew points used were representative of the overall region in space and time, with low 70's through Virginia, North Carolina, and Maryland. Higher values were occurring at the same time along the immediate coast and Outer Banks region (mid 70's). Given that this storm produced record rainfalls and many floods of record in Pennsylvania, it was appropriate that the dew points chosen represented an extremely moist air mass. Justification could be made that the values along the Outer Banks could be used, which would have resulted in a lower IPMF. The current value of 1.29 is conservative given these factors.

Storm No. 4: Americus, GA

The overall air mass for this storm covered a large region extending from the Gulf of Mexico inland through Louisiana, Mississippi, Alabama, and Florida. The storm produced extreme rainfall because it was able to tap into this consistent moisture feed for several days while remaining over the same general region of Alabama and Georgia. The location TVA chose was just outside of the main rain shield and in a region reflective of this type of air mass over southern Louisiana and Mississippi. Values were consistent through a large domain, in the mid 70's over several days and also consistent with values as far away as north and west Florida. Even with these high dew points, the IPMF was still 1.21, which is conservative given the extreme amounts of rainfall associated with this storm.

The following storms, 5a through 5d, do not control PMP.

Storm No. 5a: Douglasville/Lafayette, GA

Hourly surface observations were investigated for stations in a large region surrounding the general air mass source region. The average wind speed for the 24-hour storm representative dew point was 5.0mph (~9.2 mph maximum) with an average wind direction from the southeast. The time for moisture to travel from the source location to the storm center (~350-miles) would be approximately 72.0-hours (38.0-hours for max wind speed). The general area wind speed and wind direction in relation moisture inflow timing at the storm also support the general air mass source and timing as identified in HYSPLIT and daily surface weather maps. The region chosen by TVA best represents the region that supplied the low-level moisture to the storm from the Gulf of Mexico given the general synoptic patterns and movement of the storm and frontal system.

Storm No. 5b: College Hill, OH

This storm is an example where available surface dew point values did not accurately capture the air mass that contributed to the extreme rainfall. Therefore, meteorological judgment was applied to derive a storm representative value that represented a moisture air mass that would have been required to produce the significant amount of rainfall that

occurred. This required the use of surface dew point observations that occurred in a timeframe that was not ideal for the storm environment. The average of 66.5F provided by the NRC in Table 3 is accurate given the exact timeframe. The value chosen by TVA of 68.5F was based on values that generally occurred after the main storm precipitation period, but within the same general air mass, region, and synoptic environment that resulted in the storm. Note that the use of 66.5F or 68.5F has no impact to the TVA PMP values as the in-place maximization factor was already at the upper limit at 1.48 and is capped at 1.50.

Storm No. 5c: Wooster, OH

Hourly surface observations were investigated for stations in a large region surrounding the general air mass source region. The average wind speed for the 24-hour storm representative dew point was 13.0mph (~19.5 mph maximum) with an average wind direction from the west-southwest. The time for moisture to travel from the source location to the storm center (~140miles) would be approximately 10.8-hours (7.2-hours for max wind speed). The general area wind speed and wind direction in relation to the moisture inflow timing at the storm also support the general air mass source and timing as identified in HYSPLIT and daily surface weather maps.

Storm No. 5d: Larto Lake, LA

Hourly surface observations were investigated for stations in a large region surrounding the general air mass source region originating from the Gulf of Mexico and crossing the Texas/Louisiana coastal regions. The average wind speed for the 24-hour storm representative dew point was 11.0mph (~17.0-20.0 mph maximum) with an average wind direction from the southwest. The time for moisture to travel from the source location to the storm center (~180miles) would be approximately 15.8-hours (10.4-hours for max wind speed). The general area wind speed and wind direction in relation to the moisture inflow timing at the storm also support the general air mass source and timing as identified in HYSPLIT and daily surface weather maps.

After extensive discussions and review with the NRC and TVA personnel, TVA has agreed to utilize the more conservative NRC storm representative dew point values for this PMP study for storms 1-4 in NRC Table 3. TVA will update the storm representative dew point values in the storm database and recalculate the PMP with those values implemented. This will affect Sections 6.8, 6.8.1, 6.8.4, and Appendix F of Calculation No. CDQ0000002016000041 and will be submitted as Revision 1 to Topical Report TVA-NPG-AWA16 (TVA Calculation CDQ0000002016000041).

RAI #12: Staff Independent Analysis of Dew Point Climatology

Technical Deficiency: Staff's independent evaluation of dew point climatology reveals that the licensee's values may be non-conservative due to potential data source and processing issues which may impact the estimated PMP values.

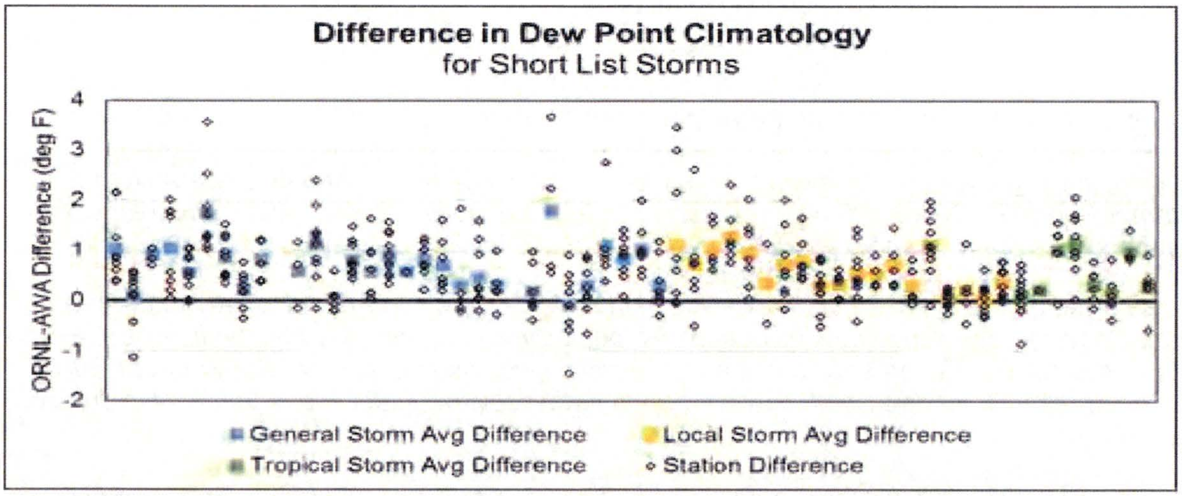
As a part of its assessment, staff reviewed the dew point climatology data provided by the licensee in response to RAI #1 and RAI #4; staff also independently evaluated these data to assess the reasonableness of the climatology data used.

Staff has concerns with the dew point climatology data source and processing used by TVA. While TVA used NOAA's TDL data set, NRC staff used NOAA's TD3505 data set. Both TD3505

and TDL data sets are officially released by NOAA, but the TDL data set used by TVA is basically a collection of instantaneous weather station observations whereas the TD3505 used by NRC is subjected to additional QC and processing by NOAA. Although both data sets are largely similar, there are some differences in the annual maximum series (AMS) caused by missing/erroneous values originally included in the TDL data set. This leads to different AMS and 100 y dew point estimates because of the existence and treatment of missing observations. Such differences result in systematic biases which could affect moisture maximization factors and transposition factors for all storms.

To assess the impacts of using different data (and some minor differences in processing), NRC staff conducted independent evaluation of dew point climatology for all short list storms, and it yielded a number of differences from TVA's evaluation. In general, NRC's independent evaluation resulted in higher dew point climatology values, with variation both temporally and spatially. For all else being equal, an increase in dew point climatology values will result in higher PMP estimates since historical storms would be subject to higher levels of moisture maximization.

NRC Figure 15 shows the difference in the NRC and TVA dew point climatology values for each comparable station for all short list storms. The stations selected represent the stations which would have most influenced the dew point climatology at the transpositioned moisture source location and for which climatology values were available from both the TVA and NRC data sets. Positive values indicate that NRC's evaluation resulted in higher dew point climatology values than TVA, while negative values indicate that NRC's evaluation resulted in lower dew point climatology values than TVA. On average, the difference for General, Local, and Tropical storms is +0.69 F, +0.61 F, and +0.52 F, respectively, with an overall average station difference of +0.65 F. Individual station differences range from -1.44 F to +3.67 F.



NRC Figure 15. Difference in dew point climatology values between NRC (ORNL) evaluation and TVA (AWA) evaluation for all short list storms

Each column of data points corresponds to one short list storm. Black-outlined diamonds represent station data (one diamond corresponds to the NRC-TVA difference for a single

station; for most storms, multiple stations were available for comparison) which influenced the dew point climatology at the transpositioned moisture source location and for which a direct comparison could be made. Colored squared represent the average difference in station data for each storm.

The deviations in climatology values resulting from the two analyses indicates a systematic bias in the overall values, with NRC's values typically 0.5 to 1.0 degree F higher than TVA's values.

<u>Request</u>:

Given the significant impacts noted above please update the dew point climatology using TD3505 dew point data and revising both the LIP and basin-wide PMP values accordingly or provide a justification for not updating it.

TVA Response:

(Note: The NRC question references RAI #1 and RAI #4. These RAI references actually refer to informal information provided in response to NRC's audit Information Need #1 and Information Need #4)

After further review and discussion with the NRC staff in regard to the most appropriate dew point climatology database, TVA has agreed to conservatively revise the dew point climatology applied in Calculation No. CDQ0000002016000041 and to utilize the NCEI TD3505 hourly dew point database. This will extend the period of record and provide additional dew point observational data for use in developing updated dew point climatology. The updated climatology will replace the previously used GIS layers. The updated storm adjustments will be processed and applied to each storm used for the PMP development. Updates to this data set are anticipated to affect Sections 5.1.1, 6.1.1, 6.5.1, 6.8.1, 6.8.4, and Appendix C of Calculation No. CDQ0000002016000041 and will be submitted as Revision 1 to Topical Report TVA-NPG-AWA16 (TVA Calculation CDQ0000002016000041).

<u>RAI #13</u>: Warner Park, TN Dew Point Duration Clarification

<u>Technical Deficiency</u>: Staff's review of the licensee's documentation and files related to the Warner Park, TN (SPAS 1208) storm representative dew point and dew point climatology data appears to indicate inconsistent use of dew point duration.

As a part of its assessment, staff reviewed the text and digital information related to the Warner Park storm representative dew point and dew point climatology provided by the licensee. Figure 404 in the Topical Report shows that a 12-h duration was used to analyze the Warner Park storm representative dew point; however, upon further review, staff believe that a 24-h duration was used.

Figure 415 in the Topical Report shows maximum average dew point data for several stations. Comparison with the "surface_summary" worksheet in the "SPAS_1208_Obs_data.xlsx" file reveals that the data plotted in Figure 415 correspond to the 24-h maximum average dew point. Also, staff confirmed that the licensee used a 12-h duration for the Warner Park dew point climatology. Therefore, it appears that the dew point duration was used inconsistently.

Staff understands that if this is the case, then the licensee's application could be slightly overly conservative; however, since it appears that a 12-h duration was intended, only the storm

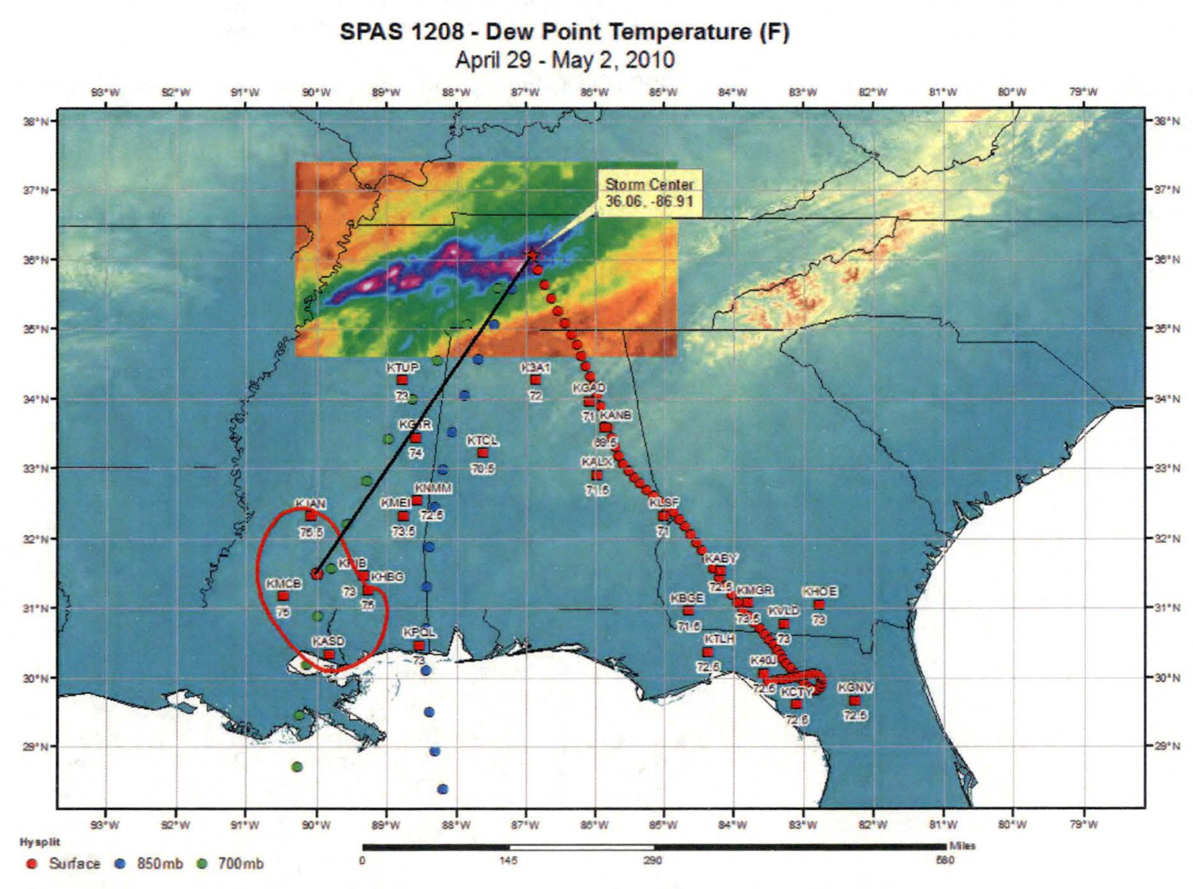
representative dew point would change. The 24-h value used by the licensee is 74.8 F based on the average of 4 stations (KHBG, KASD, KJAN, and KMCB); this value was rounded to 75.0 F by the licensee. The 12-h value computed by the licensee is 75.1 F based on the average of the same 4 stations and would be rounded to 75.0 F. Therefore, it appears that changing the storm representative dew point would not change the results of the Warner Park analysis.

<u>Request</u>: Provide confirmation of whether this dew point duration discrepancy exists, what the intended dew point duration is, and what (if any) changes are needed.

TVA Response:

The 12-hour duration was used in all calculations and is the appropriate duration to use. The image included in the report documentation mistakenly plotted the 24-hour average dew point data. The correct image is provided below (TVA Figure 32). As noted by the NRC, use of either the 12-hour or 24-hour duration results in the same storm representative value, 75.0 F.

A corrected Figure 415 will be provided in Appendix F of Calculation No. CDQ000002016000041 and will be submitted as Revision 1 to Topical Report TVA-NPG-AWA16 (TVA Calculation CDQ000002016000041).



TVA Figure 32. Updated storm representative dew point map using the 12-hour average dew point values

RAI #14: Scope of NRC's Review

Regulatory Deficiency: This topical report describes the work performed to calculate the Probable Maximum Precipitation for any location within the overall TVA basin and Local Intense Precipitation (LIP) at the BFN, SQN, and WBN sites. The Summary and Conclusions section of the Topical Report states that the precipitation values in the report replace those in HMRs 41, 45, 47, and 56 (which provide PMP estimates for the Tennessee River Basin, including LIP), as well as HMRs 51 and 52 (which provide PMP estimates for the eastern half of the continental US). NRC's regulatory authority limits its approval of the precipitation values contained in the Topical Report to only those values that could potentially result in flooding at TVA's nuclear plant sites.

Request: Please clarify that the scope of the NRC's requested review is concerned with potential SSPMP impacts at the 3 TVA nuclear power plant sites and does not necessarily reflect positions with respect to the entire Tennessee River watershed except as it impacts river flooding effects and local rainfall effects at the sites.

TVA Response

The scope of the NRC's requested review addresses only the potential SSPMP impacts at the Browns Ferry, Sequoyah and Watts Bar nuclear power plant sites and does not necessarily reflect NRC positions with respect to the entire Tennessee River watershed, except as it impacts river flooding effects and local rainfall effects at the nuclear plant sites.

Section 7.0 of Calculation No. CDQ000002016000041 will be revised to state that NRC review and approval of the calculation results is applicable only to the assessment of river flooding effects and local rainfall effects at the Browns Ferry, Sequoyah and Watts Bar nuclear plant sites and will be submitted as Revision 1 to Topical Report TVA-NPG-AWA16 (TVA Calculation CDQ000002016000041).

Attachment 1 - Referenced Data Files

1. RAI1 - Complete Storm Analysis Information for All Short List Storms
2. RAI2 - TVA Observed Hourly Dew Point Data Sheet for All Short List Storms
3. RAI3 - TVA Storm Adjustment Factor Feature Class Table for All Short List Storms
4. RAI4 - TVA Dew Point Climatology Data and GIS Layers
5. RAI5 - TVA Probable Maximum Precipitation Data and GIS Layers

SECTION F

Tennessee Valley Authority, 1101 Market Street, Chattanooga, Tennessee 37402

CNL-18-081

June 22, 2018

10 CFR 50.4

ATTN: Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Browns Ferry Nuclear Plant, Units 1, 2, and 3
Renewed Facility Operating License Nos. DPR-33, DPR-52, and DPR-68
NRC Docket Nos. 50-259, 50-260, and 50-296

Sequoyah Nuclear Plant, Units 1 and 2
Renewed Facility Operating License Nos. DPR-77 and DPR-79
NRC Docket Nos. 50-327 and 50-328

Watts Bar Nuclear Plant, Units 1 and 2
Facility Operating License Nos. NPF-90 and NPF-96
NRC Docket Nos. 50-390 and 50-391

Subject: Request for Review and Approval of Topical Report TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041," Revision 1

References:

1. TVA Letter to NRC, "Request for Review and Approval of Topical Report TVA-NPG-AWA16, 'TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041'," dated September 20, 2016 (ML16264A454)

2. TVA Letter to NRC, "Tennessee Valley Authority Response to NRC Request for Additional Information Related to Topical Report TVA NPG-AWA16, 'TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041'," dated April 19, 2018 (ML18117A225)

By letter dated September 20, 2016 (Reference 1), Tennessee Valley Authority (TVA) submitted topical report TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041," for review and approval. Approval of this Topical Report was requested to support Probable Maximum Flood calculations and associated with planned License Amendment Requests for Sequoyah Nuclear Plant (SQN), Units 1 and 2, and Watts Bar Nuclear Plant (WBN), Units 1 and 2, and a potential License Amendment Request for Browns Ferry Nuclear Plant, Units 1, 2, and 3.

By letter dated April 19, 2018 (Reference 2), TVA responded to a Request for Additional Information (RAI) associated with the NRC review of the topical report. As described in the Enclosure of Reference 2, a revision to Topical Report TVA-NPG-AWA16 was required to fully resolve the RAIs associated with dew point climatology.

Enclosure 1 of this letter provides Topical Report TVA-NPG-AWA16, Revision 1. This revision replaces the topical report provided in Reference 1 in its entirety.

This revised topical report describes the work performed to calculate the Probable Maximum Precipitation (PMP) for any location within the overall Tennessee Valley Authority (TVA) basin and Local Intense Precipitation (LIP) at the BFN, SQN, and WBN sites. The report outlines the process, data, and methods used to analyze storms and develop the PMP values. Results and background data are provided and discussed, along with comparisons to previous PMP work in the region. Relevant background data, input calculation, and reference materials are included in various attachments.

Applied Weather Associates (AWA) considers portions of the data supporting the topical report (Enclosure 1, Appendix H, Attachment 1) to be proprietary and therefore exempt from public disclosure pursuant to 10 CFR 2.390. An affidavit for withholding information, executed by AWA, is provided in Enclosure 2. Therefore, on behalf of AWA, TVA requests that Enclosure 1, Appendix H, Attachment 1 be withheld from public disclosure in accordance with the AWA affidavit and the provisions of 10 CFR 2.390.

There are no regulatory commitments associated with this submittal. Please address any questions regarding this request to Russell Thompson at 423-751-2567.

Respectfully,

E. K. Henderson
Director, Nuclear Regulatory Affairs

Enclosures:

1. TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ000002016000041," Revision 1
2. Affidavit - Applied Weather Associates

cc (Enclosures):

NRC Regional Administrator - Region II
NRC Senior Resident Inspector - Browns Ferry Nuclear Plant
NRR Project Manager - Browns Ferry Nuclear Plant
NRC Senior Resident Inspector - Sequoyah Nuclear Plant
NRR Project Manager - Sequoyah Nuclear Plant
NRR Project Manager - Watts Bar Nuclear Plant

SECTION G

Tennessee Valley Authority, 1101 Market Street, Chattanooga, Tennessee 37402

CNL-18-103

September 6, 2018

10 CFR 50.4

ATTN: Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Browns Ferry Nuclear Plant, Units 1, 2, and 3
Renewed Facility Operating License Nos. DPR-33, DPR-52, and DPR-68
NRC Docket Nos. 50-259, 50-260, and 50-296

Sequoyah Nuclear Plant, Units 1 and 2
Renewed Facility Operating License Nos. DPR-77 and DPR-79
NRC Docket Nos. 50-327 and 50-328

Watts Bar Nuclear Plant, Units 1 and 2
Facility Operating License Nos. NPF-90 and NPF-96
NRC Docket Nos. 50-390 and 50-391

Subject: Topical Report TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041," Revision 1, Supplemental Information

Reference: 1. TVA Letter to NRC, "Request for Review and Approval of Topical Report TVA-NPG-AWA16, 'TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041', Revision 1," dated June 22, 2018 (ML18192A510)

In the Reference letter dated June 22, 2018, Tennessee Valley Authority (TVA) submitted Topical Report TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041," Revision 1, for review and approval. Approval of this Topical Report was requested to support Probable Maximum Flood calculations associated with planned License Amendment Requests for Sequoyah Nuclear Plant (SQN), Units 1 and 2, and Watts Bar Nuclear Plant (WBN), Units 1 and 2, and a potential License Amendment Request for Browns Ferry Nuclear Plant, Units 1, 2, and 3.

The purpose of this letter is to provide supplemental information in support of the review of Topical Report TVA-NPG-AWA16, Revision 1. Specifically, several data sets that were used in the development of Topical Report TVA-NPG-AWA16, Revision 1, are provided in Enclosure 1.

Applied Weather Associates (AWA) considers portions of the data sets in Enclosure 1 (Enclosure 1, Data Set #1 - Dewpoint Climatology) to be proprietary and therefore exempt from public disclosure pursuant to 10 CFR 2.390. An affidavit for withholding information, executed by AWA, is provided in Enclosure 2. Therefore, on behalf of AWA, TVA requests that Enclosure 1, Data Set #1 - Dewpoint Climatology, be withheld from public disclosure in accordance with the AWA affidavit and the provisions of 10 CFR 2.390.

There are no regulatory commitments associated with this submittal. Please address any questions regarding this request to Russell Thompson at 423-751-2567.

Respectfully,

E. K. Henderson
Director, Nuclear Regulatory Affairs

Enclosures:

1. TVA-NPG-AWA16, "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041," Revision 1, Data Sets
2. Affidavit - Applied Weather Associates

cc (w/o Enclosures):

NRC Regional Administrator - Region II
NRC Senior Resident Inspector - Browns Ferry Nuclear Plant
NRR Project Manager - Browns Ferry Nuclear Plant
NRC Senior Resident Inspector - Sequoyah Nuclear Plant
NRR Project Manager - Sequoyah Nuclear Plant
NRC Senior Resident Inspector - Watts Bar Nuclear Plant
NRR Project Manager - Watts Bar Nuclear Plant