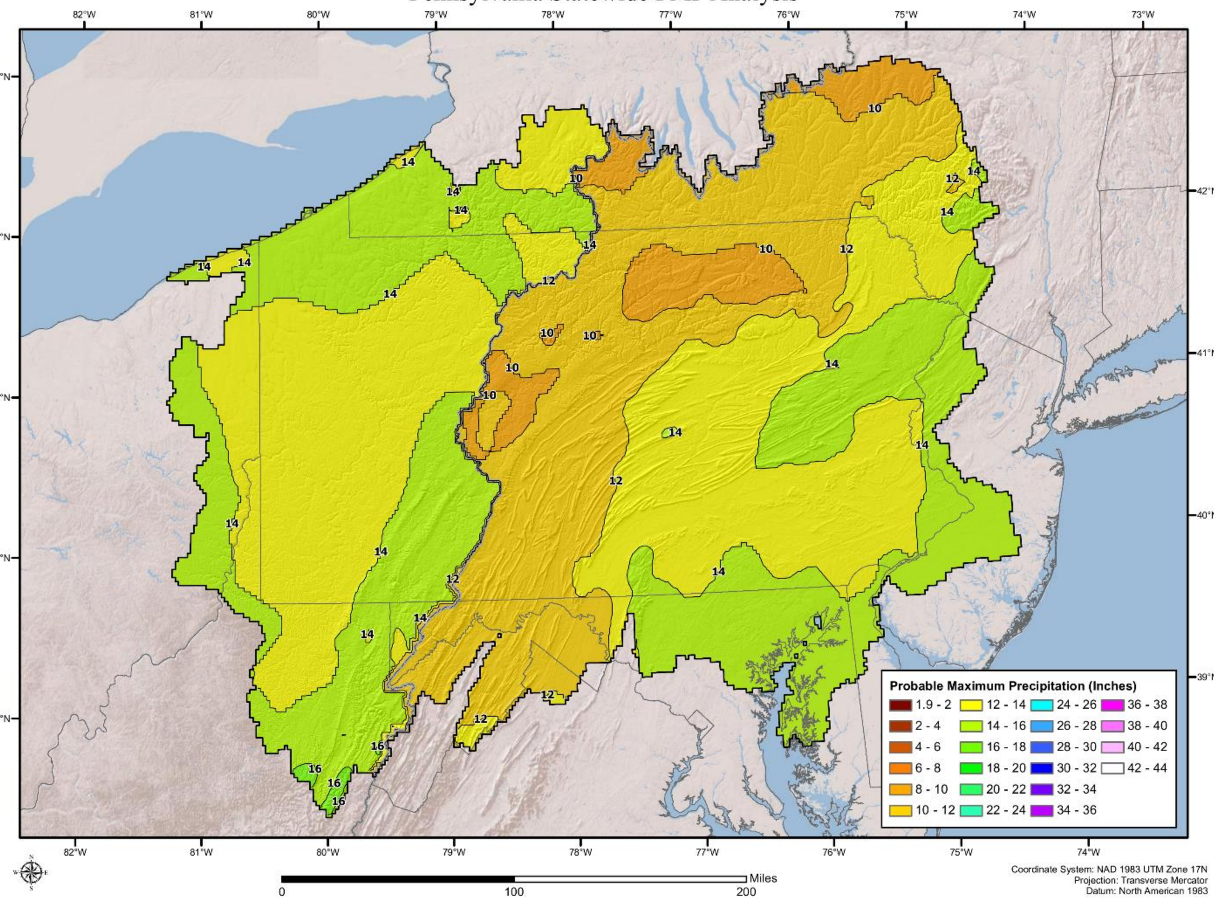
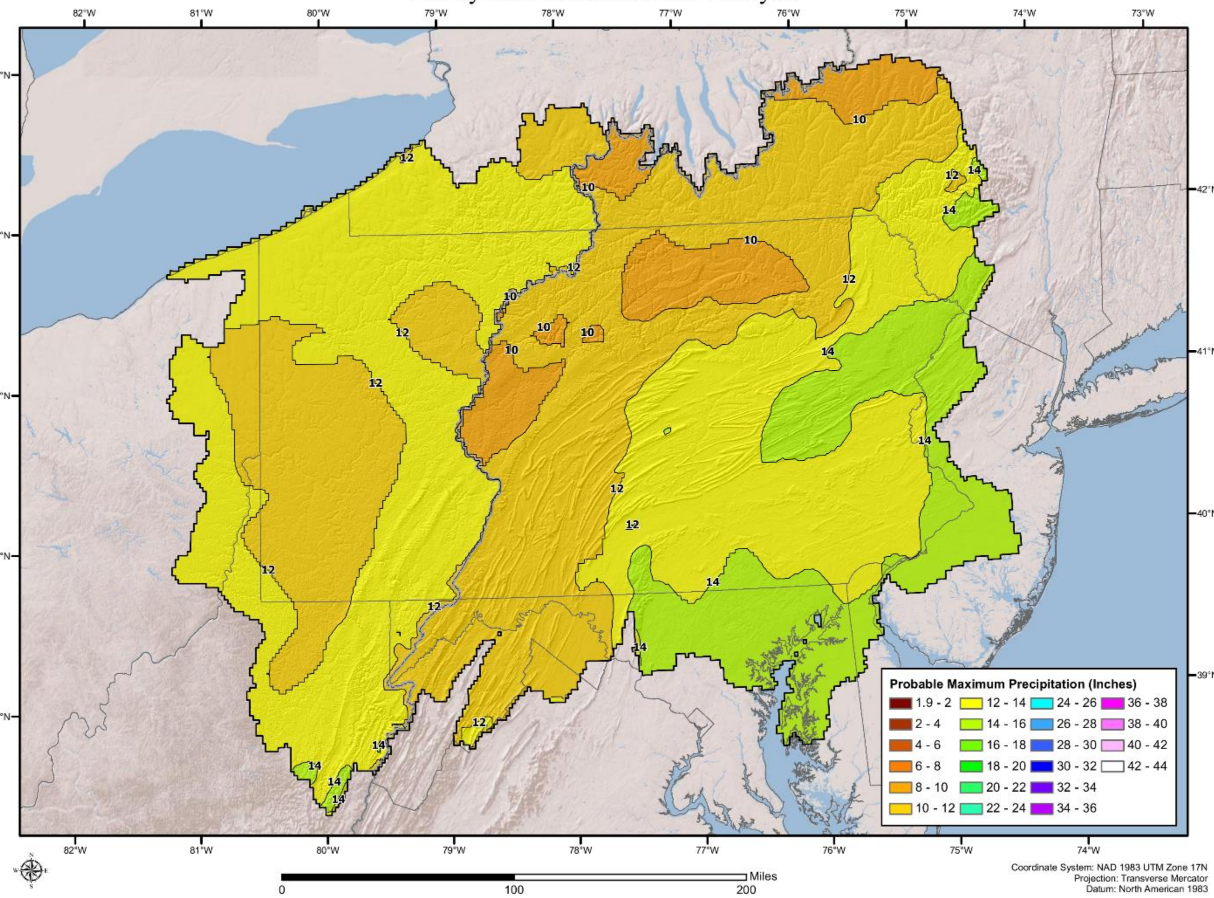
Appendix A
Probable Maximum Precipitation (PMP) Maps

General Storms

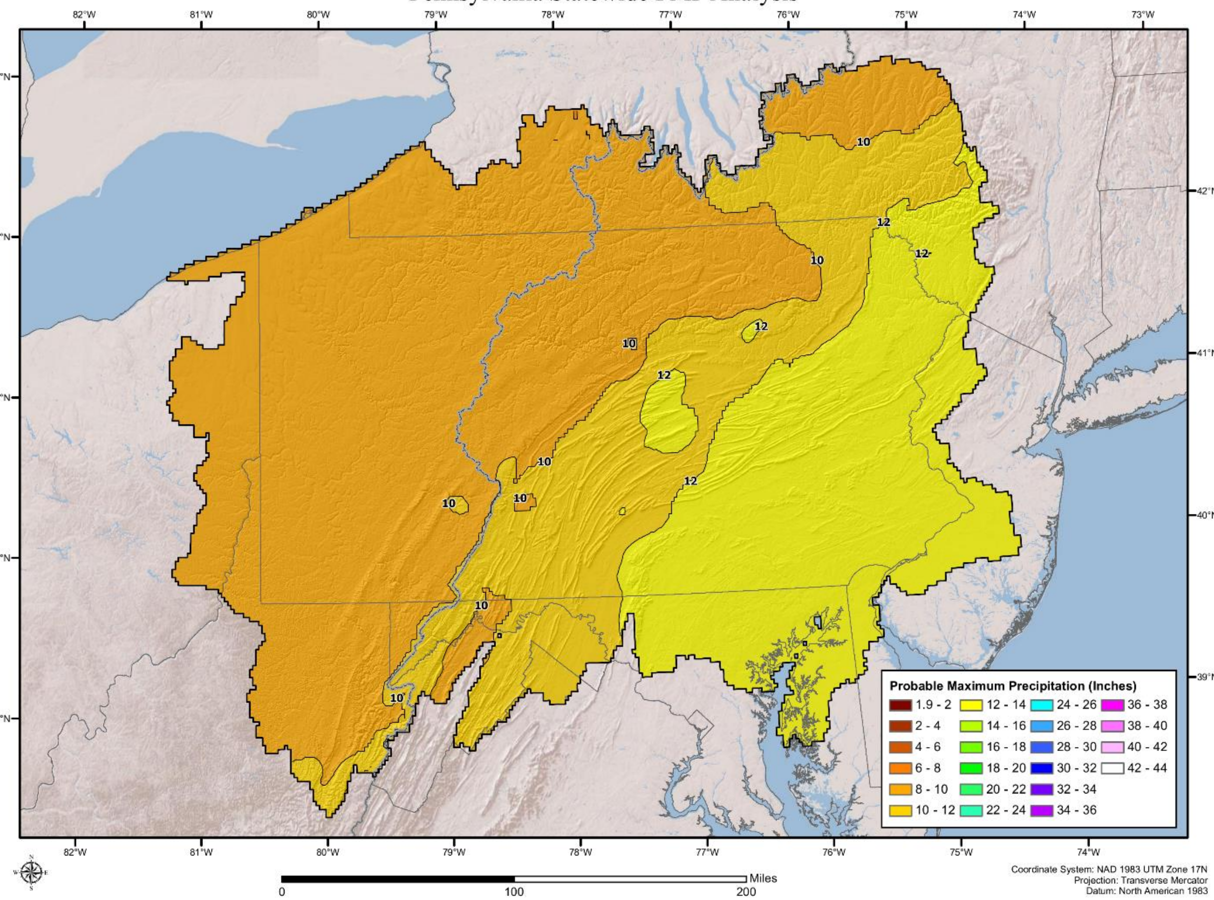
6-Hour General Storm Probable Maximum Precipitation (10 mi²)
Pennsylvania Statewide PMP Analysis

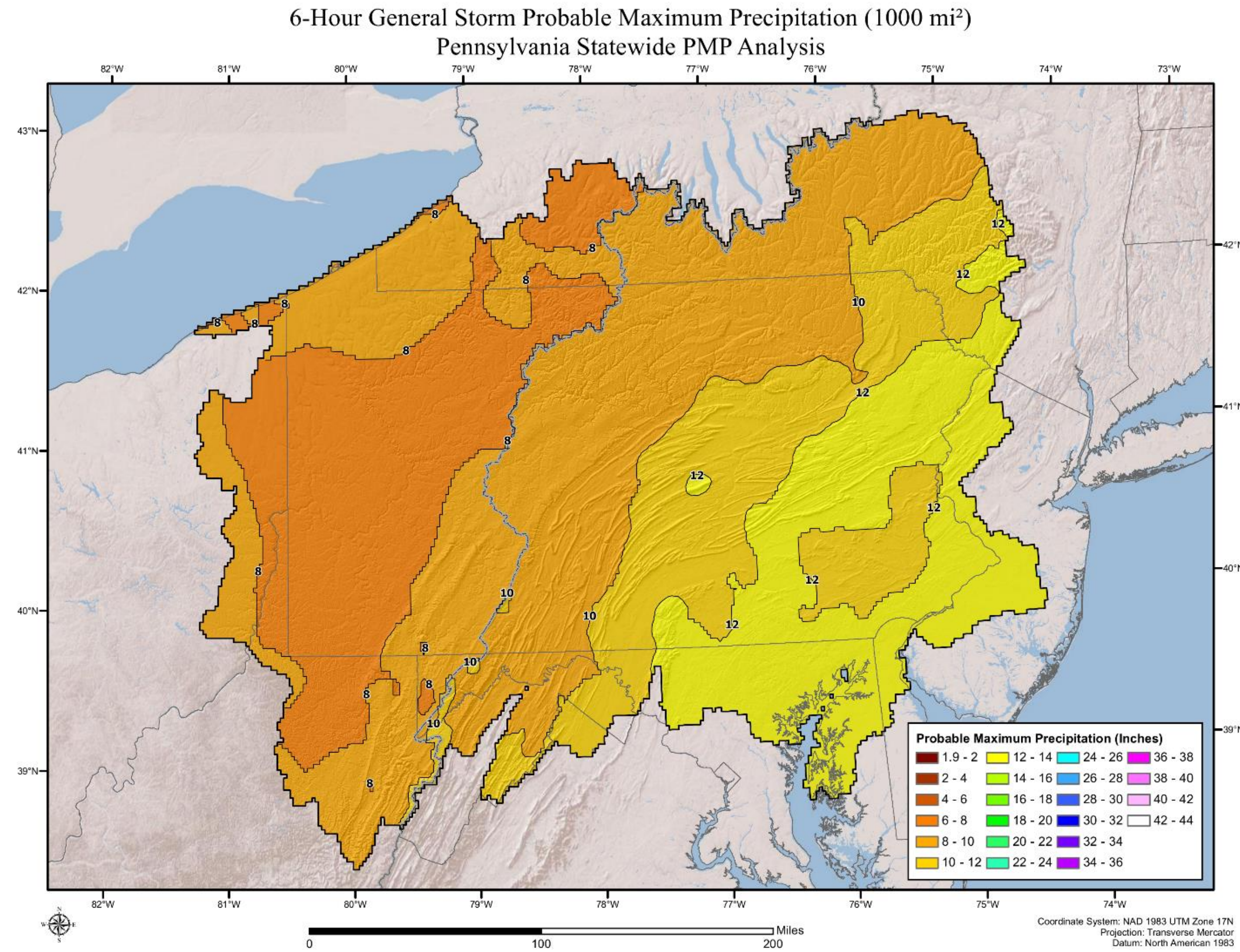


6-Hour General Storm Probable Maximum Precipitation (100 mi²)
Pennsylvania Statewide PMP Analysis

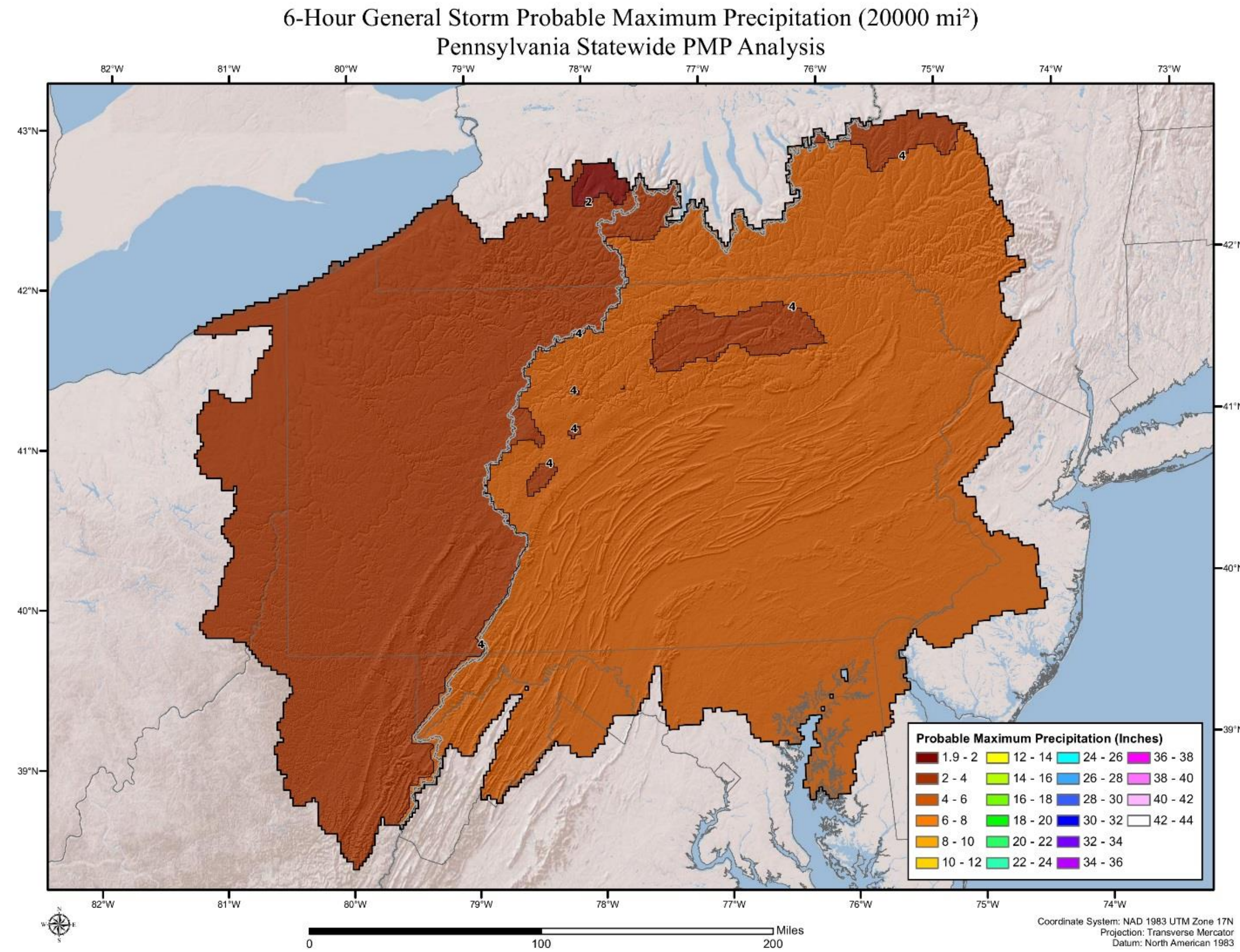


6-Hour General Storm Probable Maximum Precipitation (500 mi²)
Pennsylvania Statewide PMP Analysis



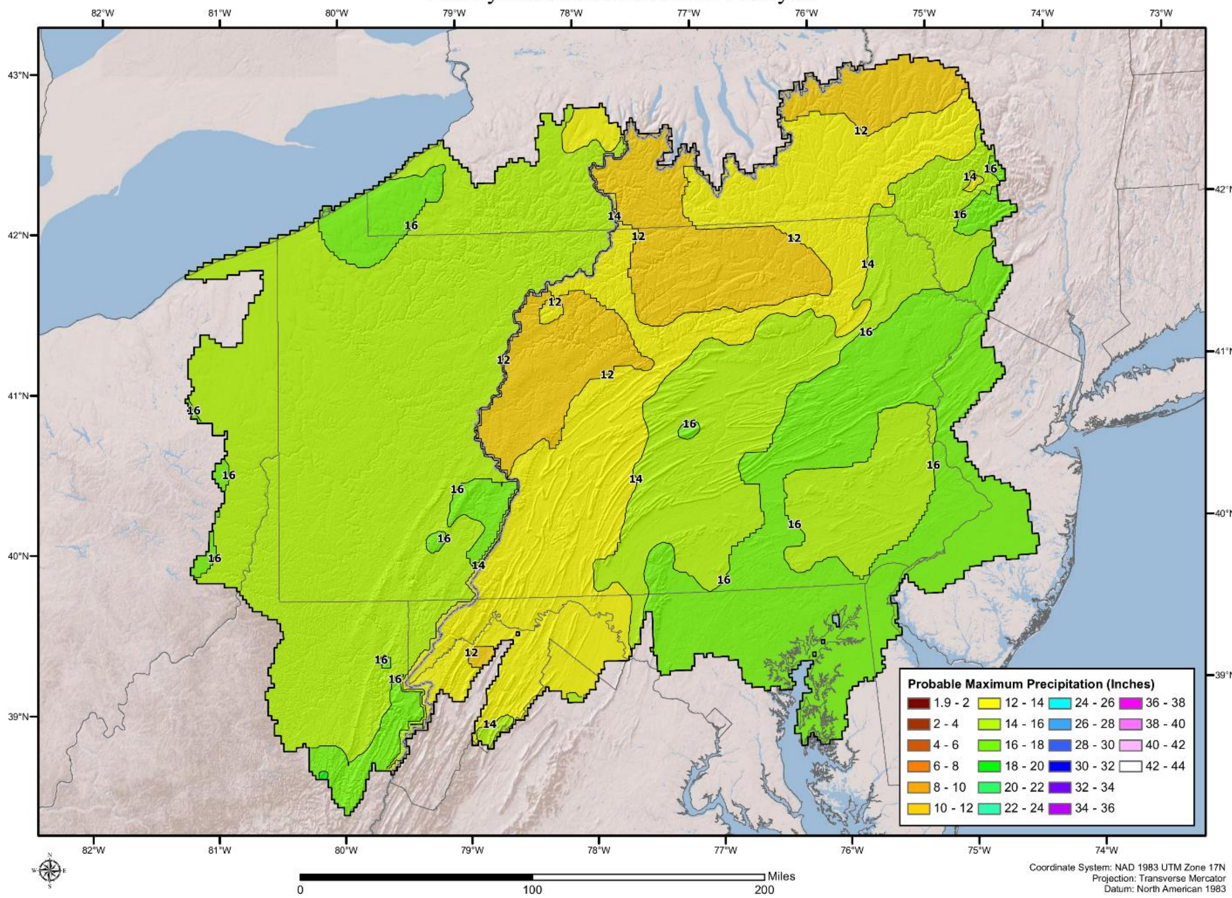


6-Hour General Storm Probable Maximum Precipitation (1000 mi²)
Pennsylvania Statewide PMP Analysis
Probable Maximum Precipitation (Inches)
1.9 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 12
12 - 14
14 - 16
16 - 18
18 - 20
20 - 22
22 - 24
24 - 26
26 - 28
28 - 30
30 - 32
32 - 34
34 - 36
36 - 38
38 - 40
40 - 42
42 - 44
Miles
0
100
200
Coordinate System: NAD 1983 UTM Zone 17N
Projection: Transverse Mercator
Datum: North American 1983

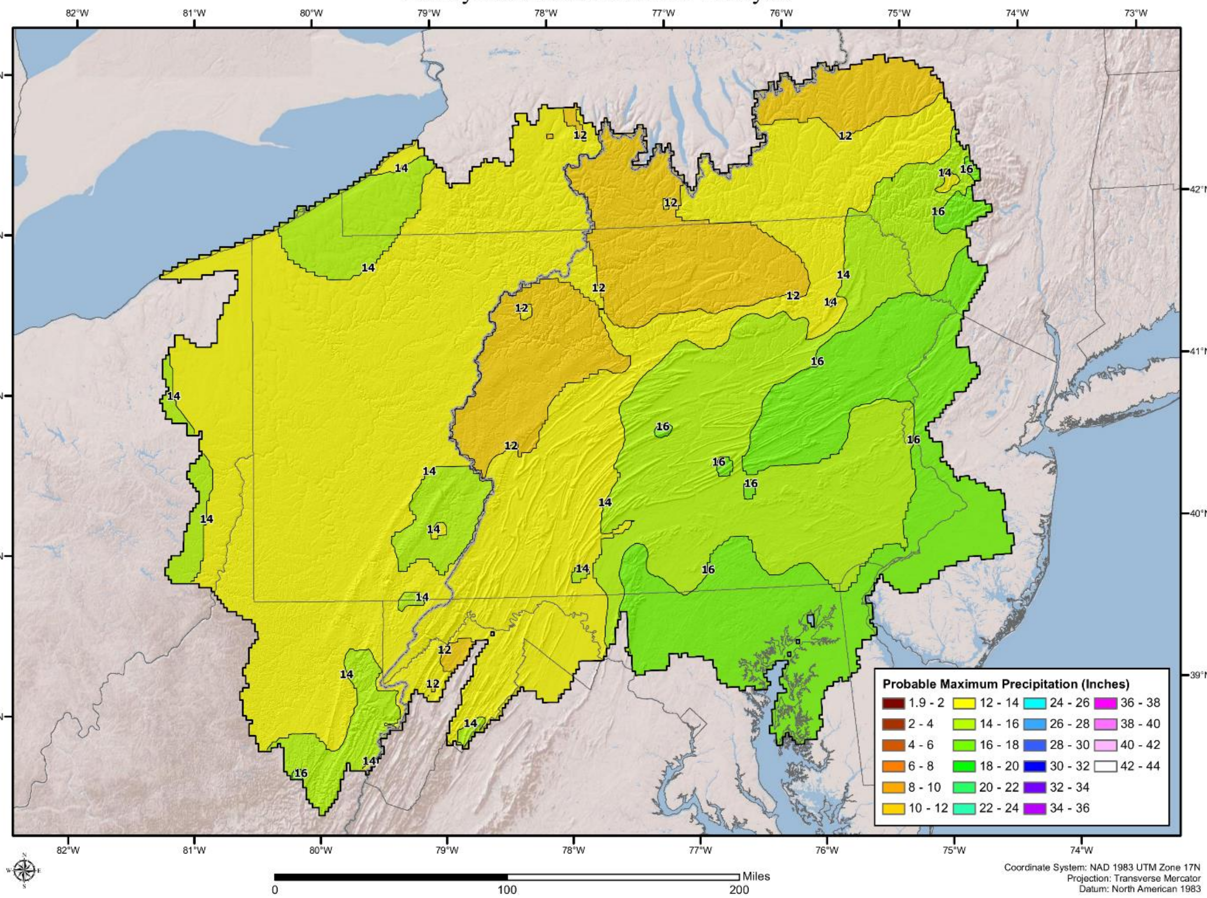


6-Hour General Storm Probable Maximum Precipitation (20000 mi²)
Pennsylvania Statewide PMP Analysis
Probable Maximum Precipitation (Inches)
1.9 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 12
12 - 14
14 - 16
16 - 18
18 - 20
20 - 22
22 - 24
24 - 26
26 - 28
28 - 30
30 - 32
32 - 34
34 - 36
36 - 38
38 - 40
40 - 42
42 - 44
Miles
0
100
200
Coordinate System: NAD 1983 UTM Zone 17N
Projection: Transverse Mercator
Datum: North American 1983

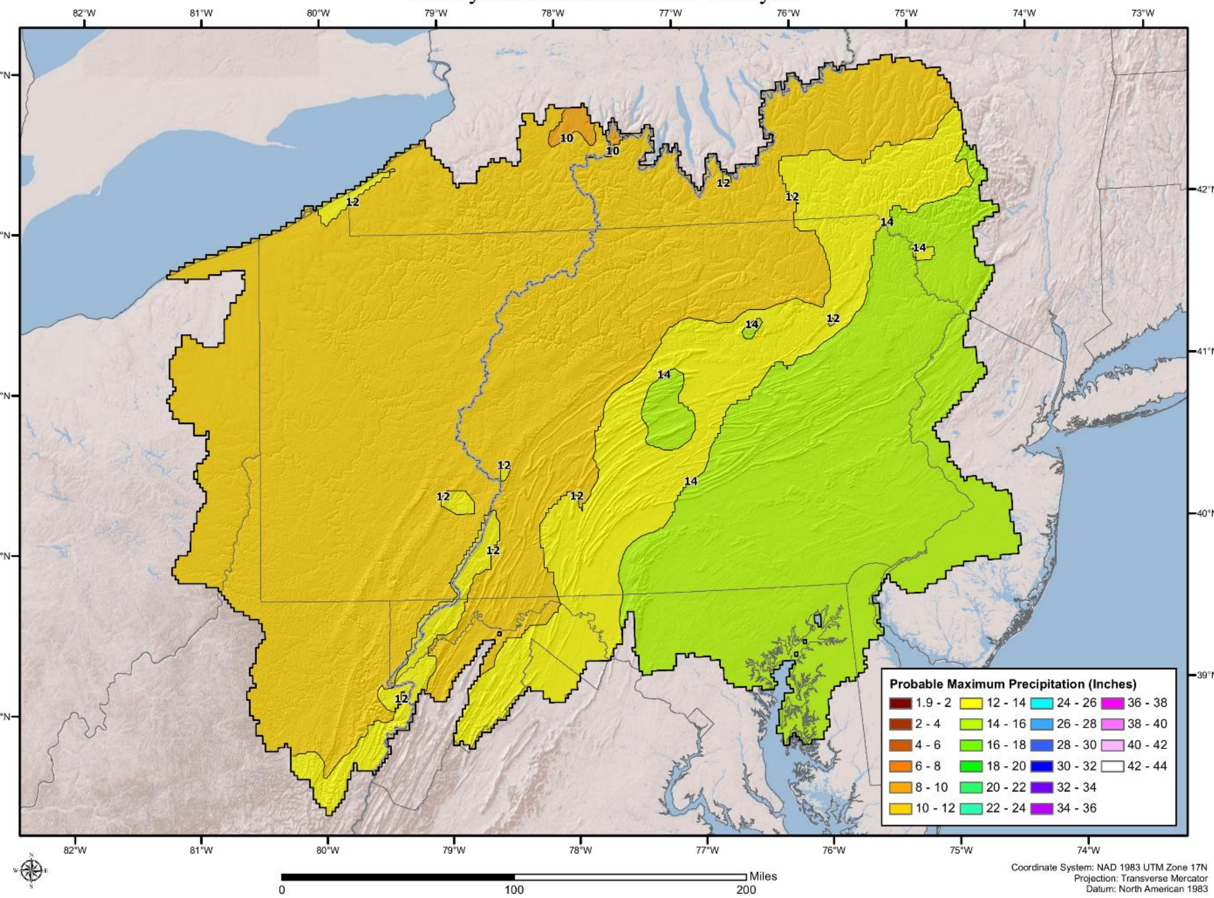
12-Hour General Storm Probable Maximum Precipitation (10 mi²)
Pennsylvania Statewide PMP Analysis



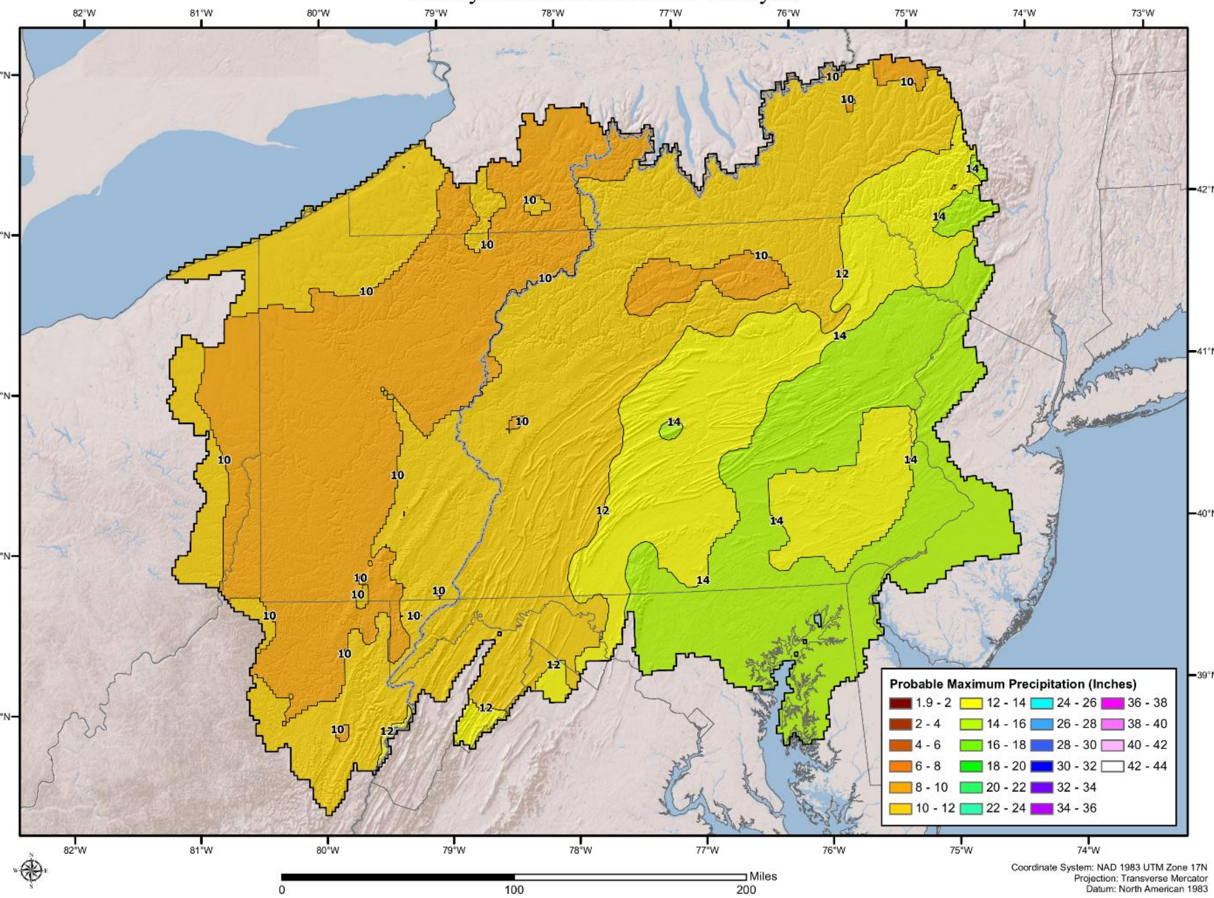
12-Hour General Storm Probable Maximum Precipitation (100 mi²)
Pennsylvania Statewide PMP Analysis



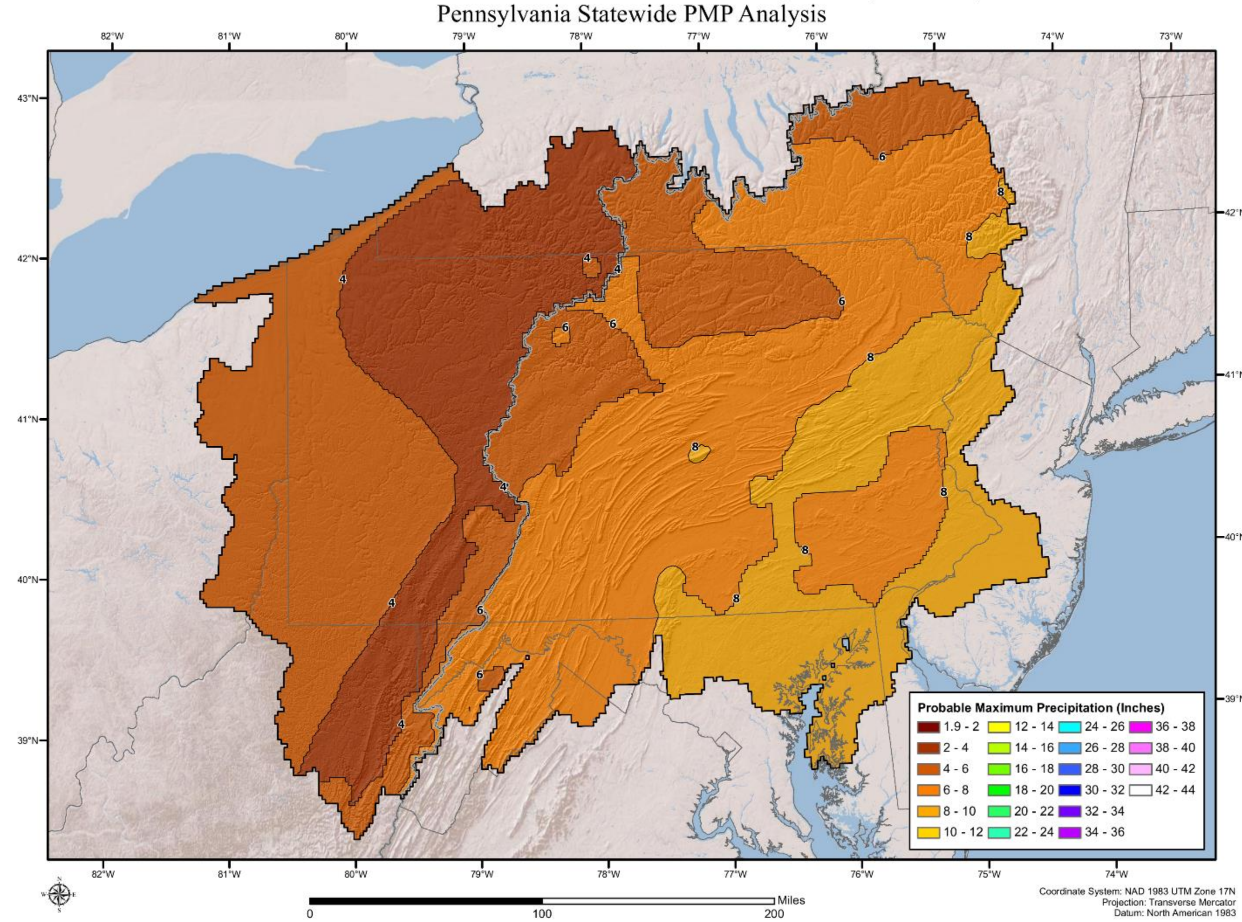
12-Hour General Storm Probable Maximum Precipitation (500 mi²)
Pennsylvania Statewide PMP Analysis



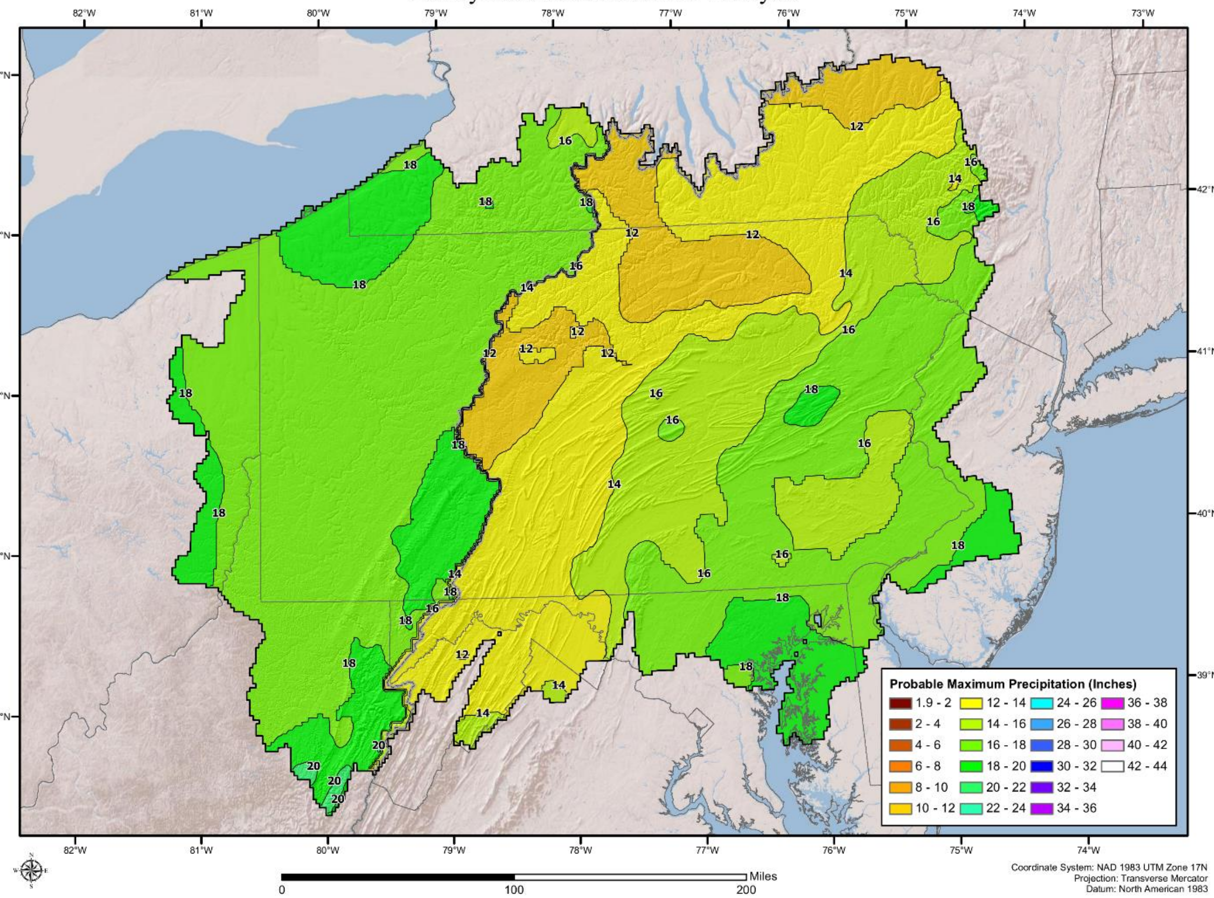
12-Hour General Storm Probable Maximum Precipitation (1000 mi²)
Pennsylvania Statewide PMP Analysis



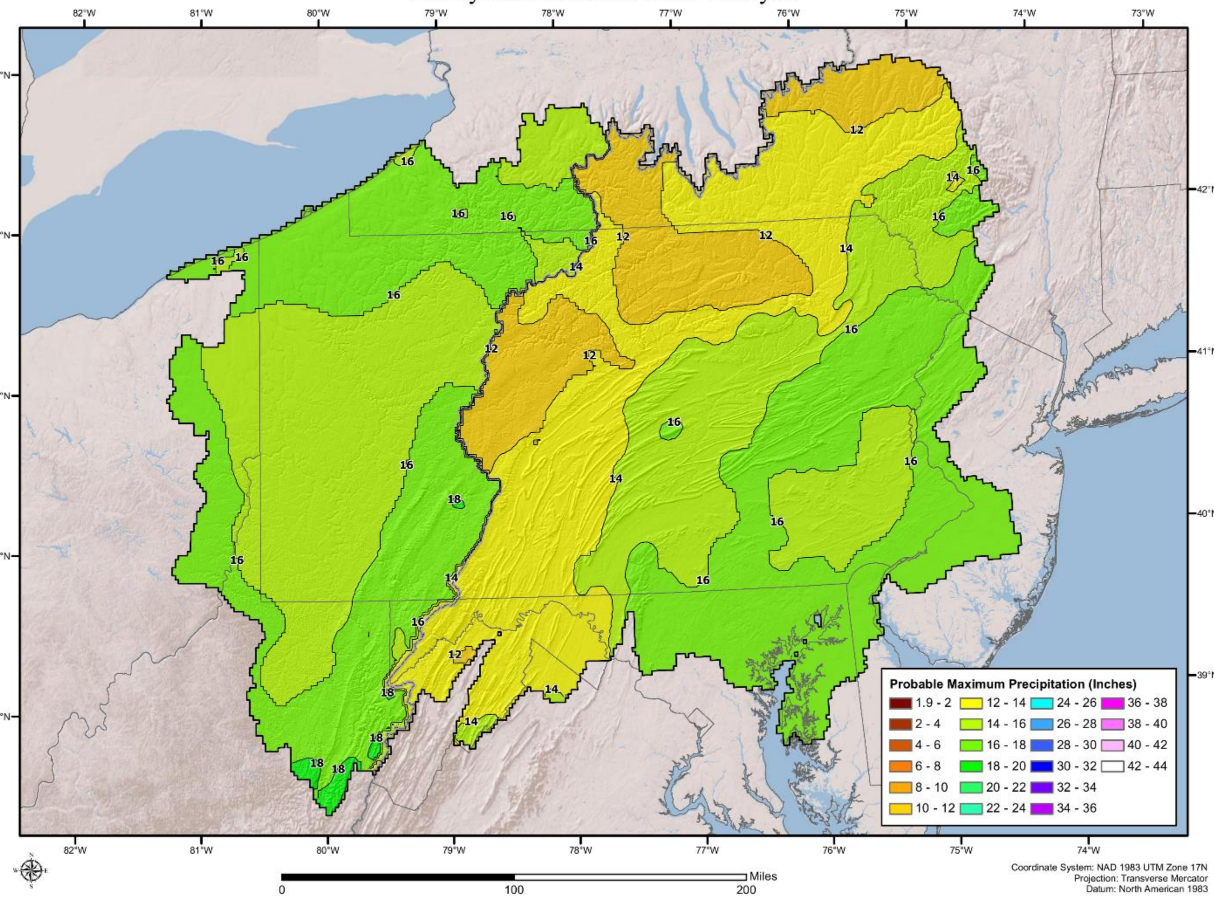
12-Hour General Storm Probable Maximum Precipitation (20000 mi²)
Pennsylvania Statewide PMP Analysis



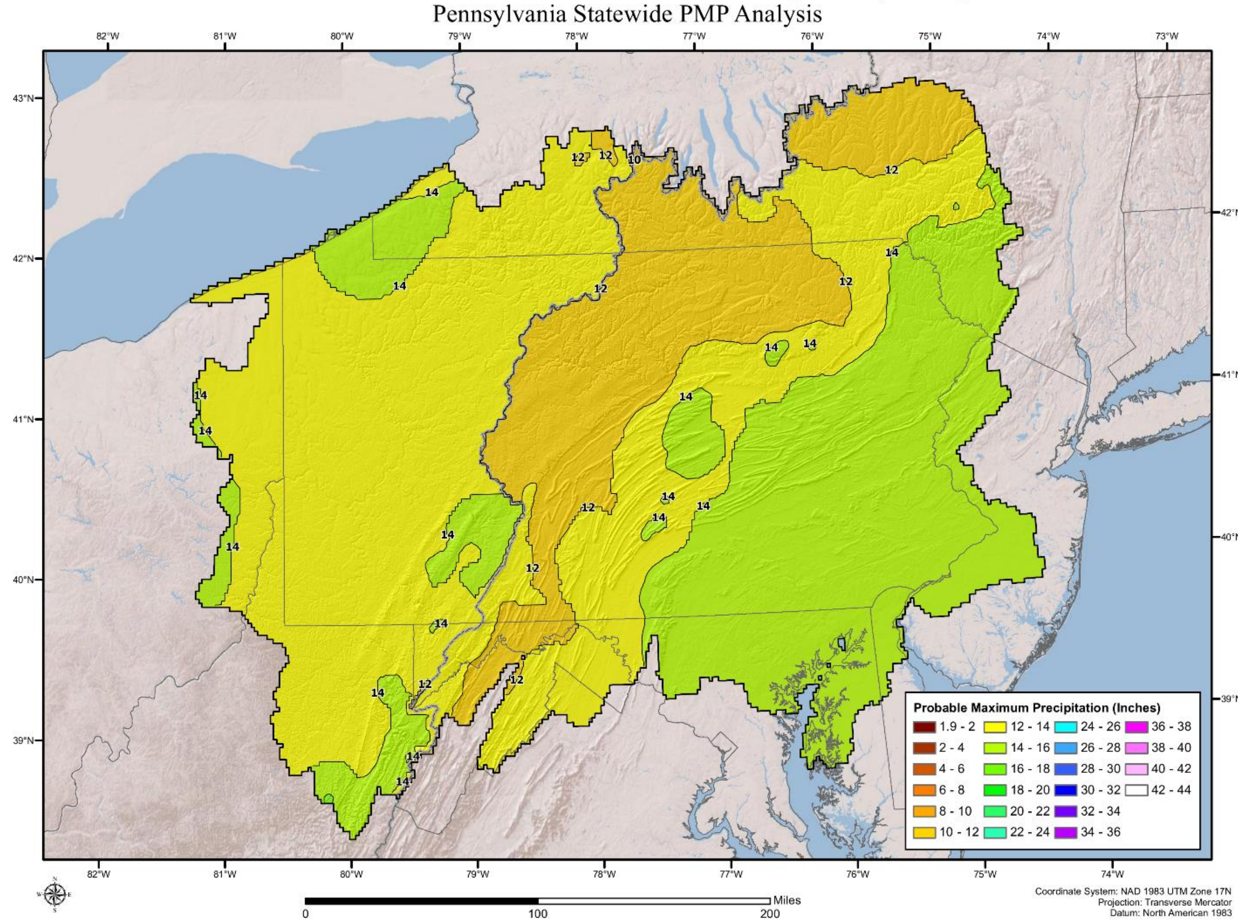
24-Hour General Storm Probable Maximum Precipitation (10 mi²)
Pennsylvania Statewide PMP Analysis



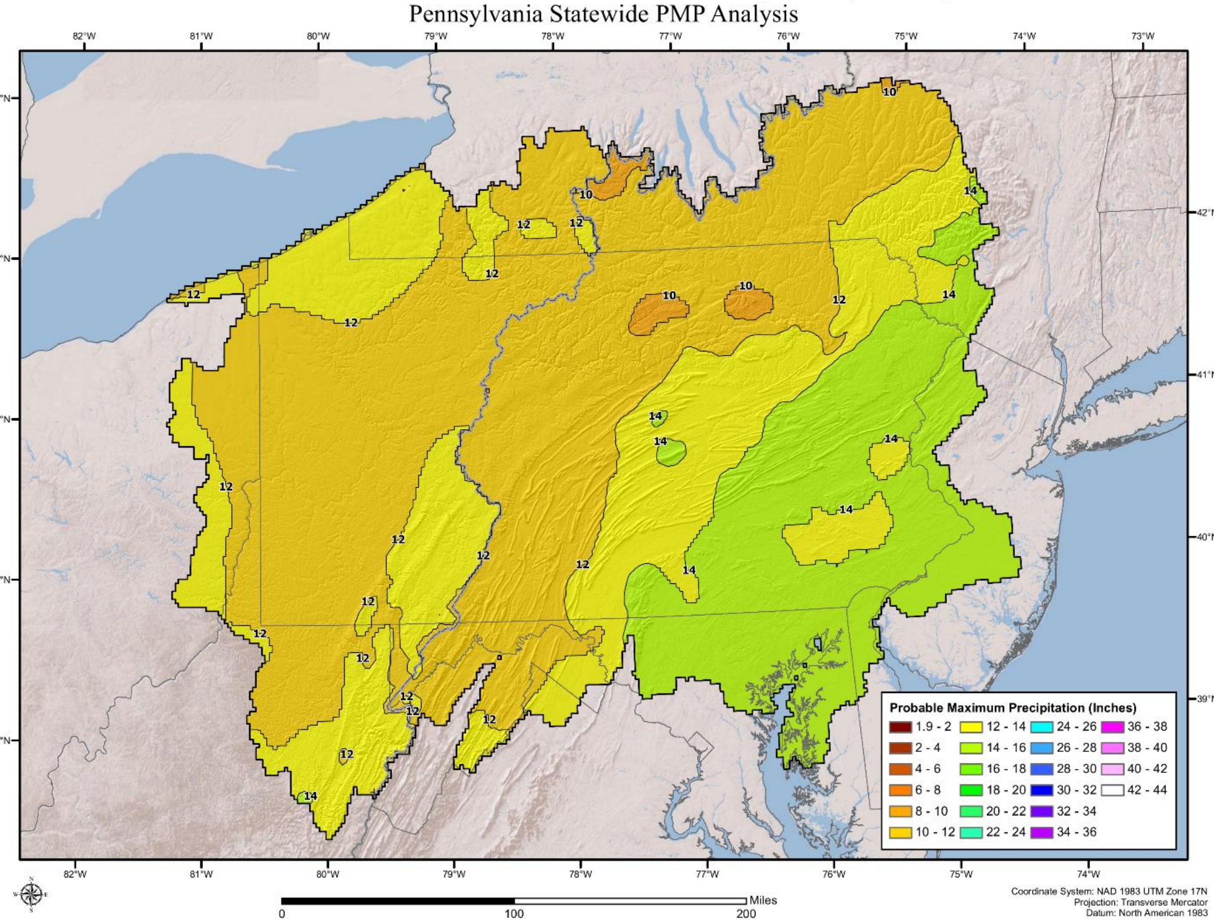
24-Hour General Storm Probable Maximum Precipitation (100 mi²)
Pennsylvania Statewide PMP Analysis



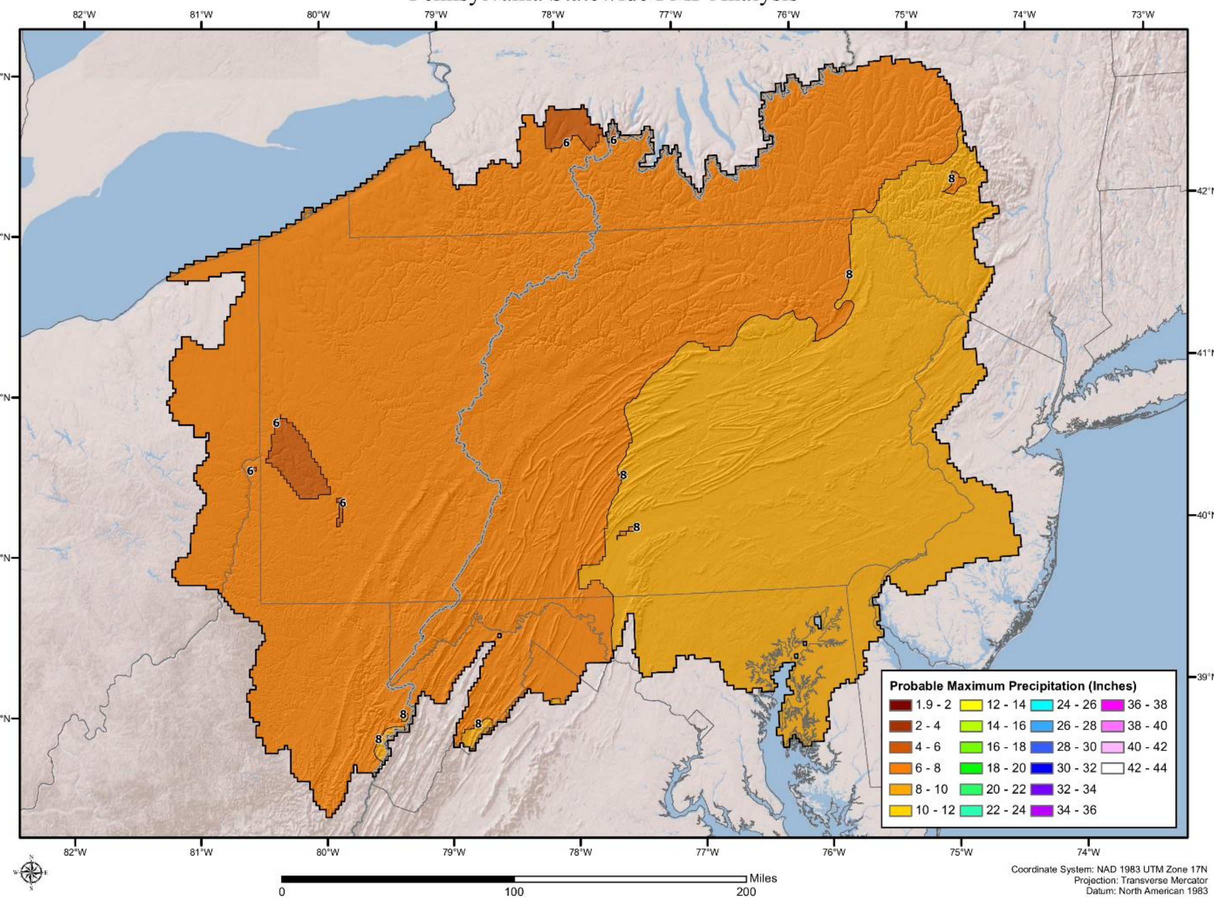
24-Hour General Storm Probable Maximum Precipitation (500 mi²)
Pennsylvania Statewide PMP Analysis



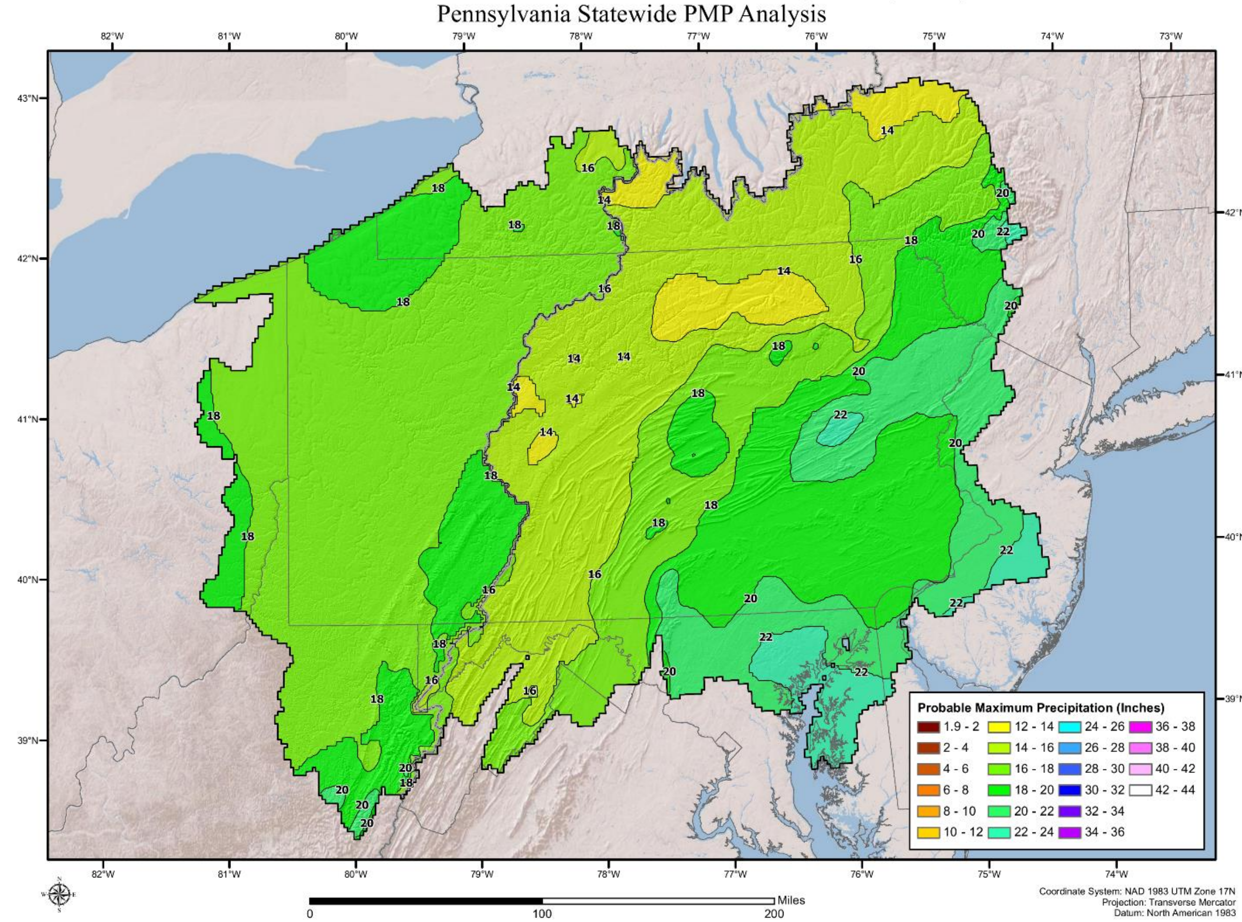
24-Hour General Storm Probable Maximum Precipitation (1000 mi²)
Pennsylvania Statewide PMP Analysis



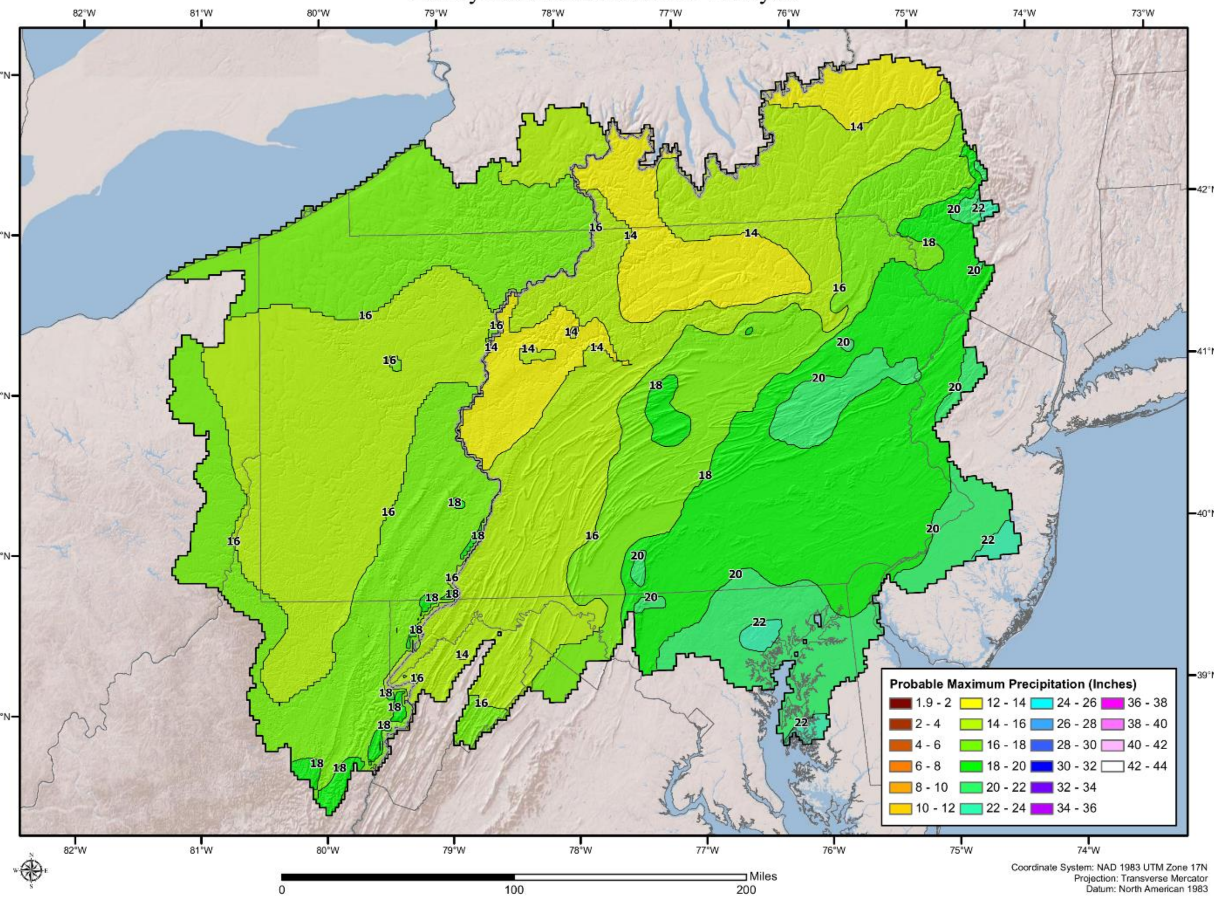
24-Hour General Storm Probable Maximum Precipitation (20000 mi²)
Pennsylvania Statewide PMP Analysis



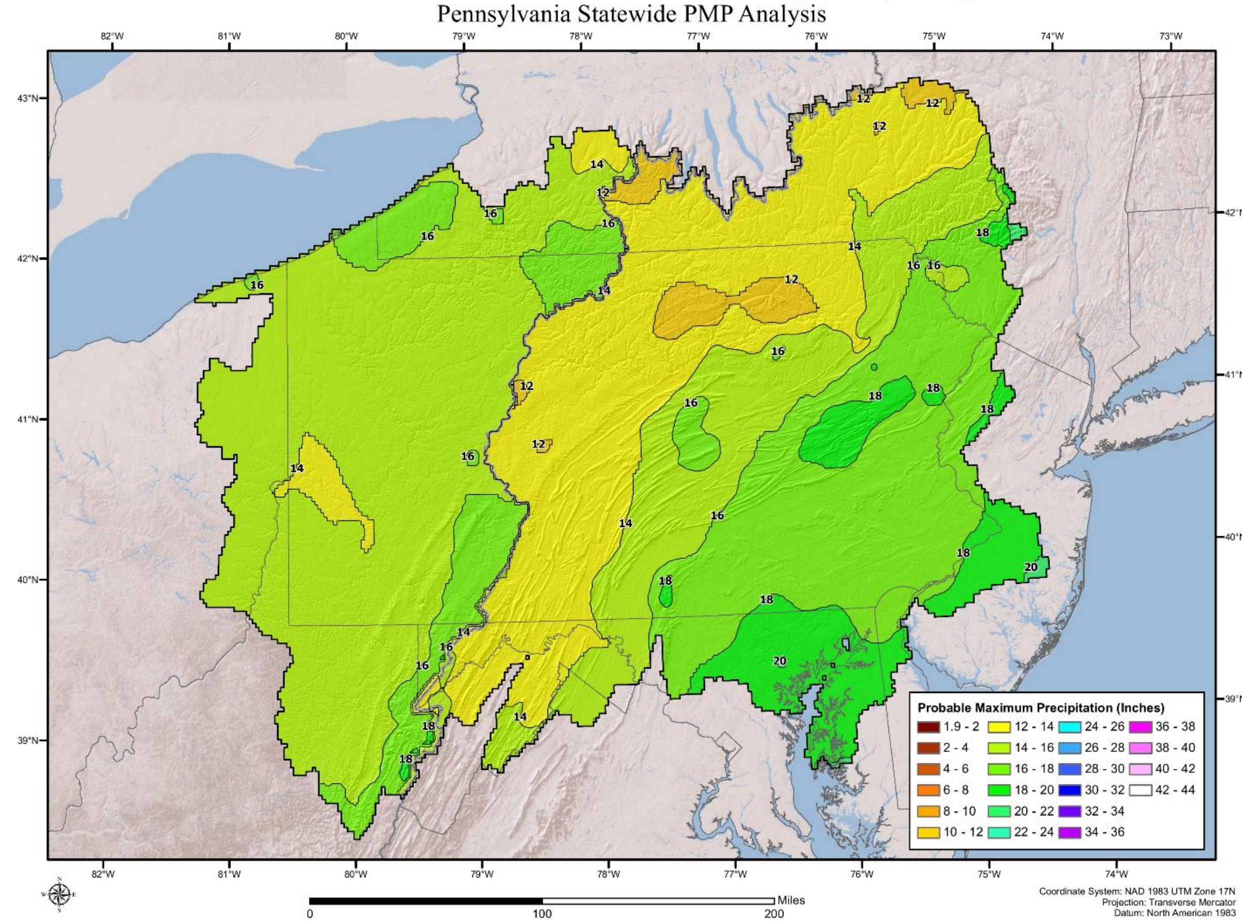
72-Hour General Storm Probable Maximum Precipitation (10 mi²)
Pennsylvania Statewide PMP Analysis



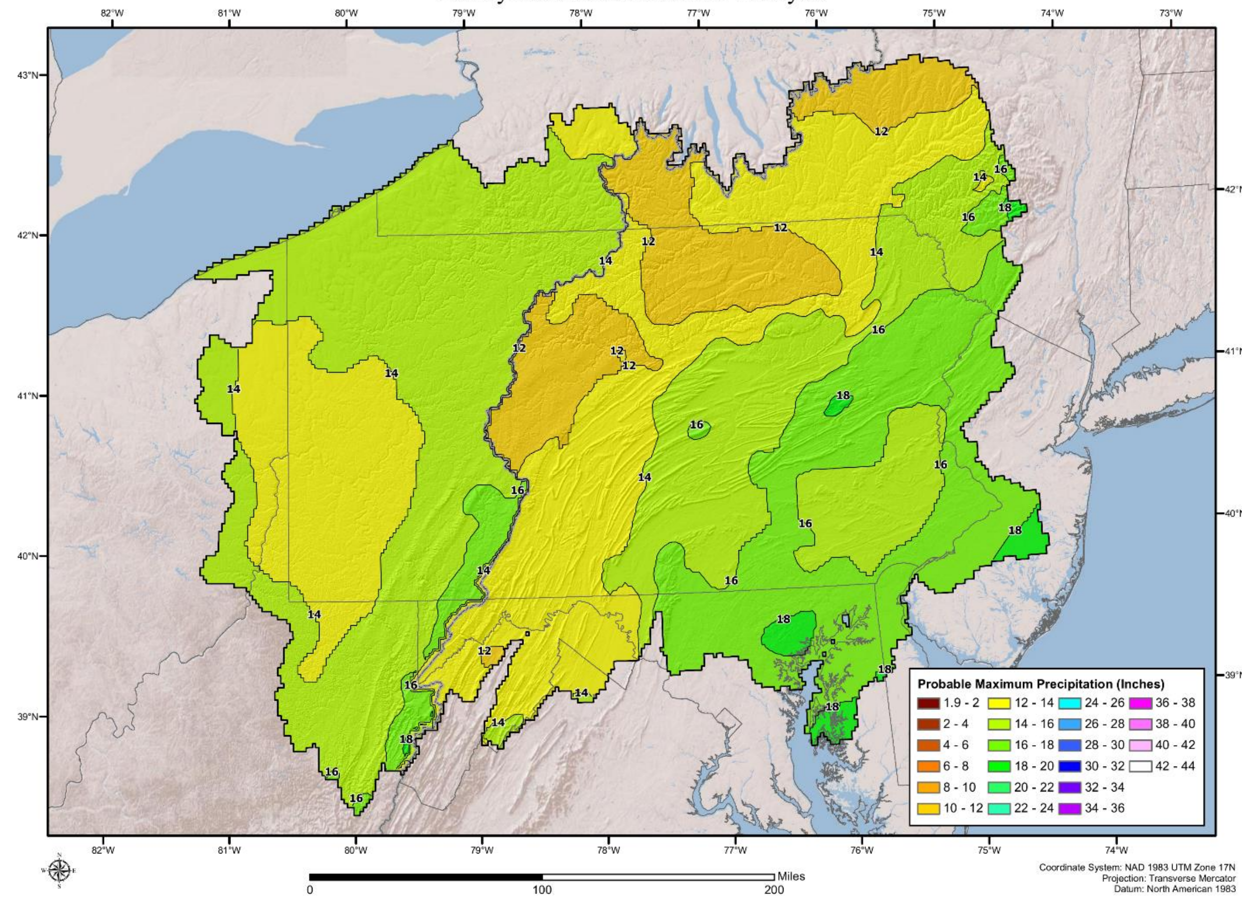
72-Hour General Storm Probable Maximum Precipitation (100 mi²)
Pennsylvania Statewide PMP Analysis



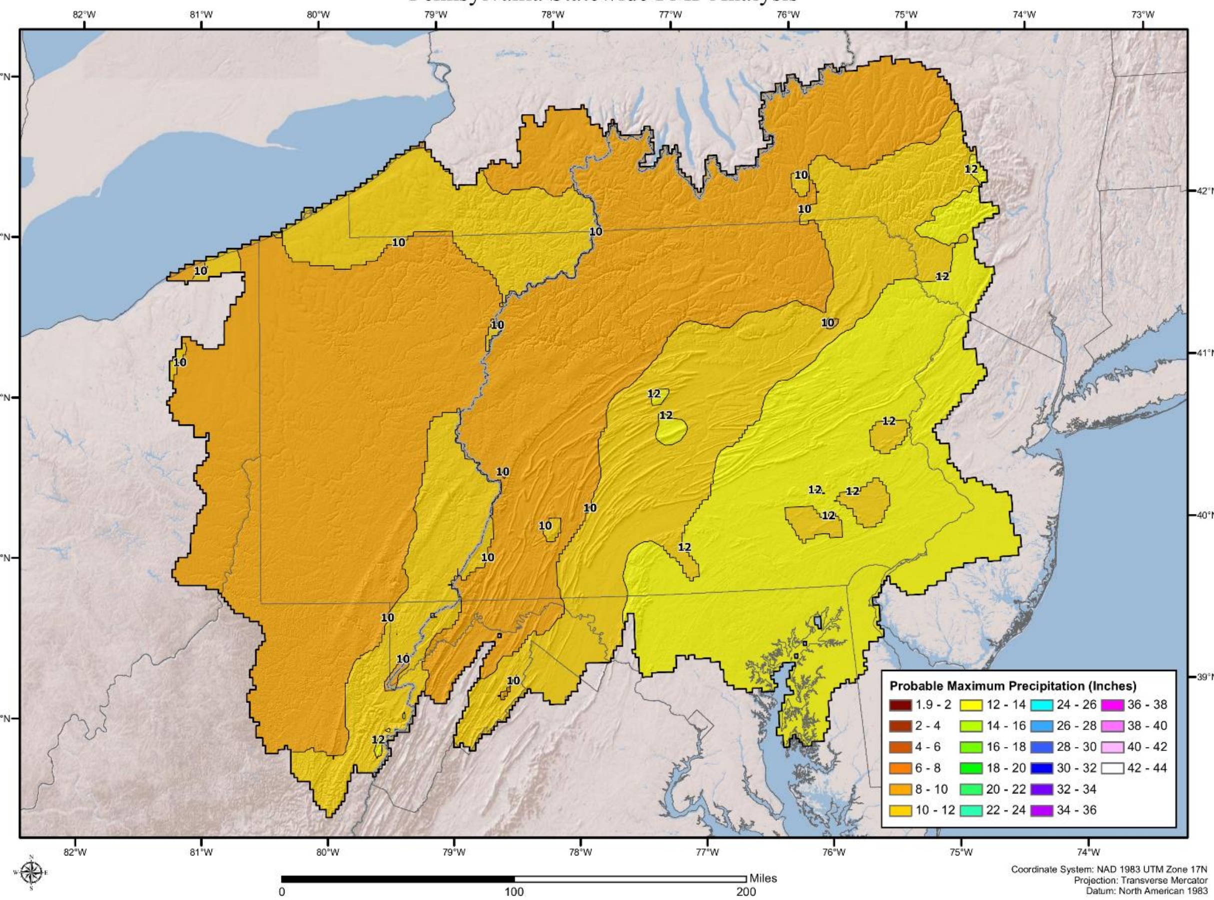
72-Hour General Storm Probable Maximum Precipitation (500 mi²)
Pennsylvania Statewide PMP Analysis



72-Hour General Storm Probable Maximum Precipitation (1000 mi²)
Pennsylvania Statewide PMP Analysis

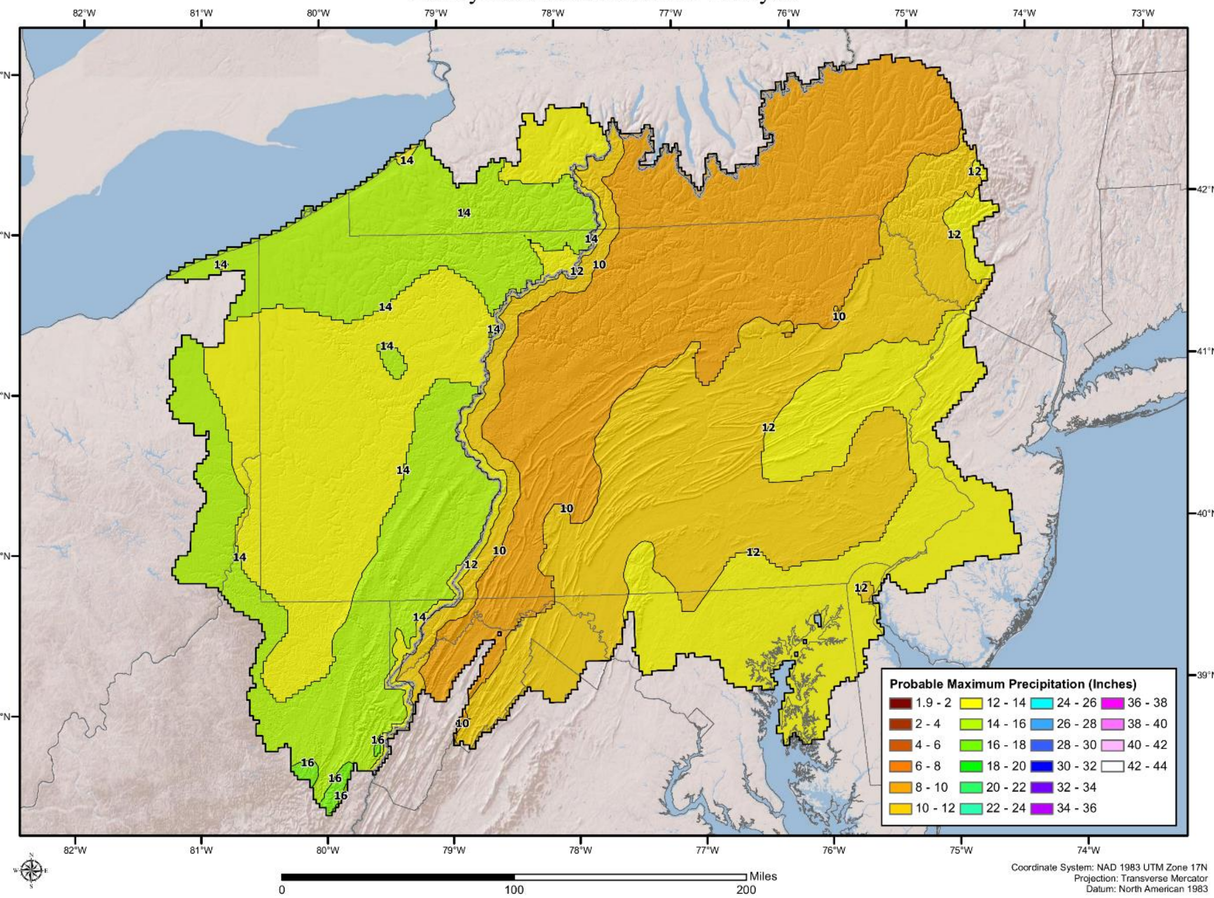


72-Hour General Storm Probable Maximum Precipitation (20000 mi²)
Pennsylvania Statewide PMP Analysis

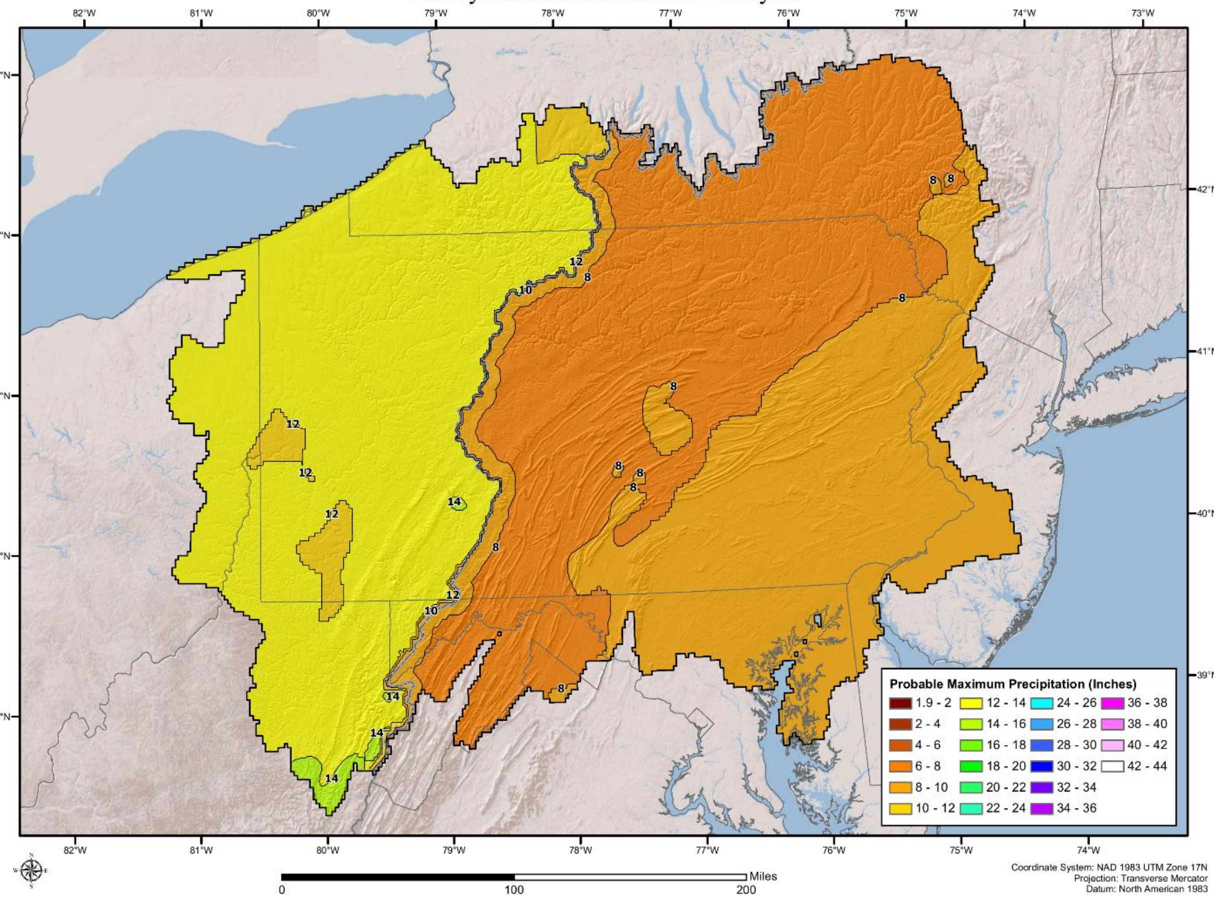


Local Storms

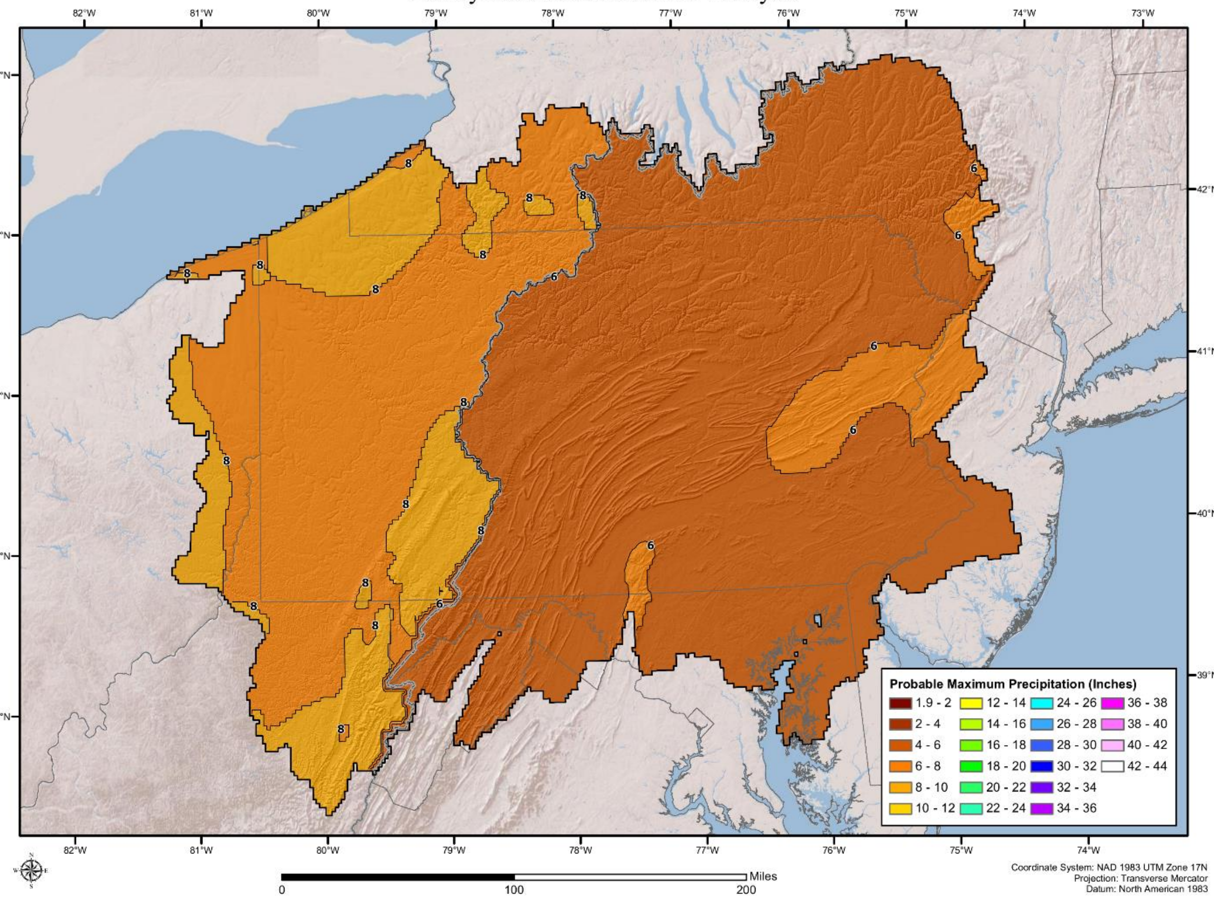
1-Hour Local Storm Probable Maximum Precipitation (1 mi²)
Pennsylvania Statewide PMP Analysis



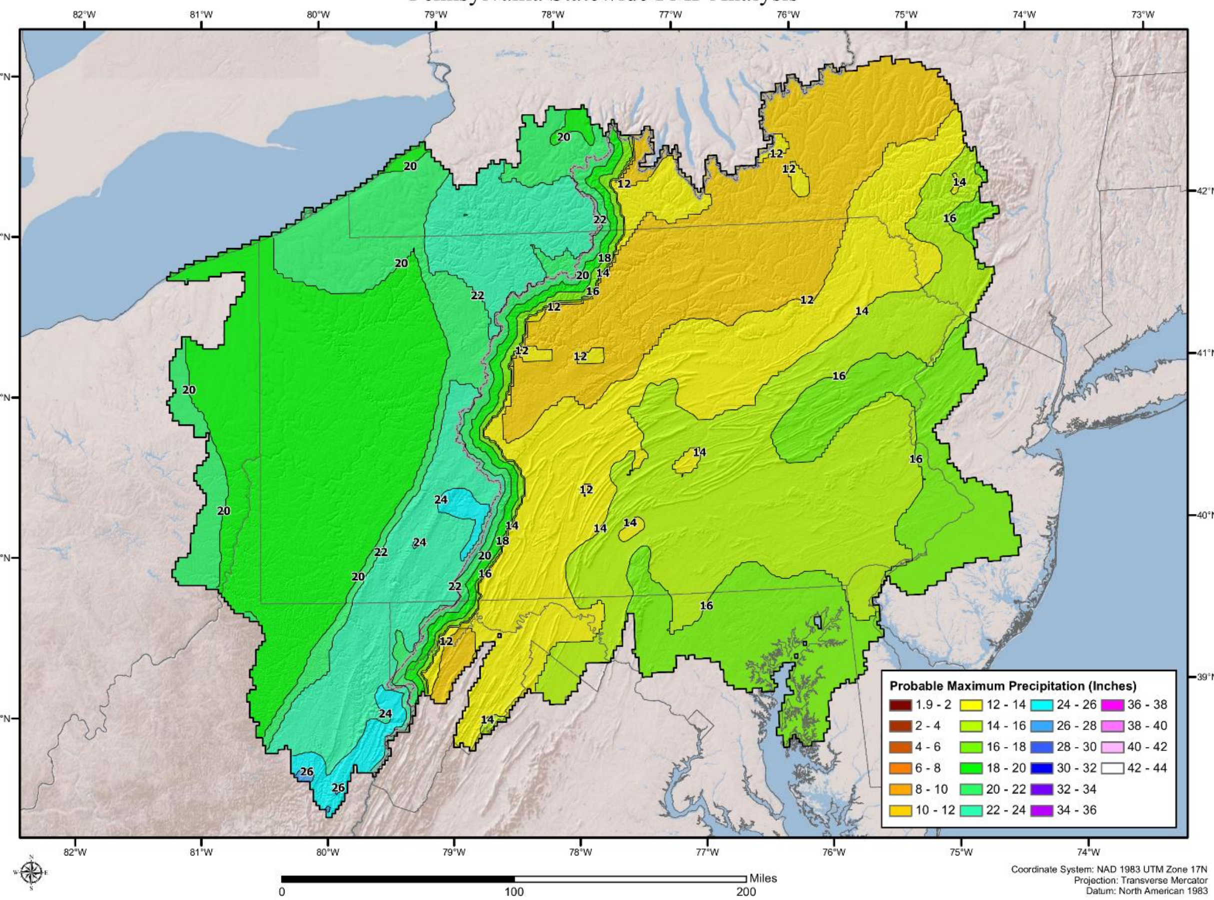
1-Hour Local Storm Probable Maximum Precipitation (10 mi²)
Pennsylvania Statewide PMP Analysis



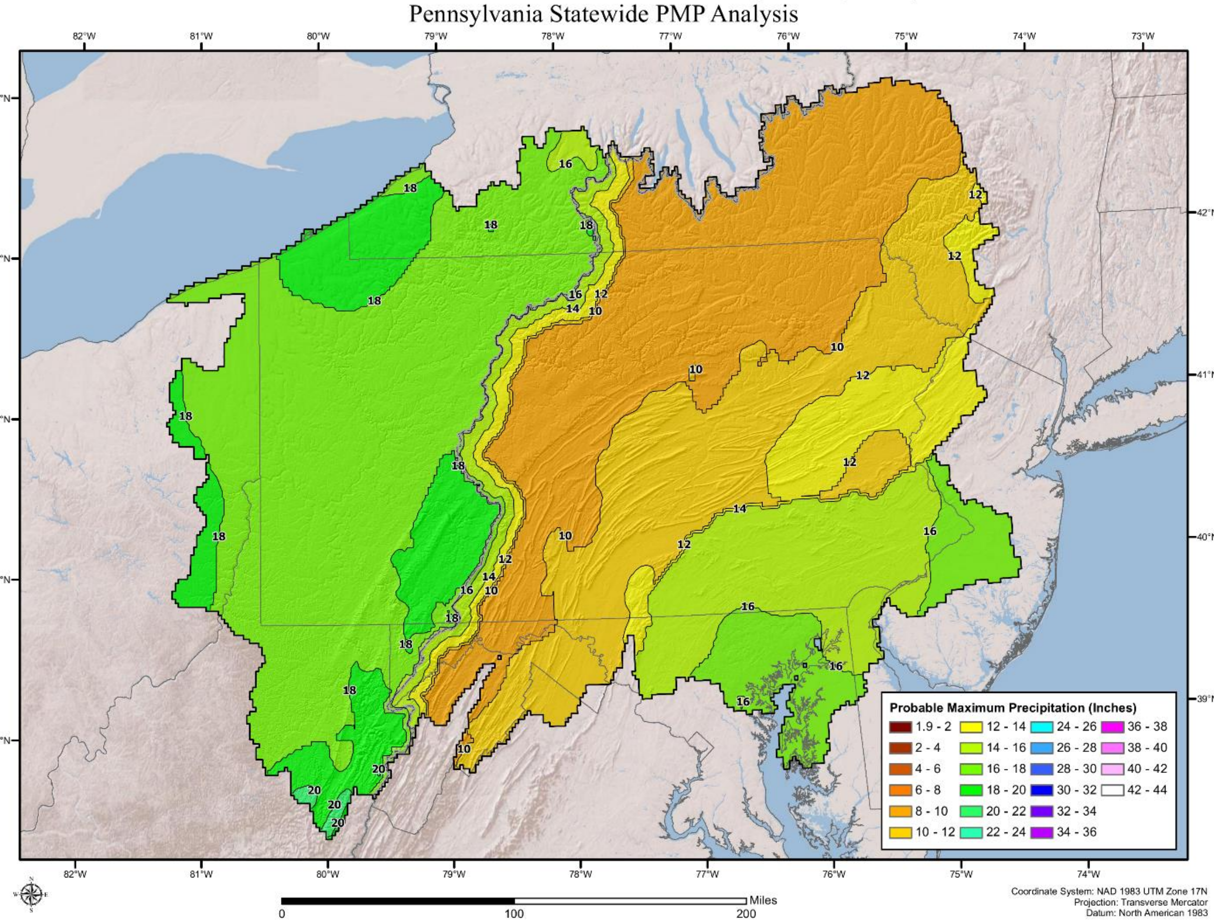
1-Hour Local Storm Probable Maximum Precipitation (100 mi²)
Pennsylvania Statewide PMP Analysis



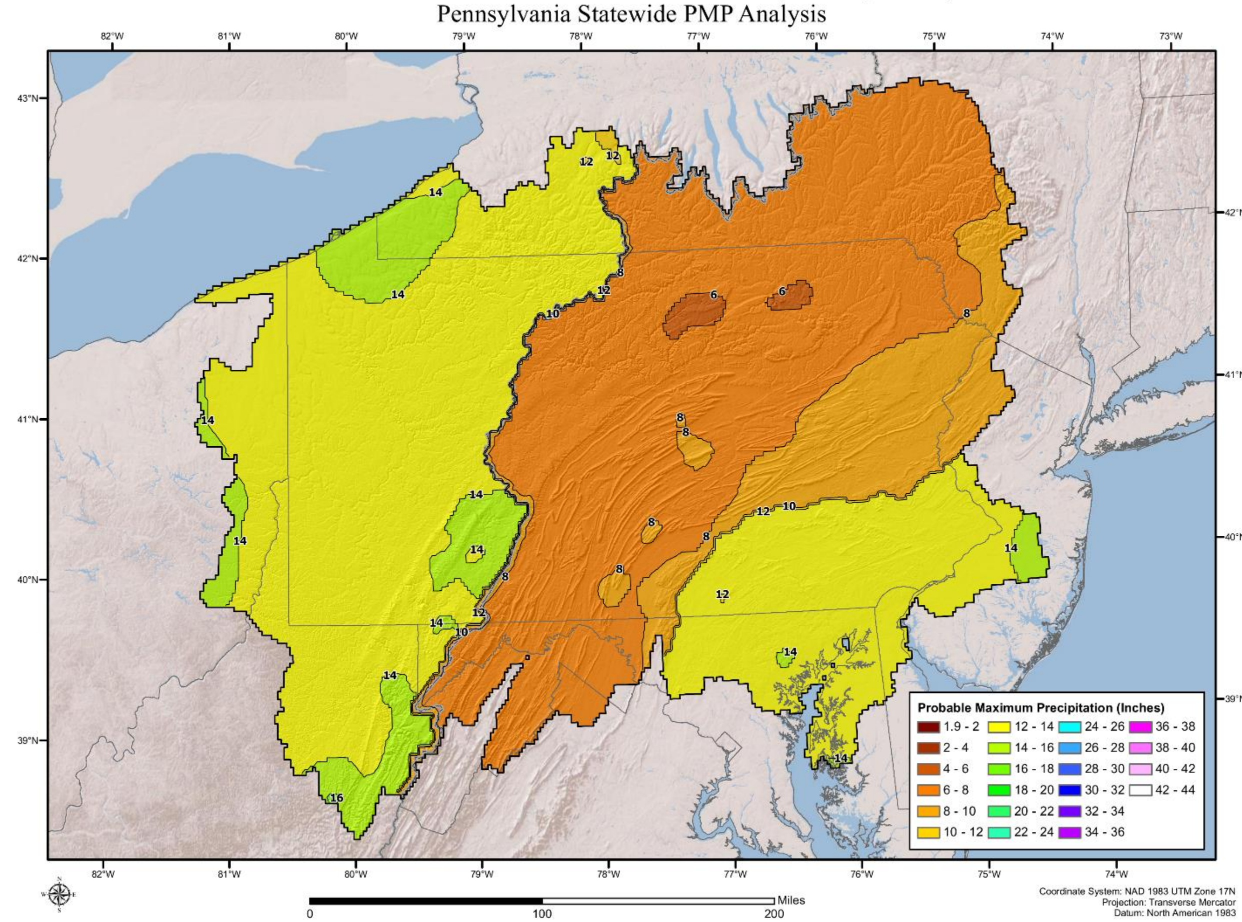
3-Hour Local Storm Probable Maximum Precipitation (1 mi²)
Pennsylvania Statewide PMP Analysis



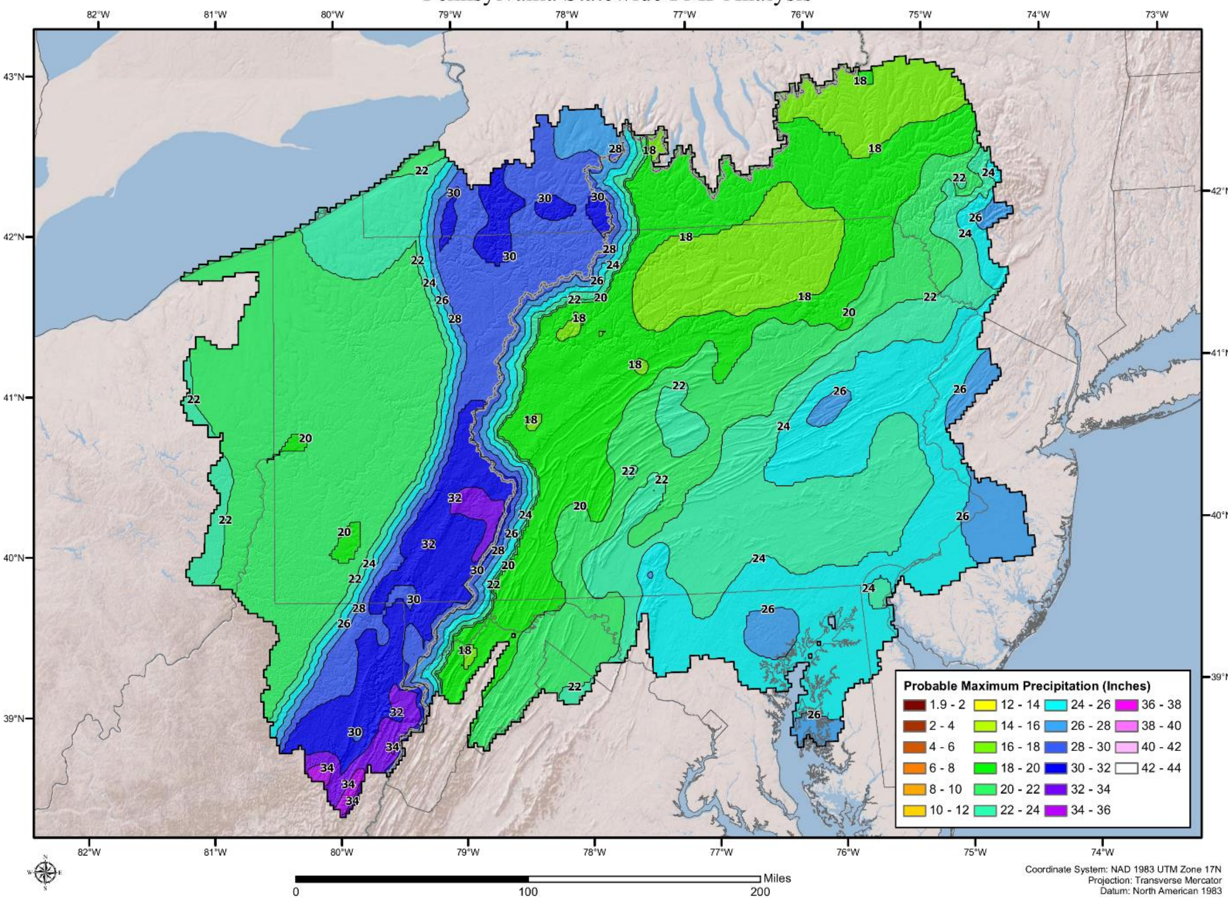
3-Hour Local Storm Probable Maximum Precipitation (10 mi²)
Pennsylvania Statewide PMP Analysis



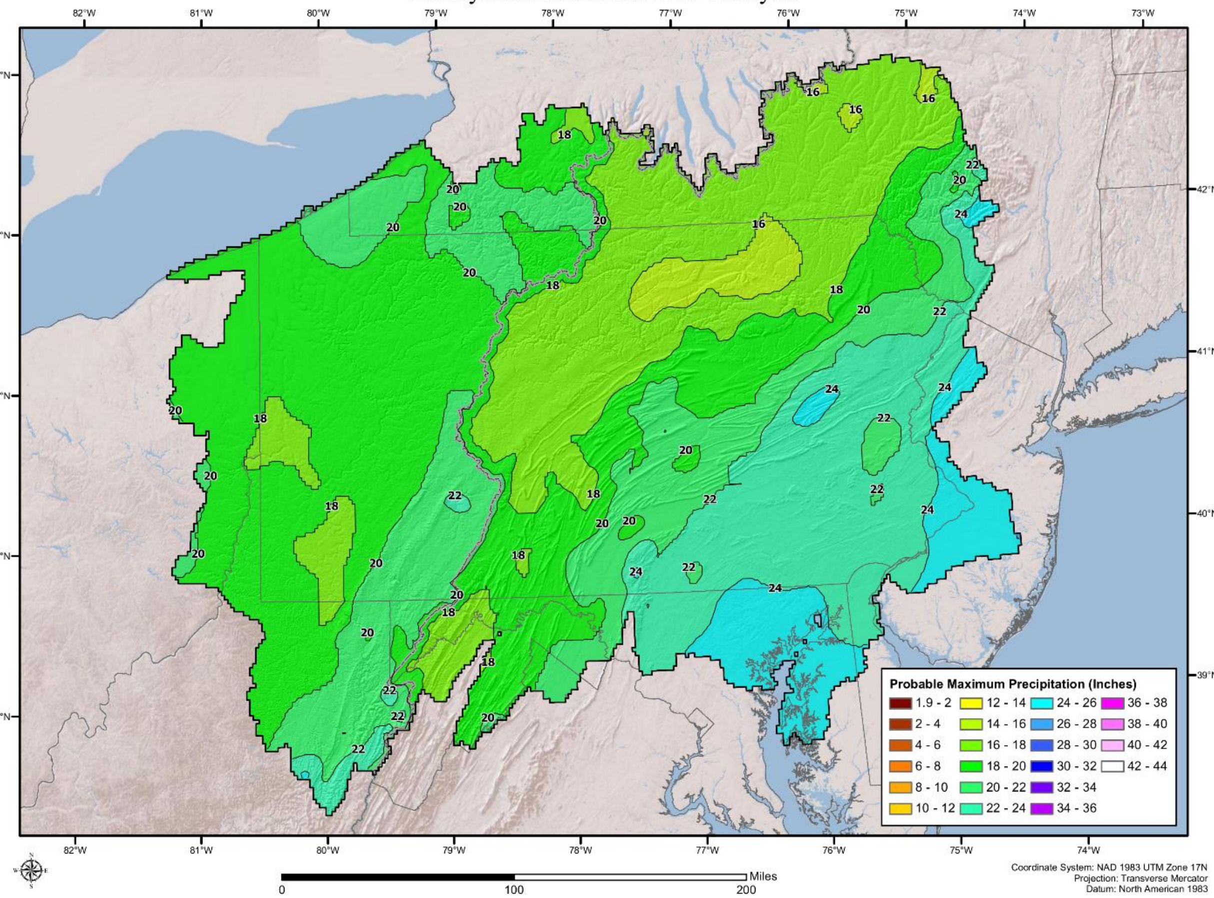
3-Hour Local Storm Probable Maximum Precipitation (100 mi²)
Pennsylvania Statewide PMP Analysis



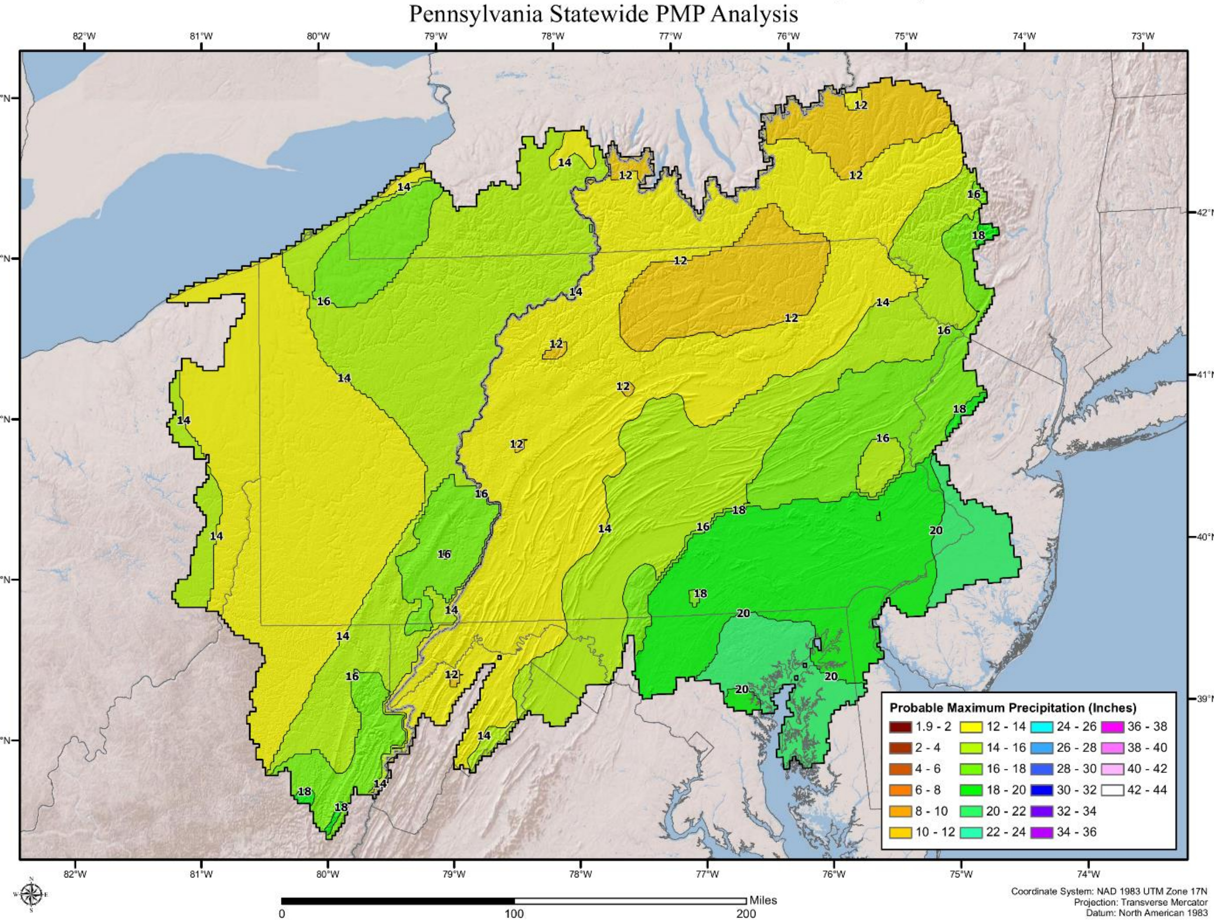
6-Hour Local Storm Probable Maximum Precipitation (1 mi²)
Pennsylvania Statewide PMP Analysis



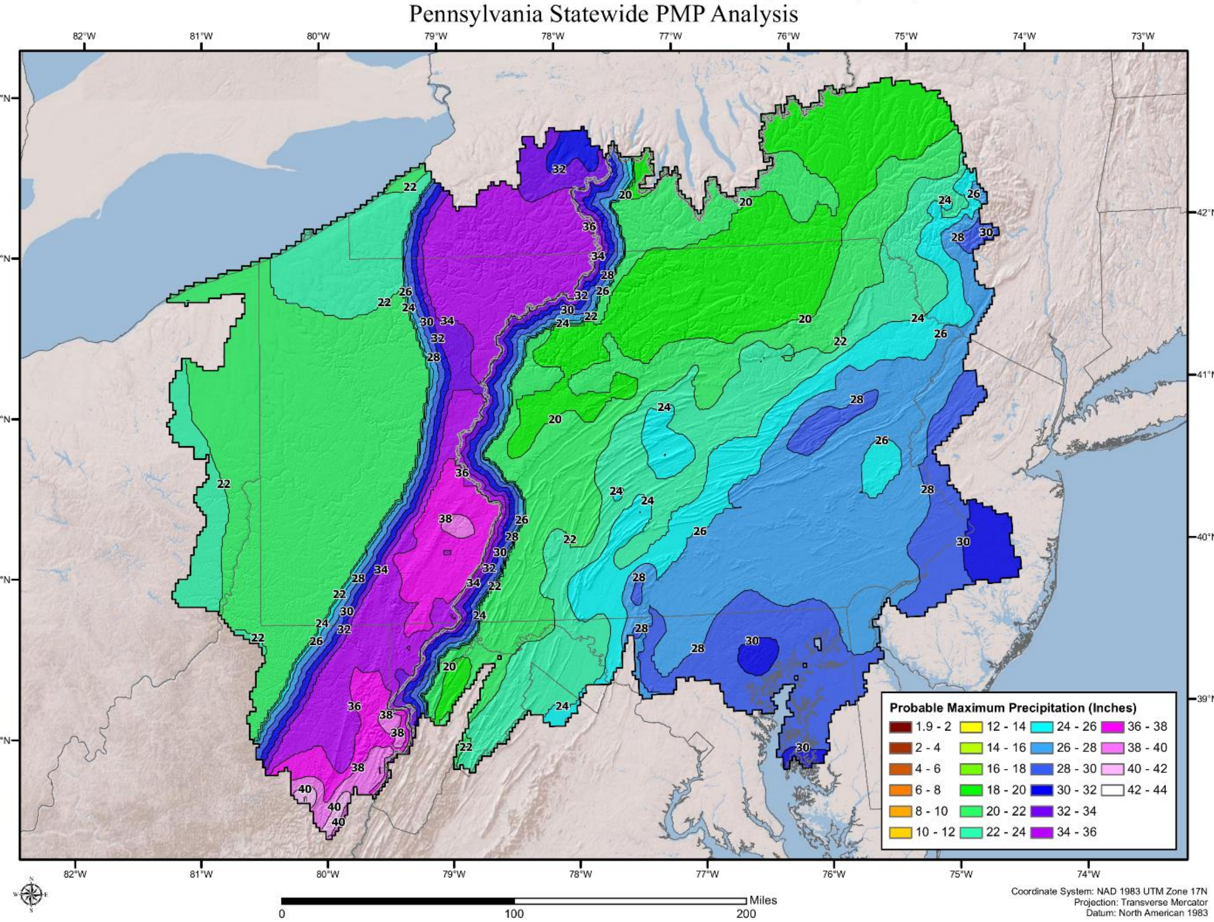
6-Hour Local Storm Probable Maximum Precipitation (10 mi²)
Pennsylvania Statewide PMP Analysis



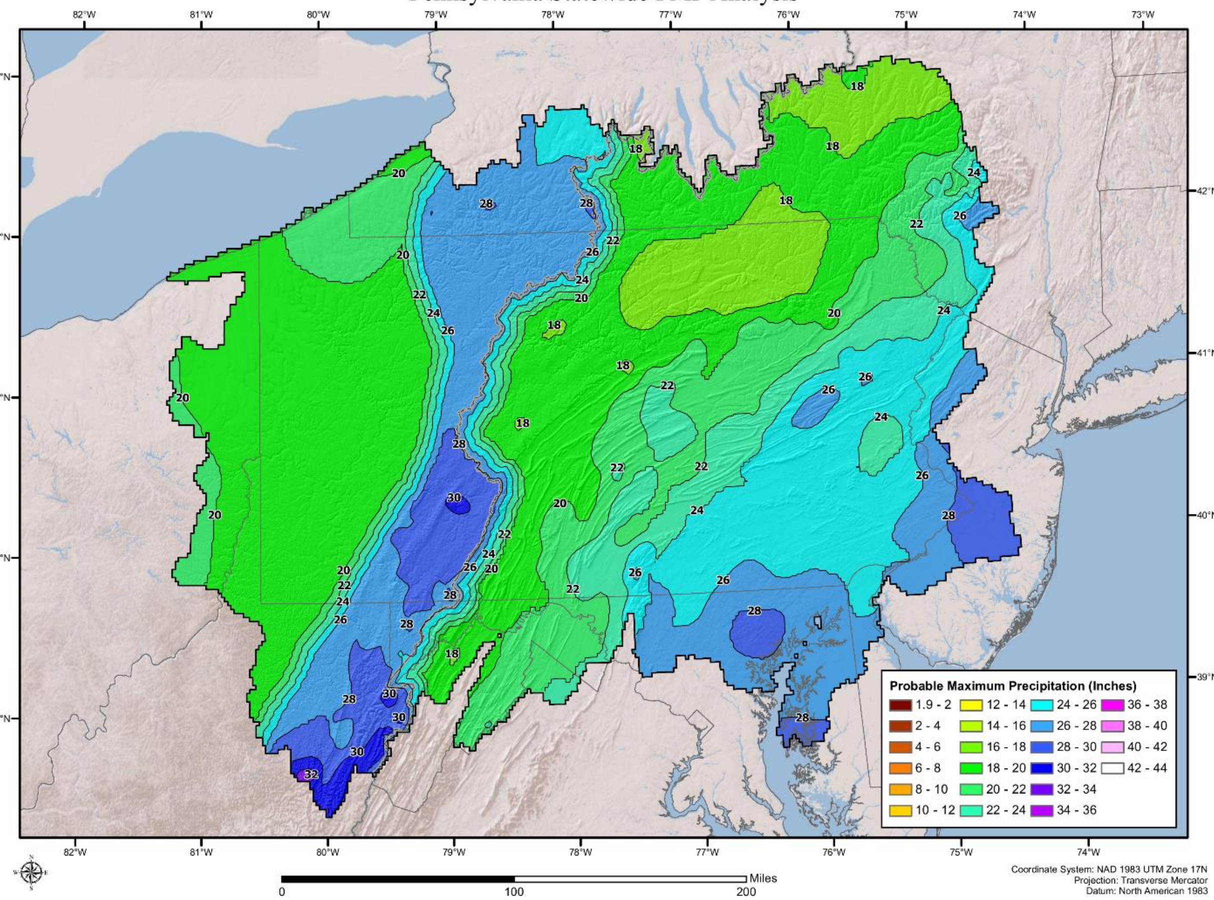
6-Hour Local Storm Probable Maximum Precipitation (100 mi²)
Pennsylvania Statewide PMP Analysis



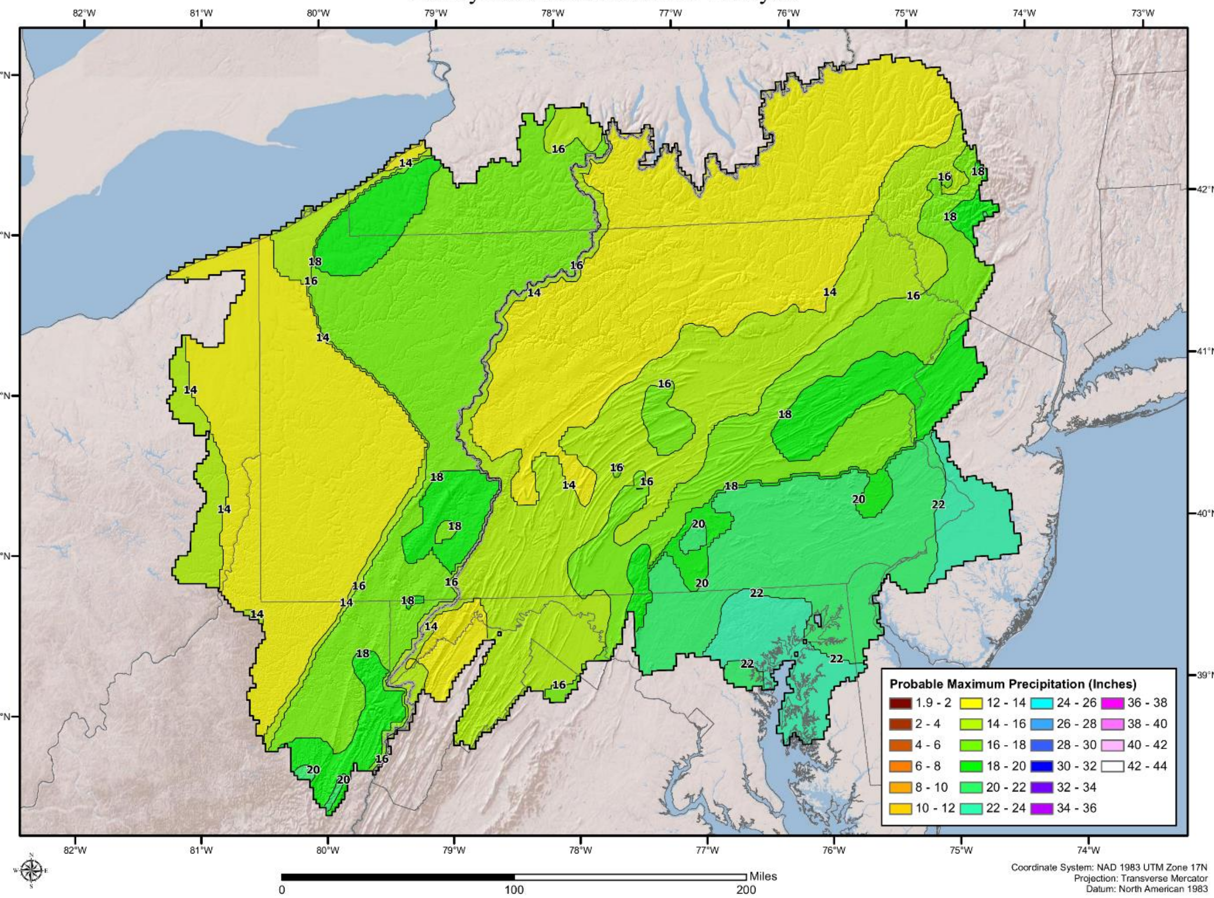
12-Hour Local Storm Probable Maximum Precipitation (1 mi²)
Pennsylvania Statewide PMP Analysis



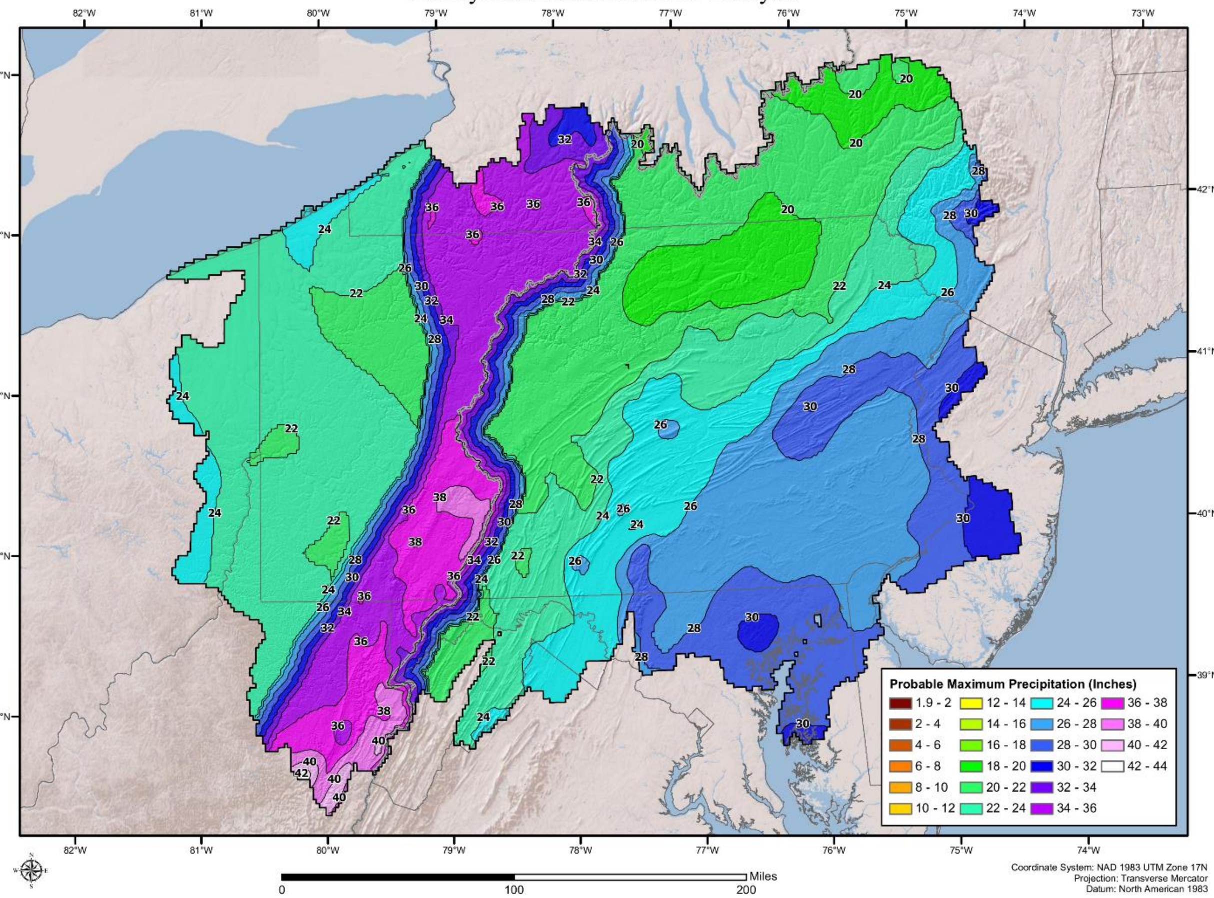
12-Hour Local Storm Probable Maximum Precipitation (10 mi²)
Pennsylvania Statewide PMP Analysis



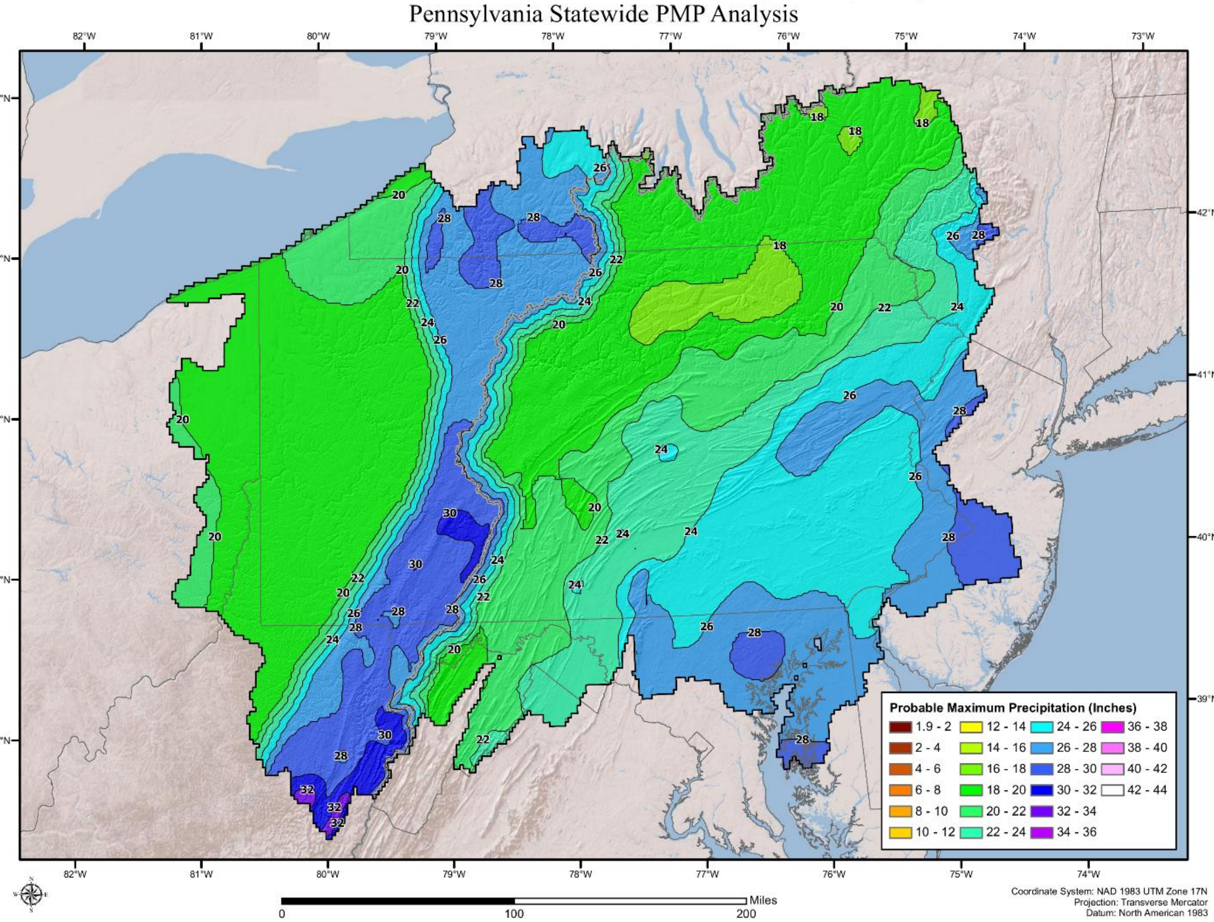
12-Hour Local Storm Probable Maximum Precipitation (100 mi²)
Pennsylvania Statewide PMP Analysis



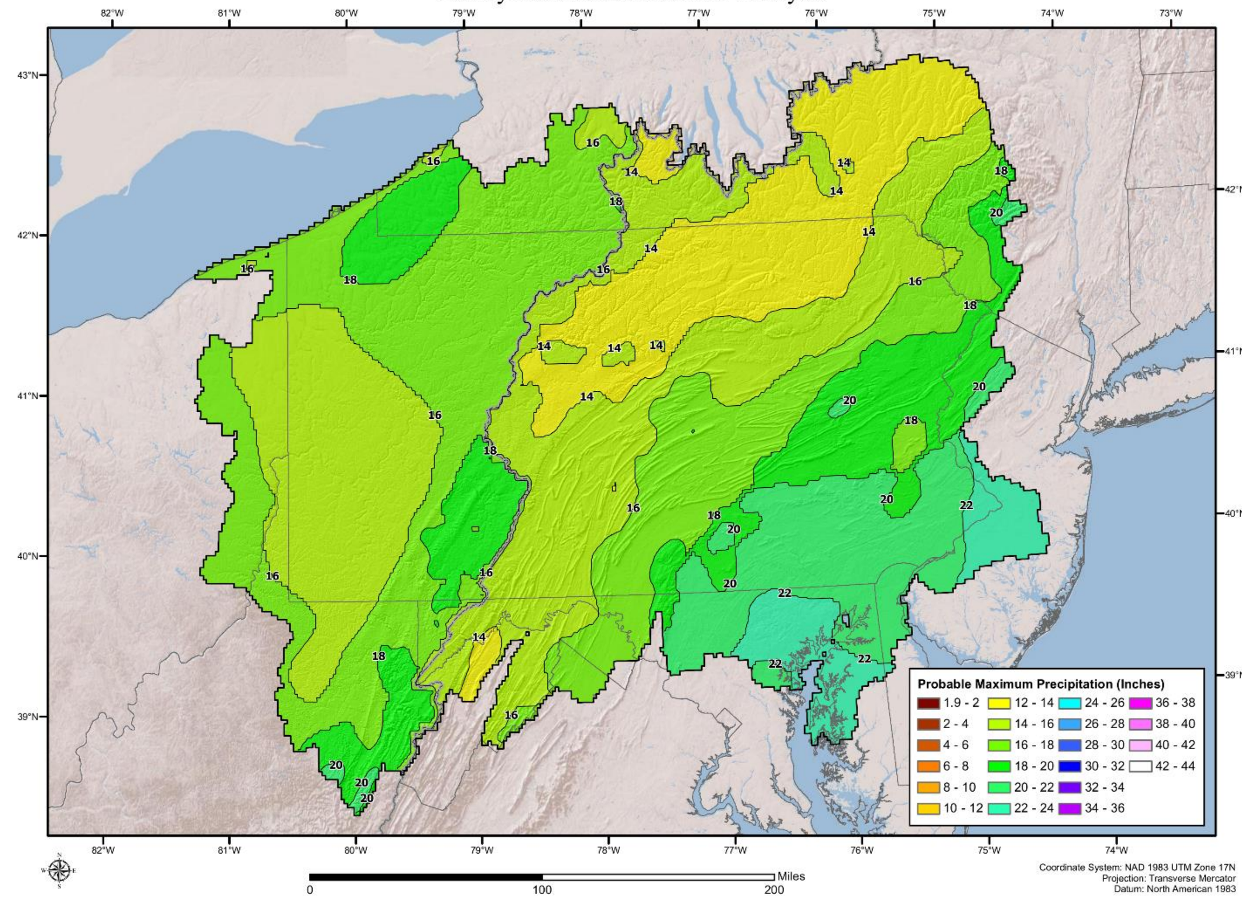
24-Hour Local Storm Probable Maximum Precipitation (1 mi²)
Pennsylvania Statewide PMP Analysis



24-Hour Local Storm Probable Maximum Precipitation (10 mi²)
Pennsylvania Statewide PMP Analysis

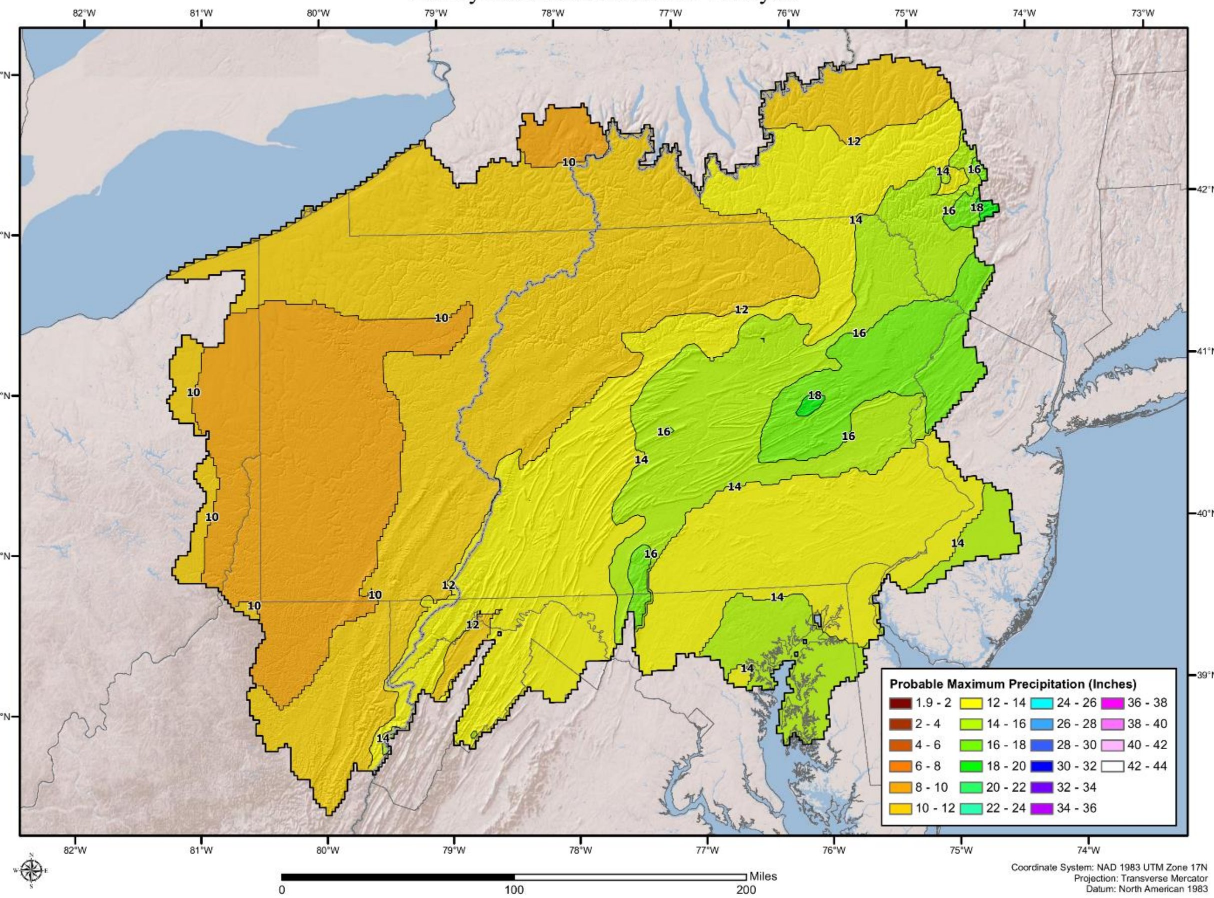


24-Hour Local Storm Probable Maximum Precipitation (100 mi²)
Pennsylvania Statewide PMP Analysis

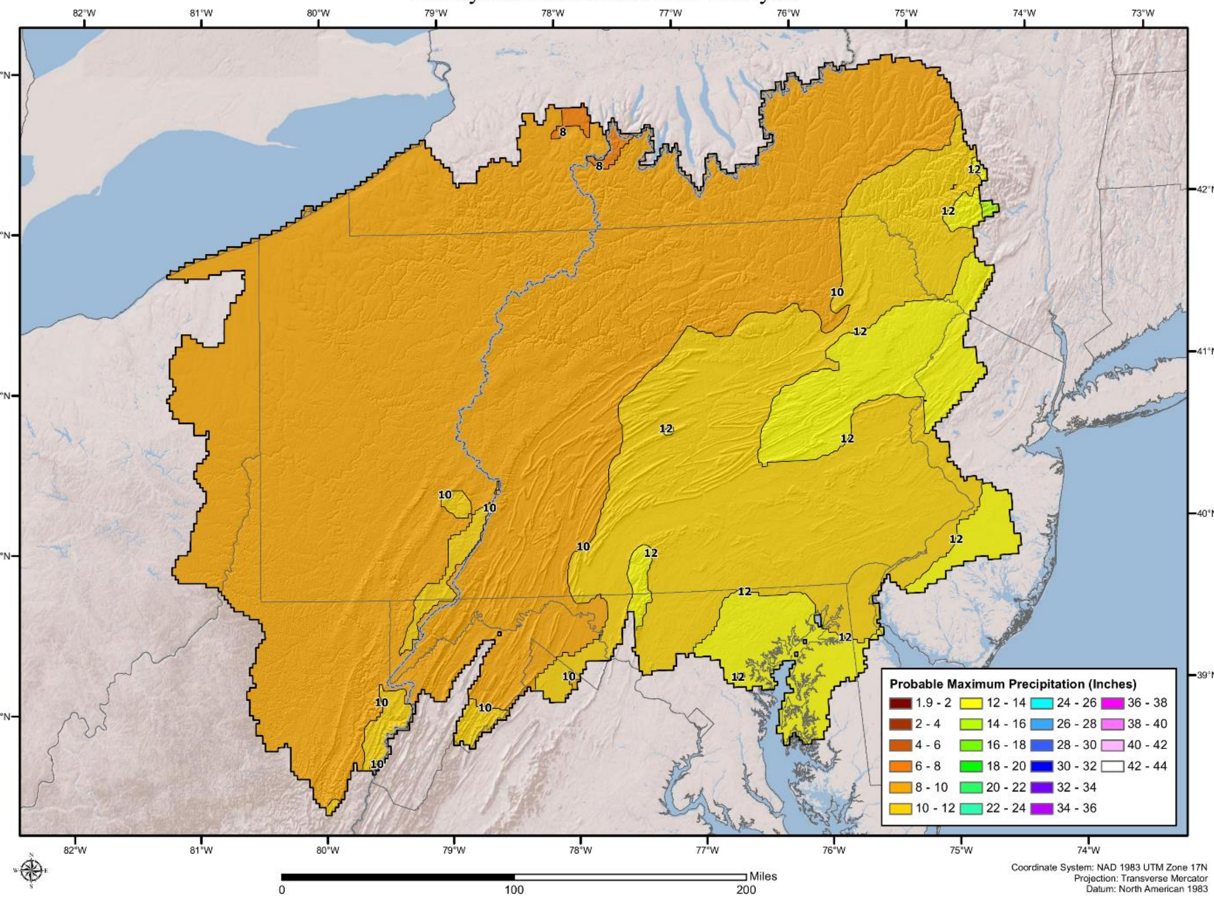


Tropical Storms

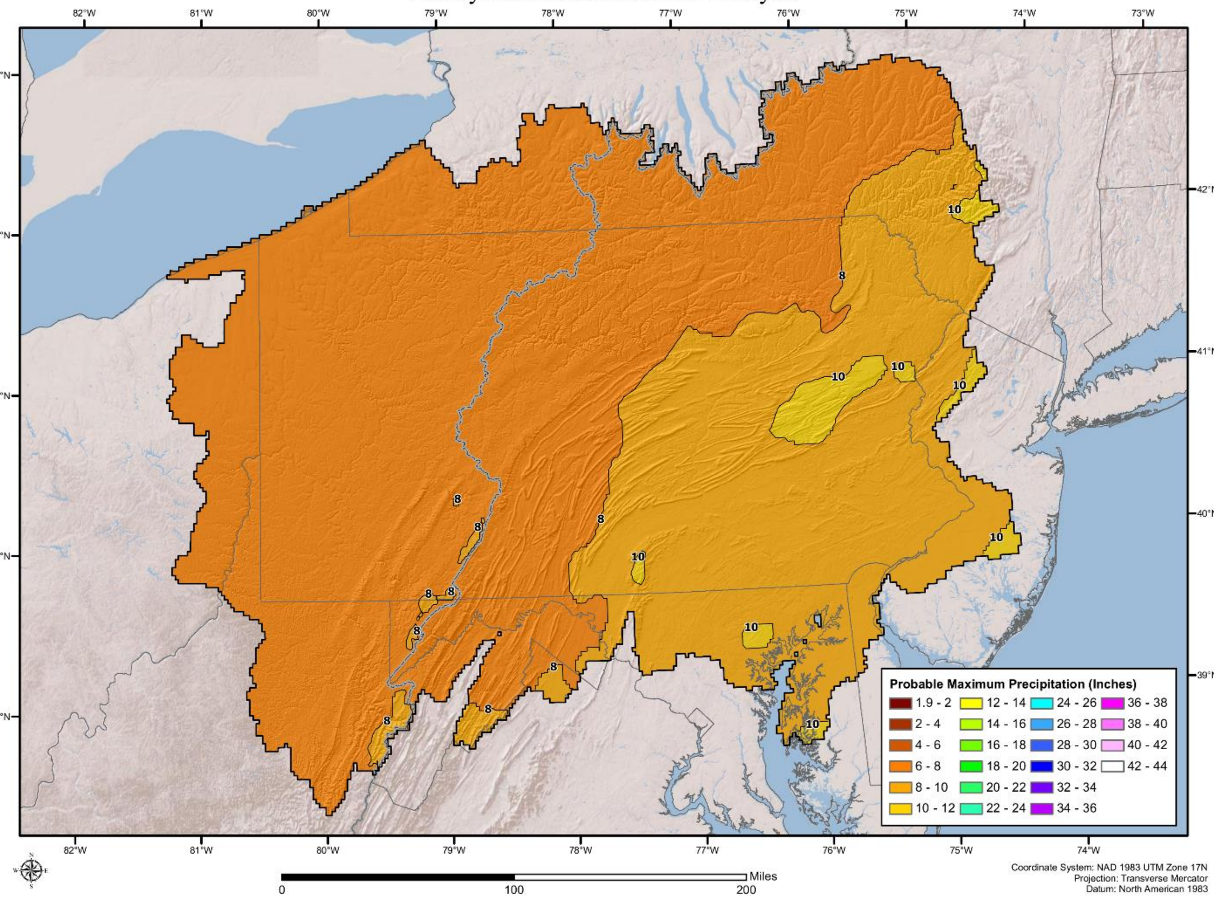
6-Hour Tropical Storm Probable Maximum Precipitation (10 mi²)
Pennsylvania Statewide PMP Analysis



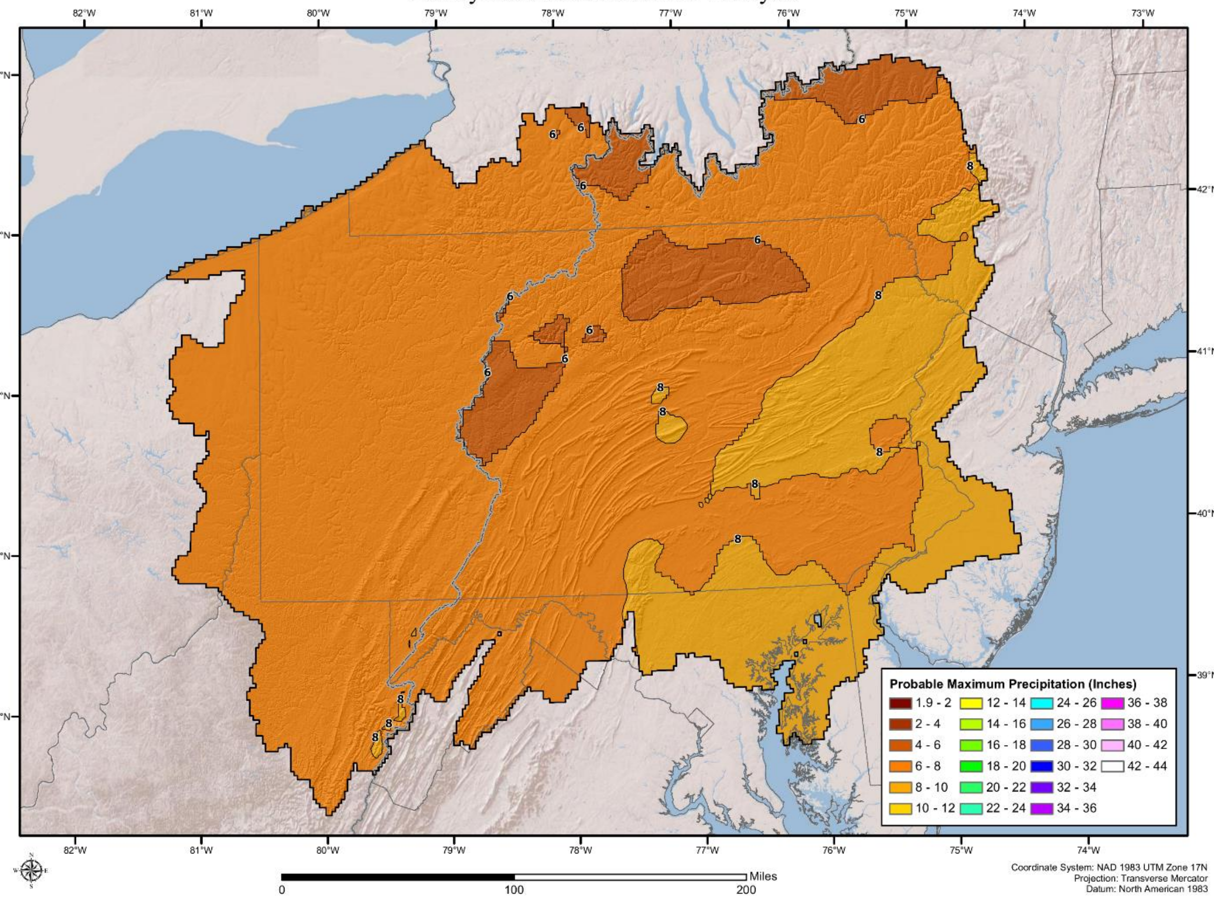
6-Hour Tropical Storm Probable Maximum Precipitation (100 mi²)
Pennsylvania Statewide PMP Analysis



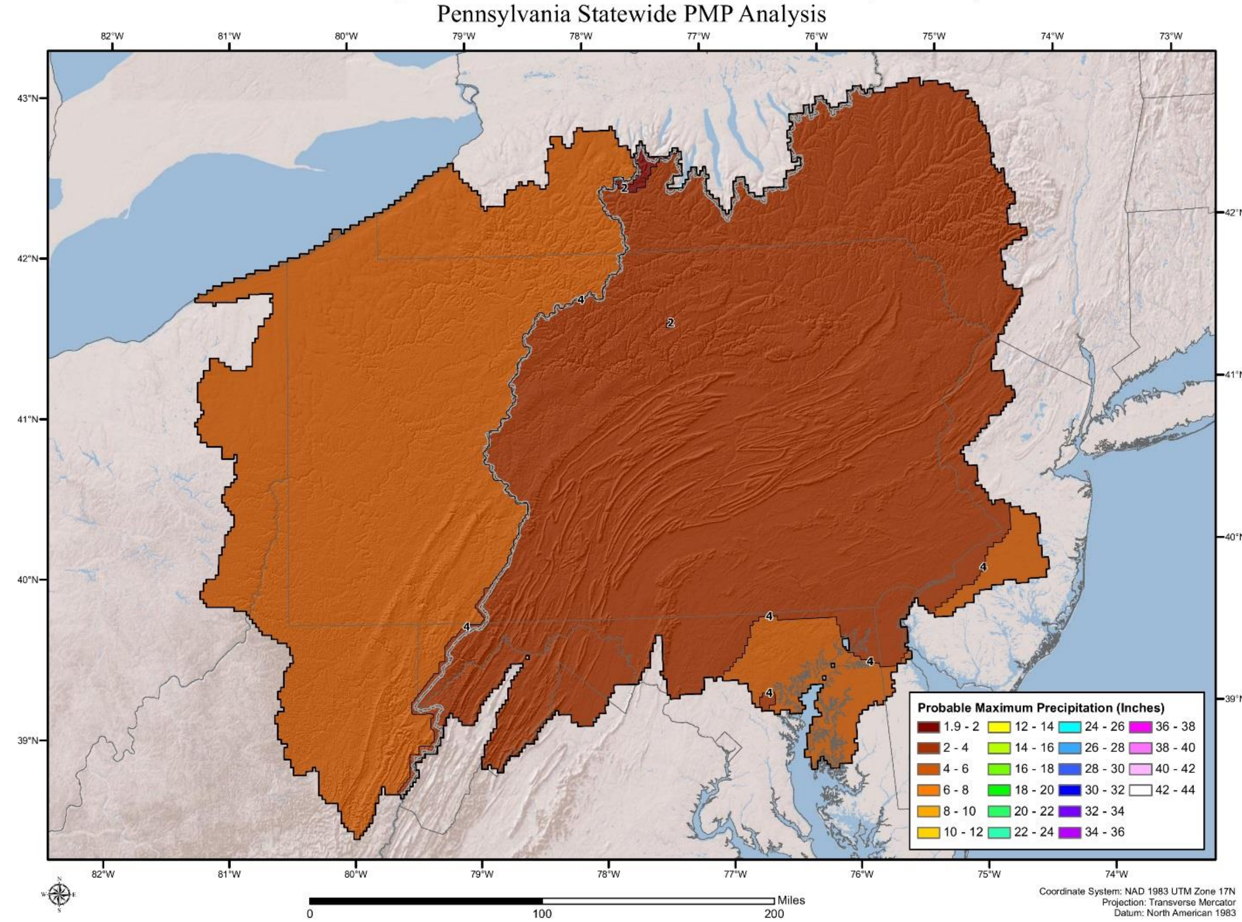
6-Hour Tropical Storm Probable Maximum Precipitation (500 mi²)
Pennsylvania Statewide PMP Analysis



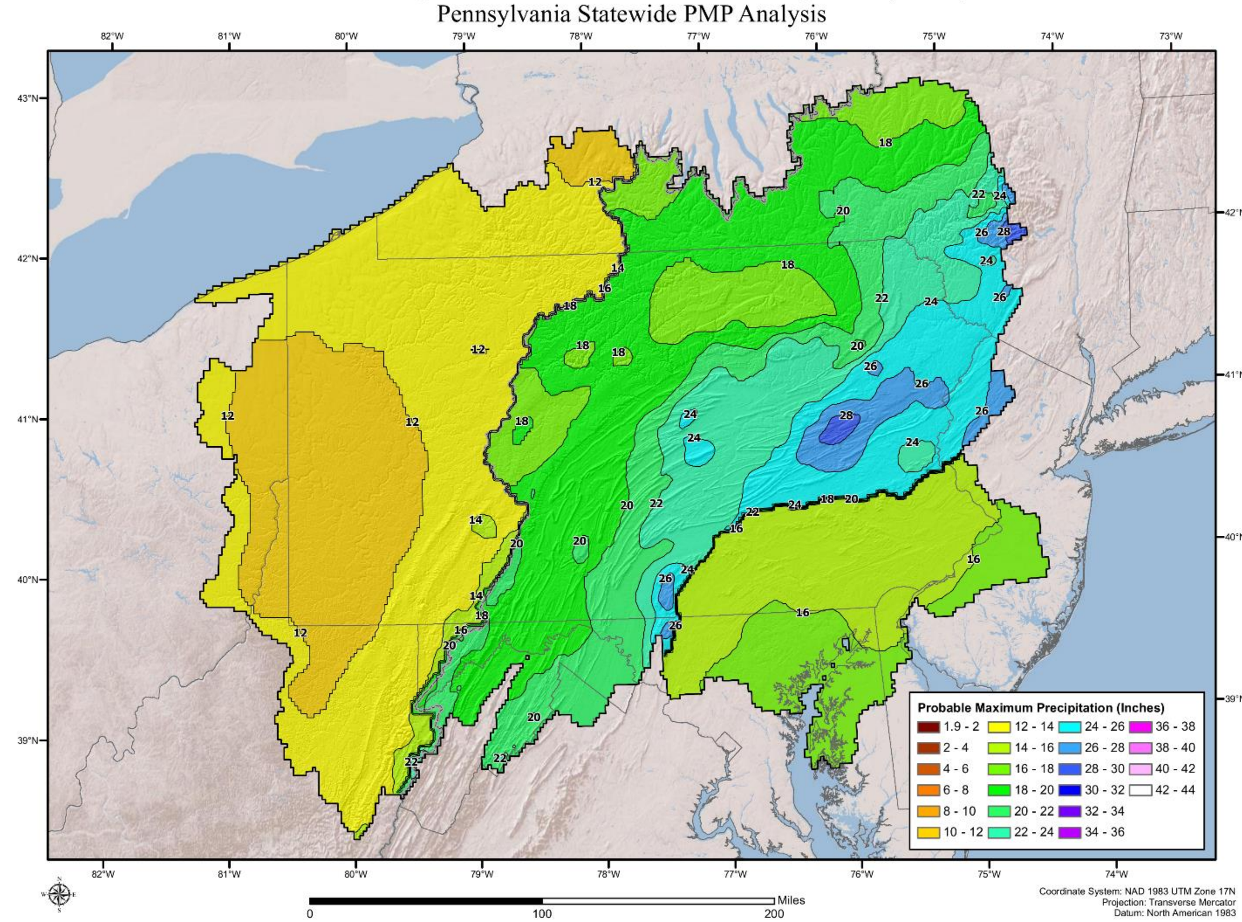
6-Hour Tropical Storm Probable Maximum Precipitation (1000 mi²)
Pennsylvania Statewide PMP Analysis



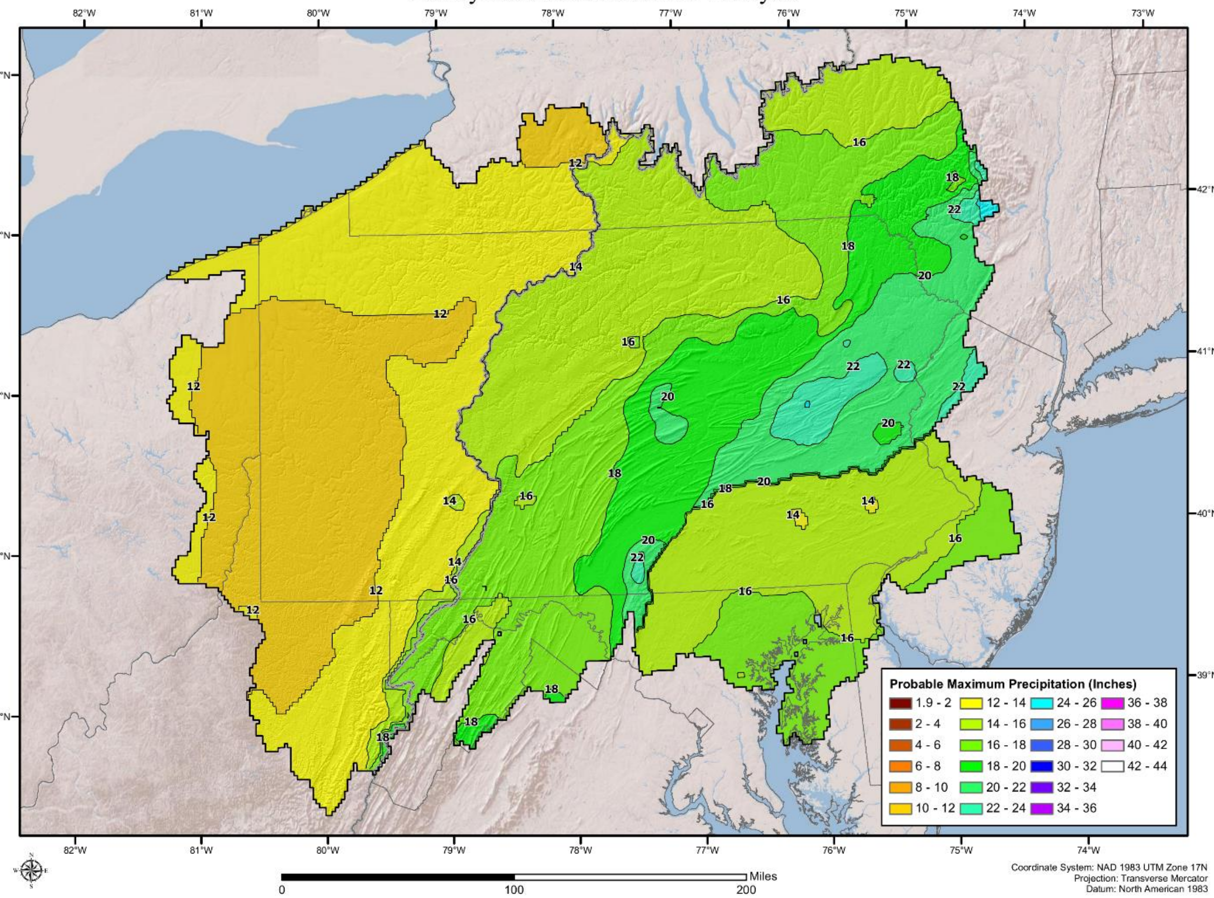
6-Hour Tropical Storm Probable Maximum Precipitation (20000 mi²)
Pennsylvania Statewide PMP Analysis



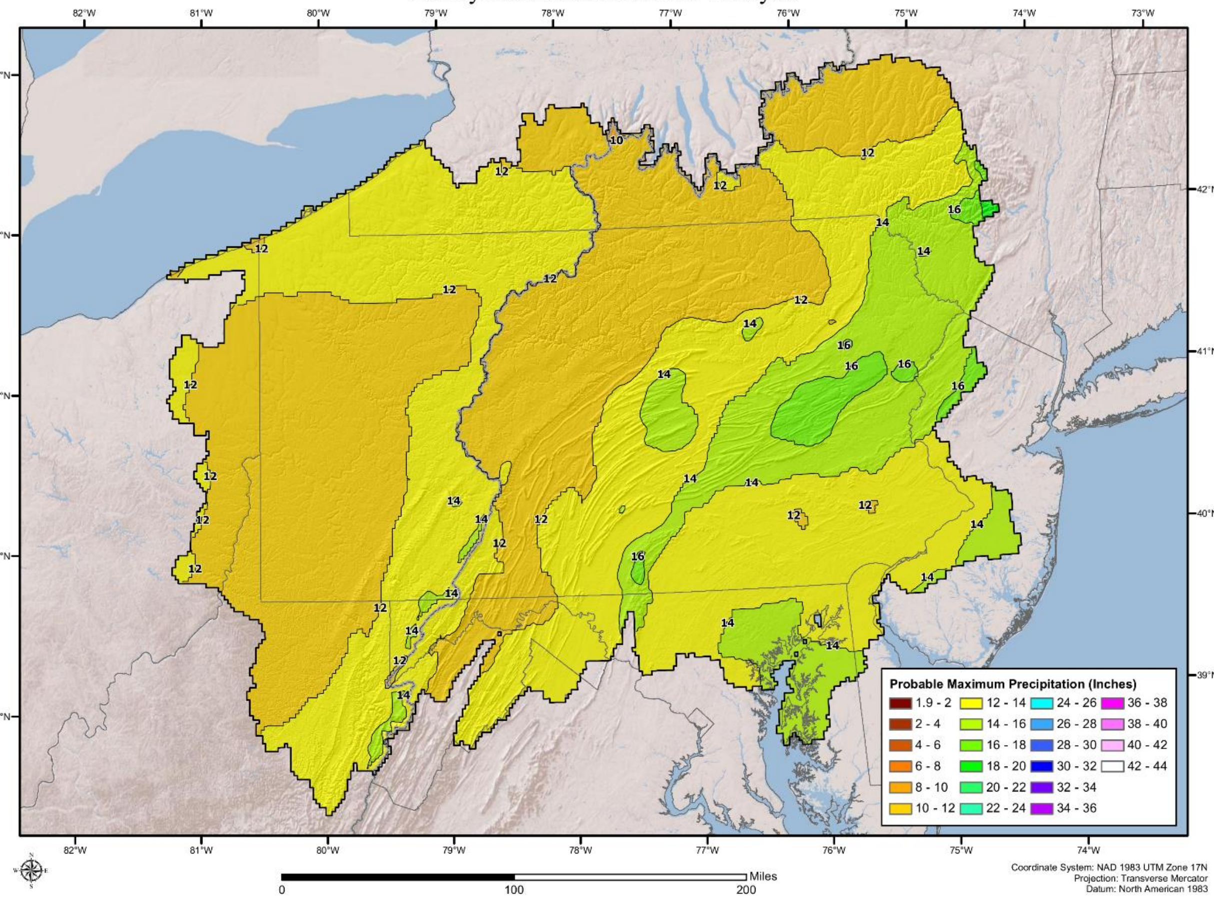
12-Hour Tropical Storm Probable Maximum Precipitation (10 mi²)
Pennsylvania Statewide PMP Analysis



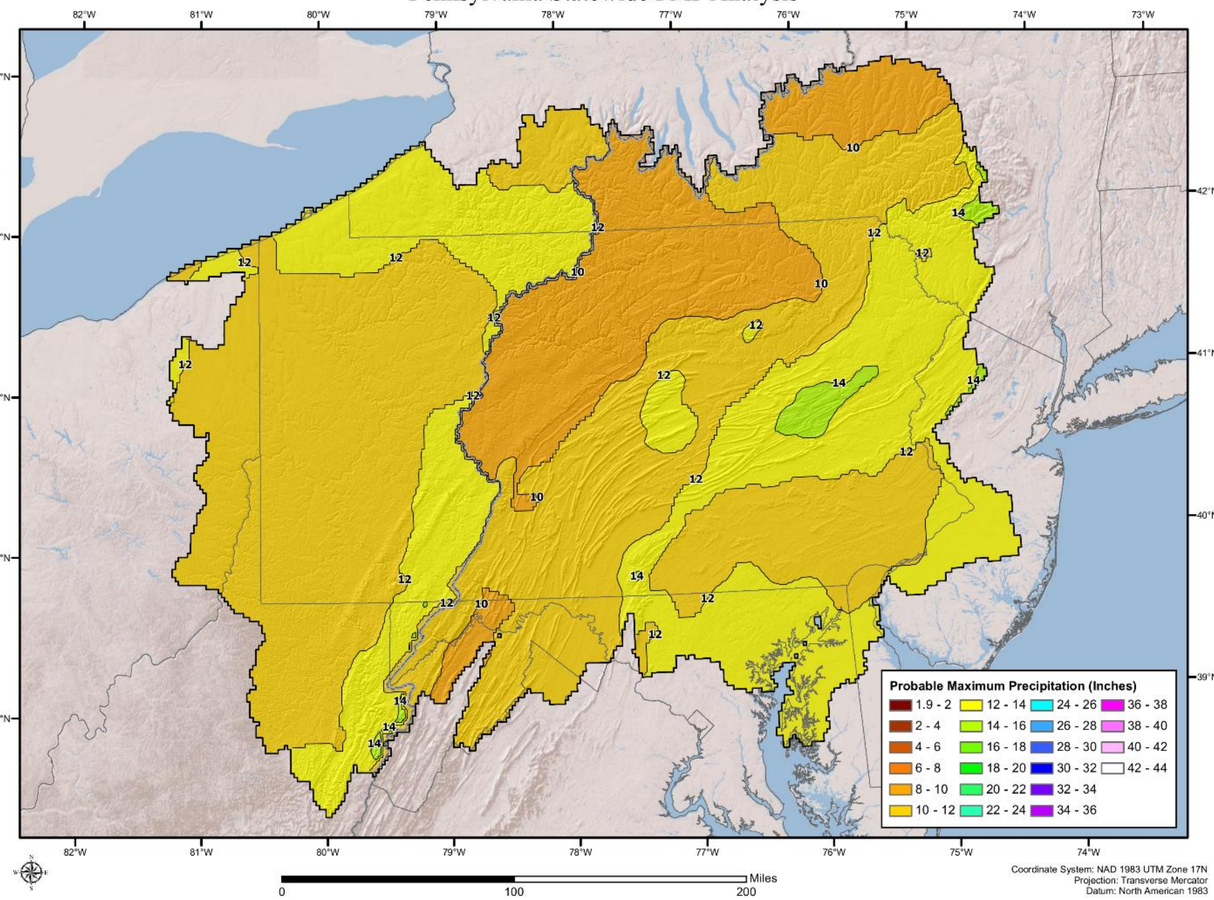
12-Hour Tropical Storm Probable Maximum Precipitation (100 mi²)
Pennsylvania Statewide PMP Analysis



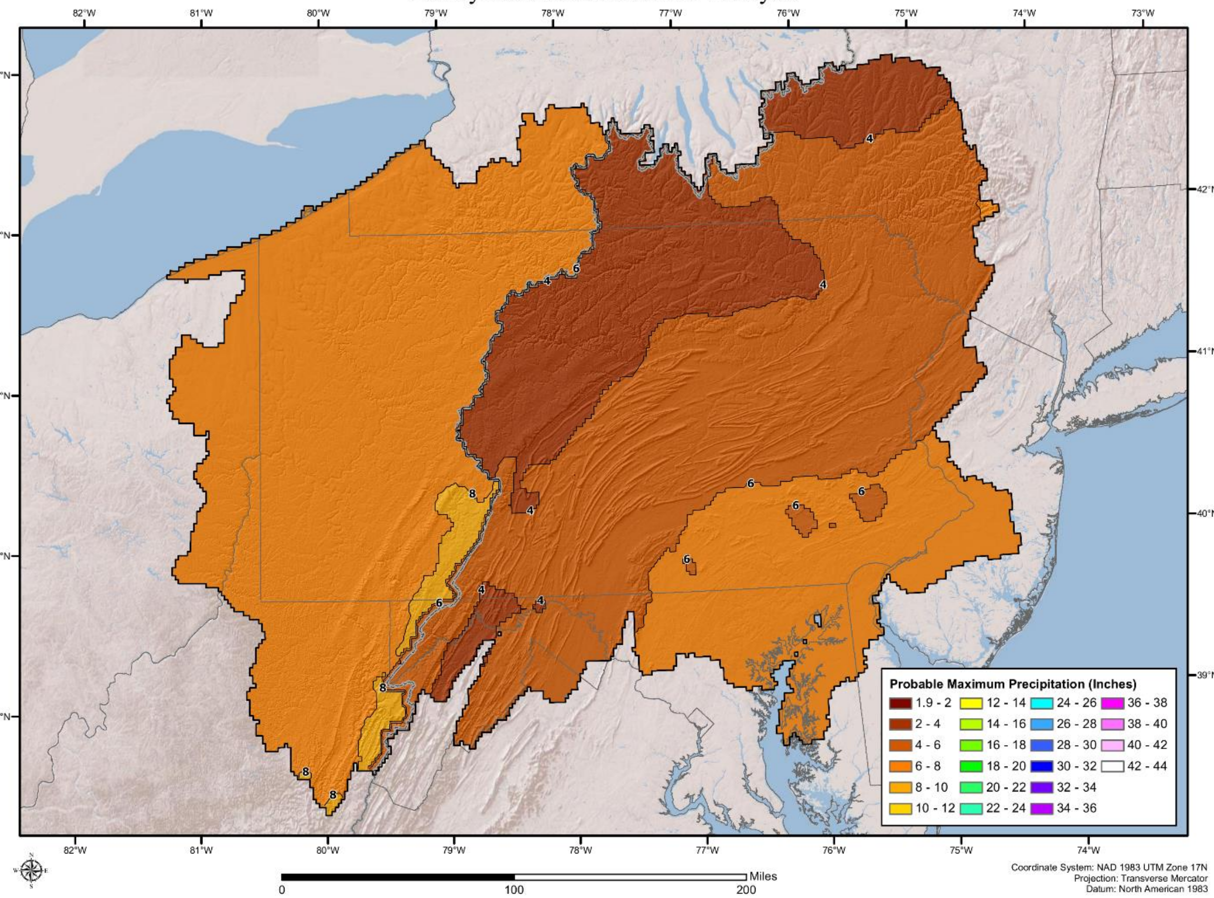
12-Hour Tropical Storm Probable Maximum Precipitation (500 mi²)
Pennsylvania Statewide PMP Analysis

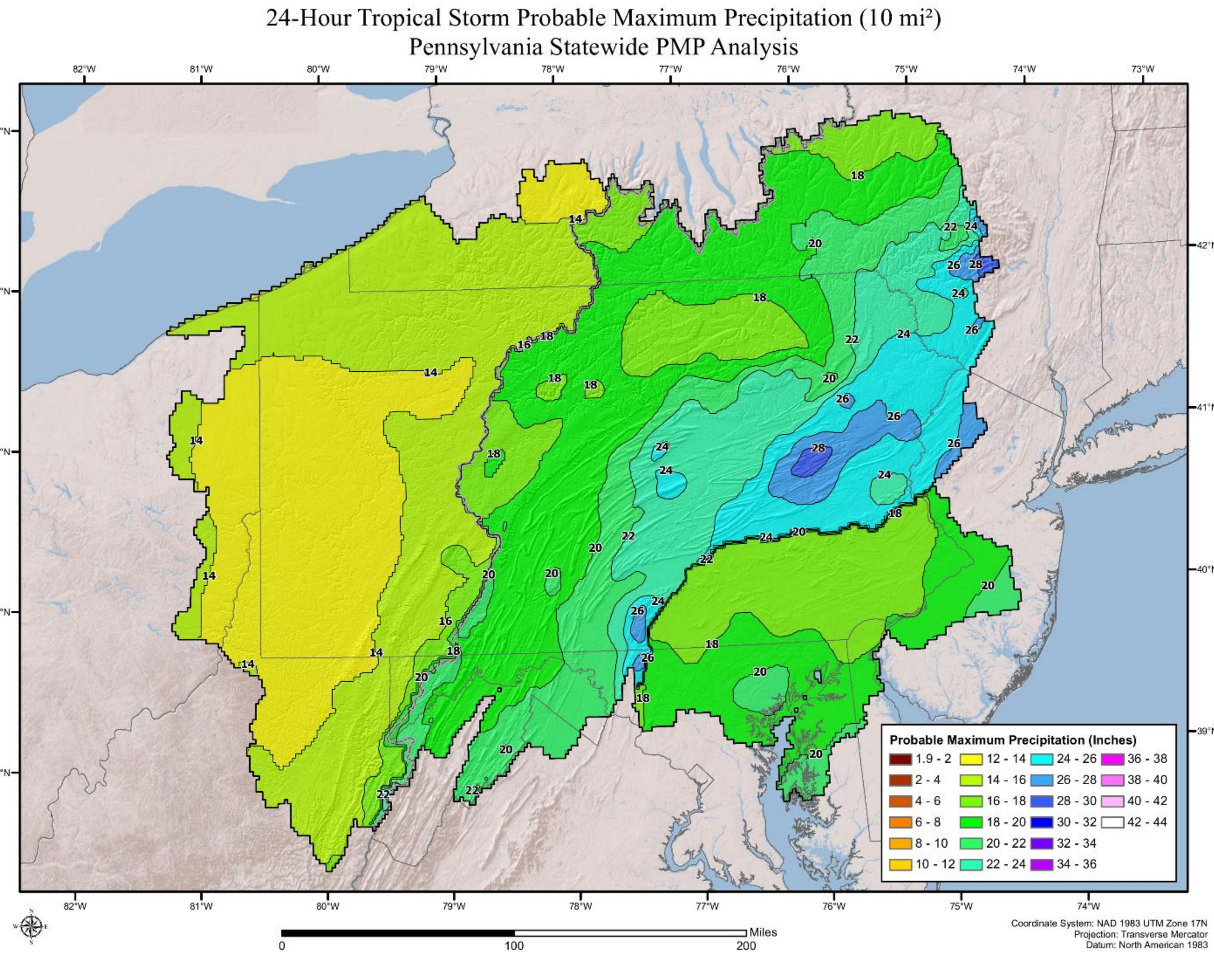


12-Hour Tropical Storm Probable Maximum Precipitation (1000 mi²)
Pennsylvania Statewide PMP Analysis



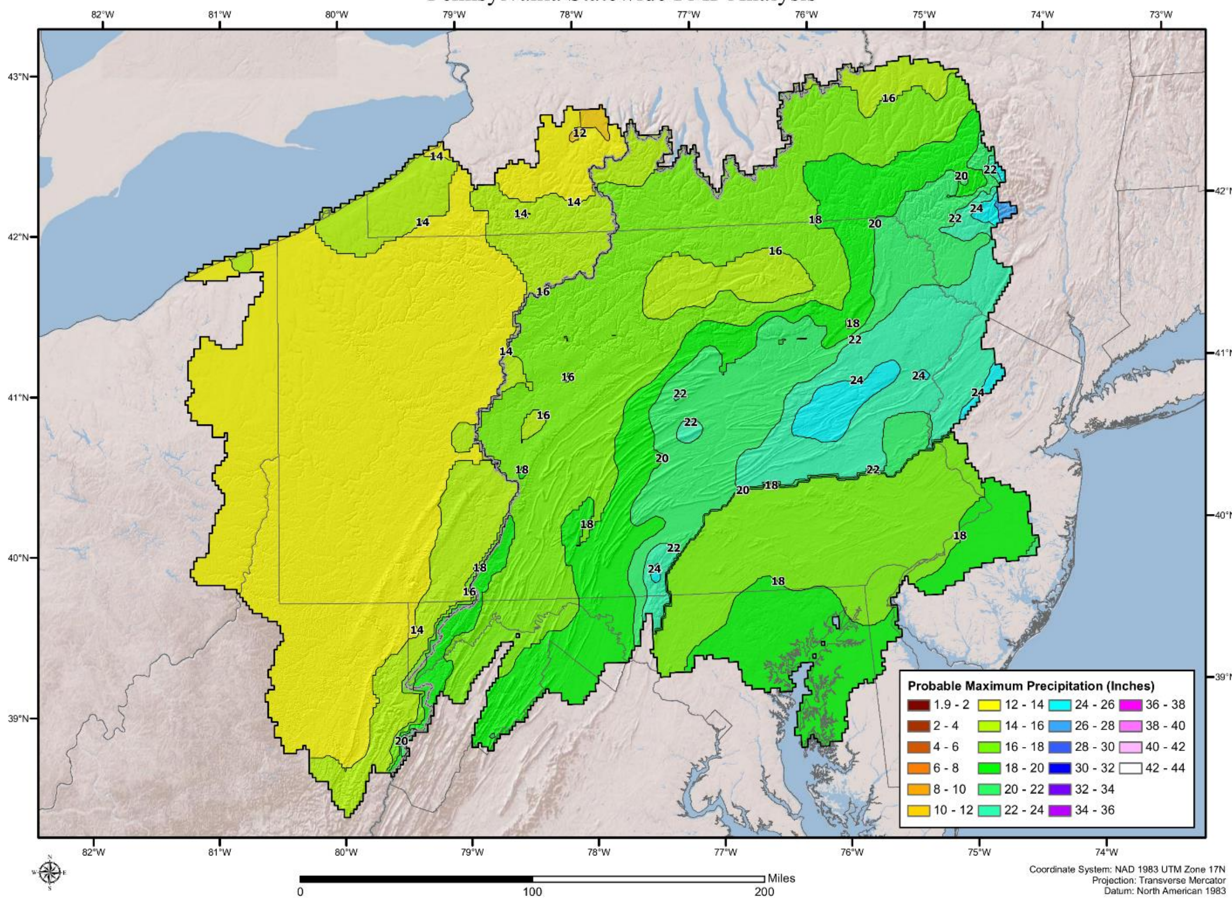
12-Hour Tropical Storm Probable Maximum Precipitation (20000 mi²)
Pennsylvania Statewide PMP Analysis



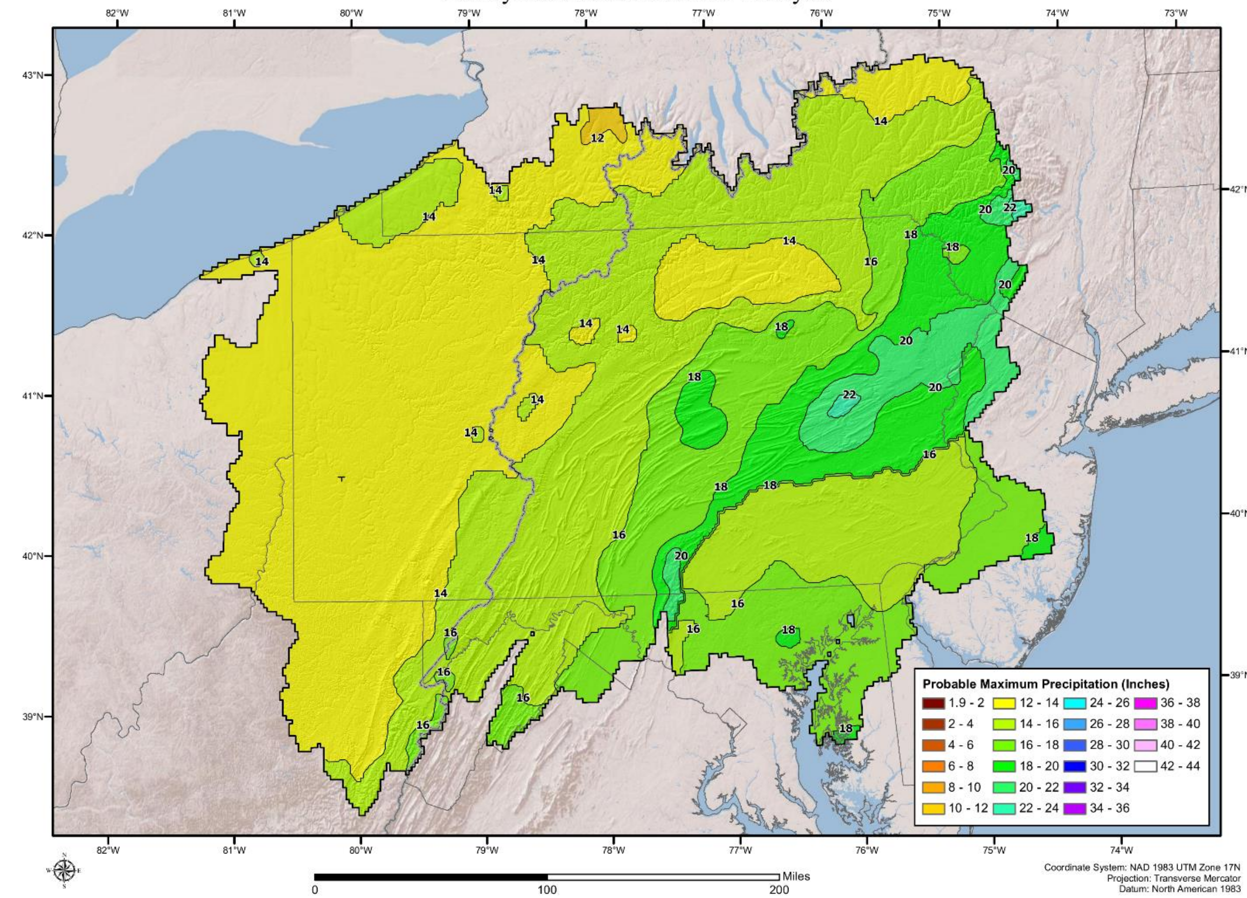


24-Hour Tropical Storm Probable Maximum Precipitation (10 mi²)
Pennsylvania Statewide PMP Analysis
Probable Maximum Precipitation (Inches)
1.9 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 12
12 - 14
14 - 16
16 - 18
18 - 20
20 - 22
22 - 24
24 - 26
26 - 28
28 - 30
30 - 32
32 - 34
34 - 36
36 - 38
38 - 40
40 - 42
42 - 44
Miles
0
100
200
Coordinate System: NAD 1983 UTM Zone 17N
Projection: Transverse Mercator
Datum: North American 1983

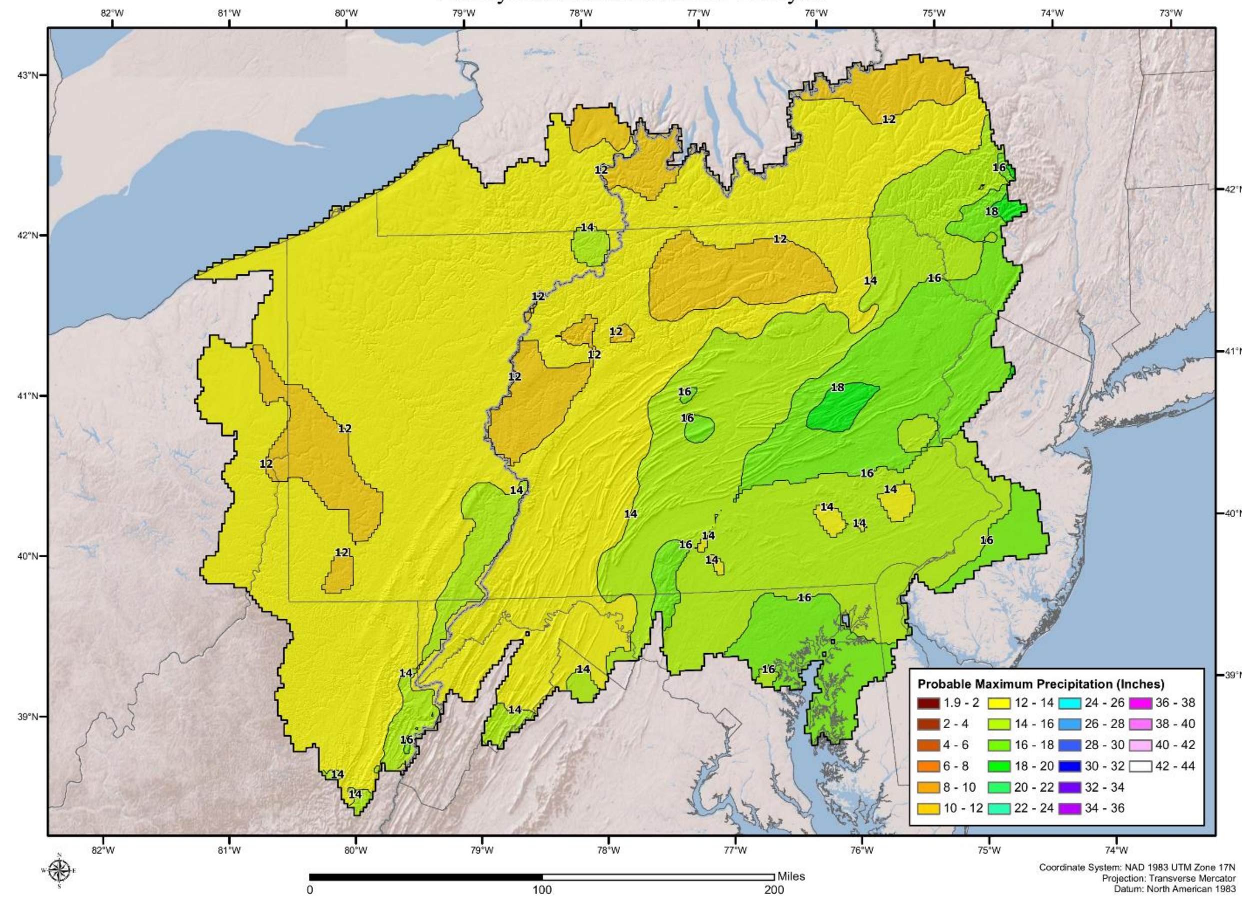
24-Hour Tropical Storm Probable Maximum Precipitation (100 mi²)
Pennsylvania Statewide PMP Analysis



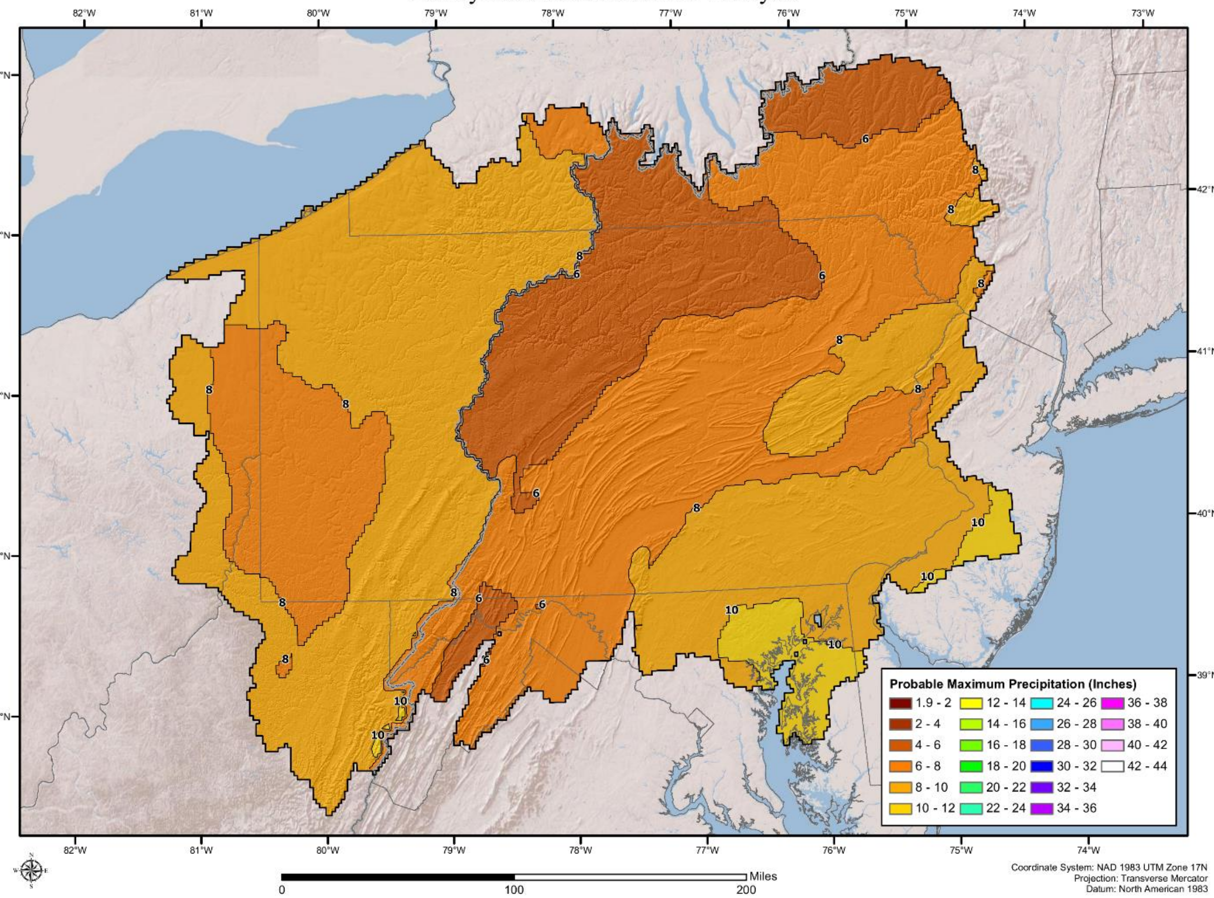
24-Hour Tropical Storm Probable Maximum Precipitation (500 mi²)
Pennsylvania Statewide PMP Analysis



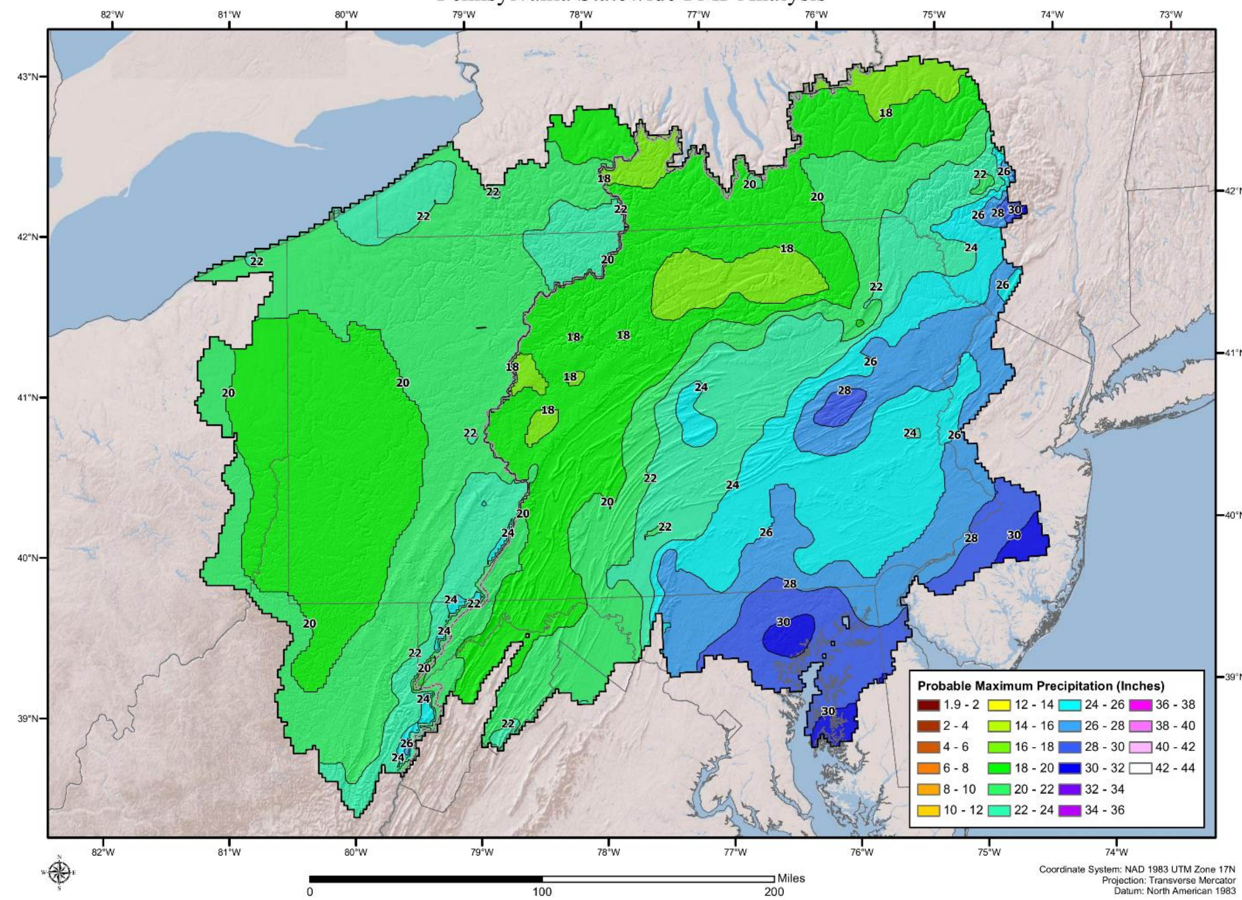
24-Hour Tropical Storm Probable Maximum Precipitation (1000 mi²)
Pennsylvania Statewide PMP Analysis



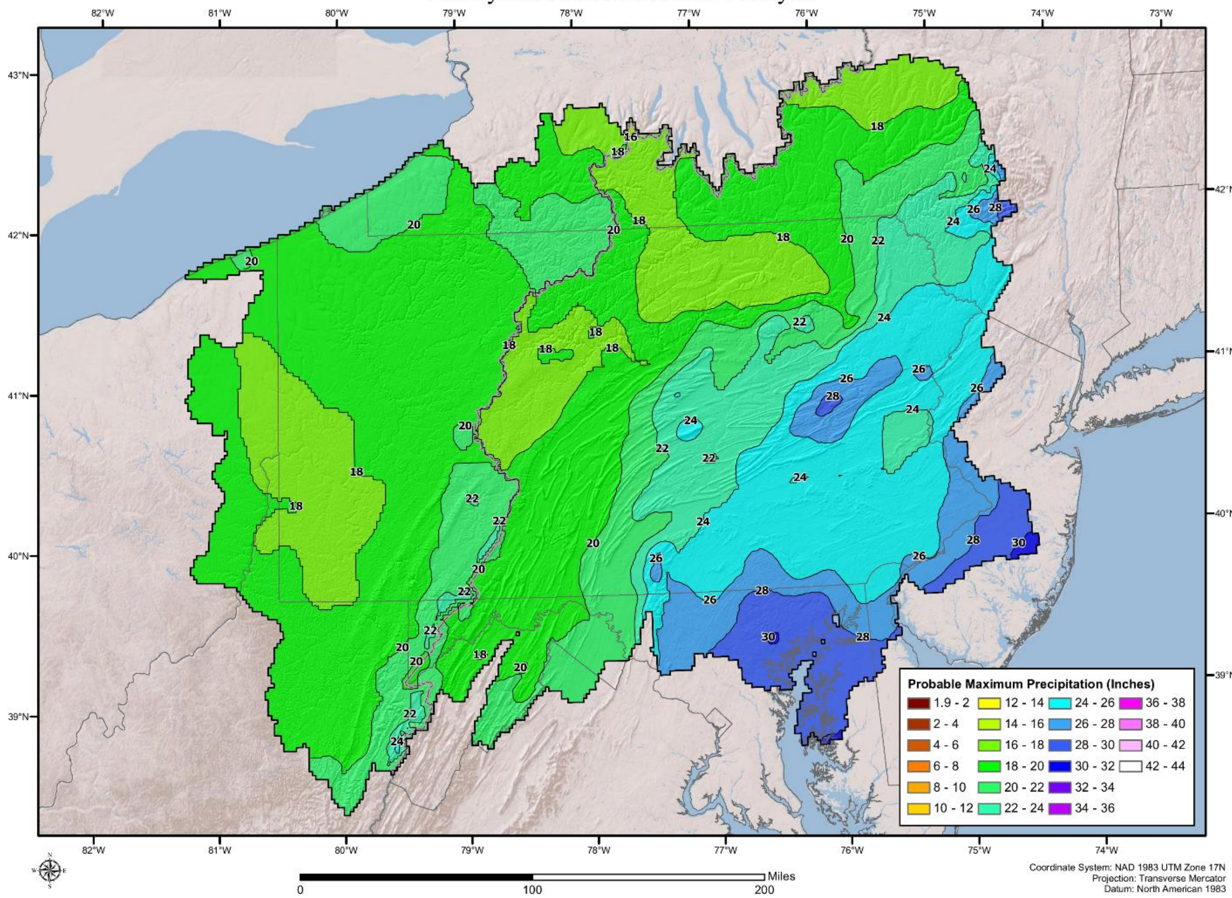
24-Hour Tropical Storm Probable Maximum Precipitation (20000 mi²)
Pennsylvania Statewide PMP Analysis



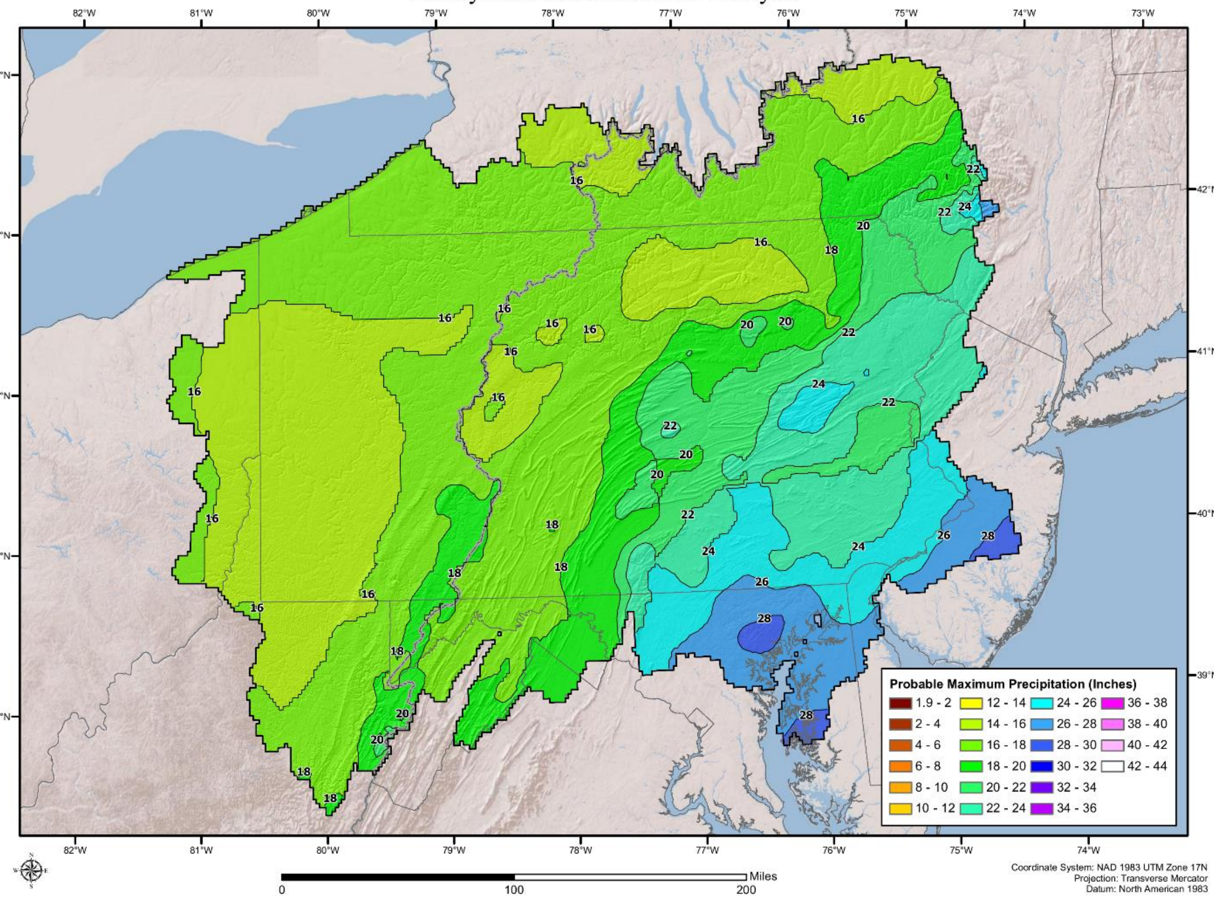
72-Hour Tropical Storm Probable Maximum Precipitation (10 mi²)
Pennsylvania Statewide PMP Analysis



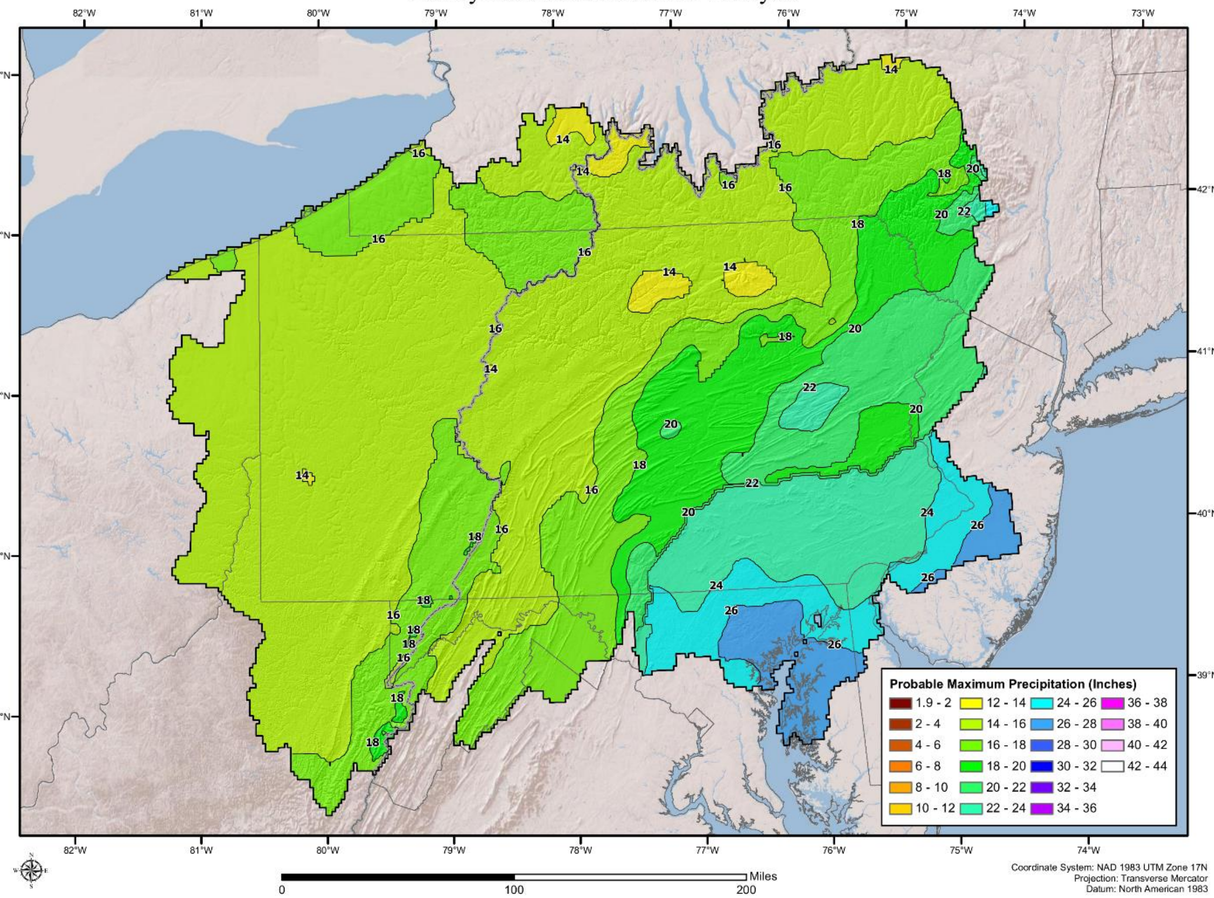
72-Hour Tropical Storm Probable Maximum Precipitation (100 mi²)
Pennsylvania Statewide PMP Analysis



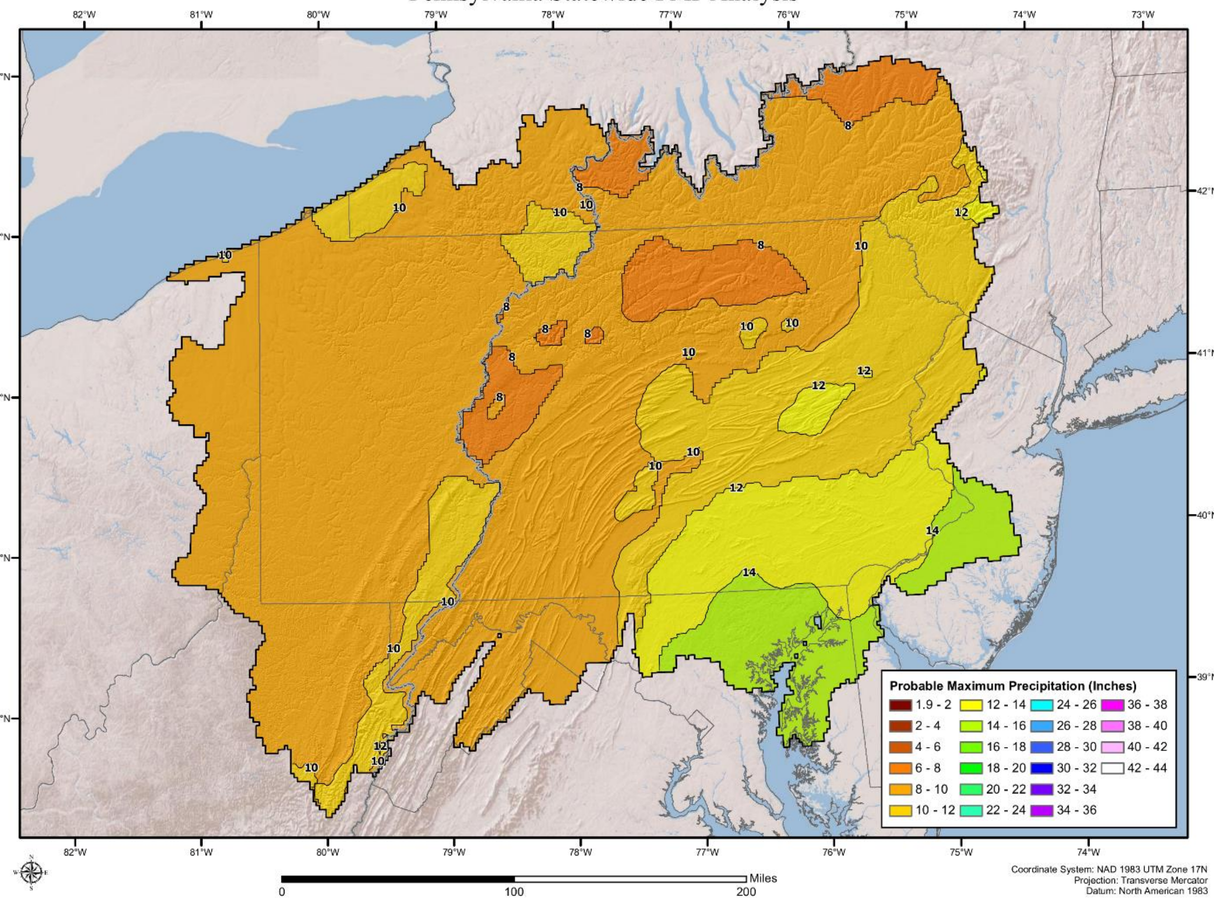
72-Hour Tropical Storm Probable Maximum Precipitation (500 mi²)
Pennsylvania Statewide PMP Analysis



72-Hour Tropical Storm Probable Maximum Precipitation (1000 mi²)
Pennsylvania Statewide PMP Analysis



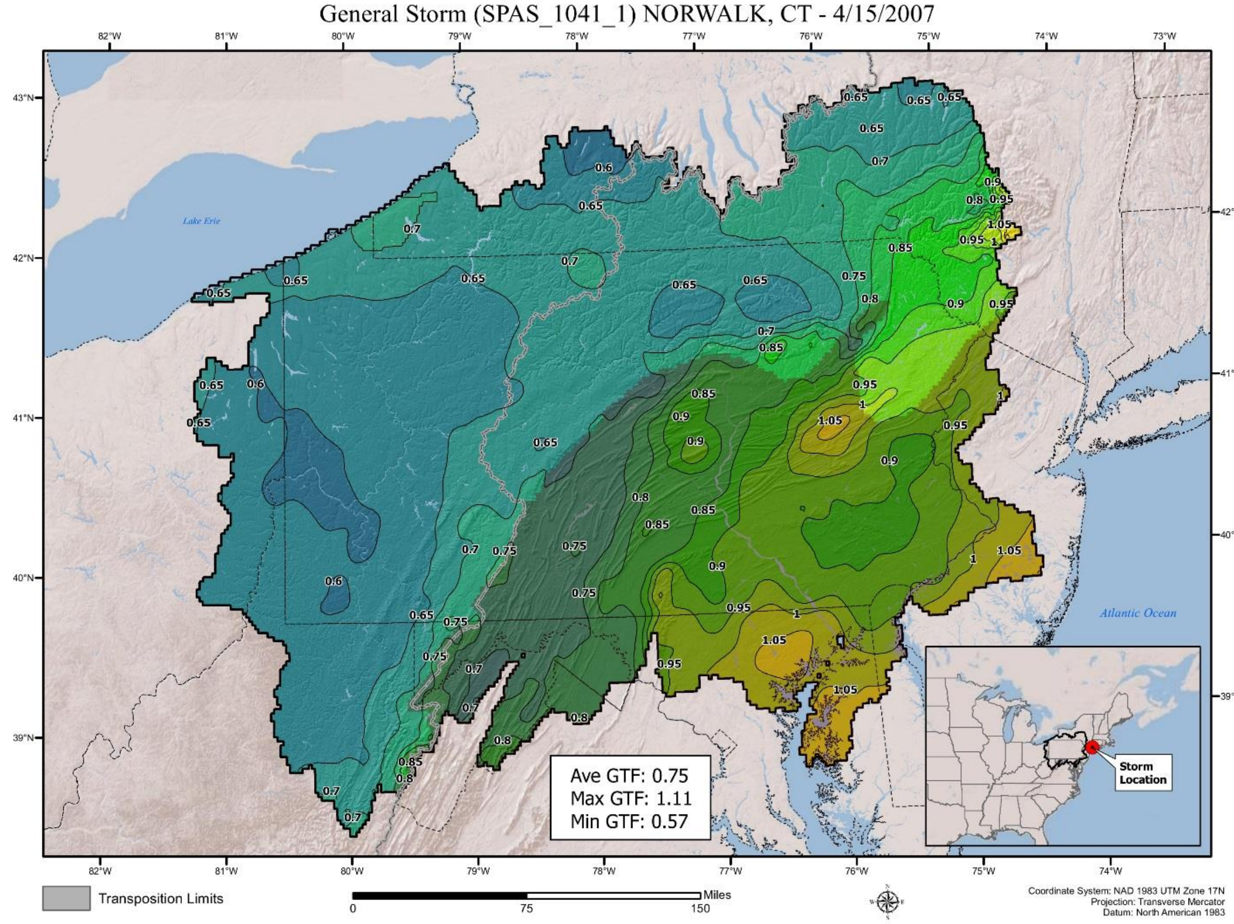
72-Hour Tropical Storm Probable Maximum Precipitation (20000 mi²)
Pennsylvania Statewide PMP Analysis



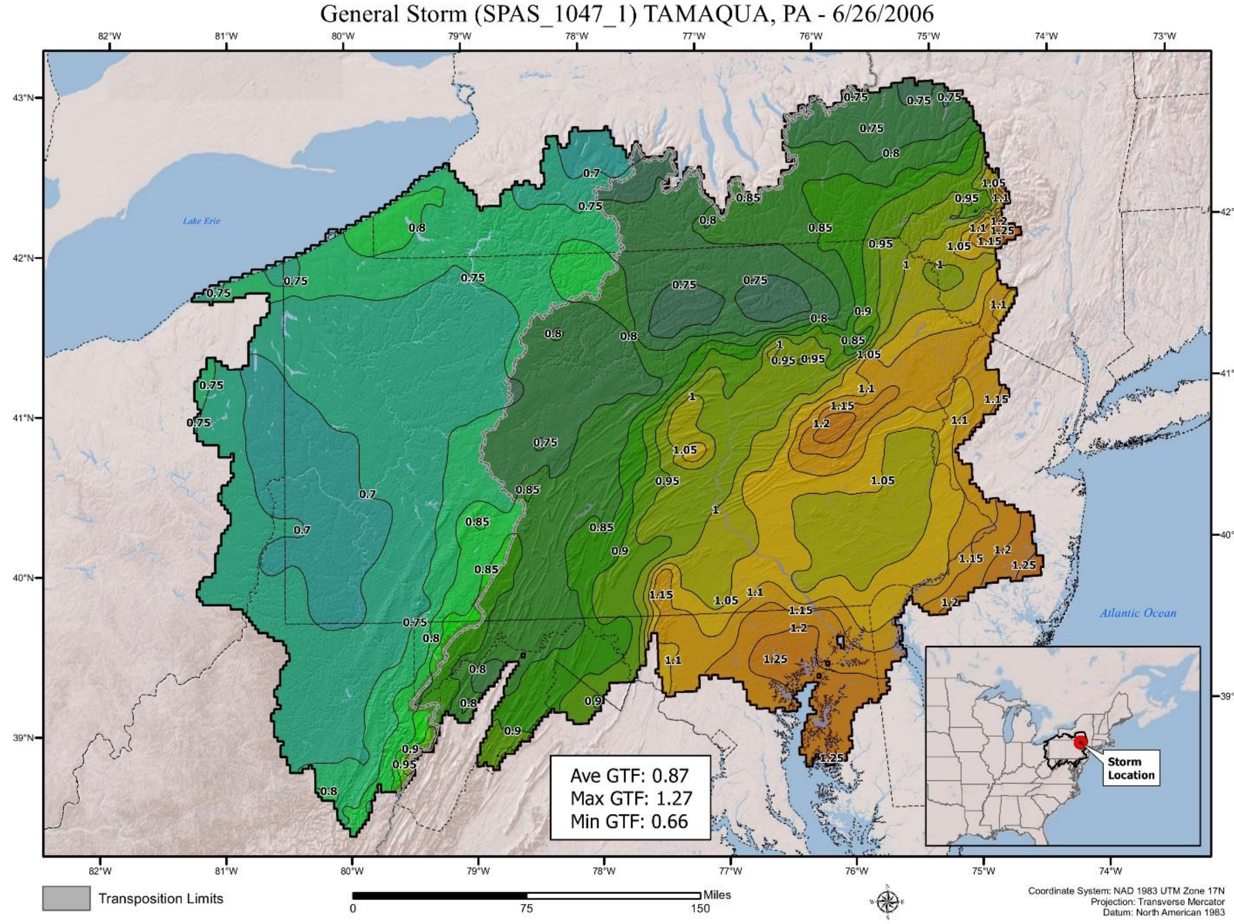
Appendix B
Geographic Transposition Factor (GTF) Maps

General Storms

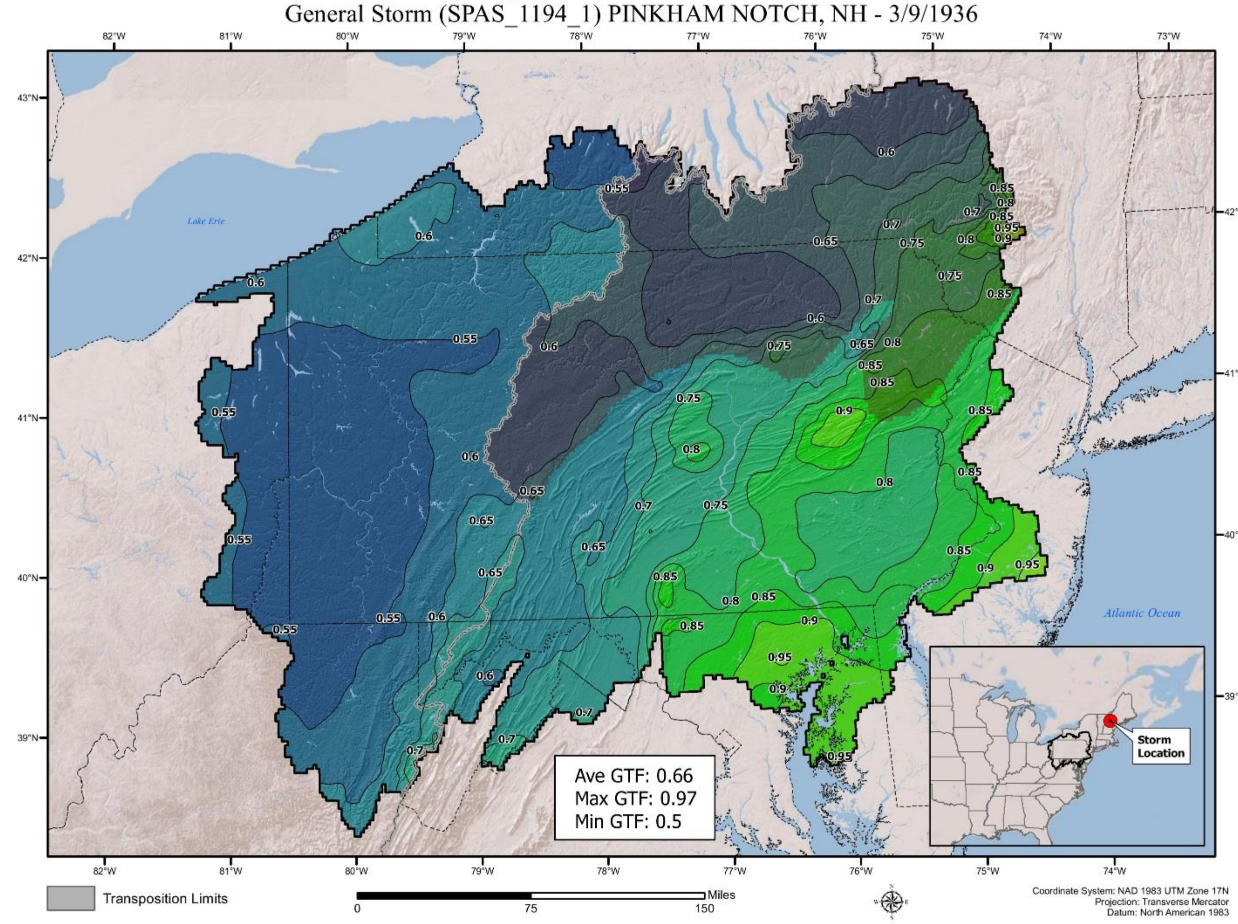
Geographic Transposition Factor
General Storm (SPAS_1041_1) NORWALK, CT - 4/15/2007



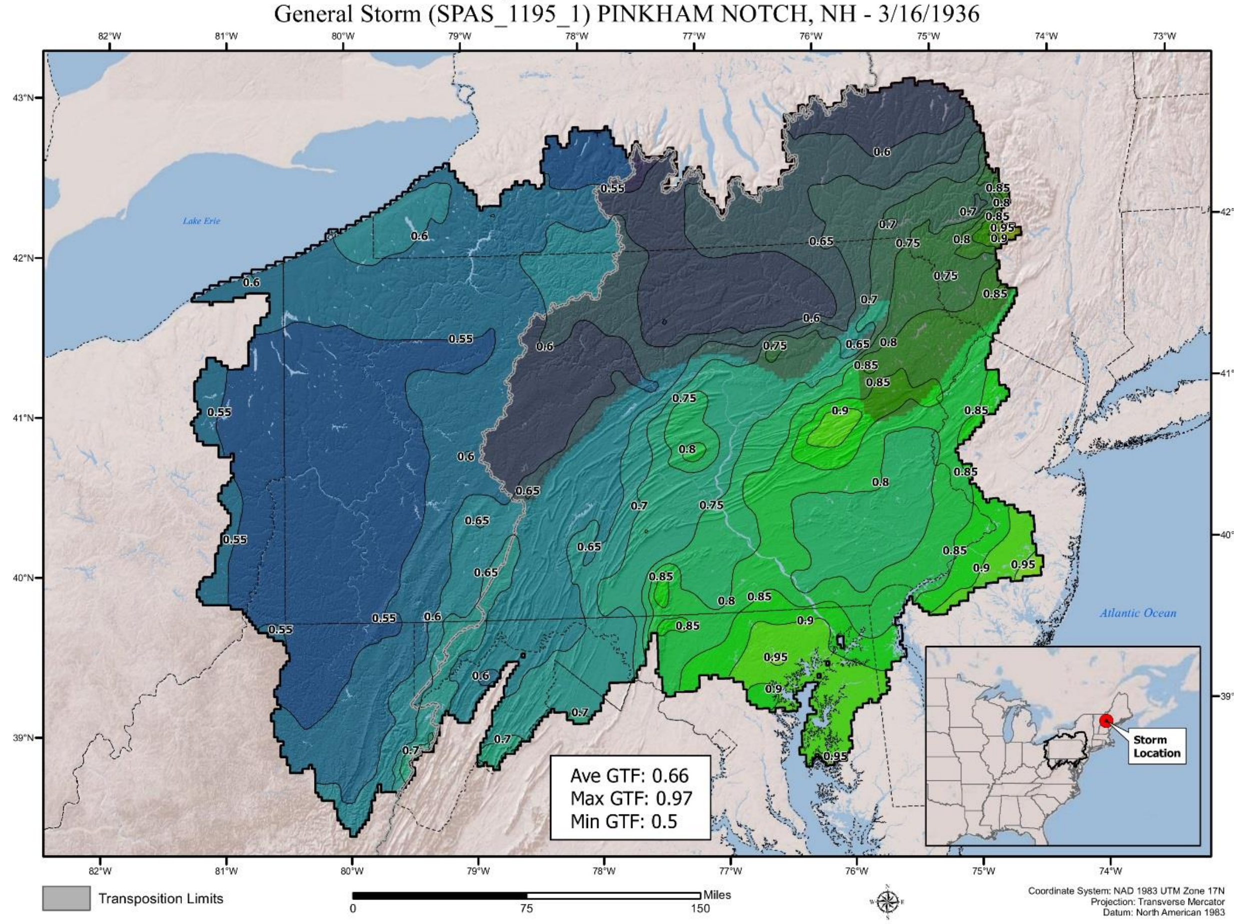
Geographic Transposition Factor
General Storm (SPAS_1047_1) TAMAQUA, PA - 6/26/2006



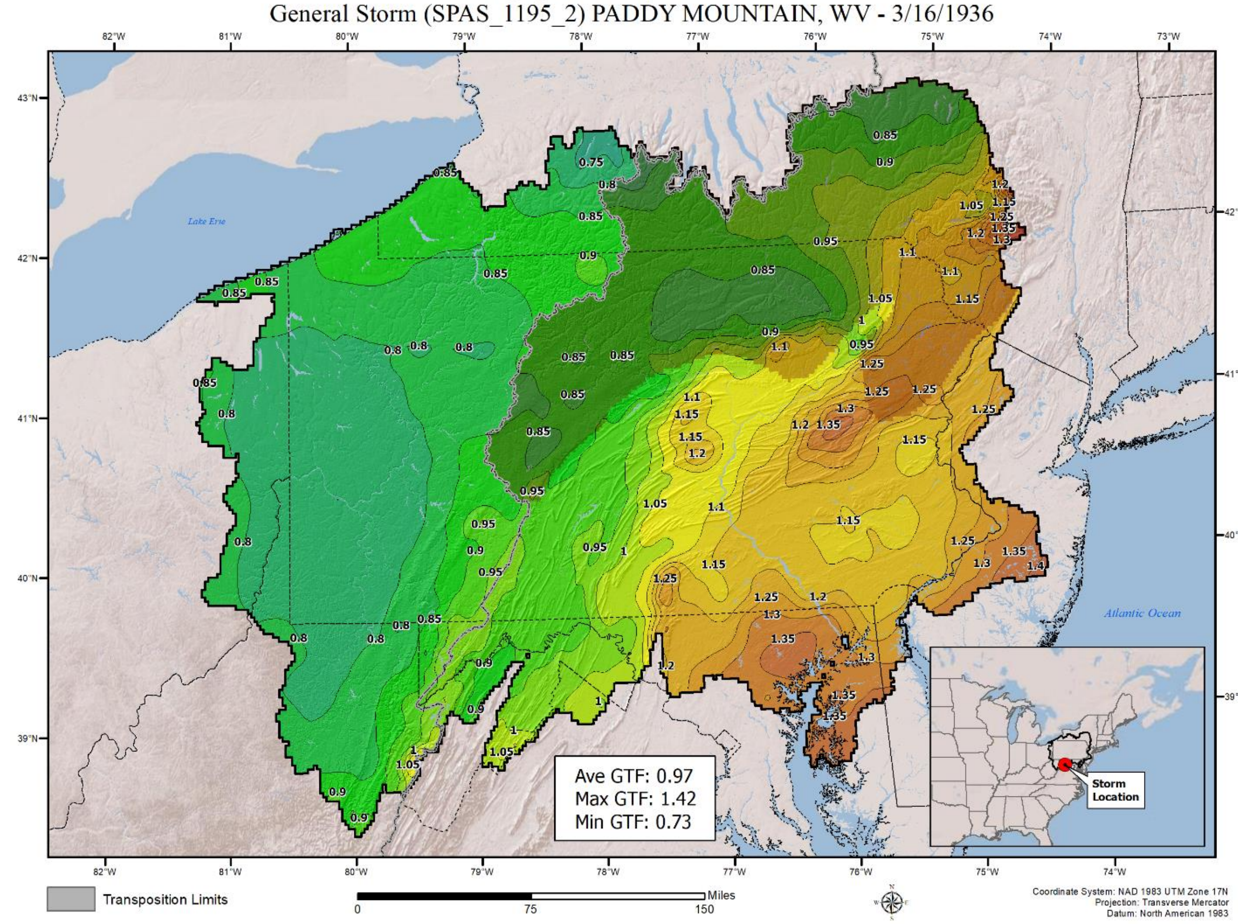
Geographic Transposition Factor
General Storm (SPAS_1194_1) PINKHAM NOTCH, NH - 3/9/1936



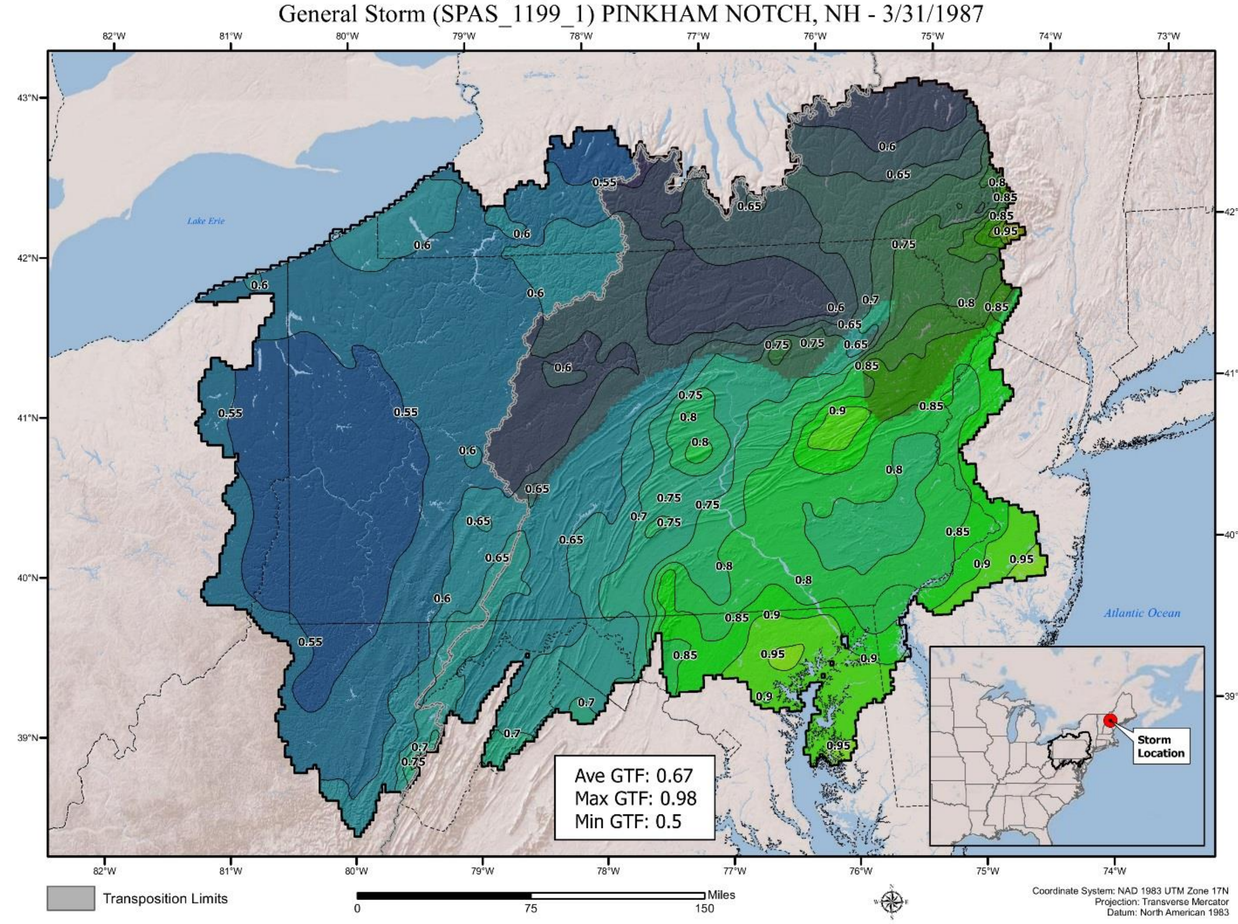
Geographic Transposition Factor
General Storm (SPAS_1195_1) PINKHAM NOTCH, NH - 3/16/1936



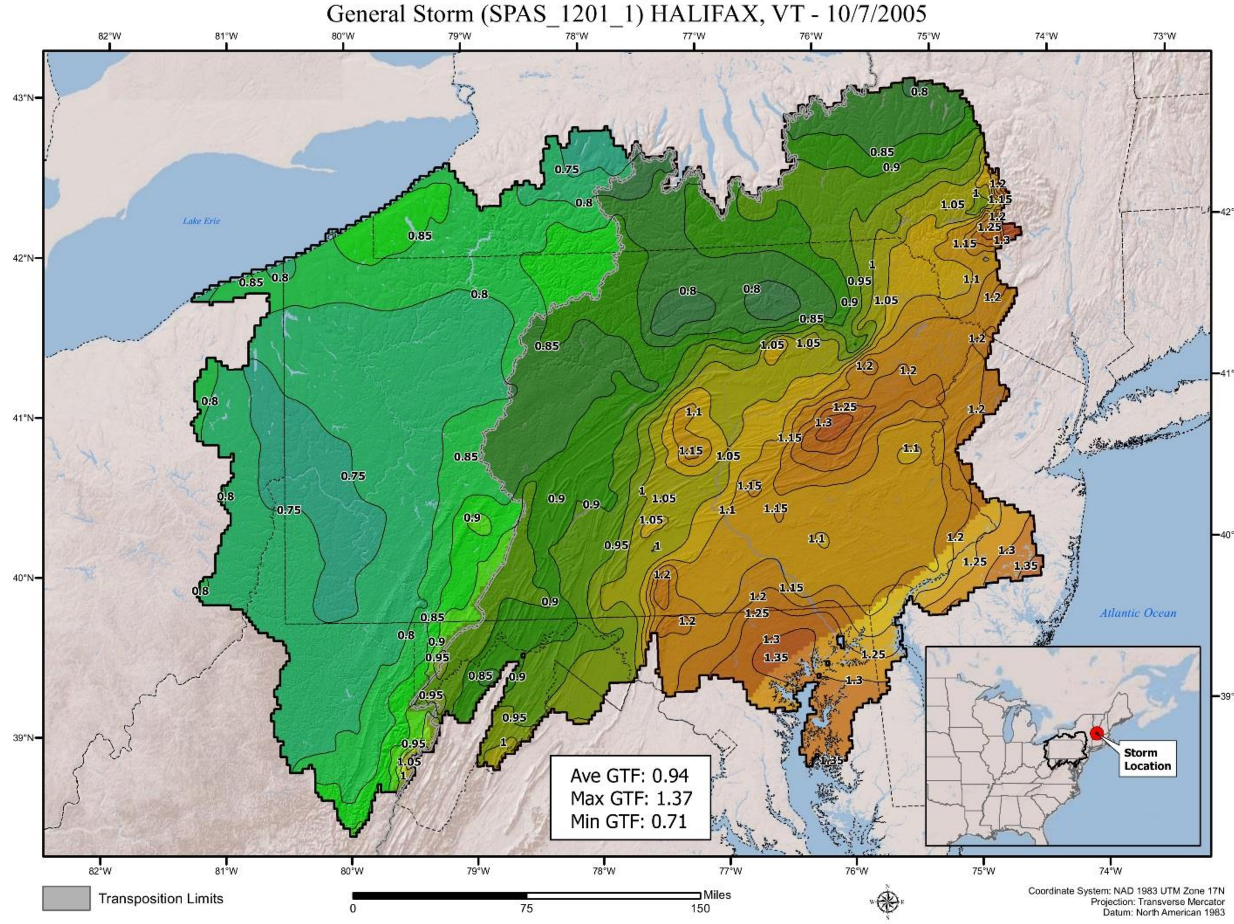
Geographic Transposition Factor
General Storm (SPAS_1195_2) PADDY MOUNTAIN, WV - 3/16/1936



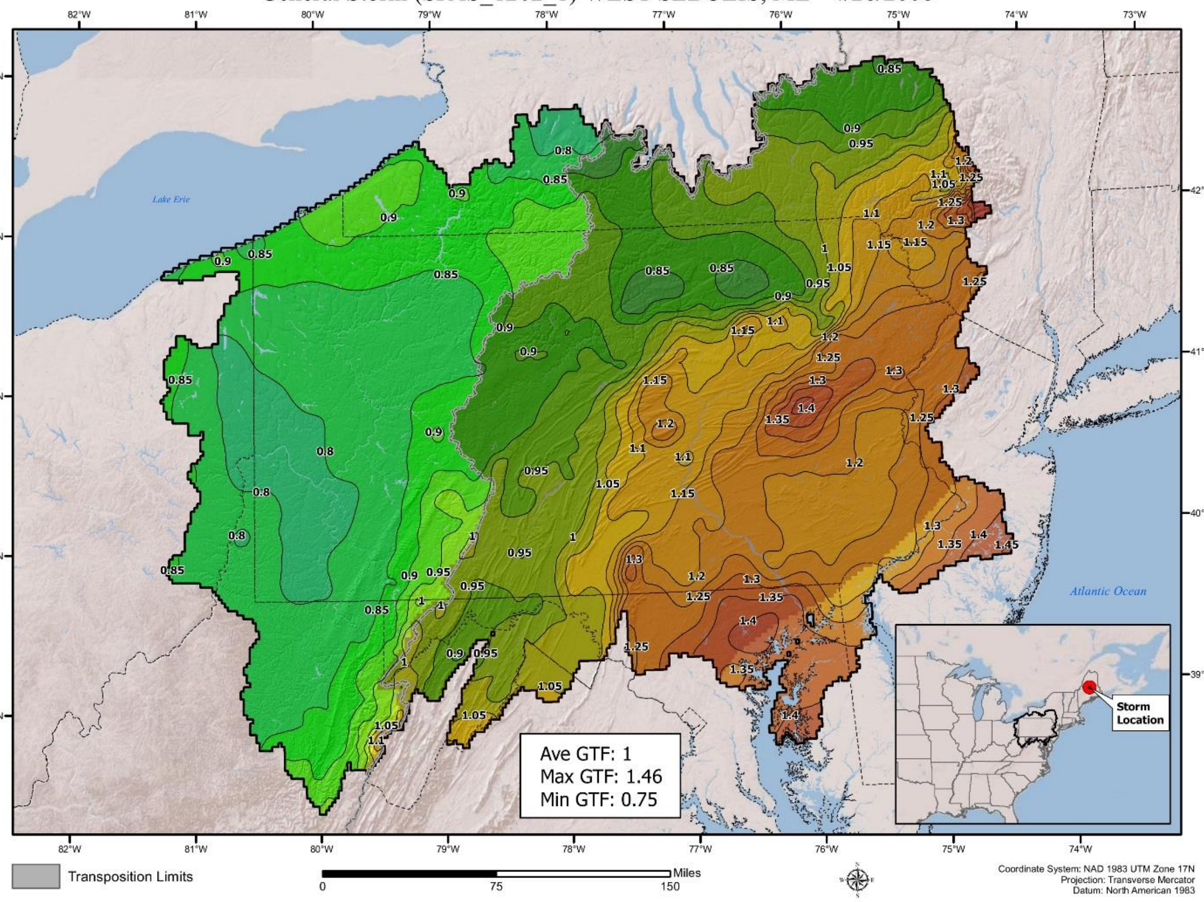
Geographic Transposition Factor
General Storm (SPAS_1199_1) PINKHAM NOTCH, NH - 3/31/1987



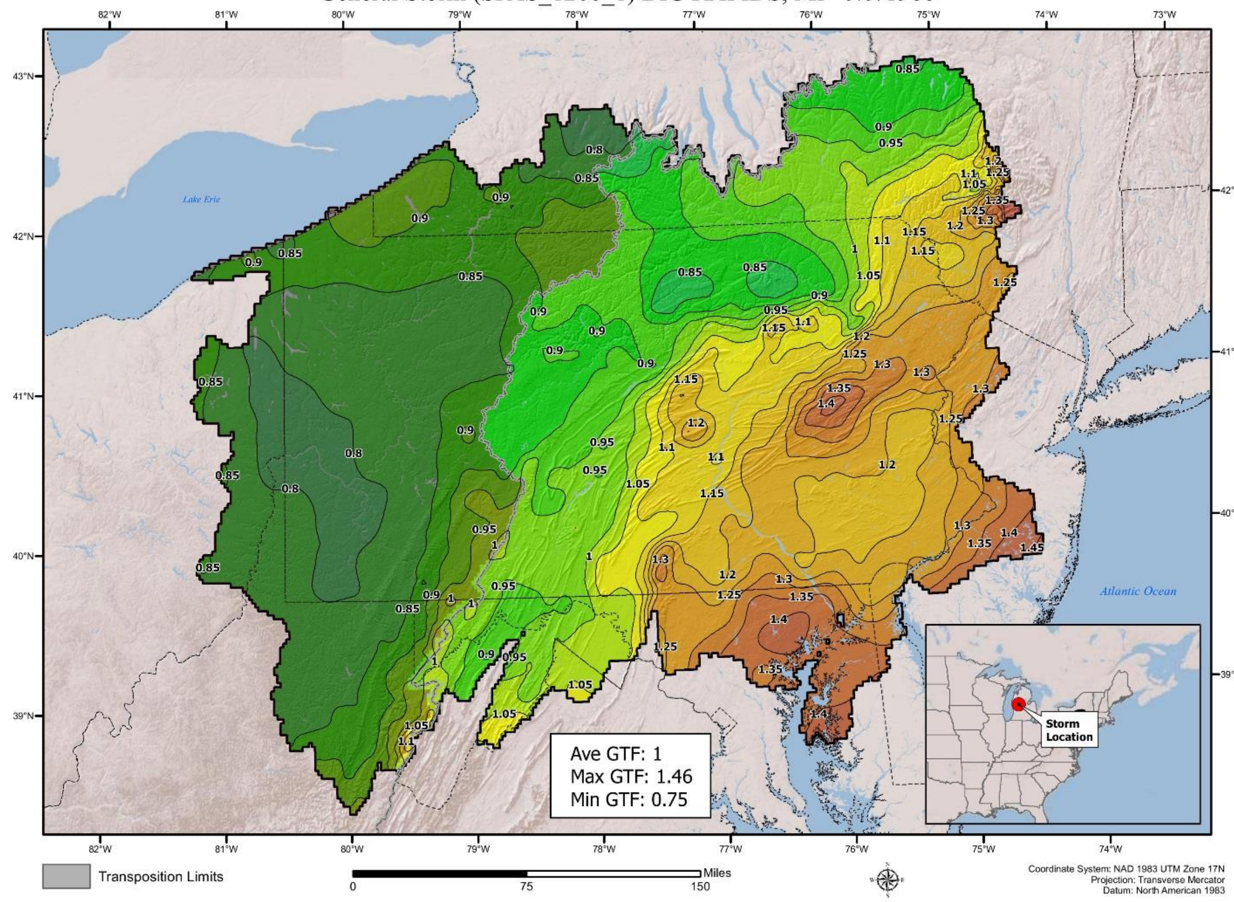
Geographic Transposition Factor
General Storm (SPAS_1201_1) HALIFAX, VT - 10/7/2005



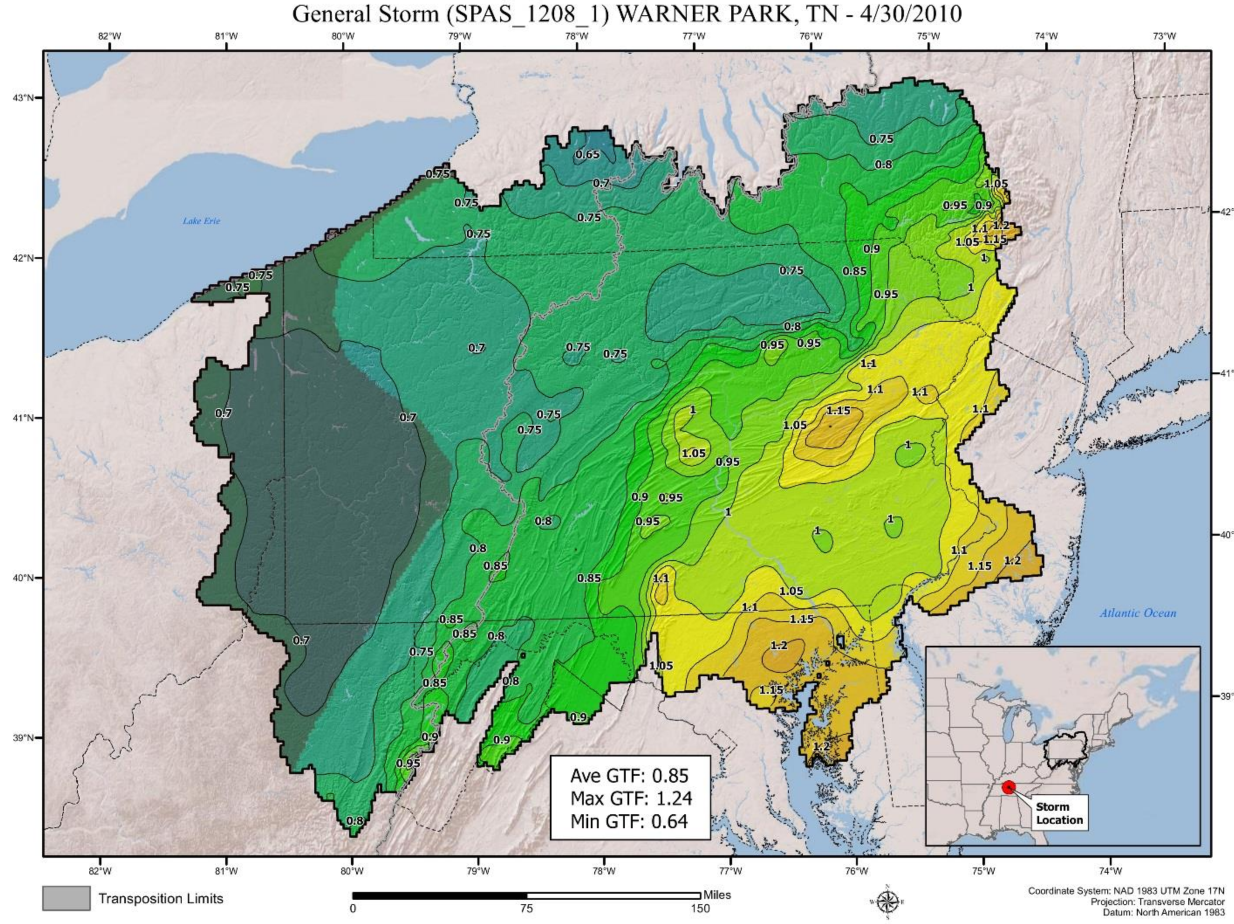
Geographic Transposition Factor
General Storm (SPAS_1202_1) WEST SEBOEIS, ME - 4/28/2008



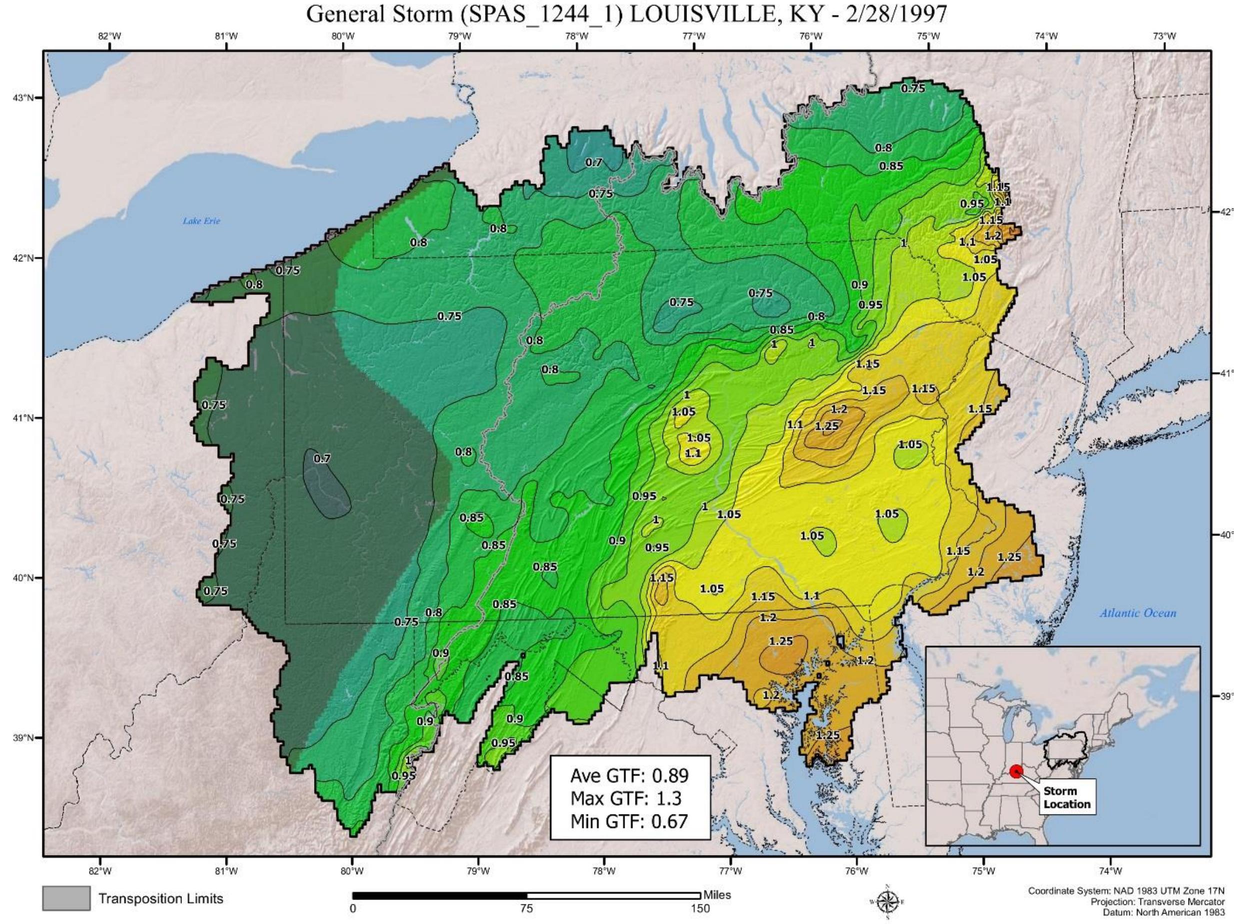
Geographic Transposition Factor
General Storm (SPAS_1206_1) BIG RAPIDS, MI - 9/9/1986



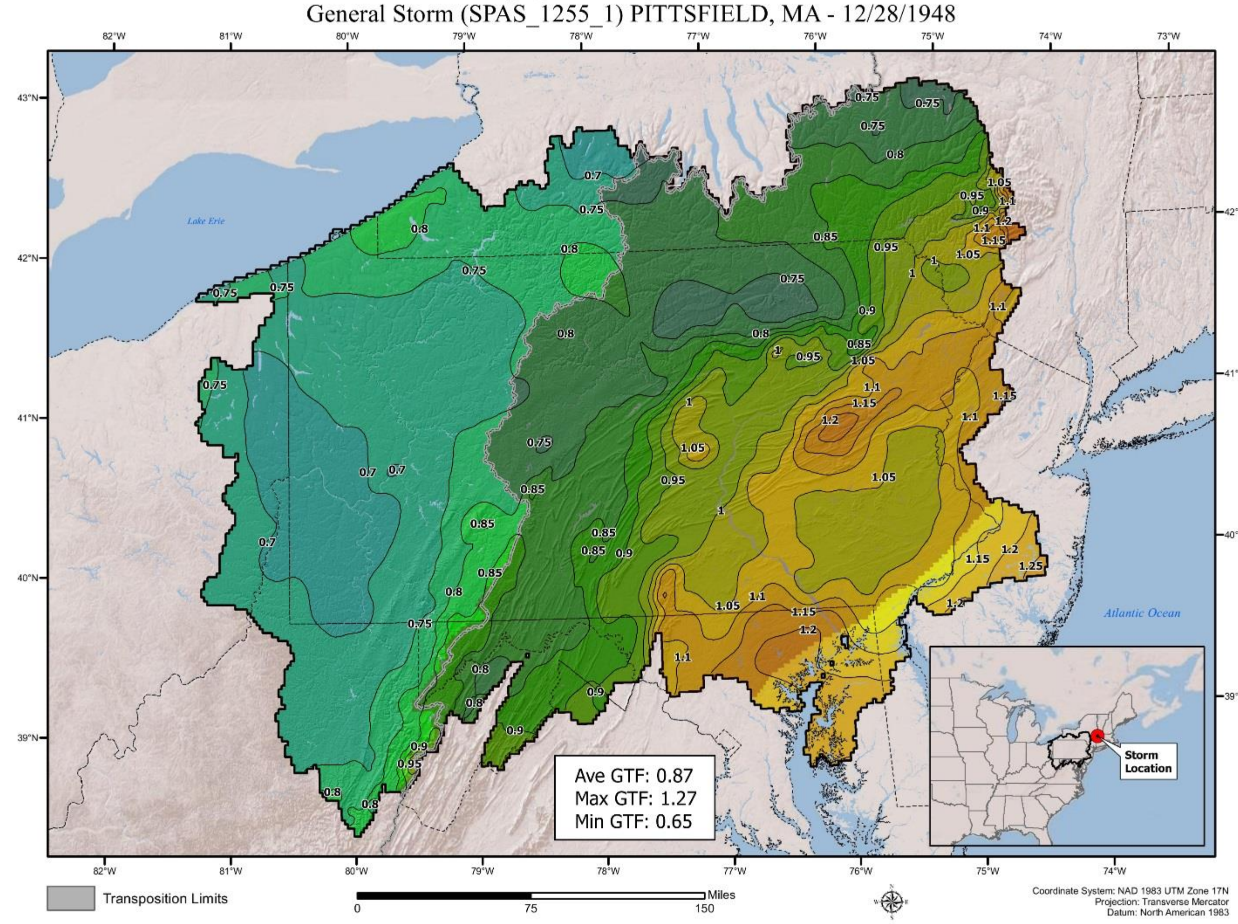
Geographic Transposition Factor
General Storm (SPAS_1208_1) WARNER PARK, TN - 4/30/2010



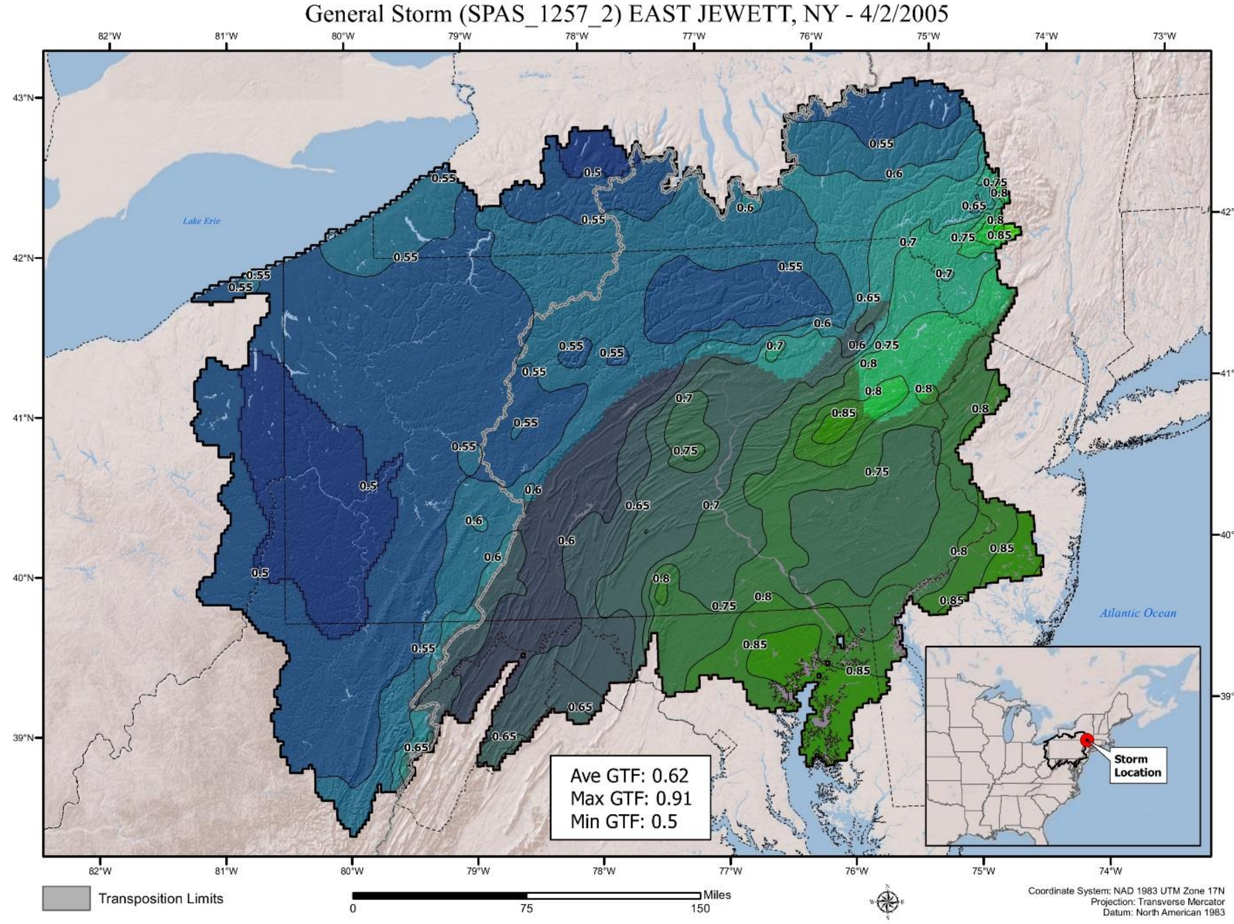
Geographic Transposition Factor
General Storm (SPAS_1244_1) LOUISVILLE, KY - 2/28/1997



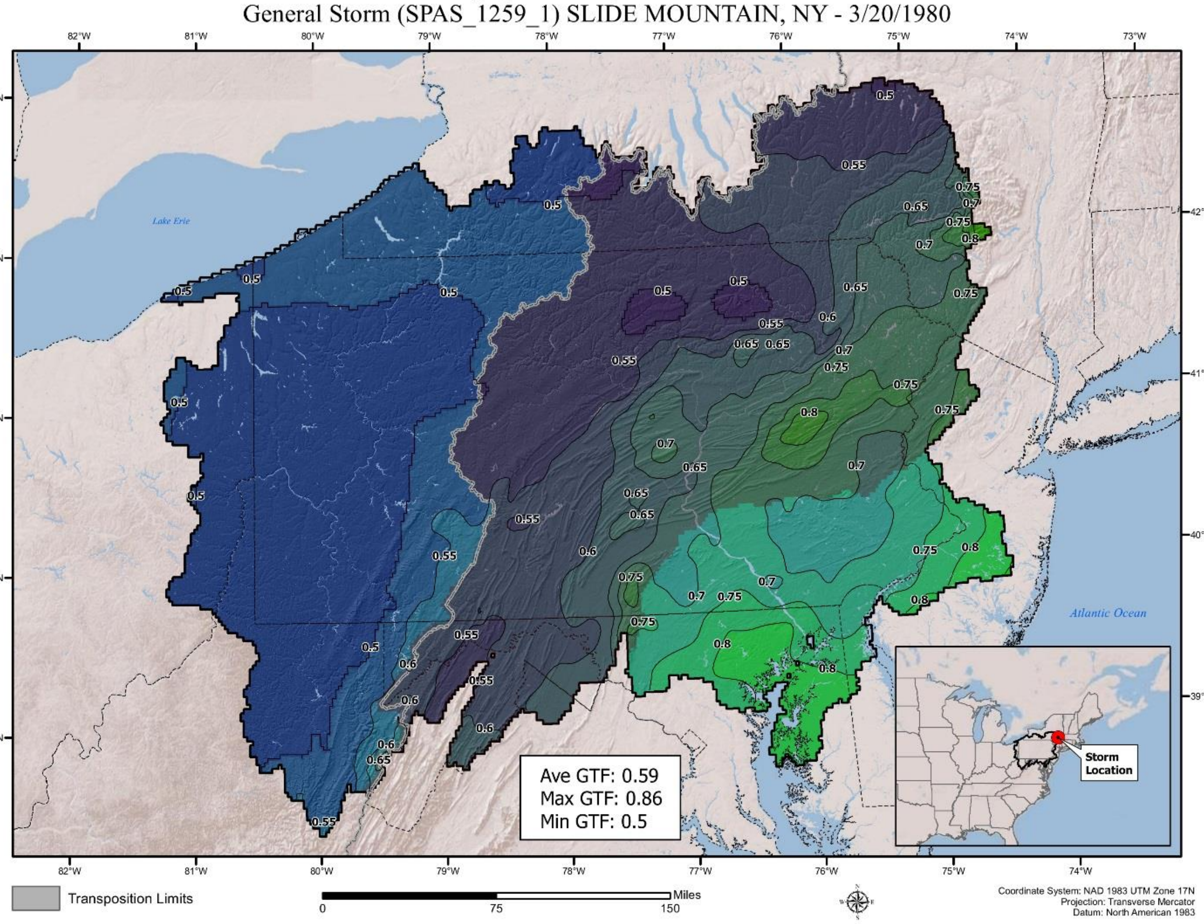
Geographic Transposition Factor
General Storm (SPAS_1255_1) PITTSFIELD, MA - 12/28/1948



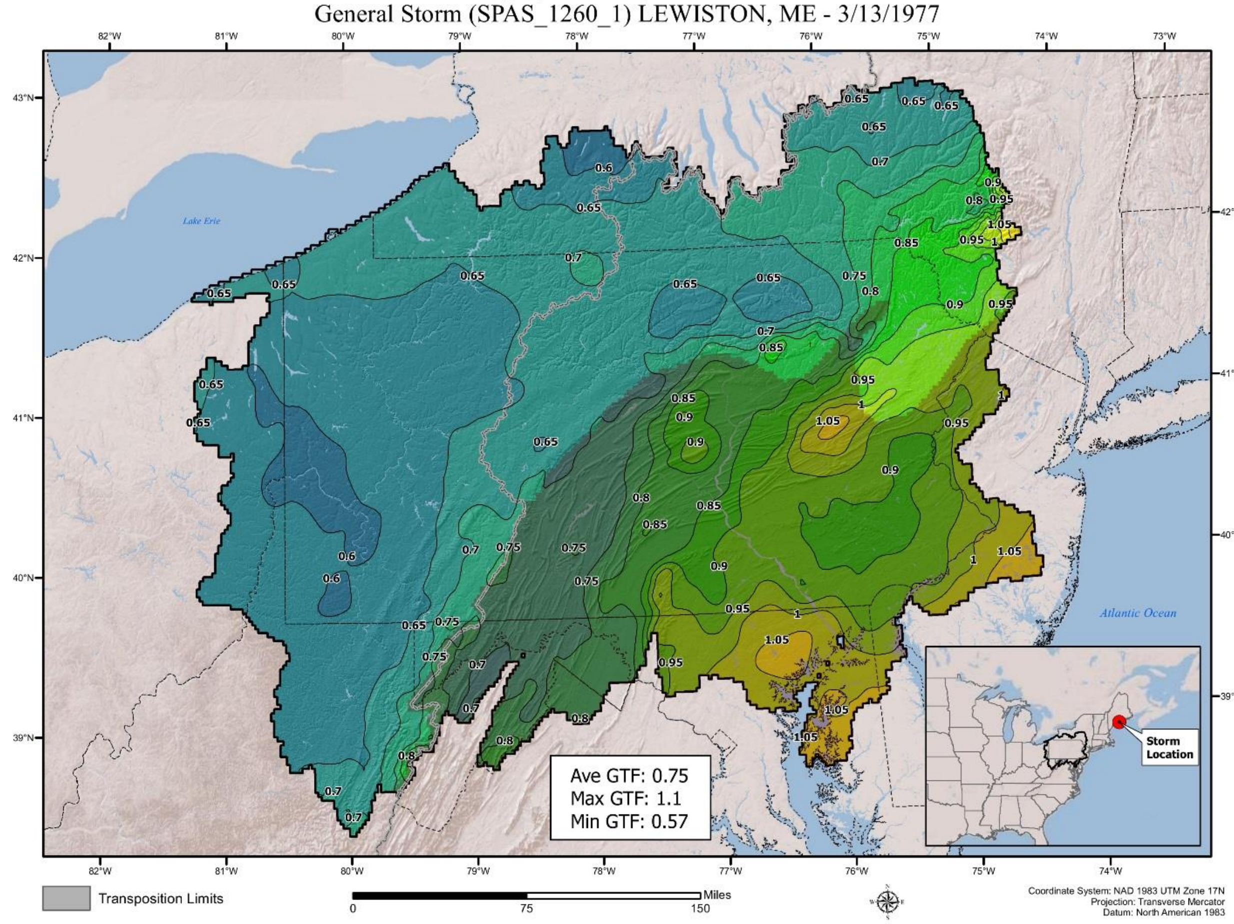
Geographic Transposition Factor
General Storm (SPAS_1257_2) EAST JEWETT, NY - 4/2/2005



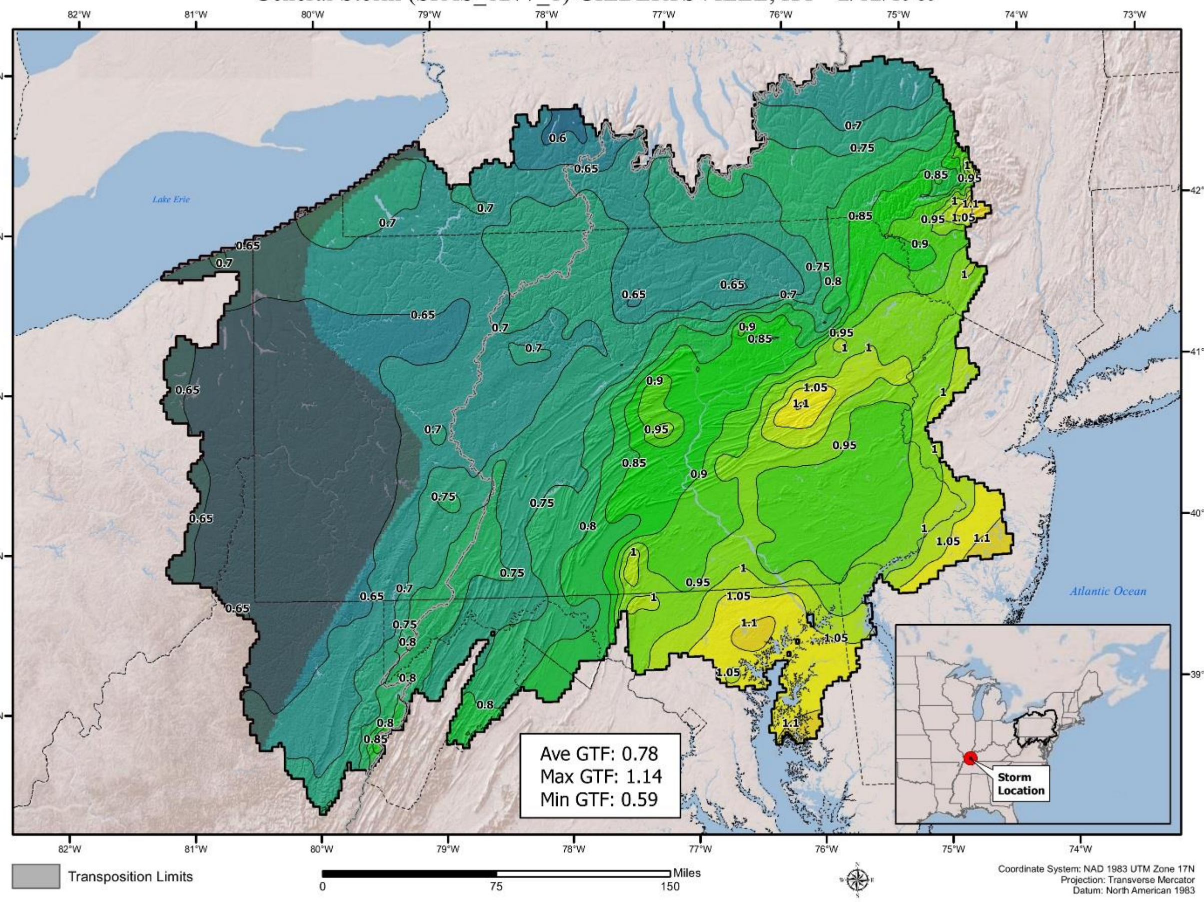
Geographic Transposition Factor
General Storm (SPAS_1259_1) SLIDE MOUNTAIN, NY - 3/20/1980



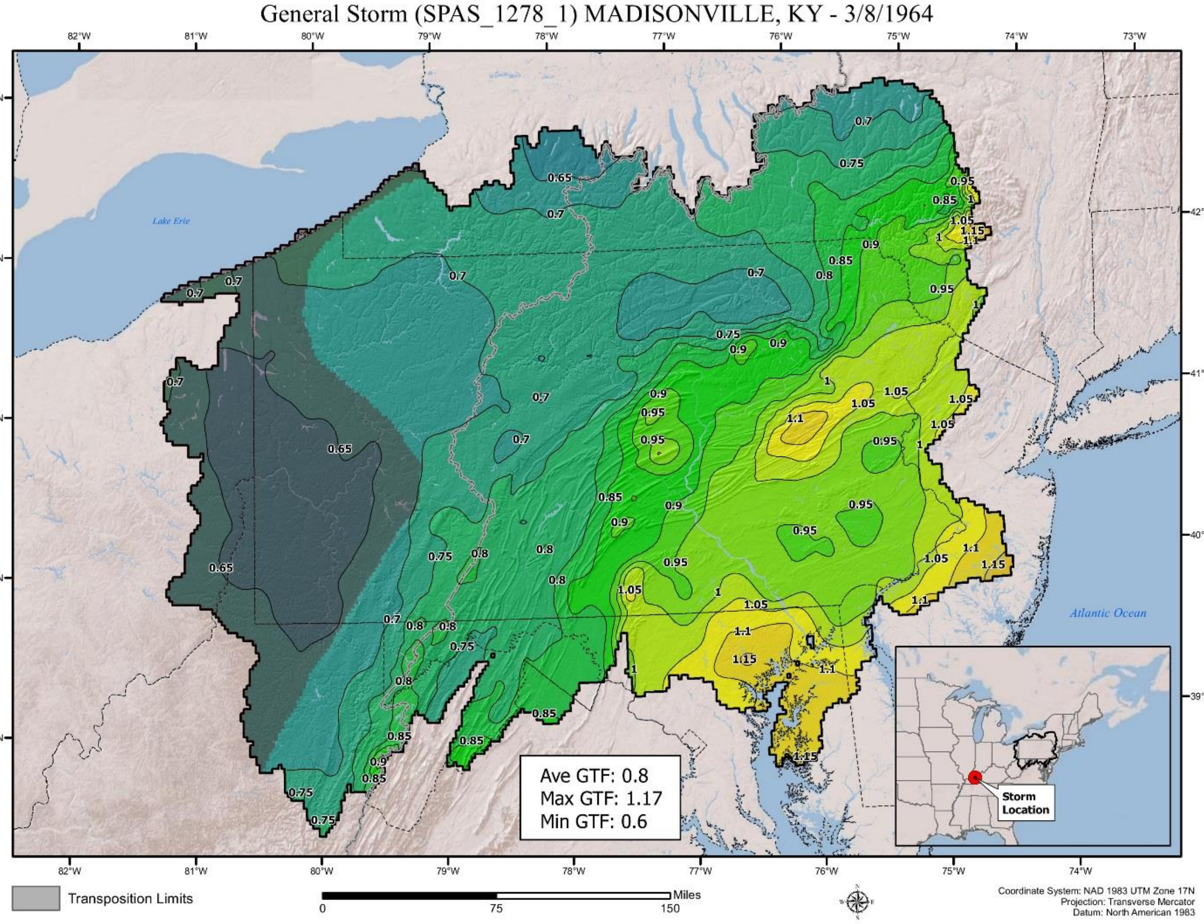
Geographic Transposition Factor
General Storm (SPAS_1260_1) LEWISTON, ME - 3/13/1977



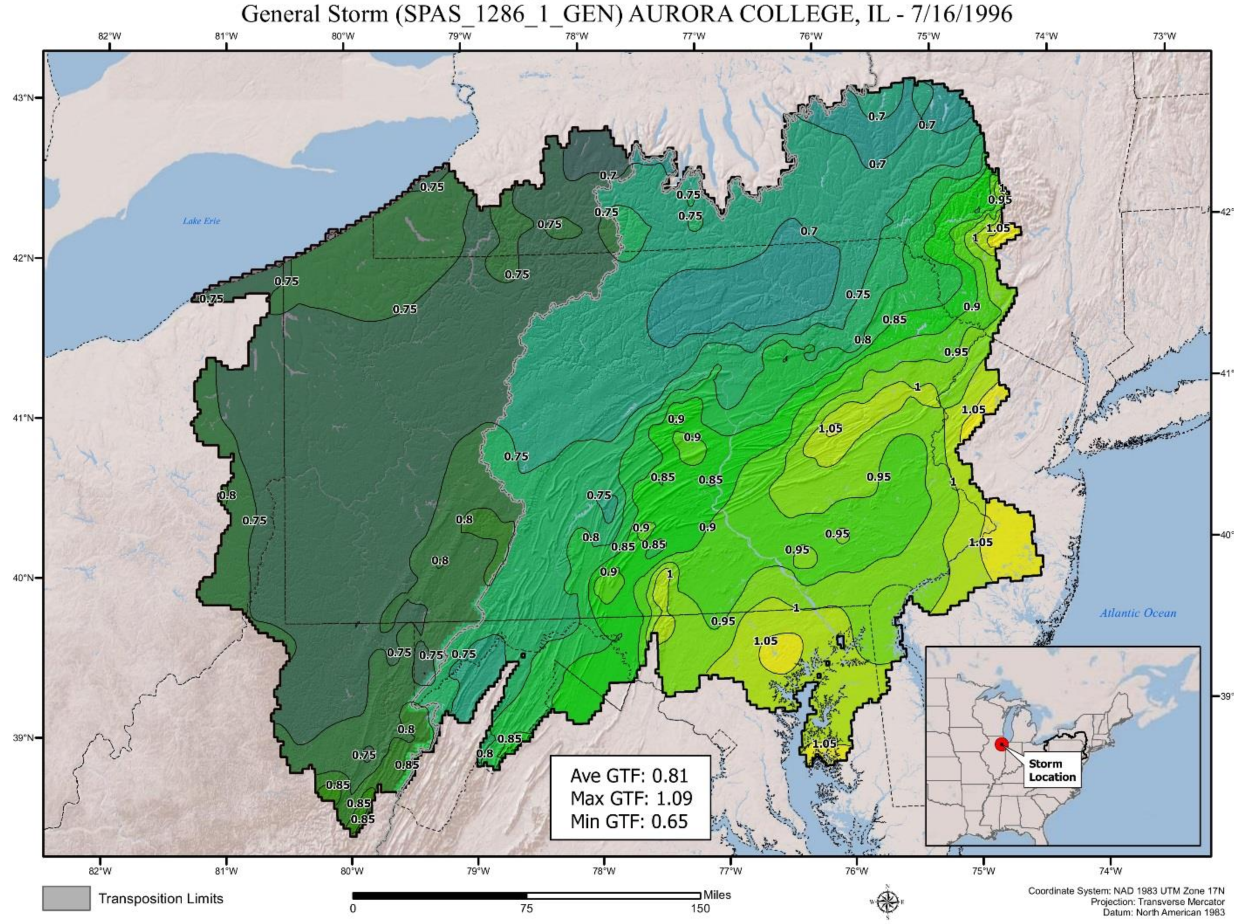
Geographic Transposition Factor
General Storm (SPAS_1277_1) GILBERTSVILLE, KY - 2/12/1989



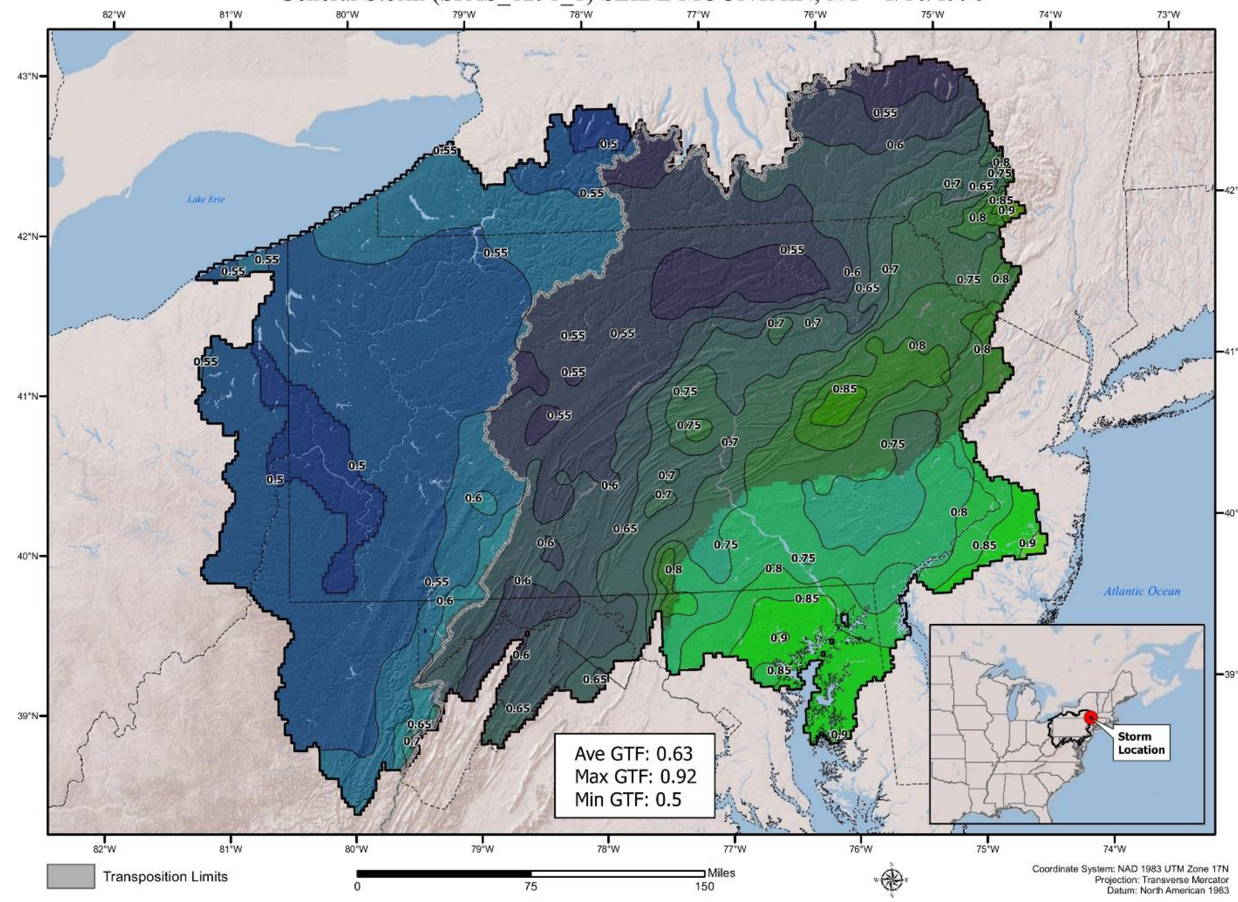
Geographic Transposition Factor
General Storm (SPAS_1278_1) MADISONVILLE, KY - 3/8/1964



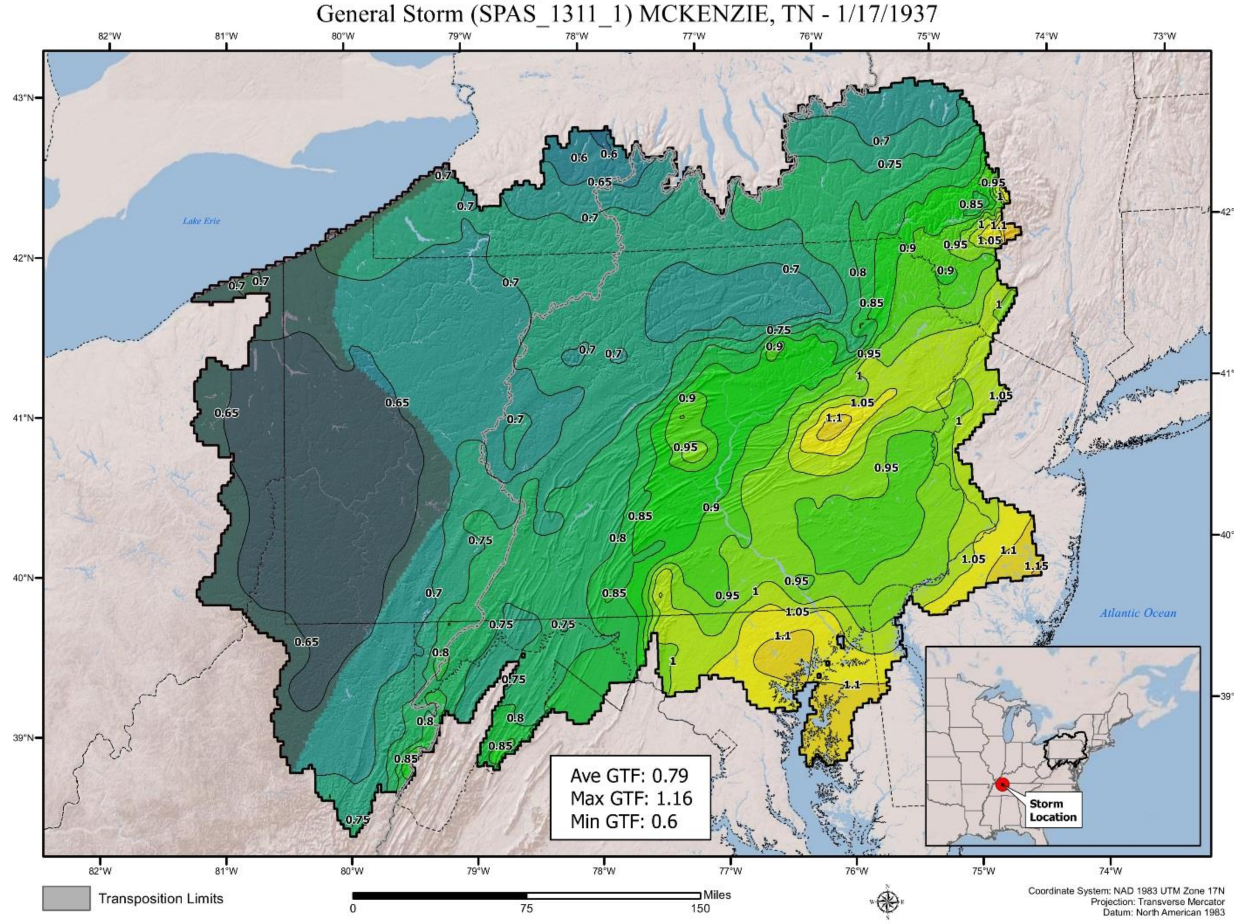
Geographic Transposition Factor
General Storm (SPAS_1286_1_GEN) AURORA COLLEGE, IL - 7/16/1996



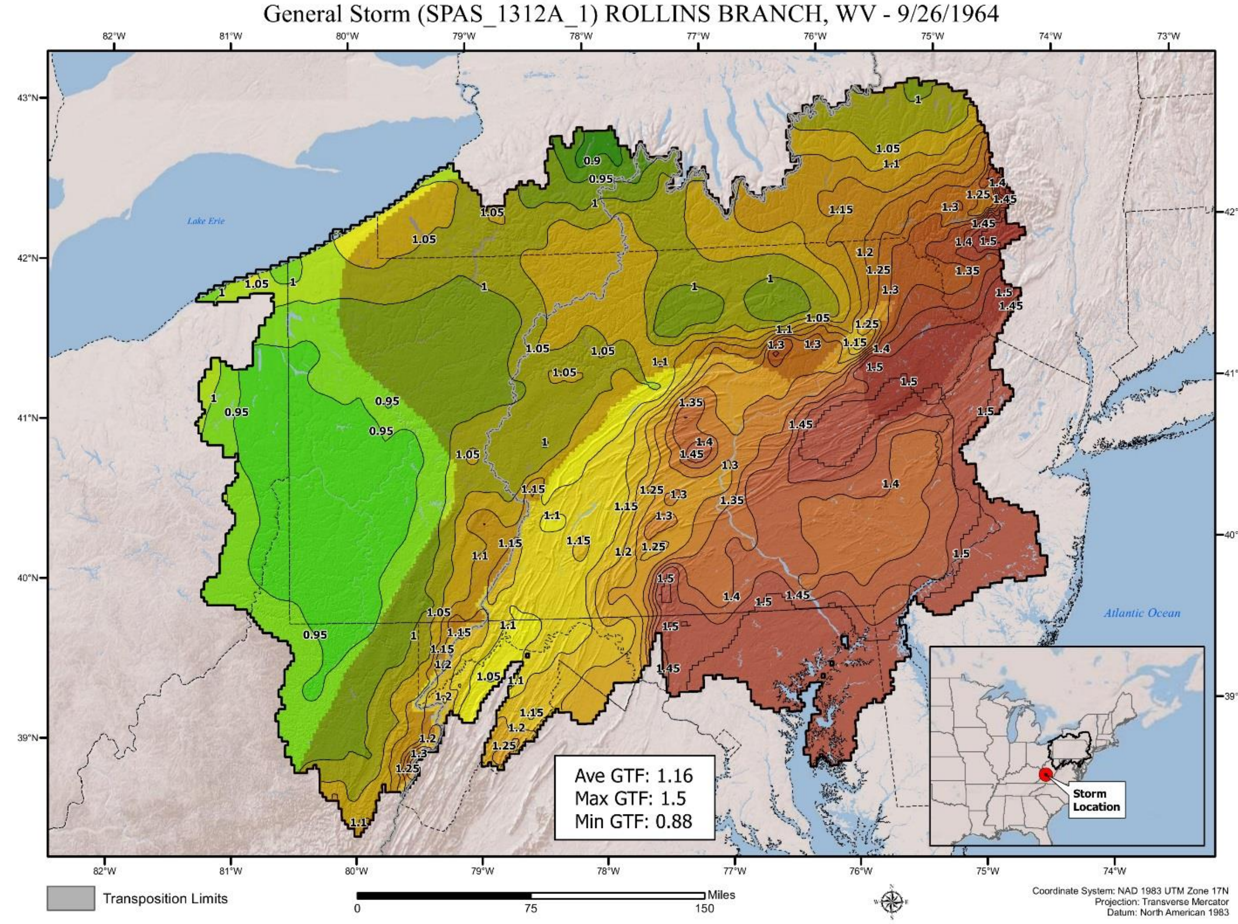
Geographic Transposition Factor
General Storm (SPAS_1291_1) SLIDE MOUNTAIN, NY - 1/16/1996



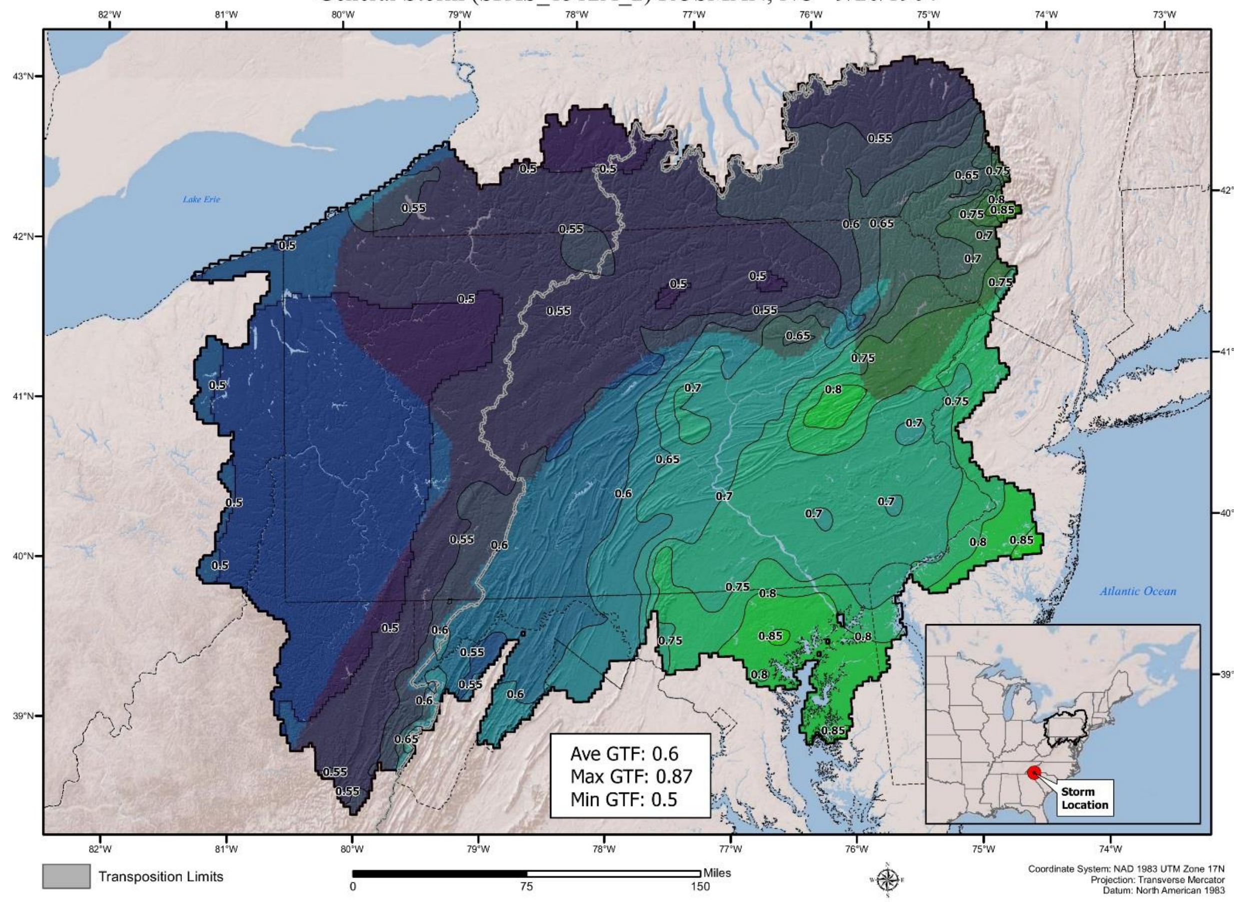
Geographic Transposition Factor
General Storm (SPAS_1311_1) MCKENZIE, TN - 1/17/1937



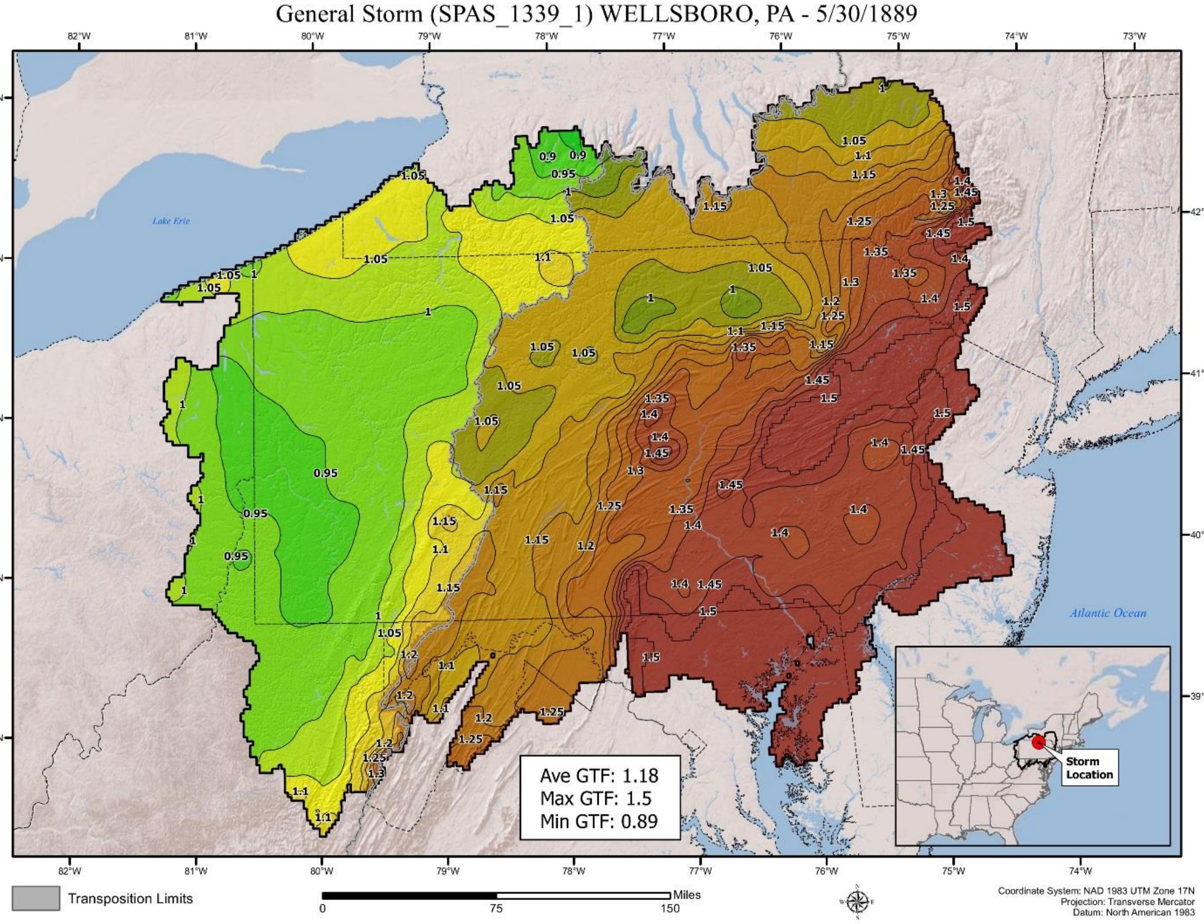
Geographic Transposition Factor
General Storm (SPAS_1312A_1) ROLLINS BRANCH, WV - 9/26/1964



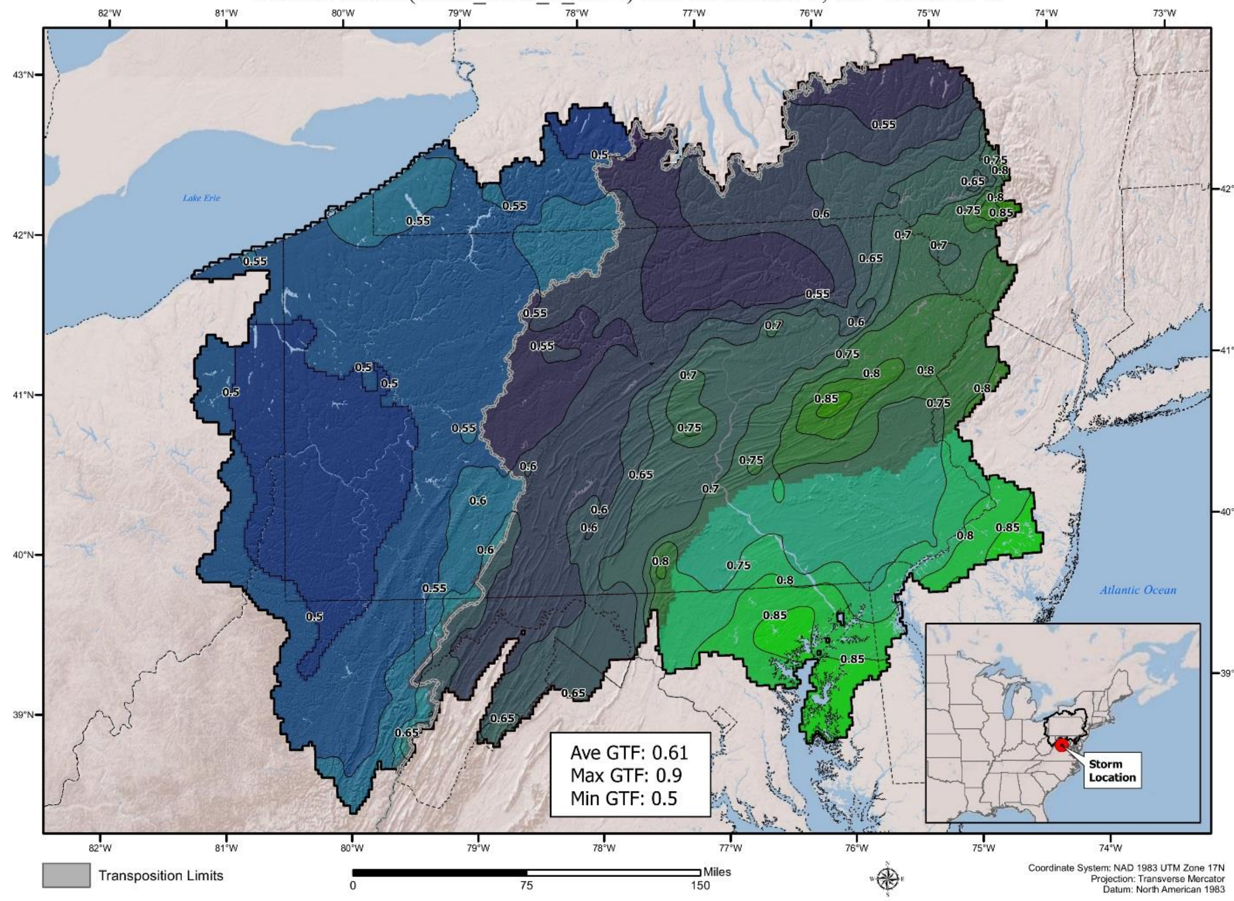
Geographic Transposition Factor
General Storm (SPAS_1312A_2) ROSMAN, NC - 9/26/1964



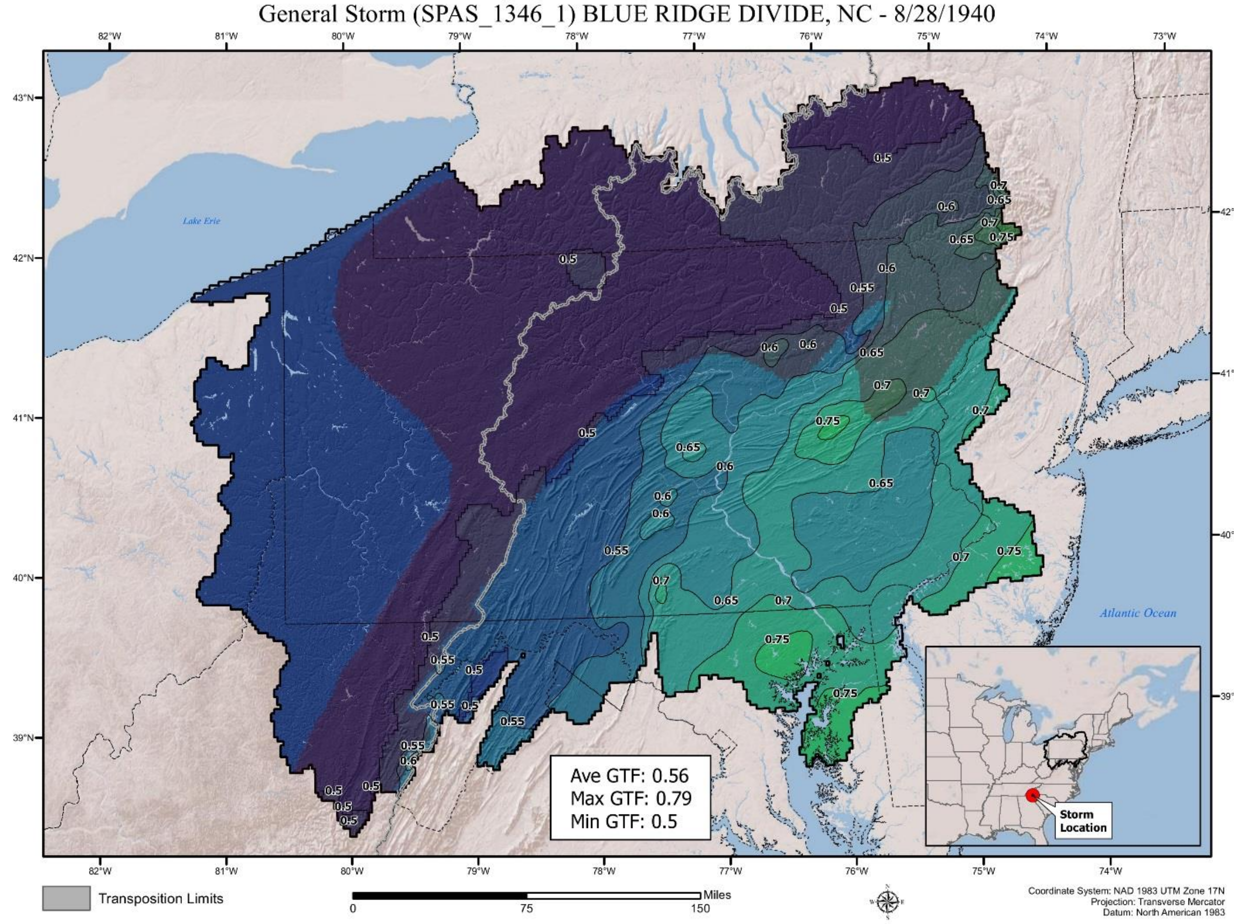
Geographic Transposition Factor
General Storm (SPAS_1339_1) WELLSBORO, PA - 5/30/1889



Geographic Transposition Factor
General Storm (SPAS_1340_1_GEN) BIG MEADOWS, VA - 10/12/1942



Geographic Transposition Factor
General Storm (SPAS_1346_1) BLUE RIDGE DIVIDE, NC - 8/28/1940



Geographic Transposition Factor
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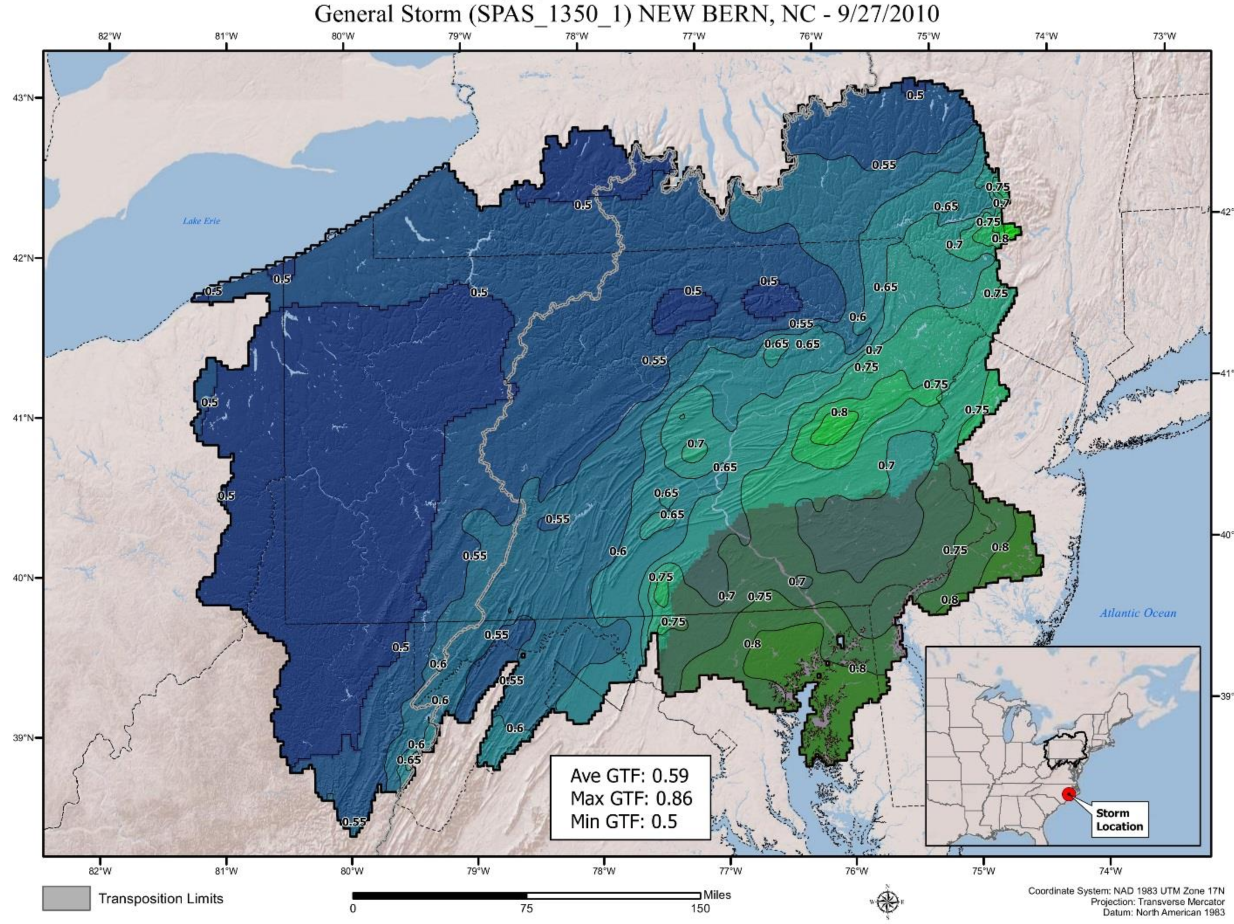

Geographic Transposition Factor
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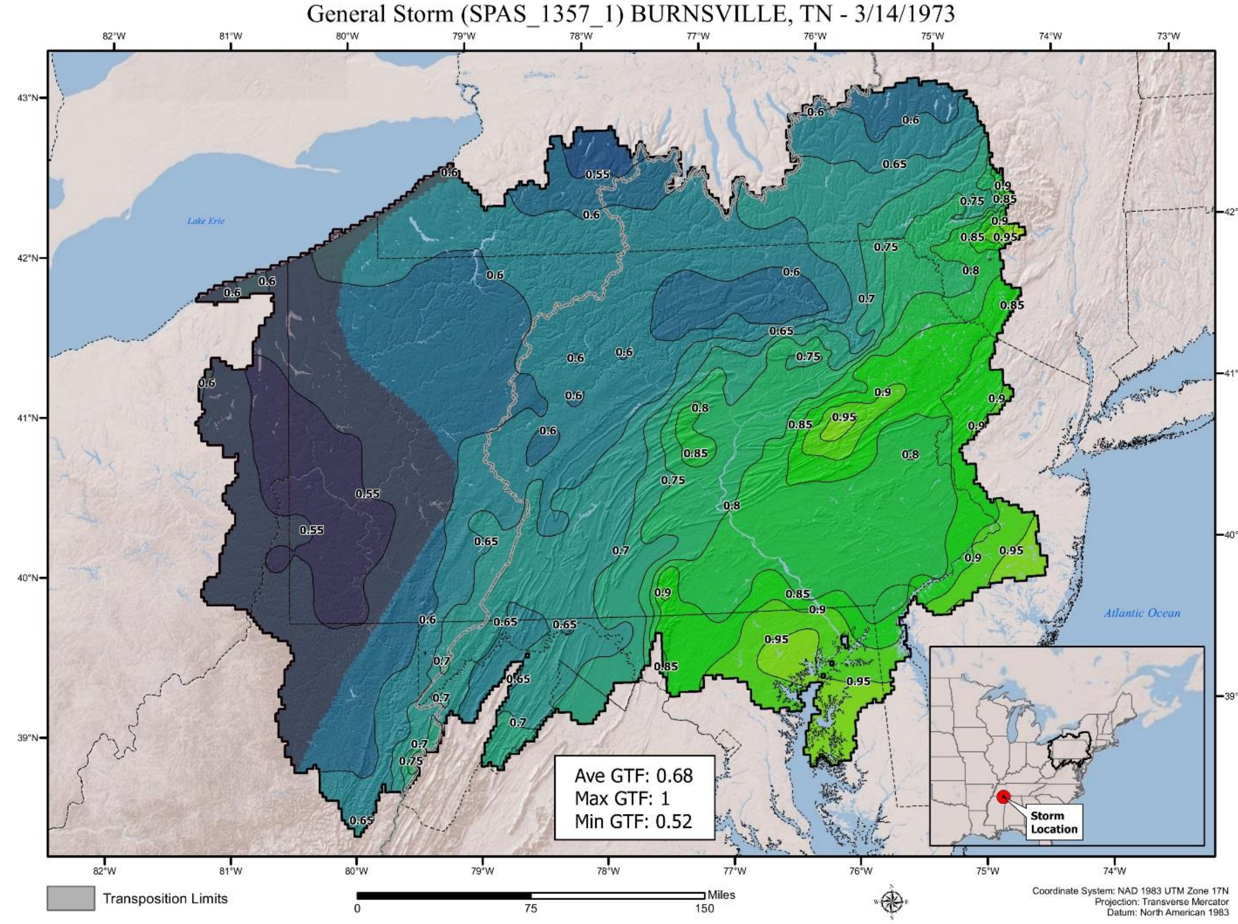
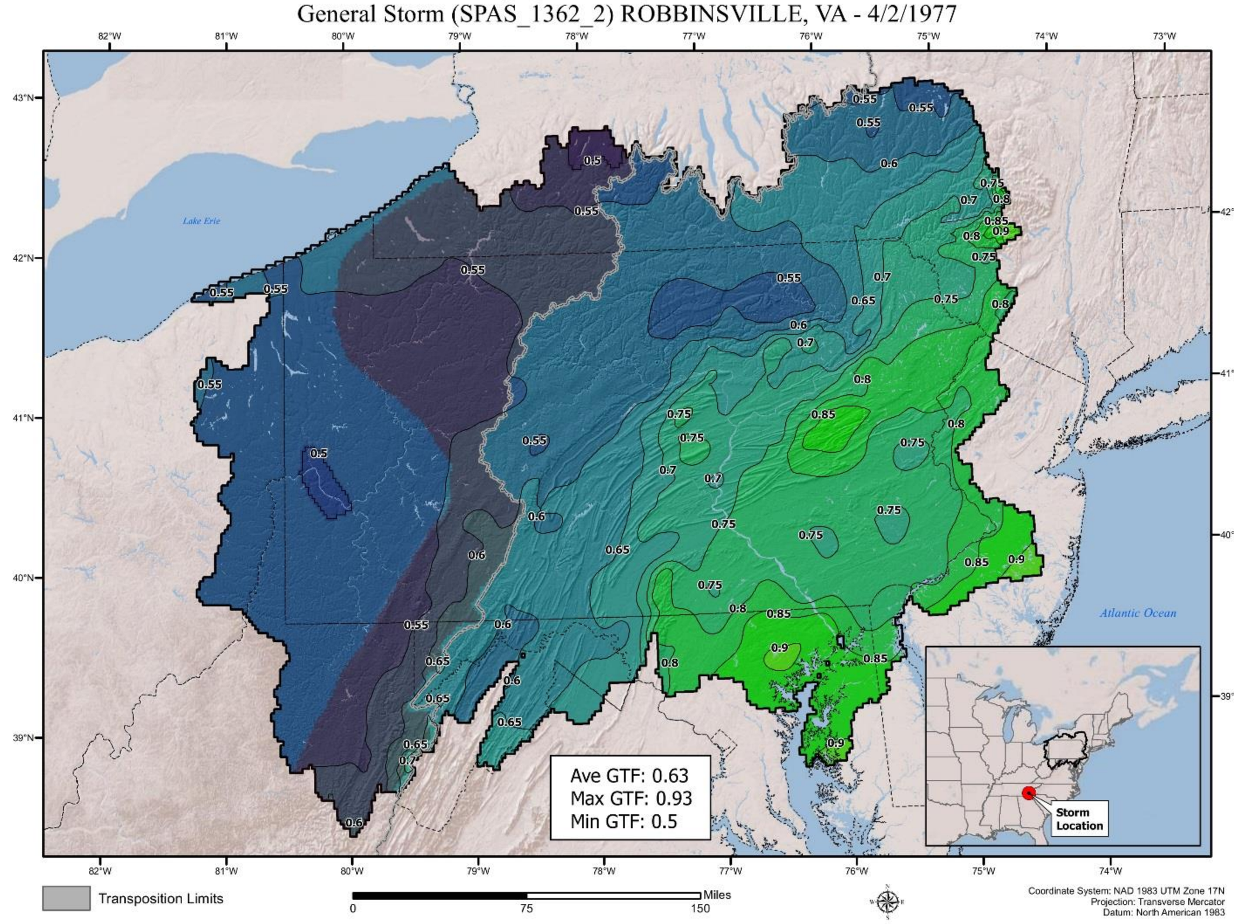
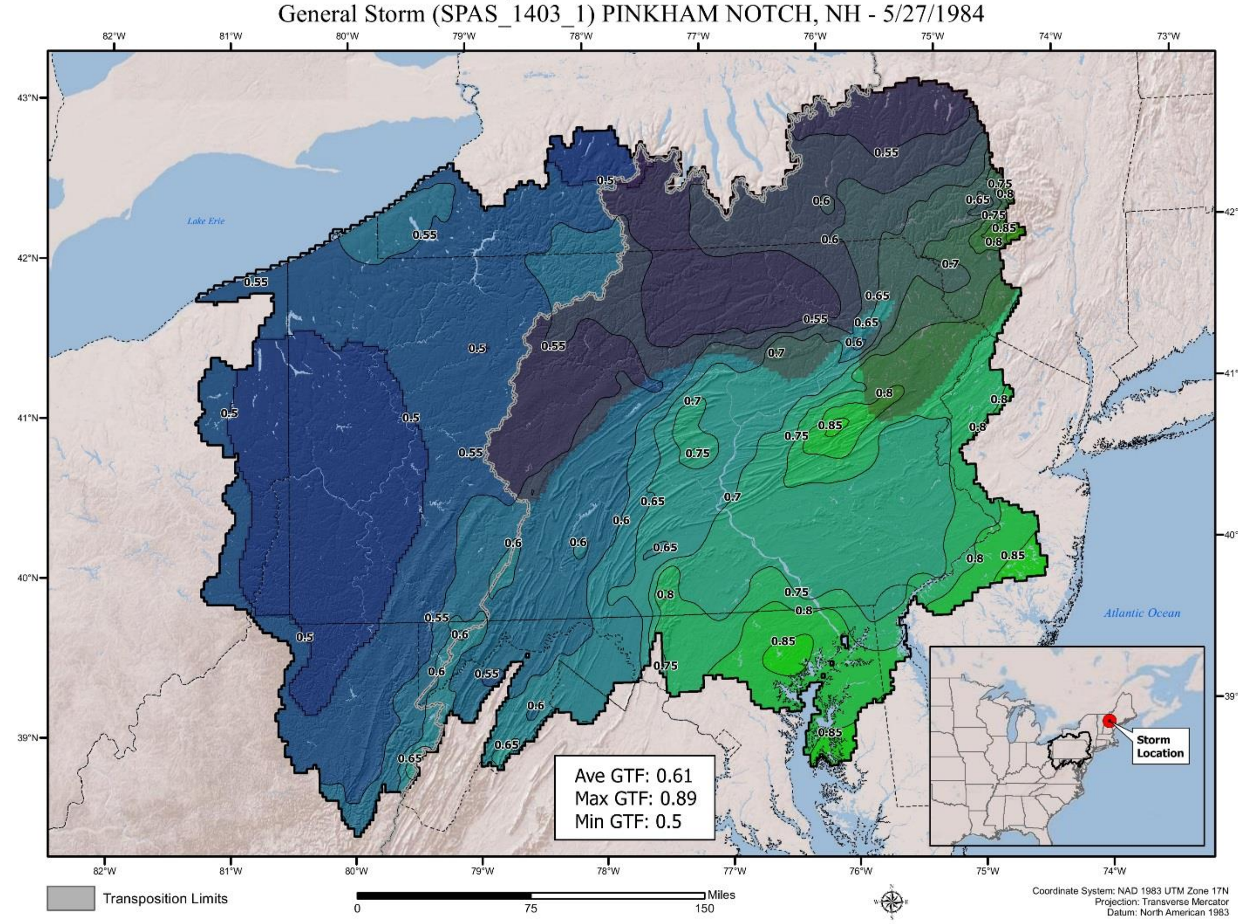


Geographic Transposition Factor
General Storm (SPAS_1362_2) ROBBINSVILLE, VA - 4/2/1977



Geographic Transposition Factor
General Storm (SPAS_1403_1) PINKHAM NOTCH, NH - 5/27/1984



Geographic Transposition Factor
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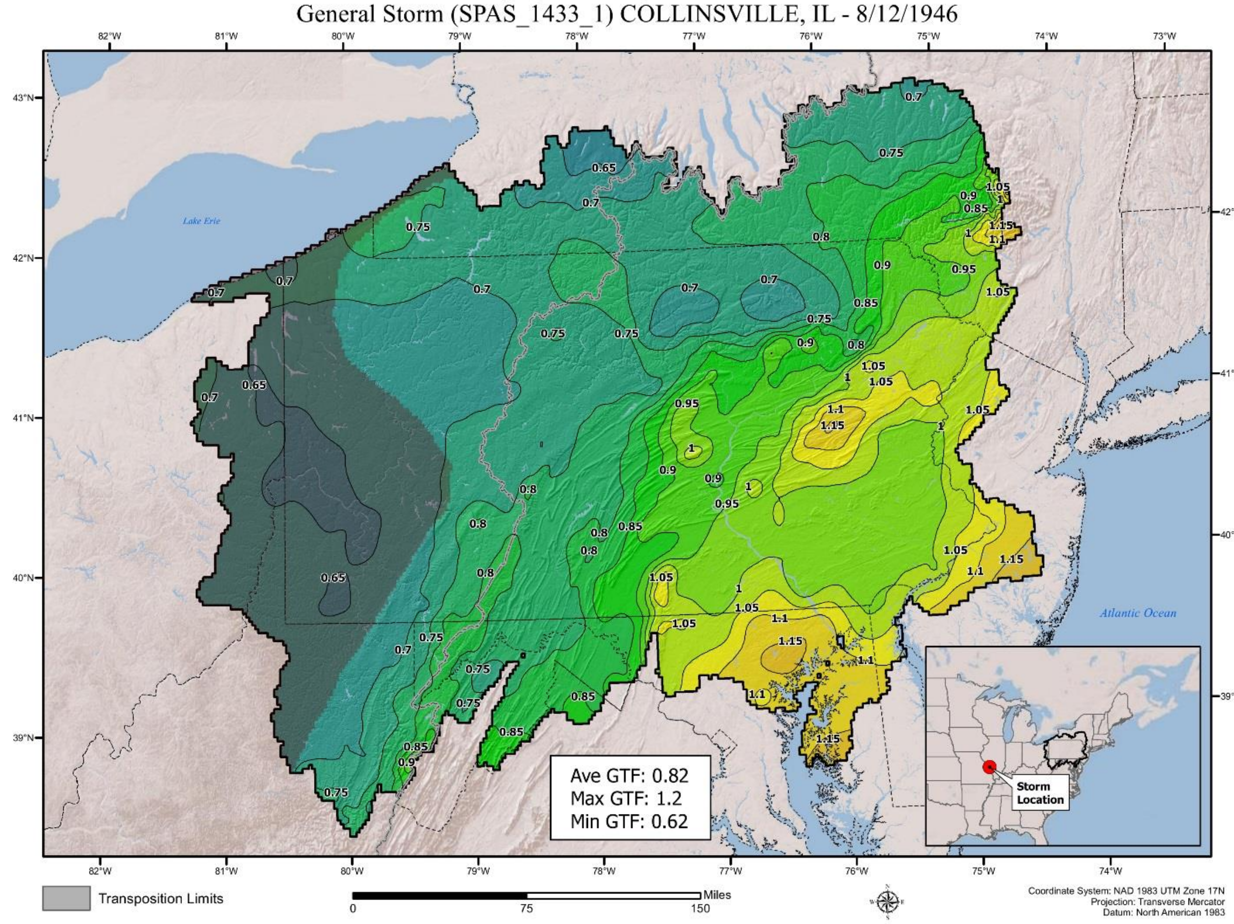

Geographic Transposition Factor
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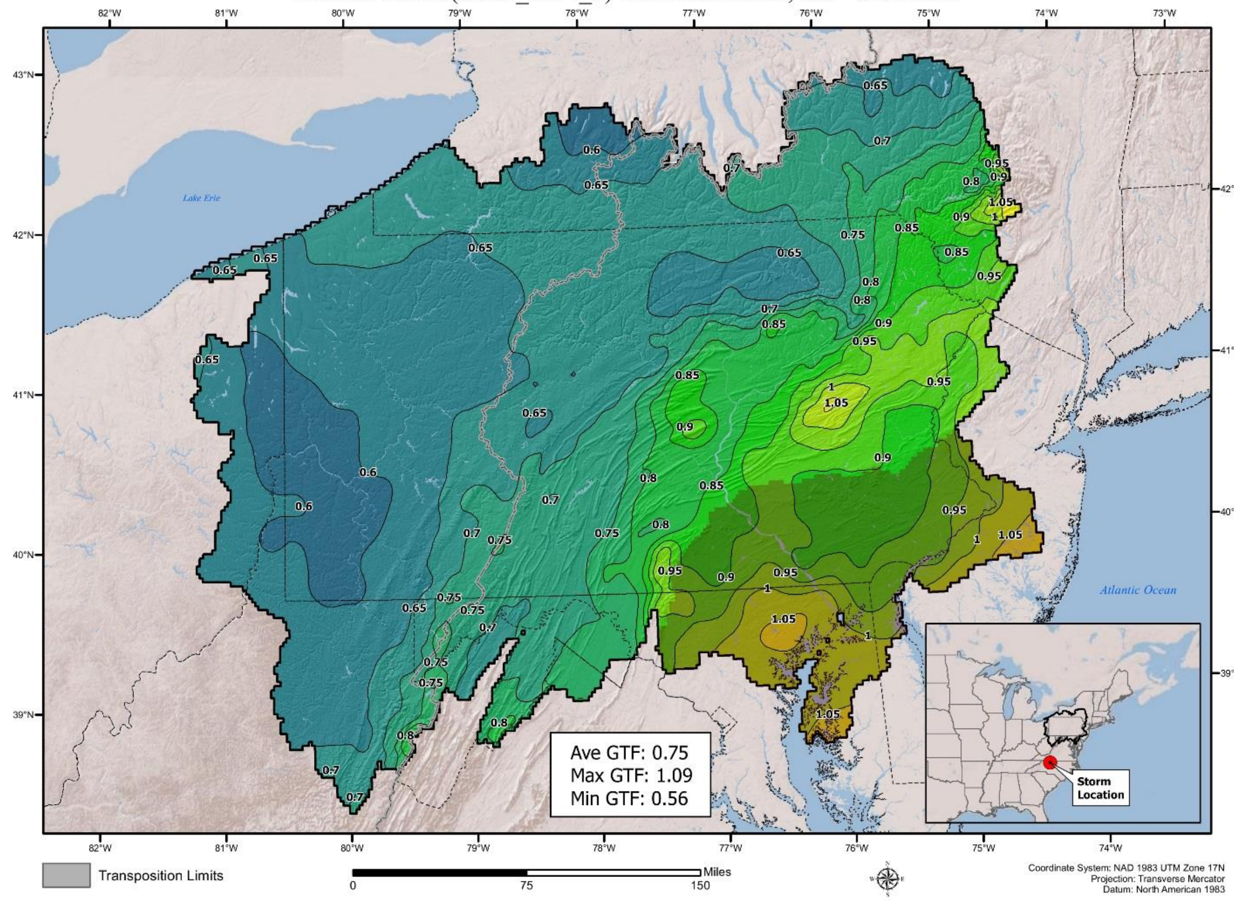

Geographic Transposition Factor
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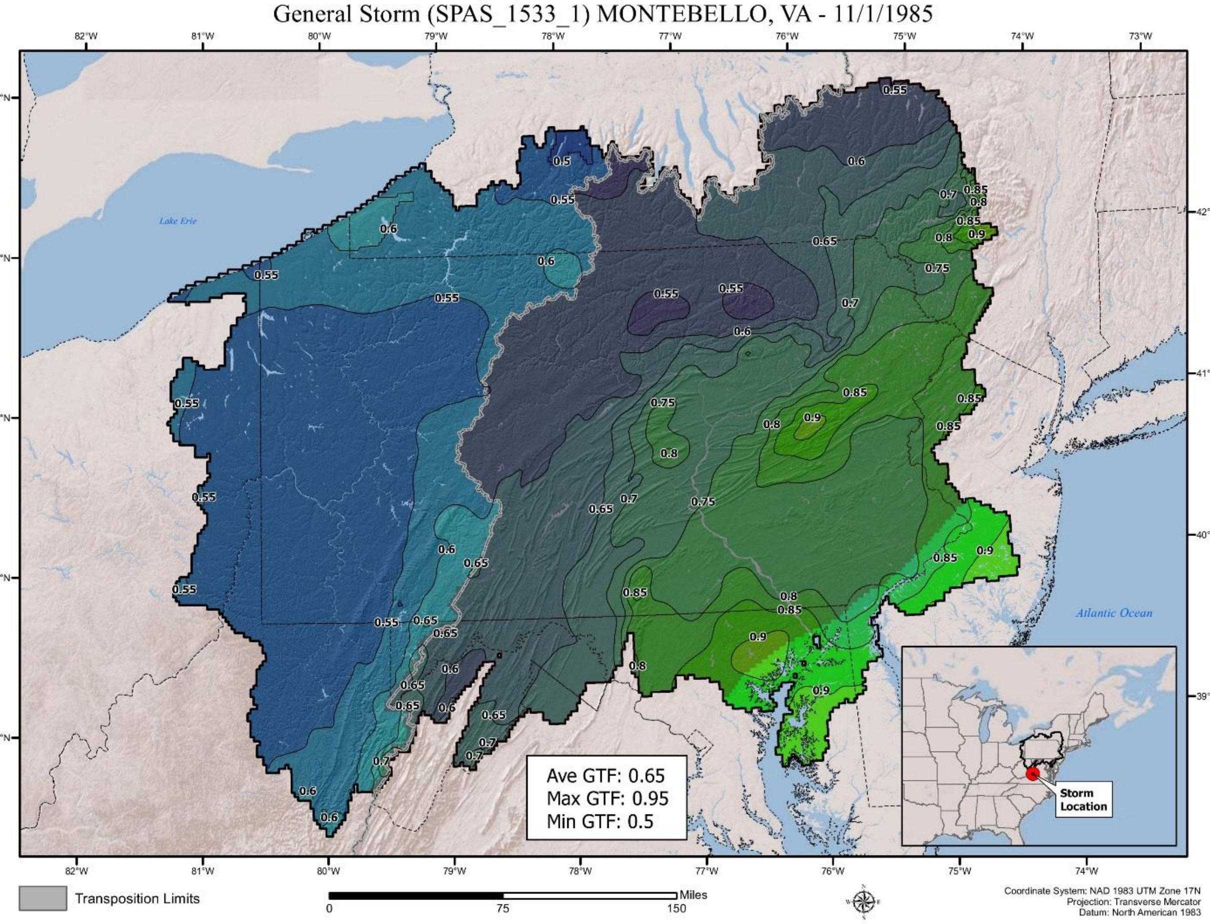
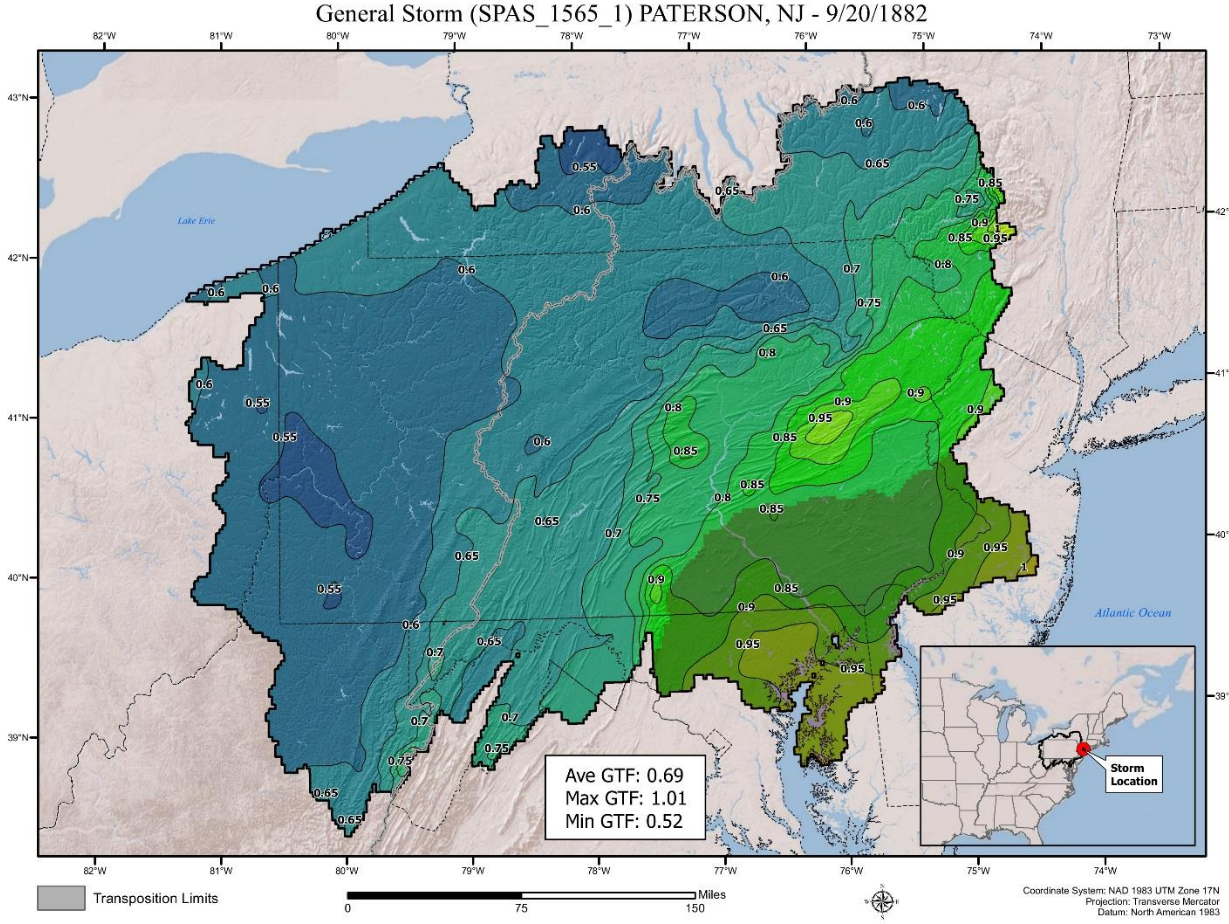


Geographic Transposition Factor
General Storm (SPAS_1565_1) PATERSON, NJ - 9/20/1882



Geographic Transposition Factor
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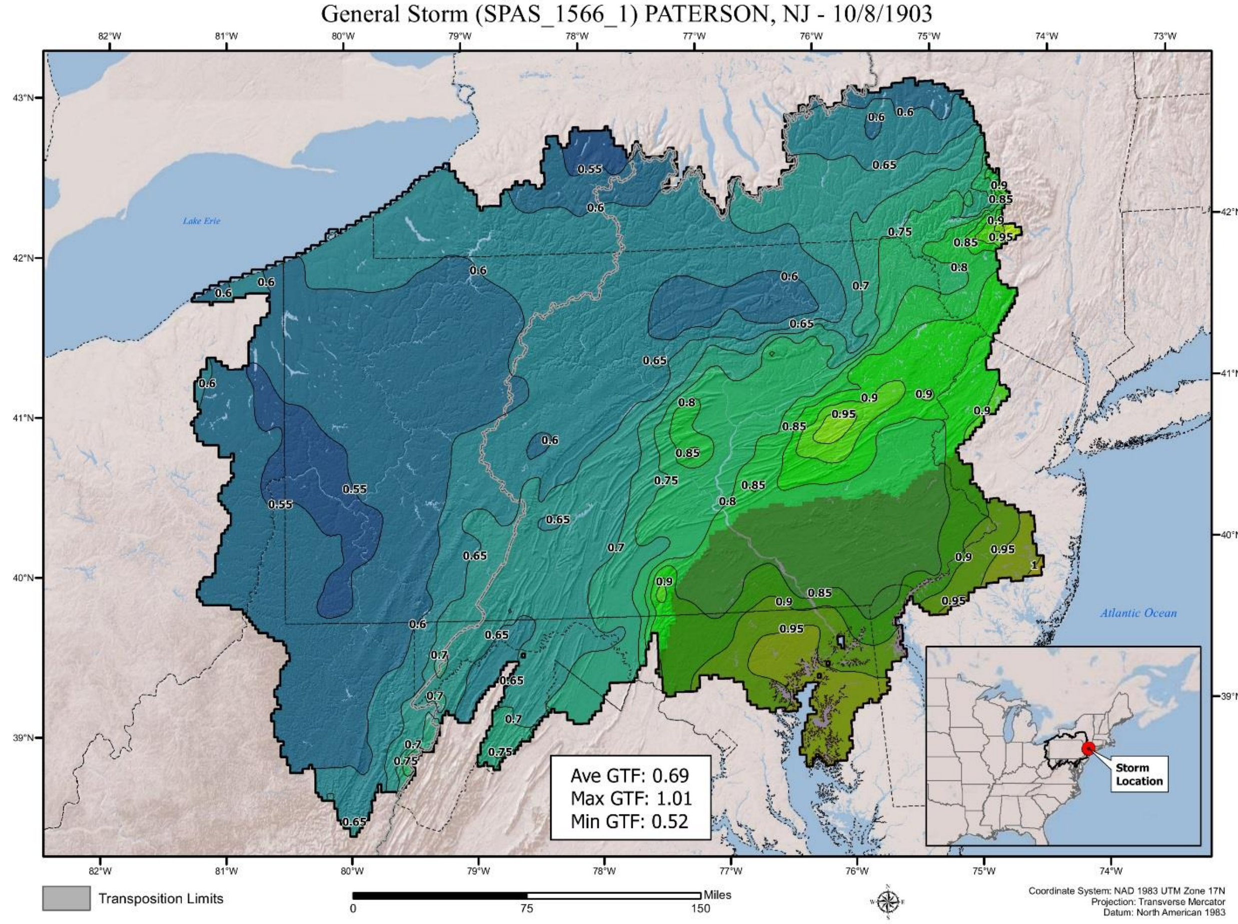

Geographic Transposition Factor
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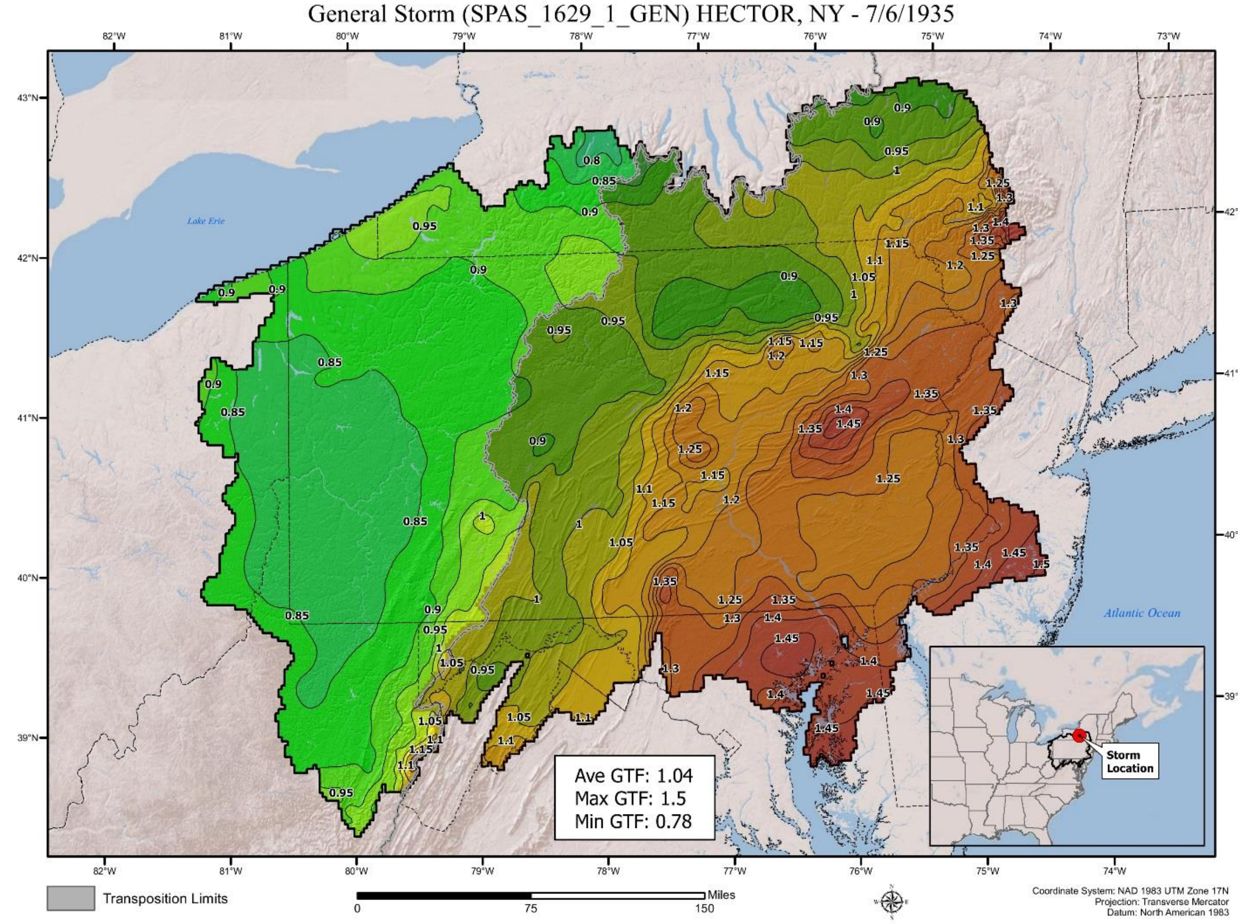

Geographic Transposition Factor
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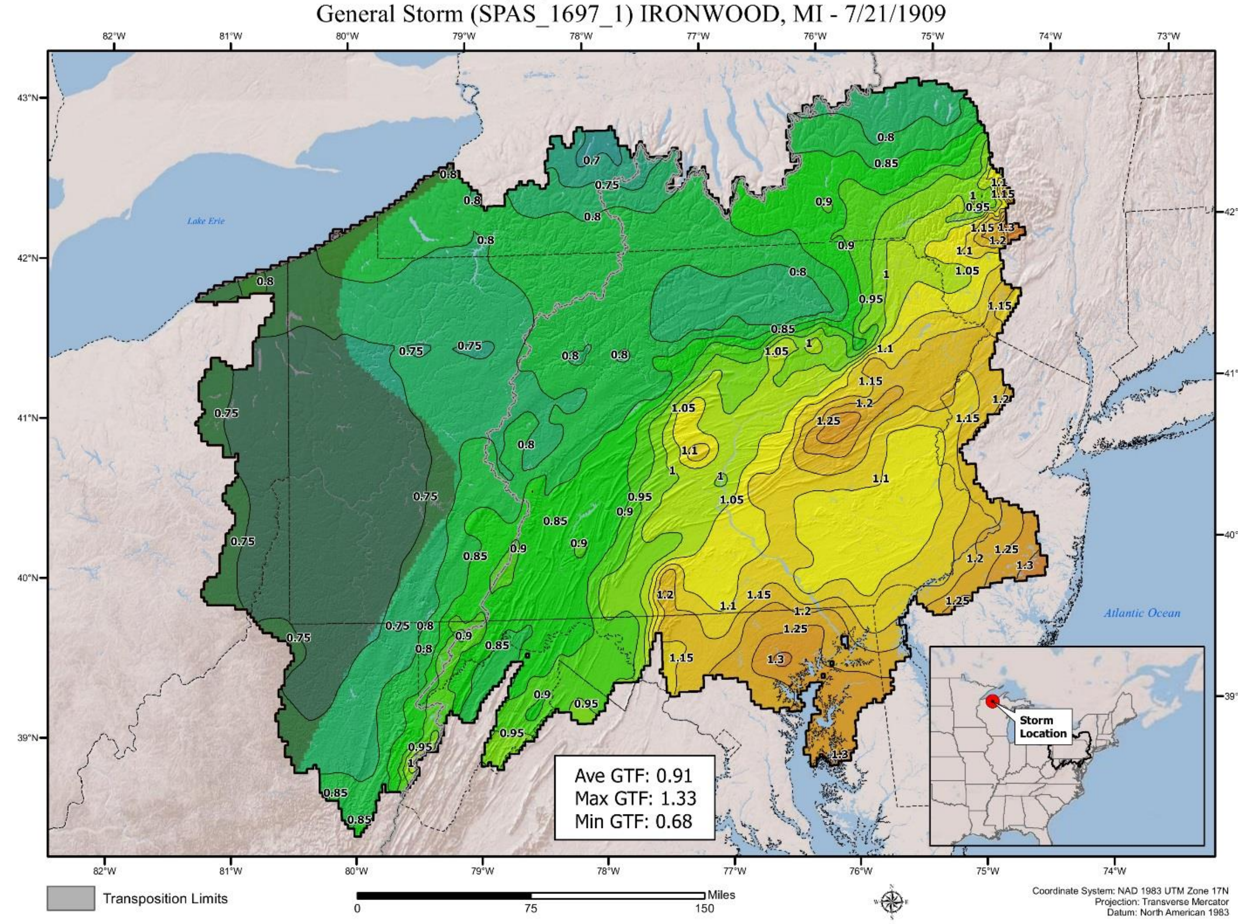

Geographic Transposition Factor
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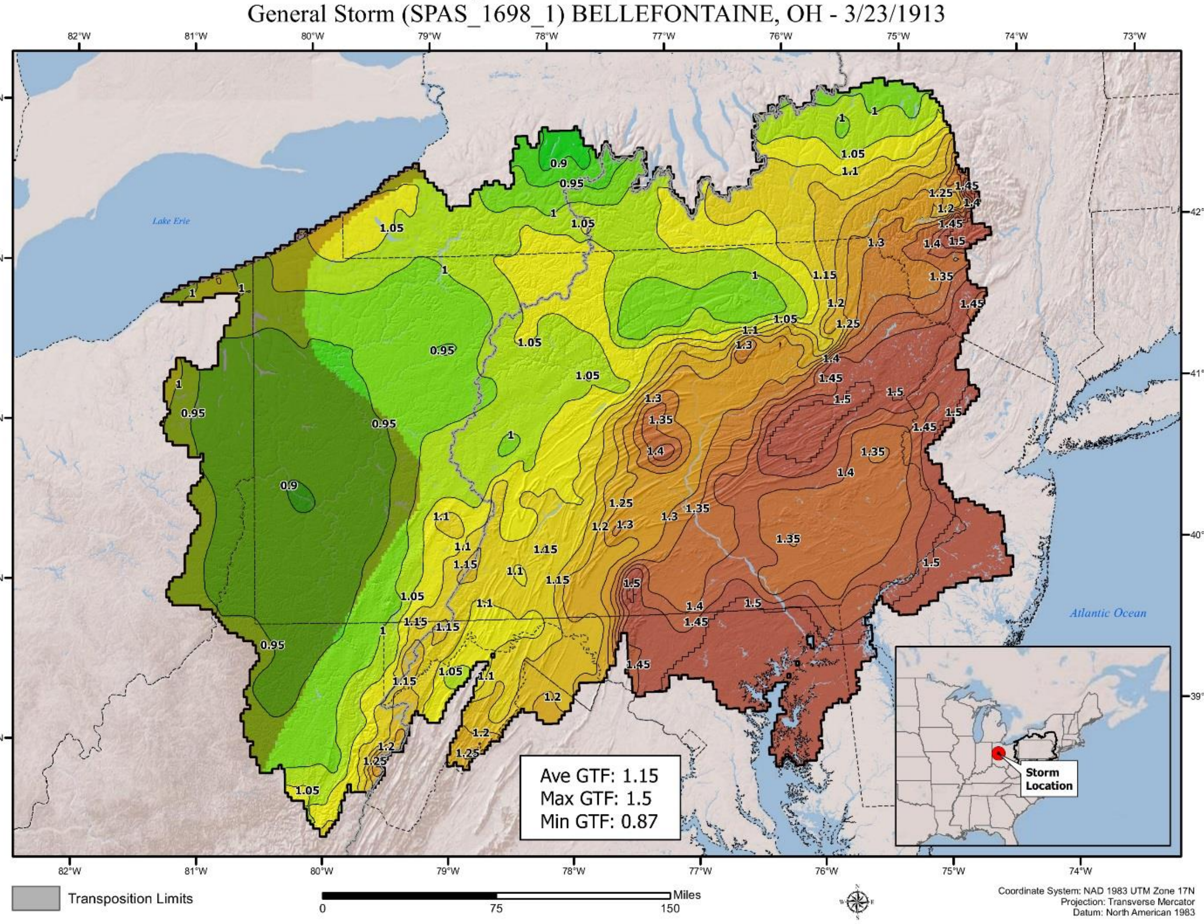

Geographic Transposition Factor
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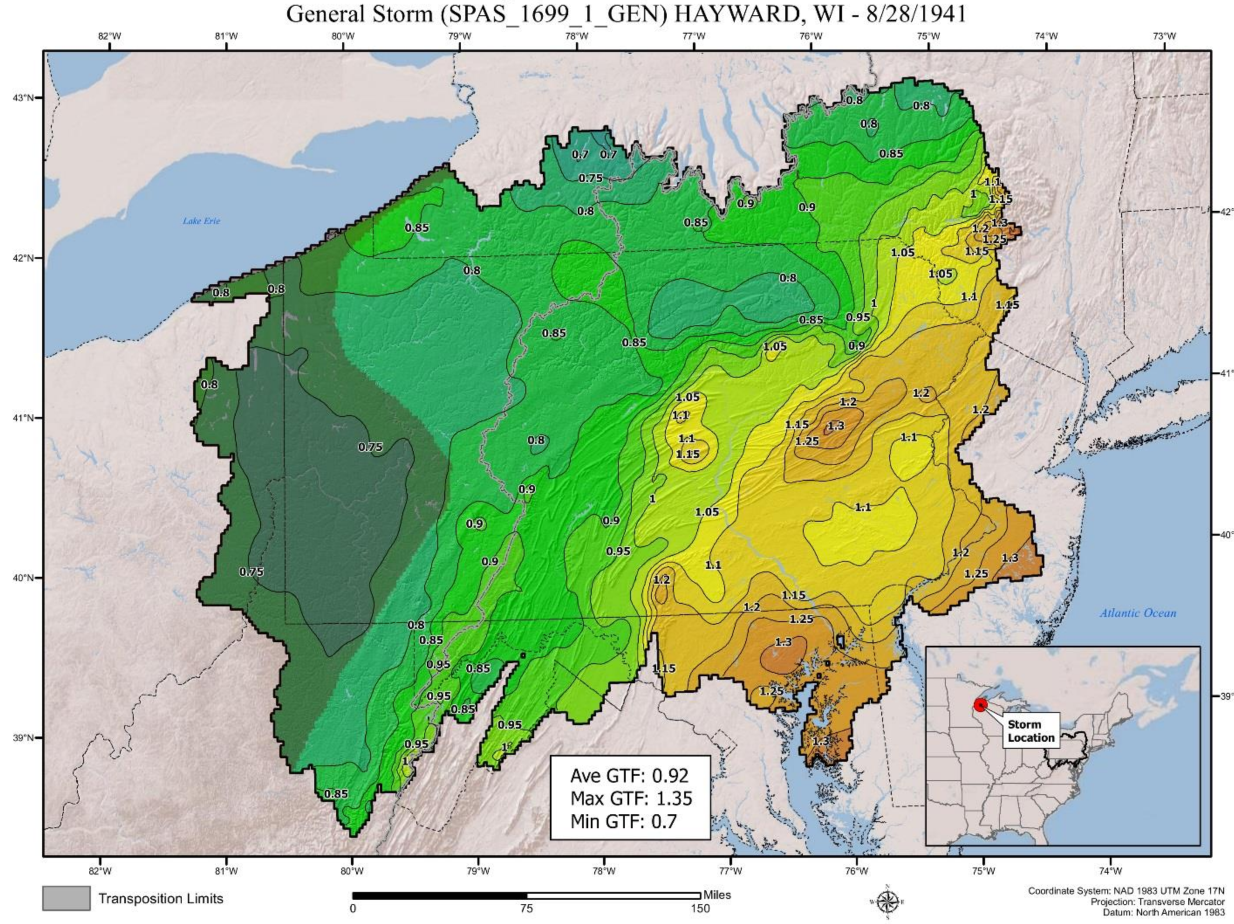
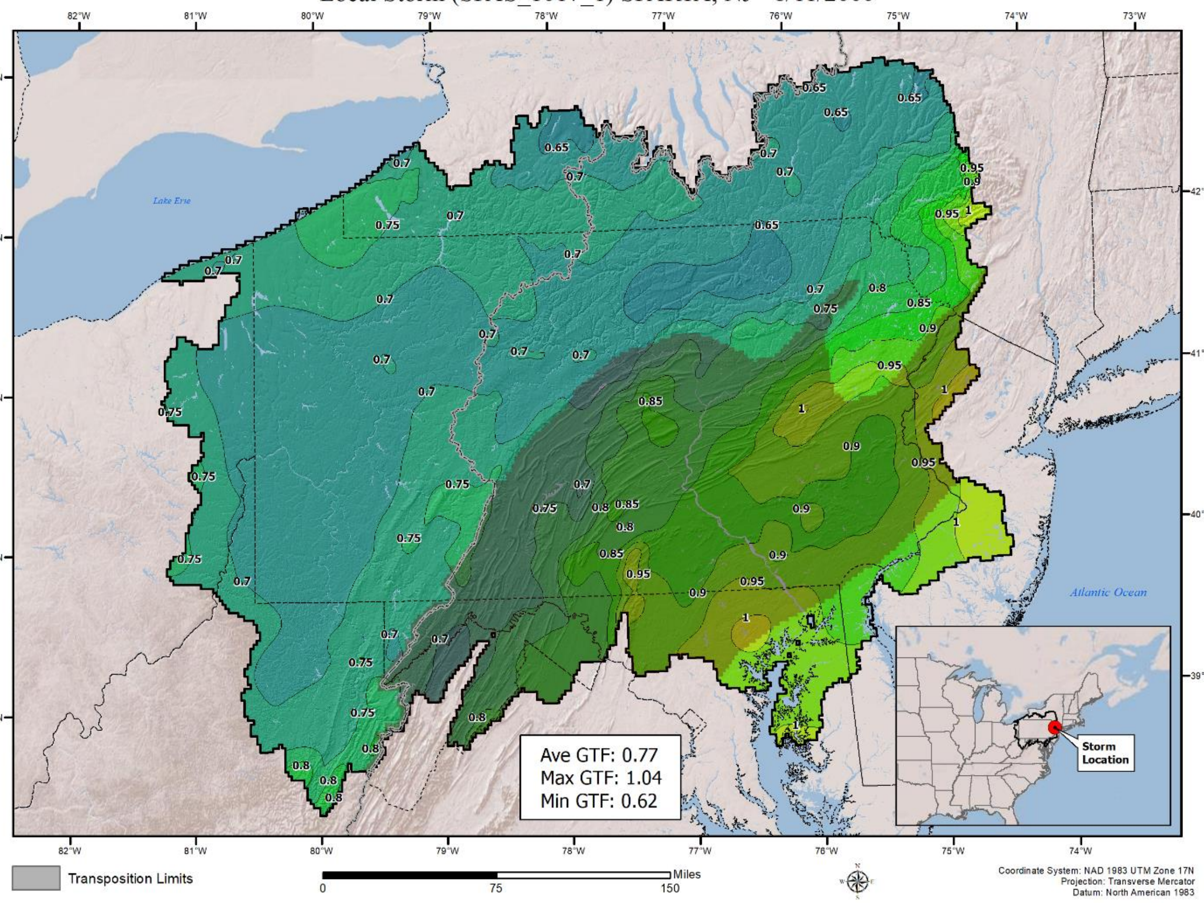
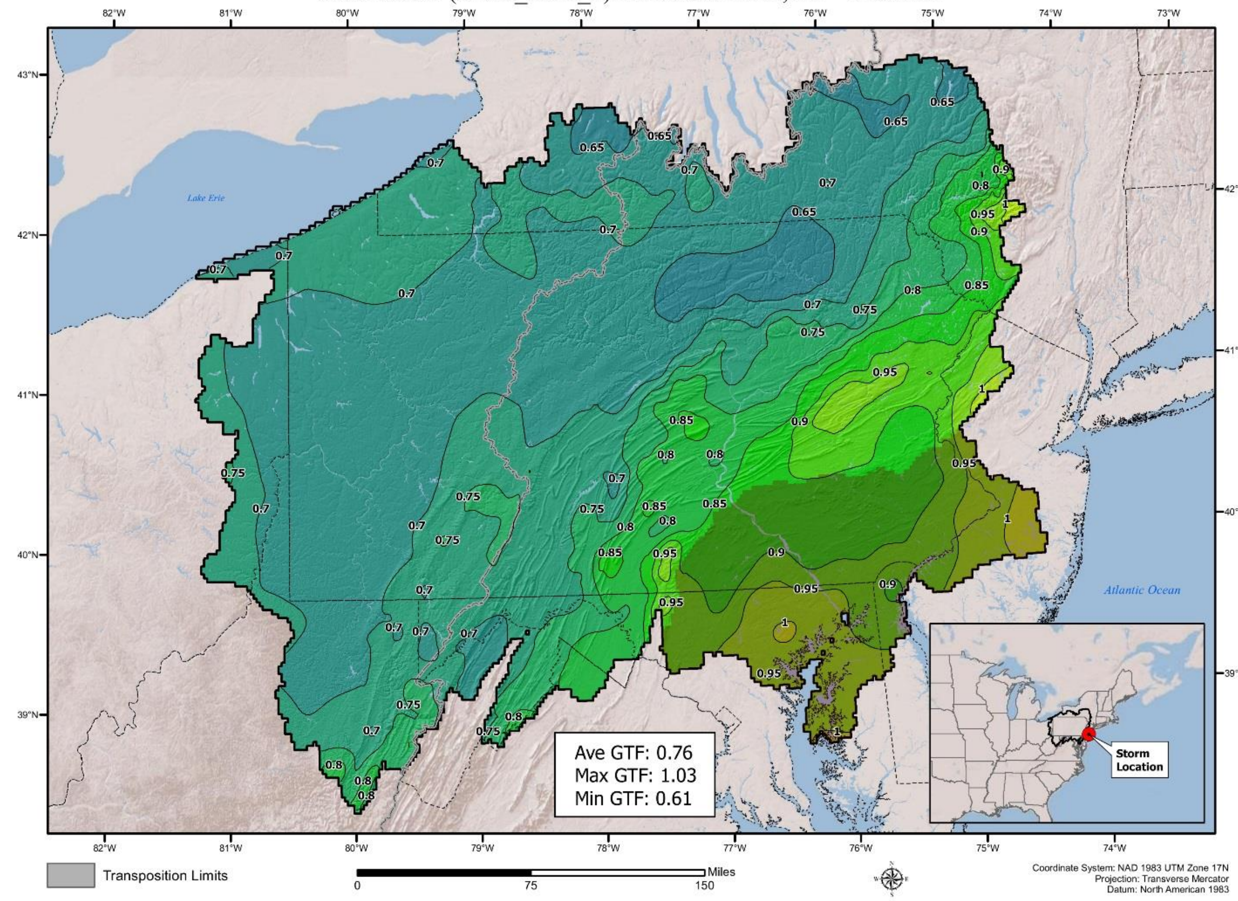


Local Storms

Geographic Transposition Factor
Local Storm (SPAS_1017_1) SPARTA, NJ - 8/11/2000



Geographic Transposition Factor
Local Storm (SPAS_1040_1) TABERNACLE, NJ - 7/13/2004



Geographic Transposition Factor
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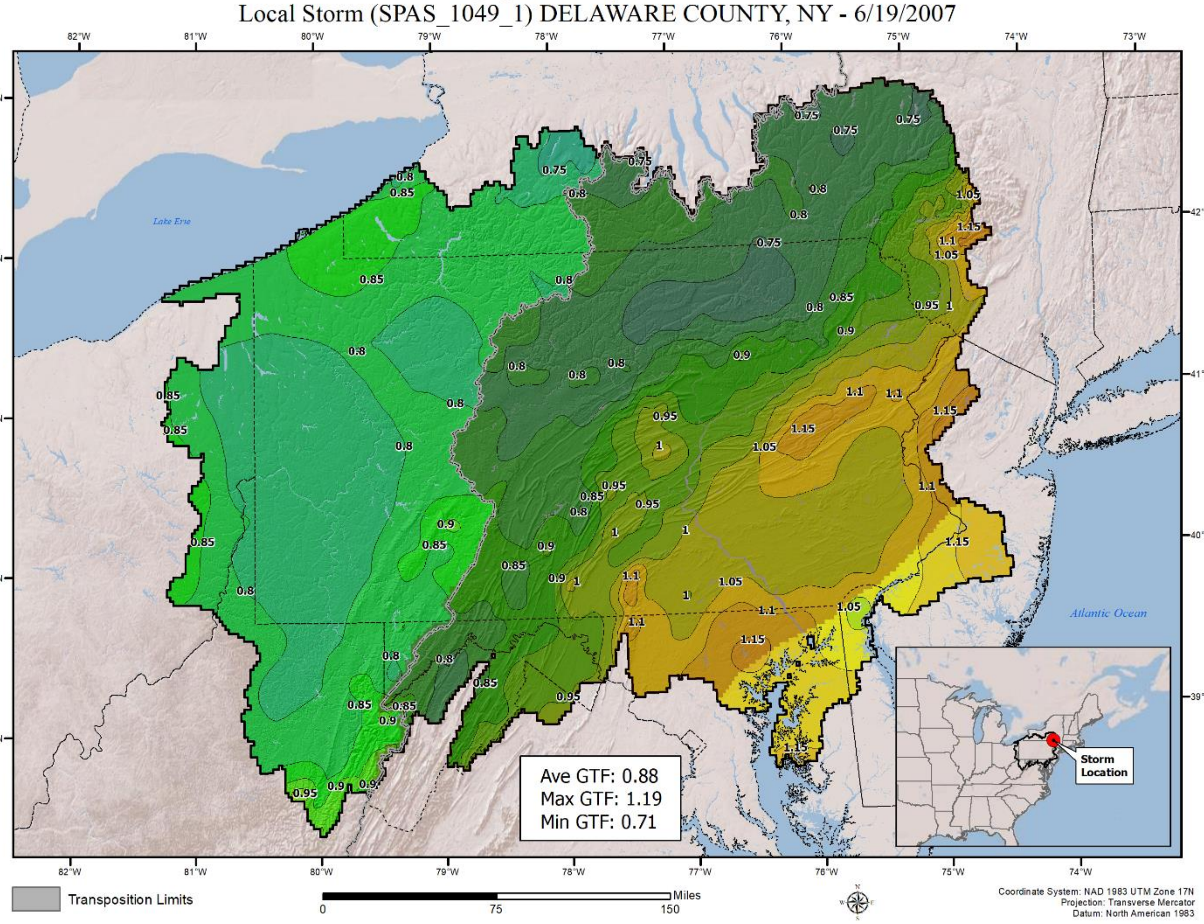
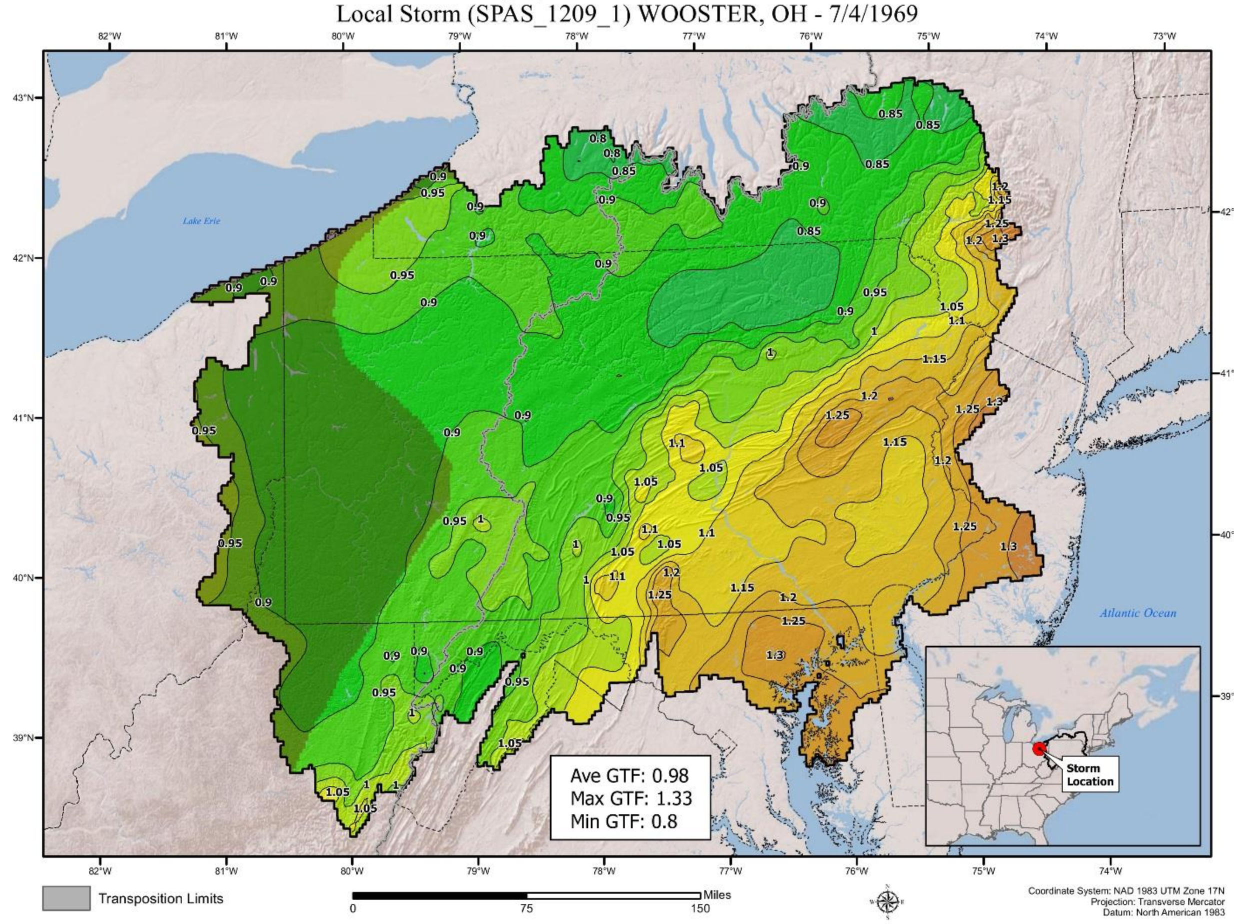
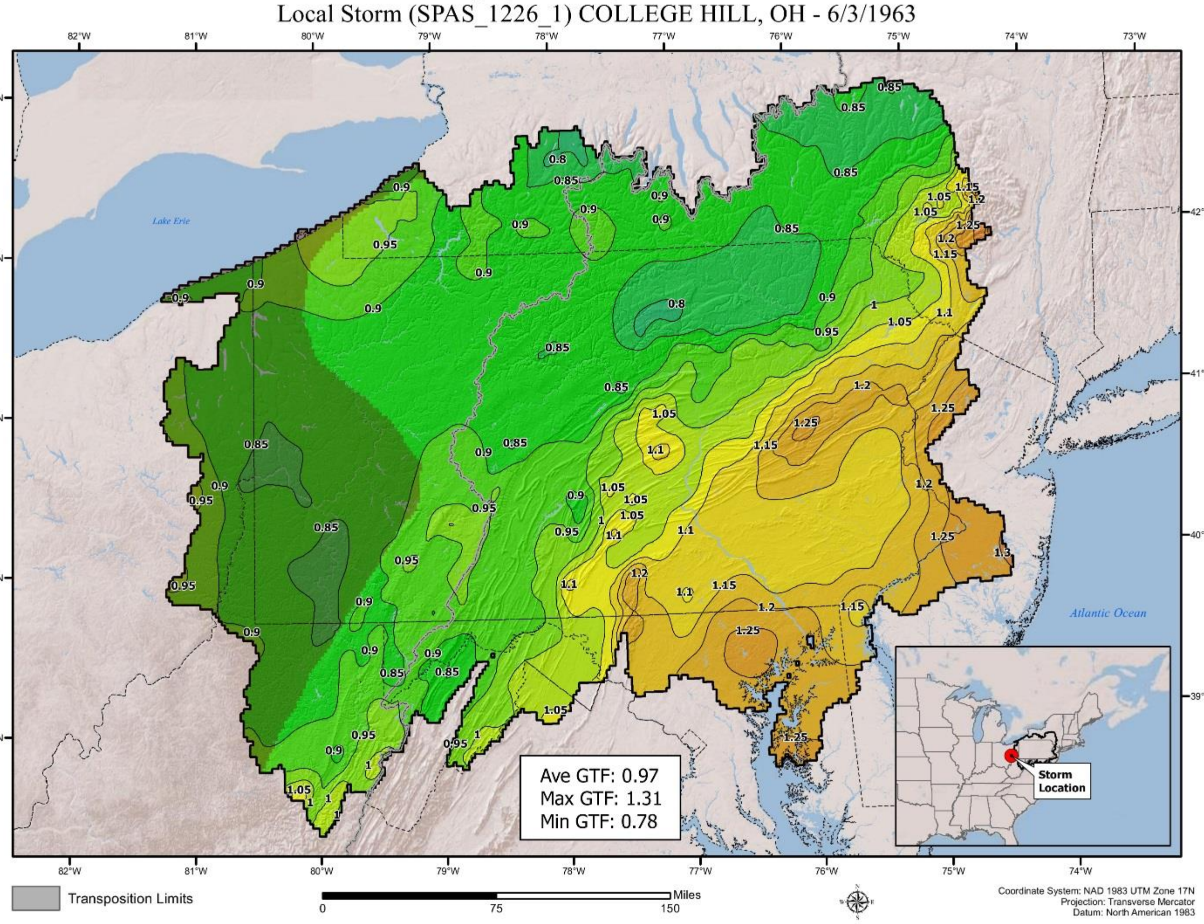


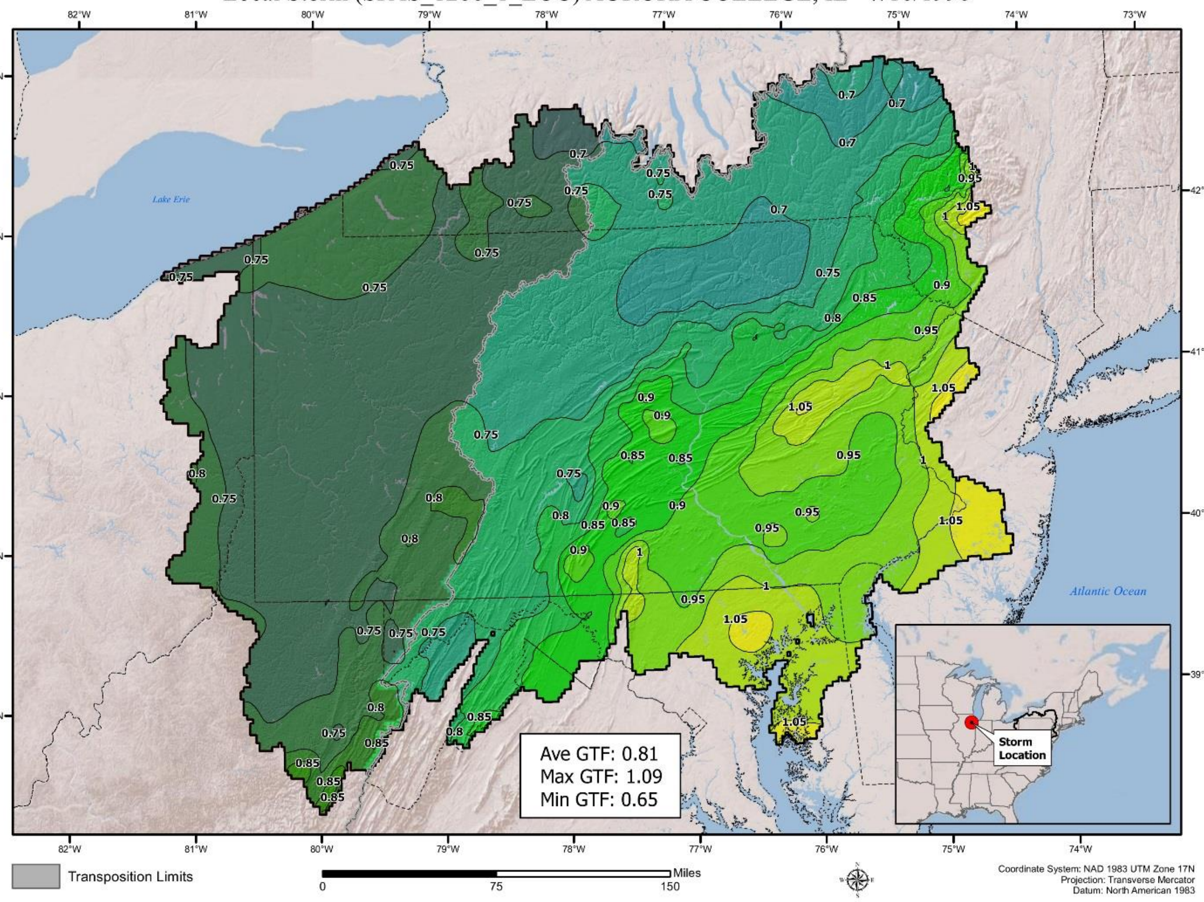
Geographic Transposition Factor
Local Storm (SPAS_1209_1) WOOSTER, OH - 7/4/1969



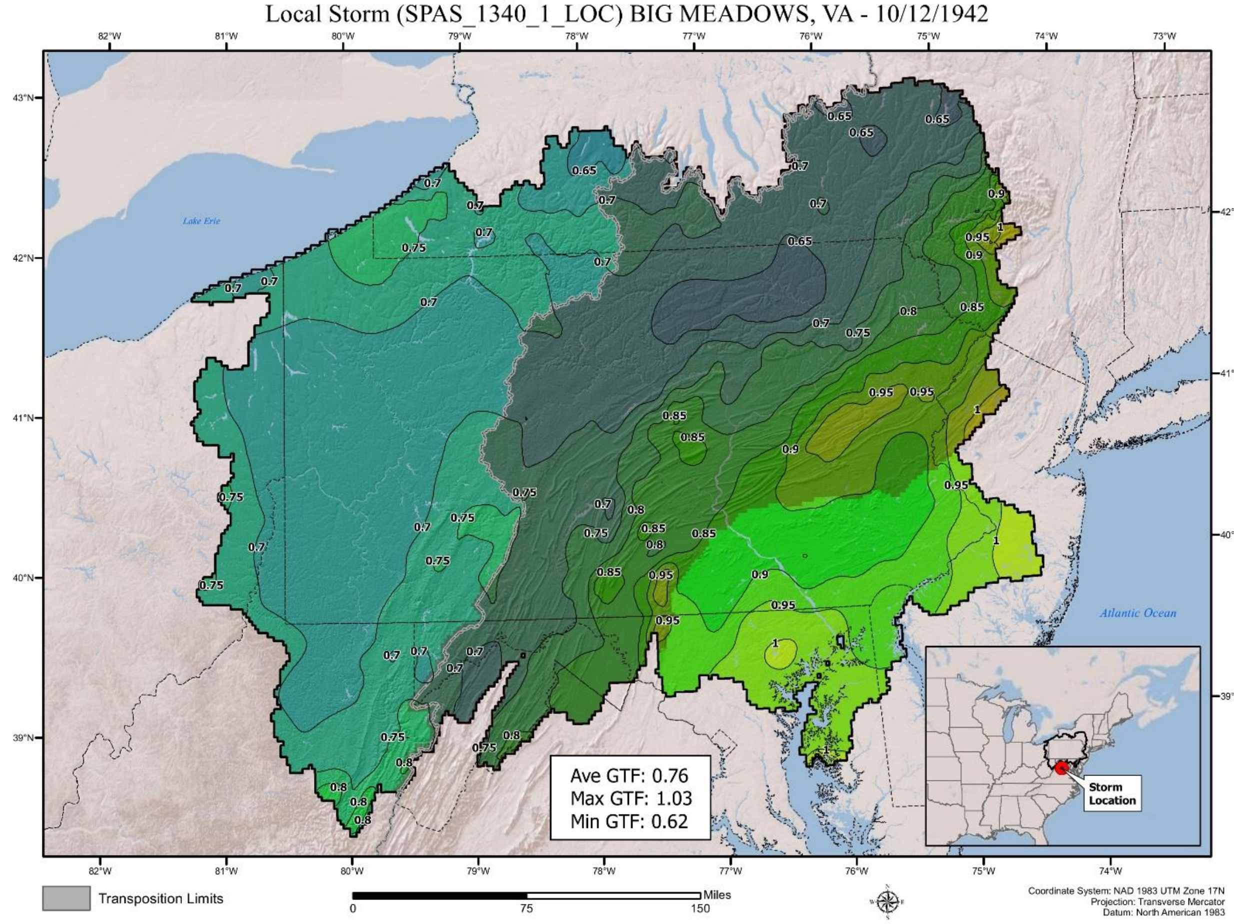
Geographic Transposition Factor
Local Storm (SPAS_1226_1) COLLEGE HILL, OH - 6/3/1963



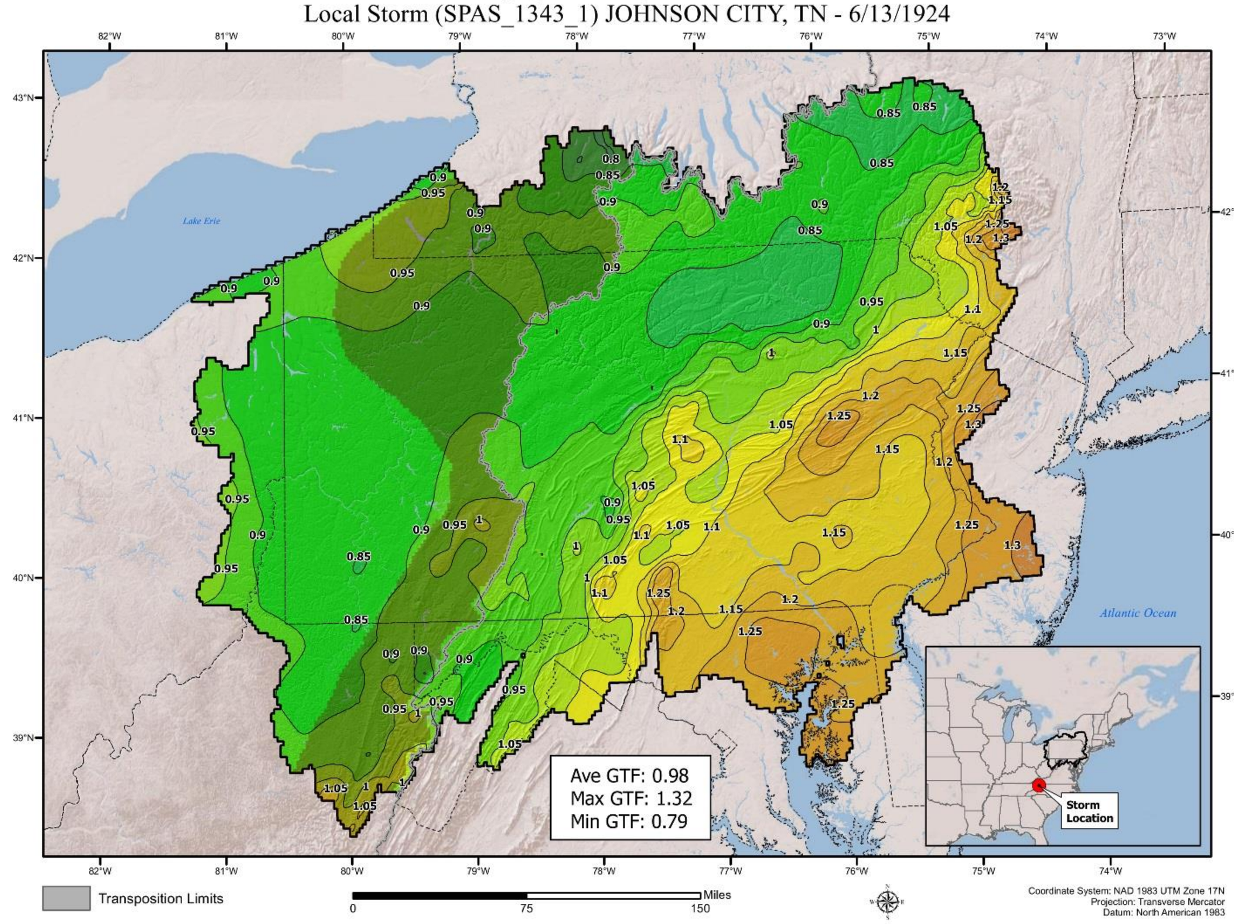
Geographic Transposition Factor
Local Storm (SPAS_1286_1_LOC) AURORA COLLEGE, IL - 7/16/1996



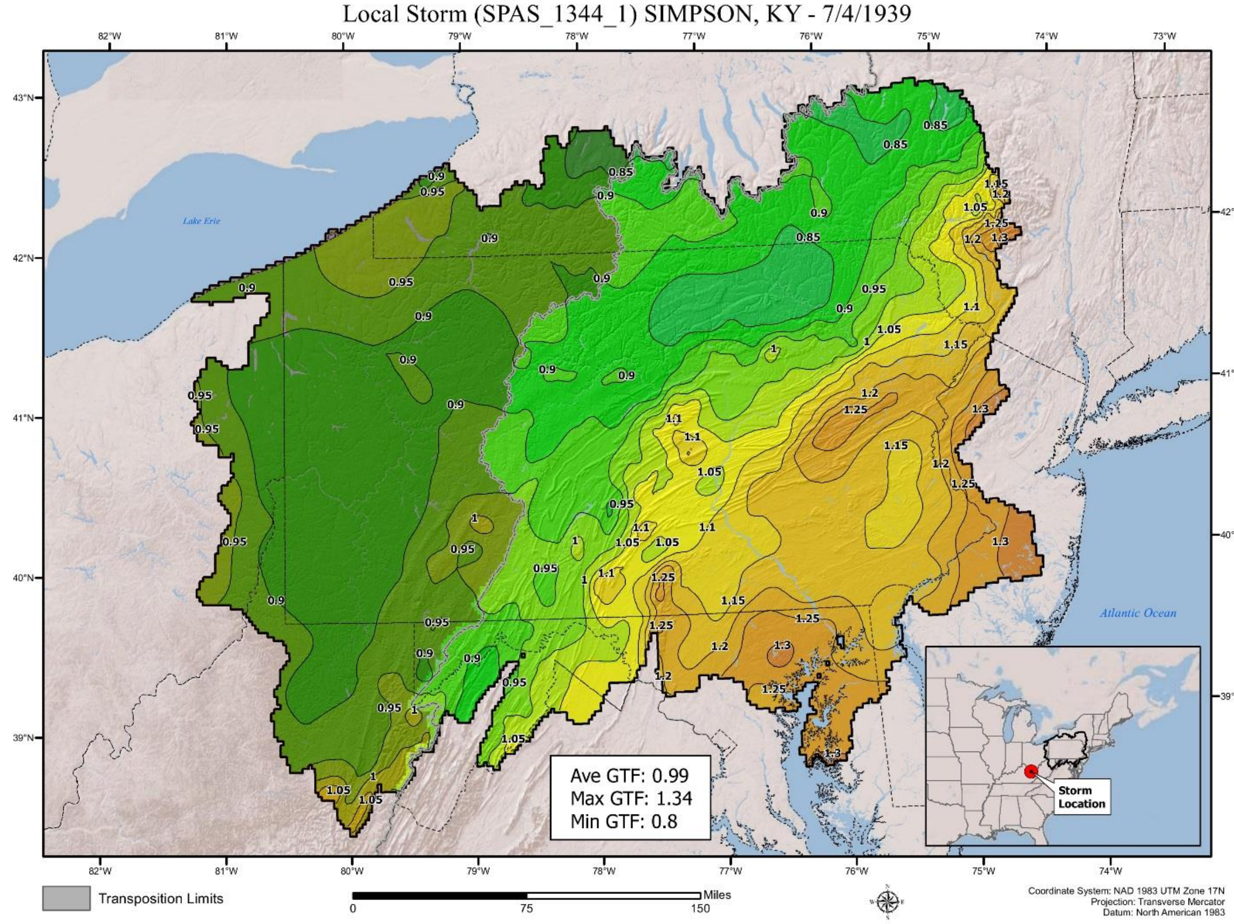
Geographic Transposition Factor
Local Storm (SPAS_1340_1_LOC) BIG MEADOWS, VA - 10/12/1942



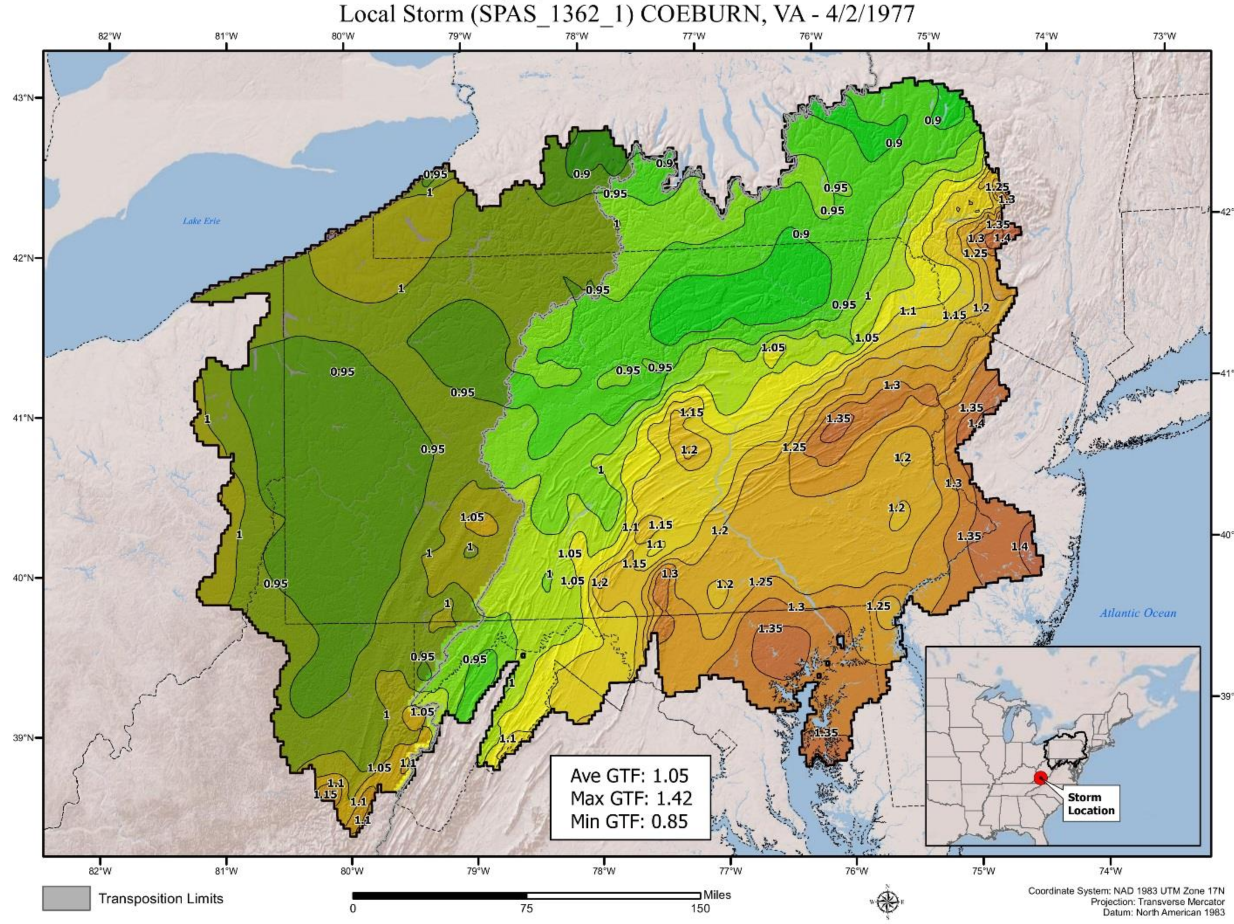
Geographic Transposition Factor
Local Storm (SPAS_1343_1) JOHNSON CITY, TN - 6/13/1924



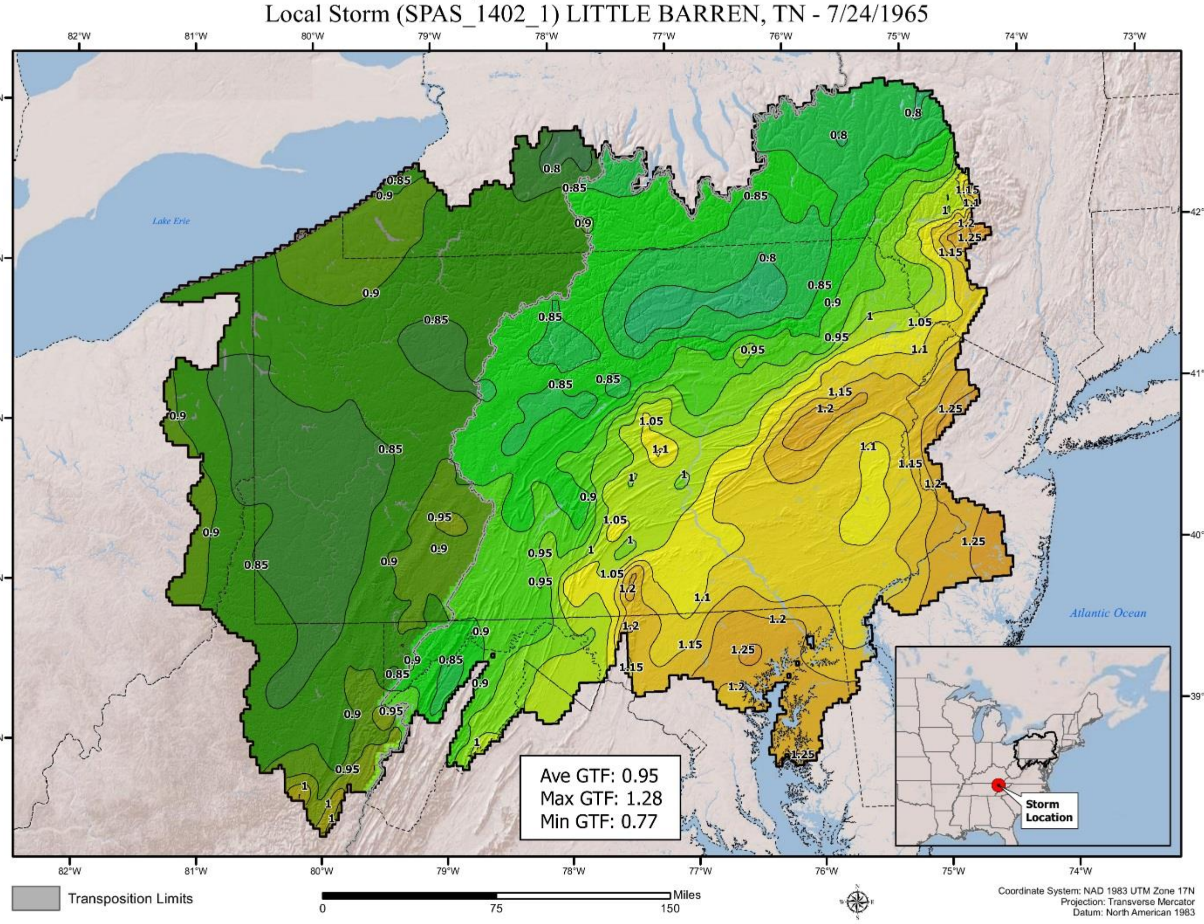
Geographic Transposition Factor
Local Storm (SPAS_1344_1) SIMPSON, KY - 7/4/1939



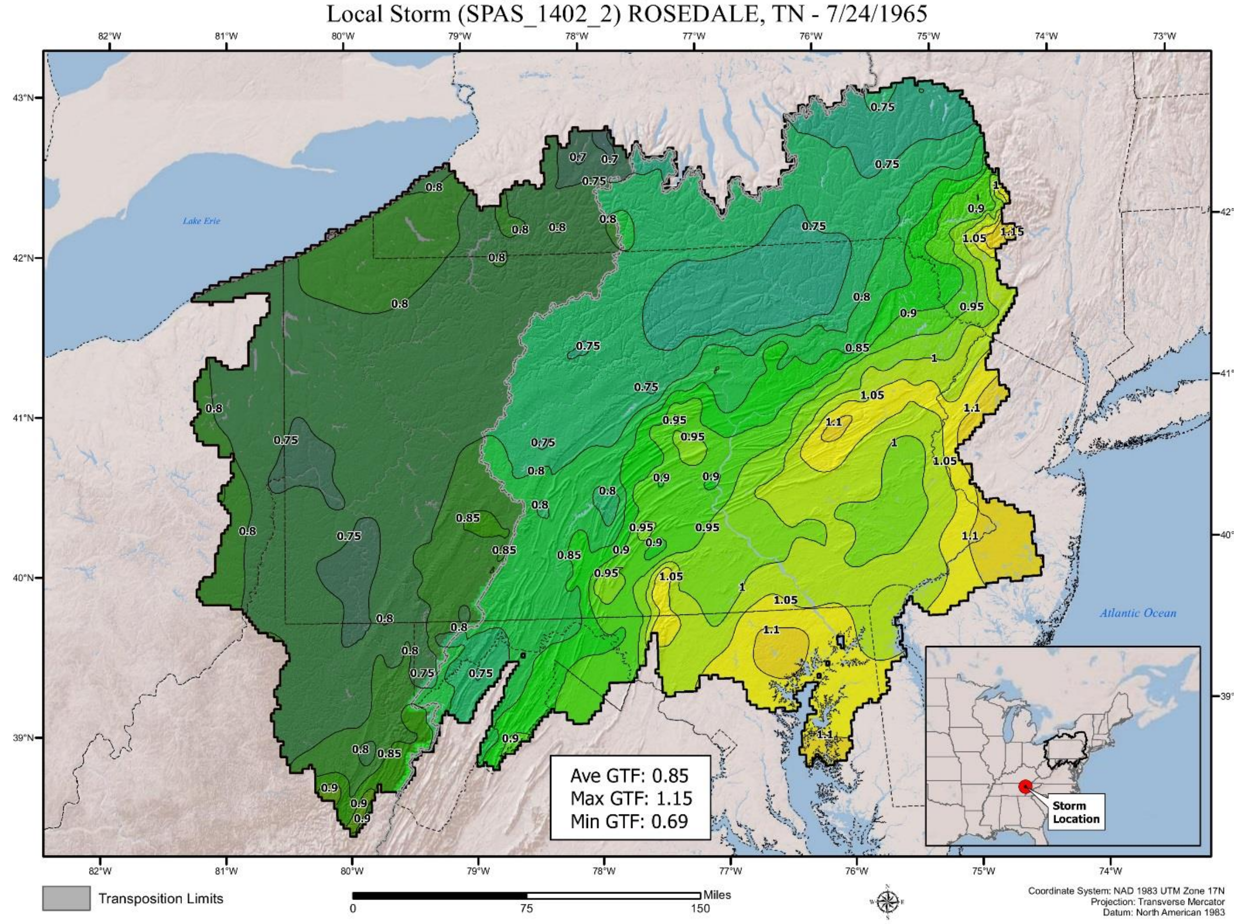
Geographic Transposition Factor
Local Storm (SPAS_1362_1) COEBURN, VA - 4/2/1977



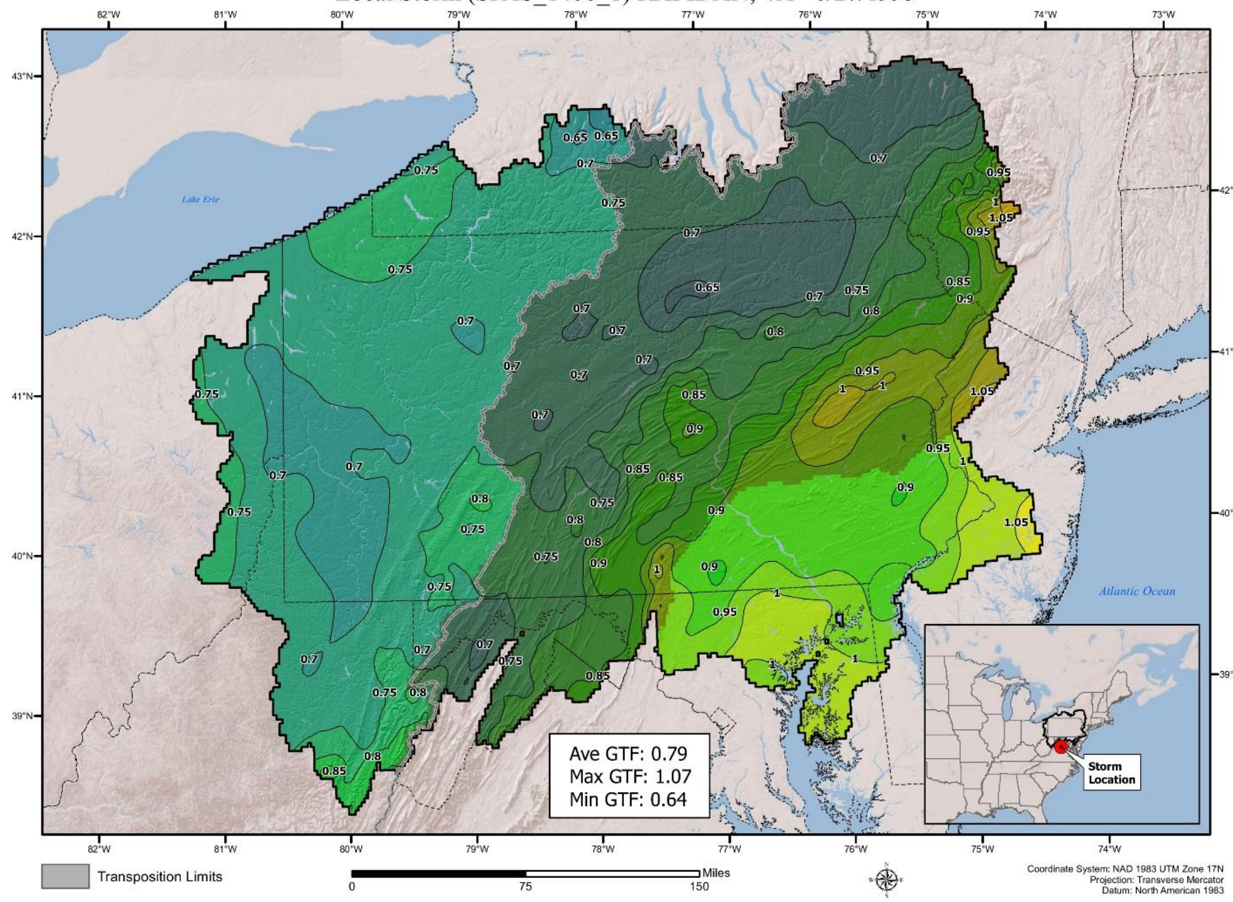
Geographic Transposition Factor
Local Storm (SPAS_1402_1) LITTLE BARREN, TN - 7/24/1965



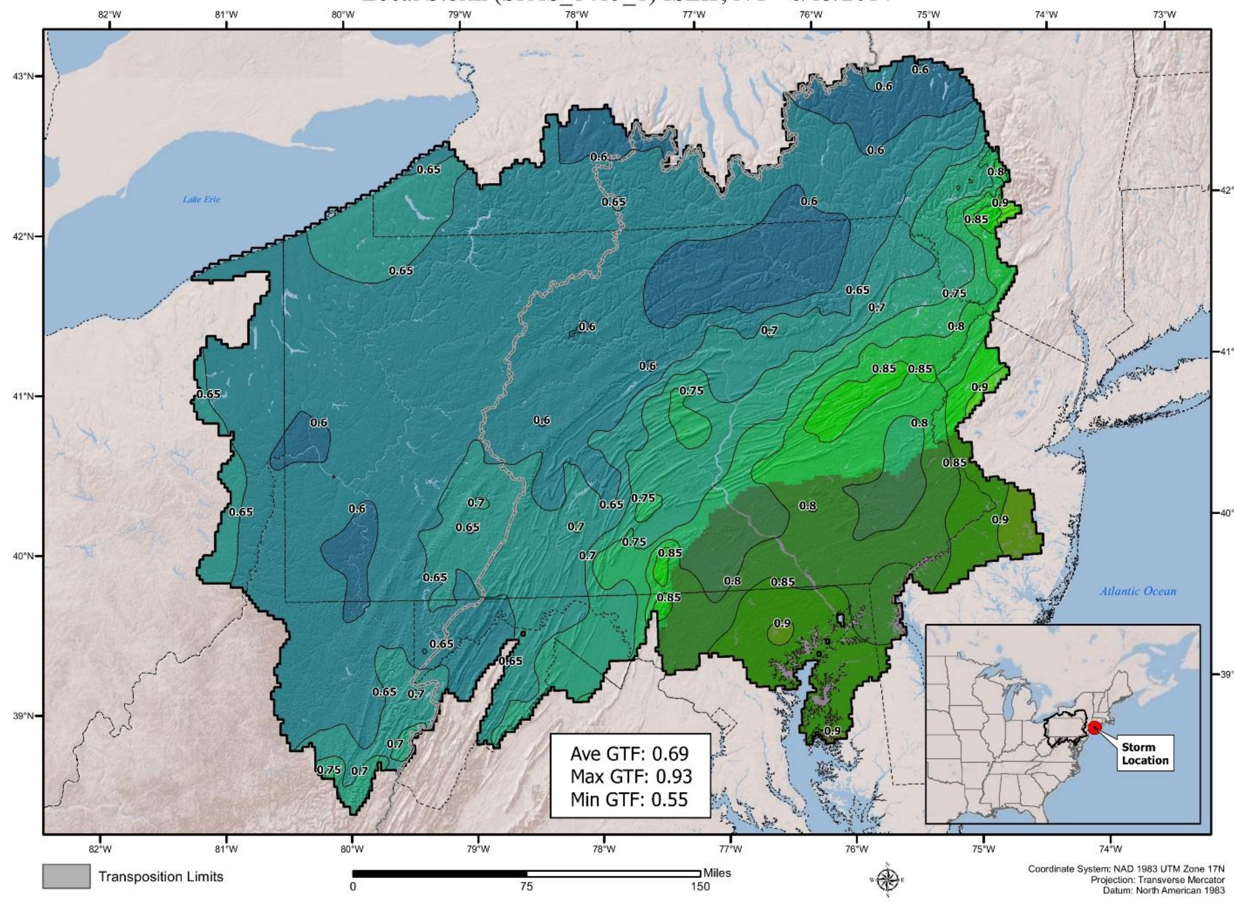
Geographic Transposition Factor
Local Storm (SPAS_1402_2) ROSEDALE, TN - 7/24/1965



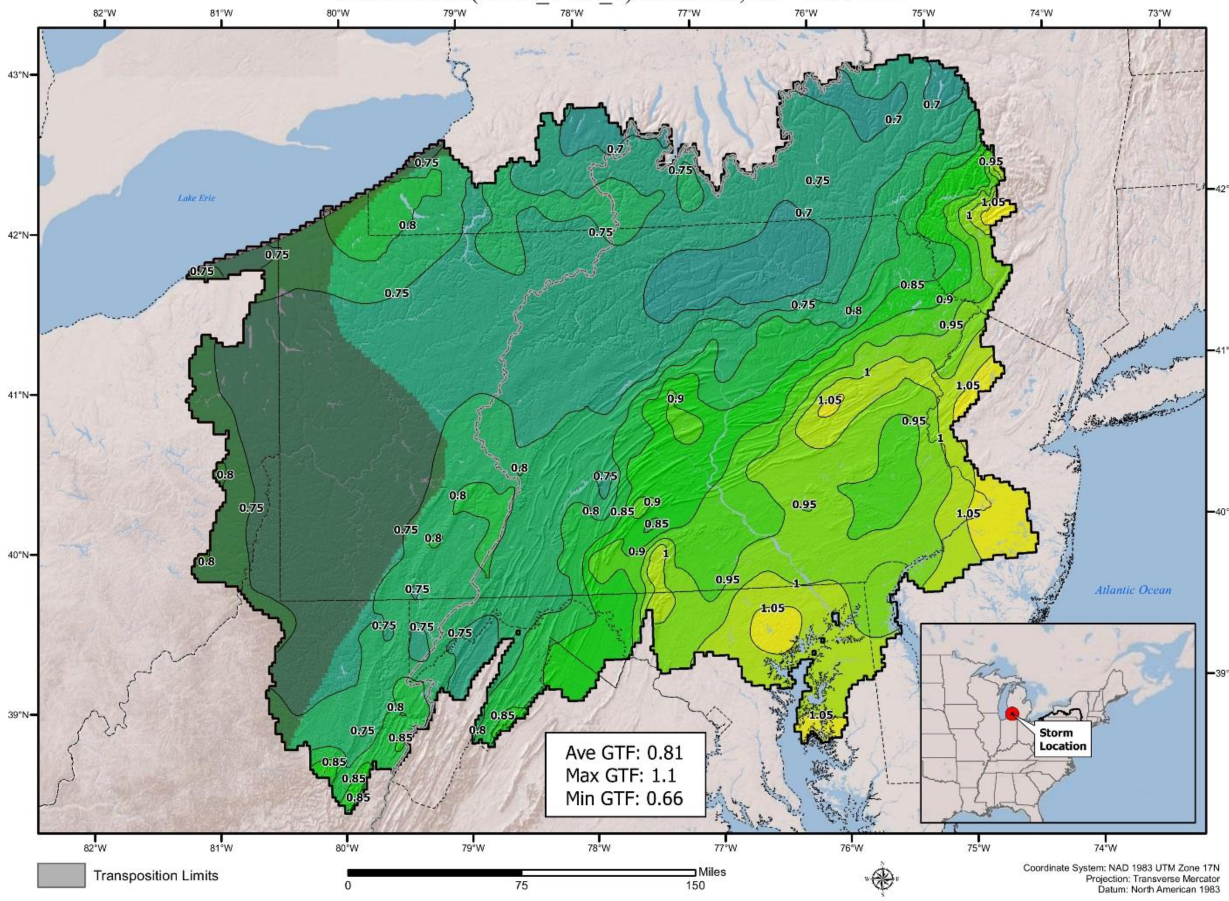
Geographic Transposition Factor
Local Storm (SPAS_1406_1) RAPIDAN, VA - 6/27/1995



Geographic Transposition Factor
Local Storm (SPAS_1415_1) ISLIP, NY - 8/13/2014



Geographic Transposition Factor
Local Storm (SPAS_1426_1) COOPER, MI - 8/31/1914



Geographic Transposition Factor
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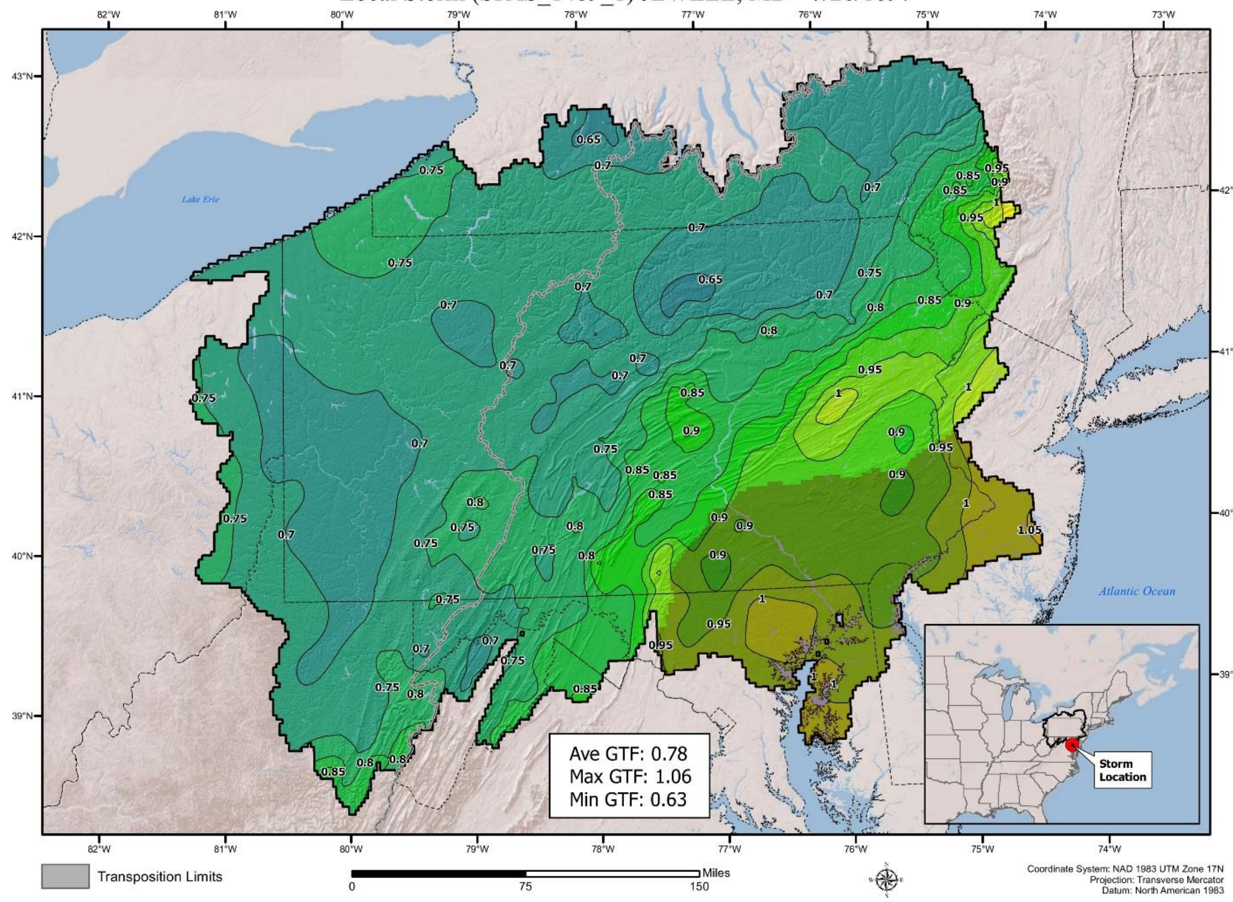
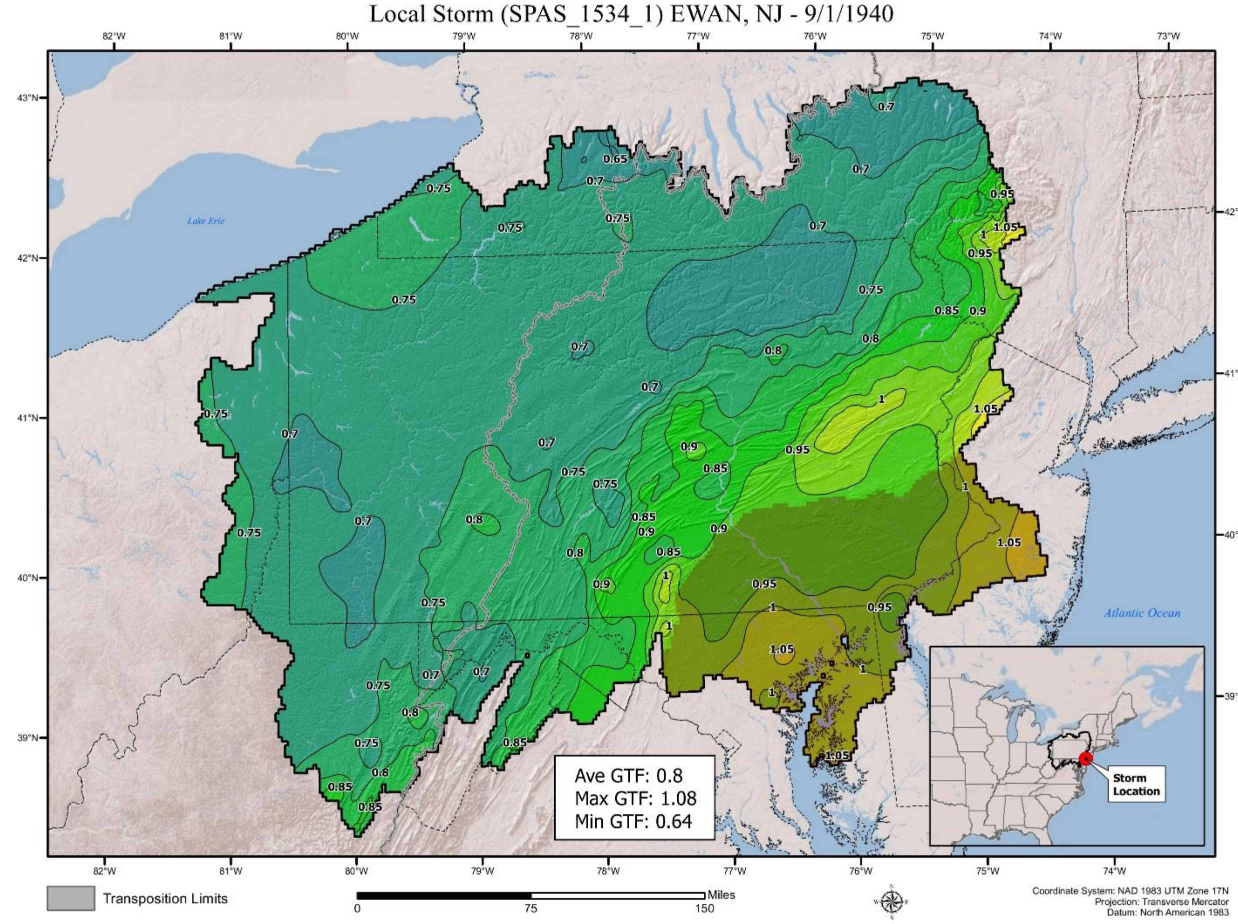
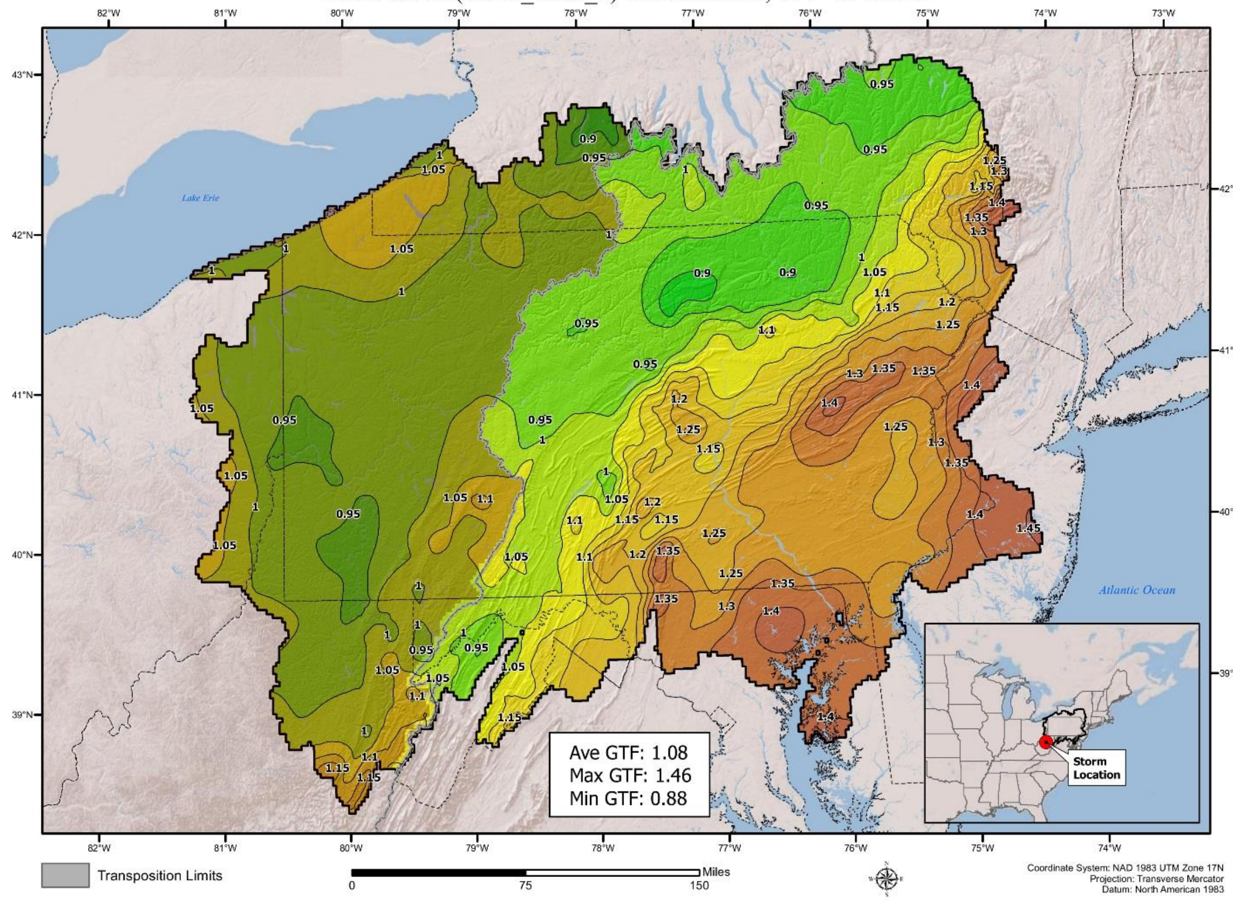


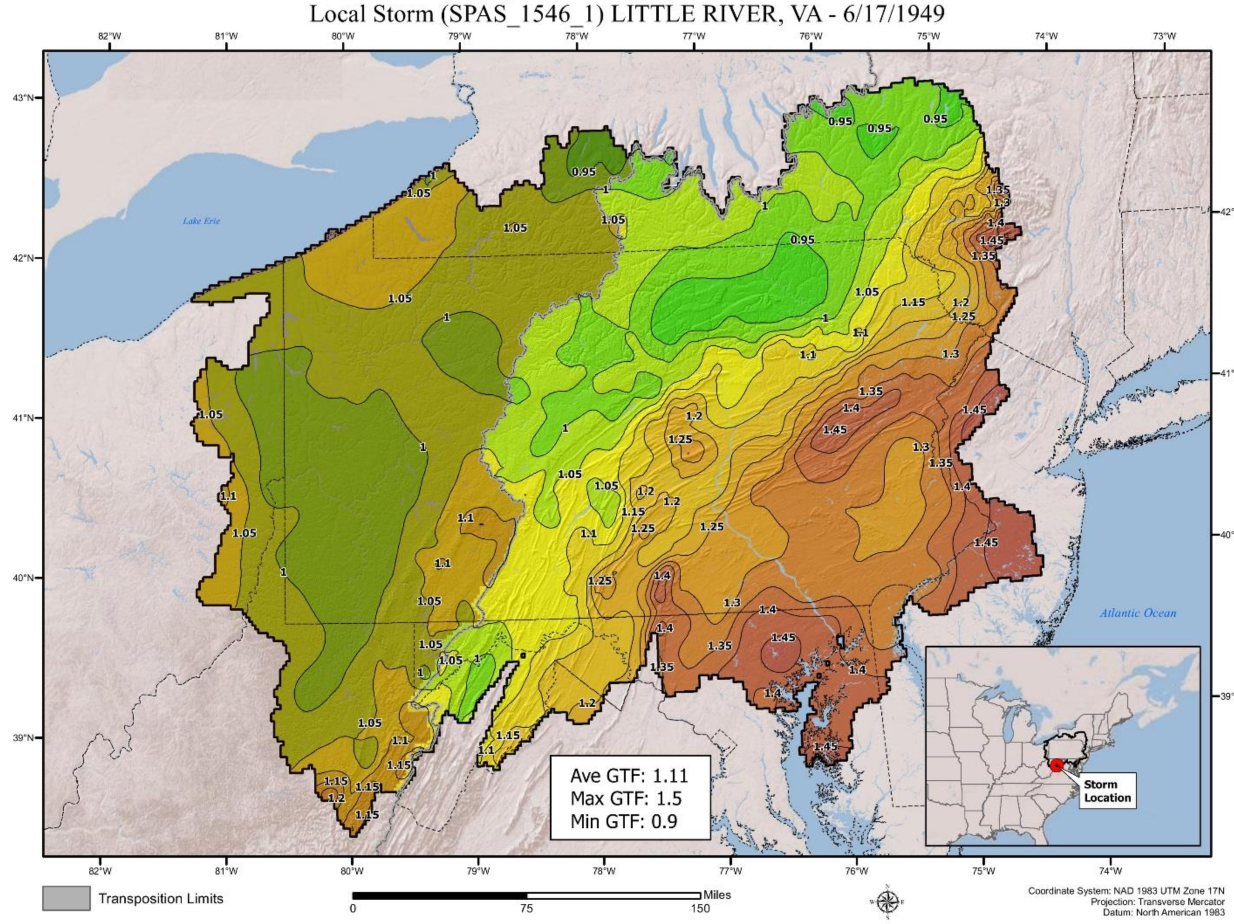
Geographic Transposition Factor
Local Storm (SPAS_1534_1) EWAN, NJ - 9/1/1940



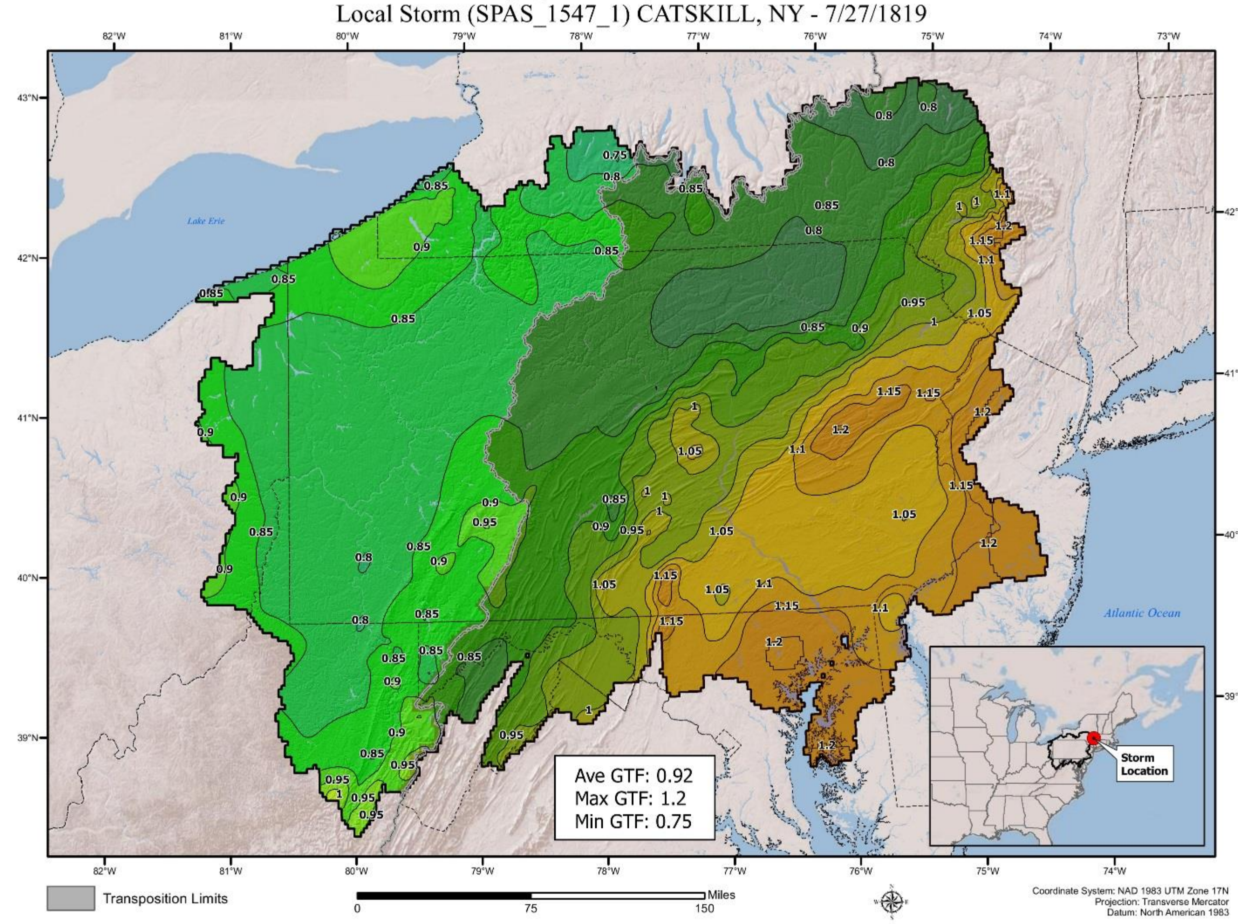
Geographic Transposition Factor
Local Storm (SPAS_1536_1) GLENVILLE, WV - 8/4/1943



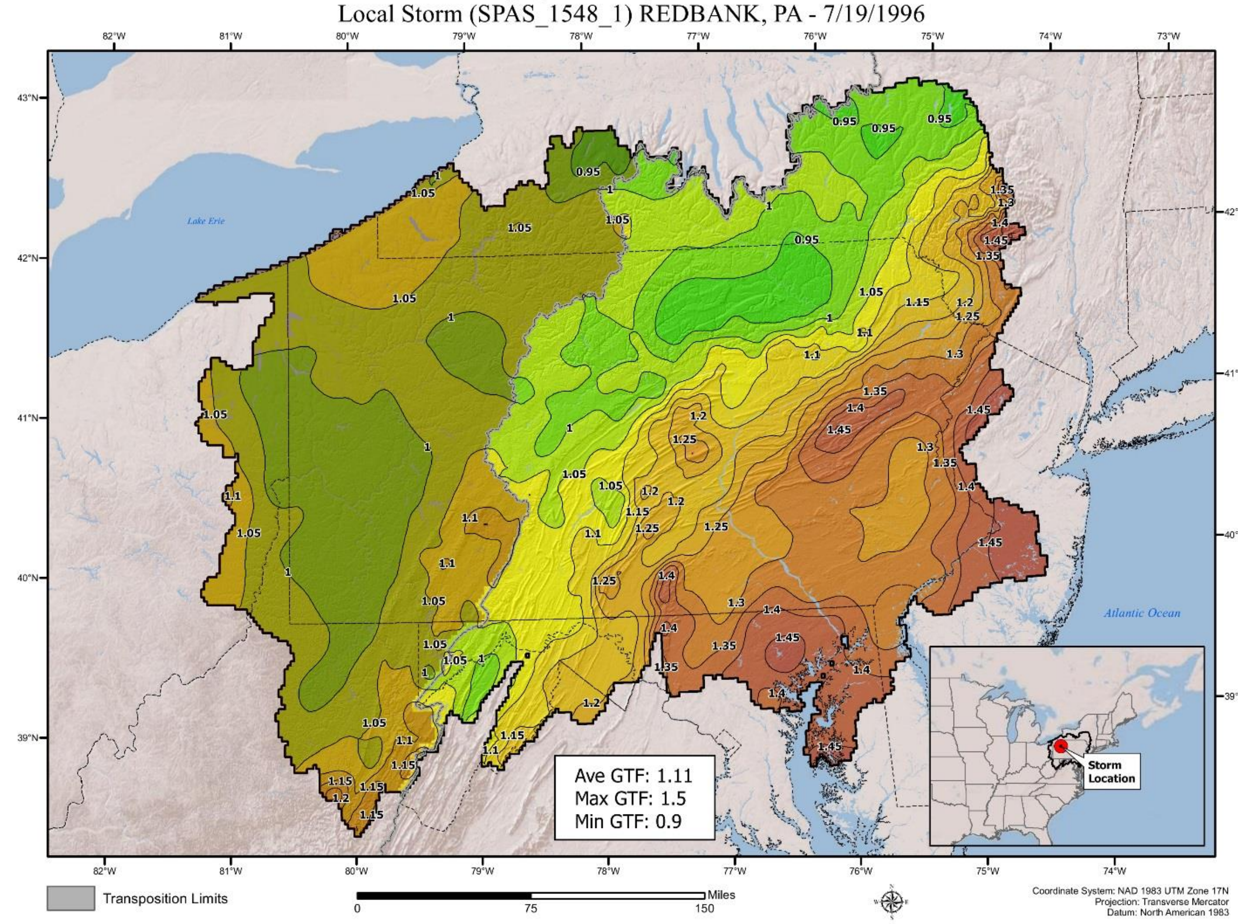
Geographic Transposition Factor
Local Storm (SPAS_1546_1) LITTLE RIVER, VA - 6/17/1949



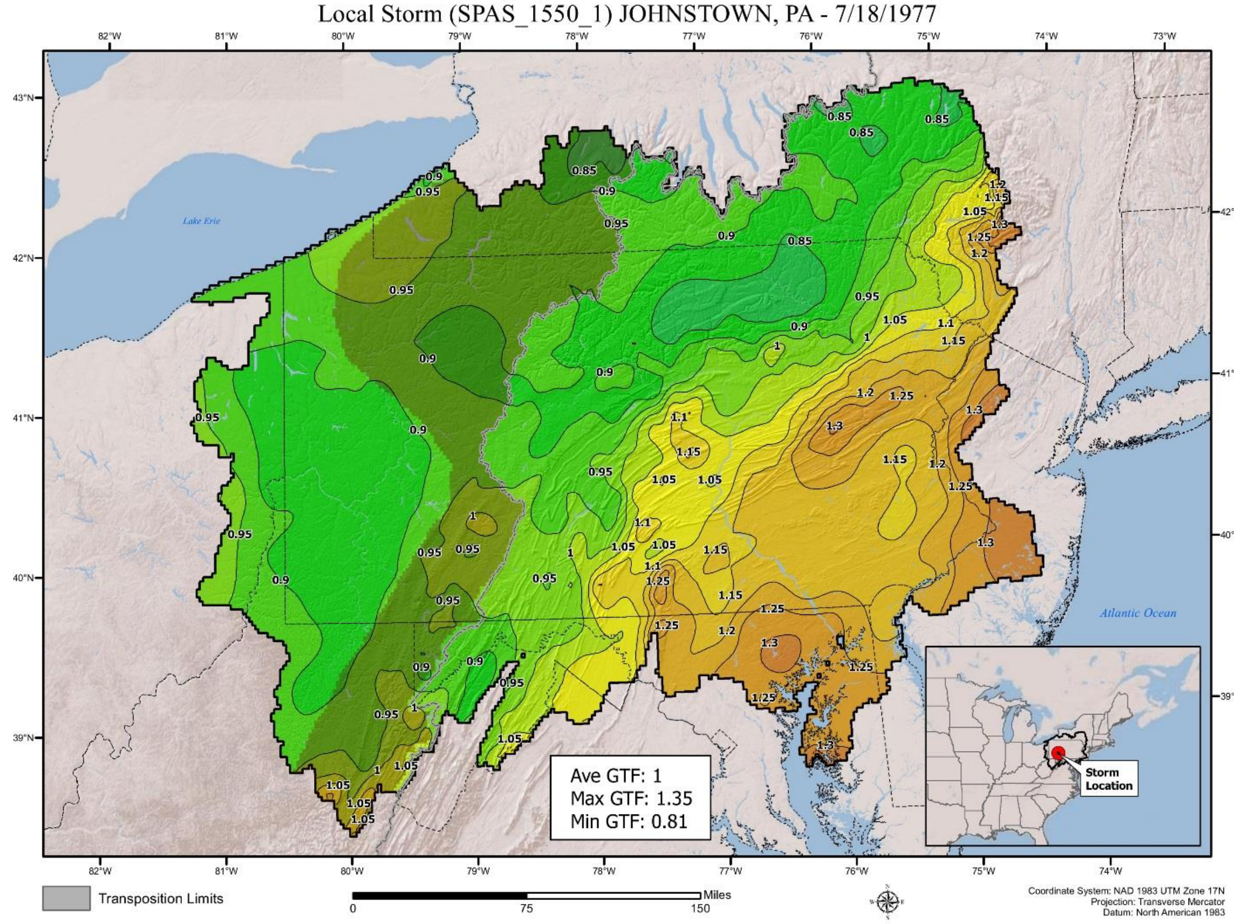
Geographic Transposition Factor
Local Storm (SPAS_1547_1) CATSKILL, NY - 7/27/1819



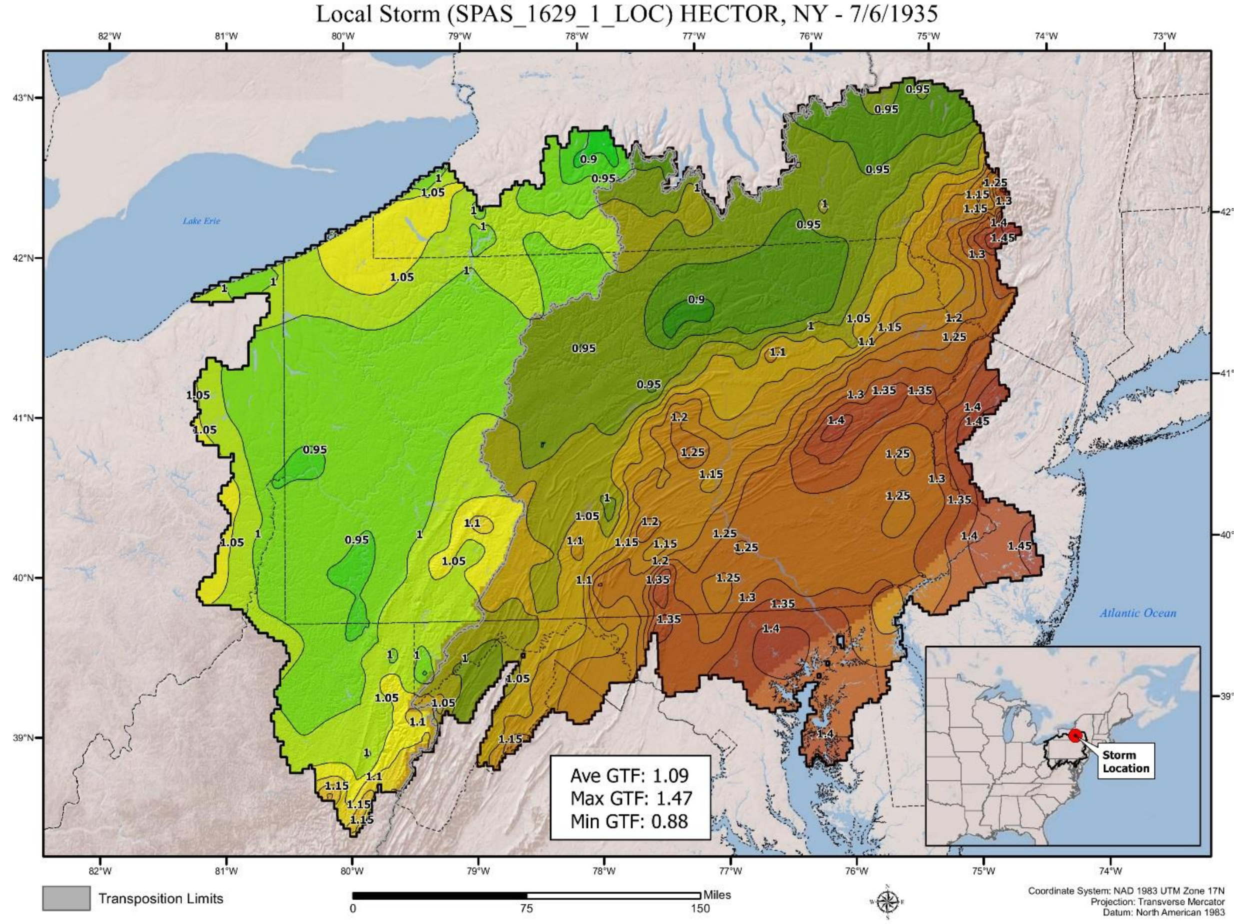
Geographic Transposition Factor
Local Storm (SPAS_1548_1) REDBANK, PA - 7/19/1996



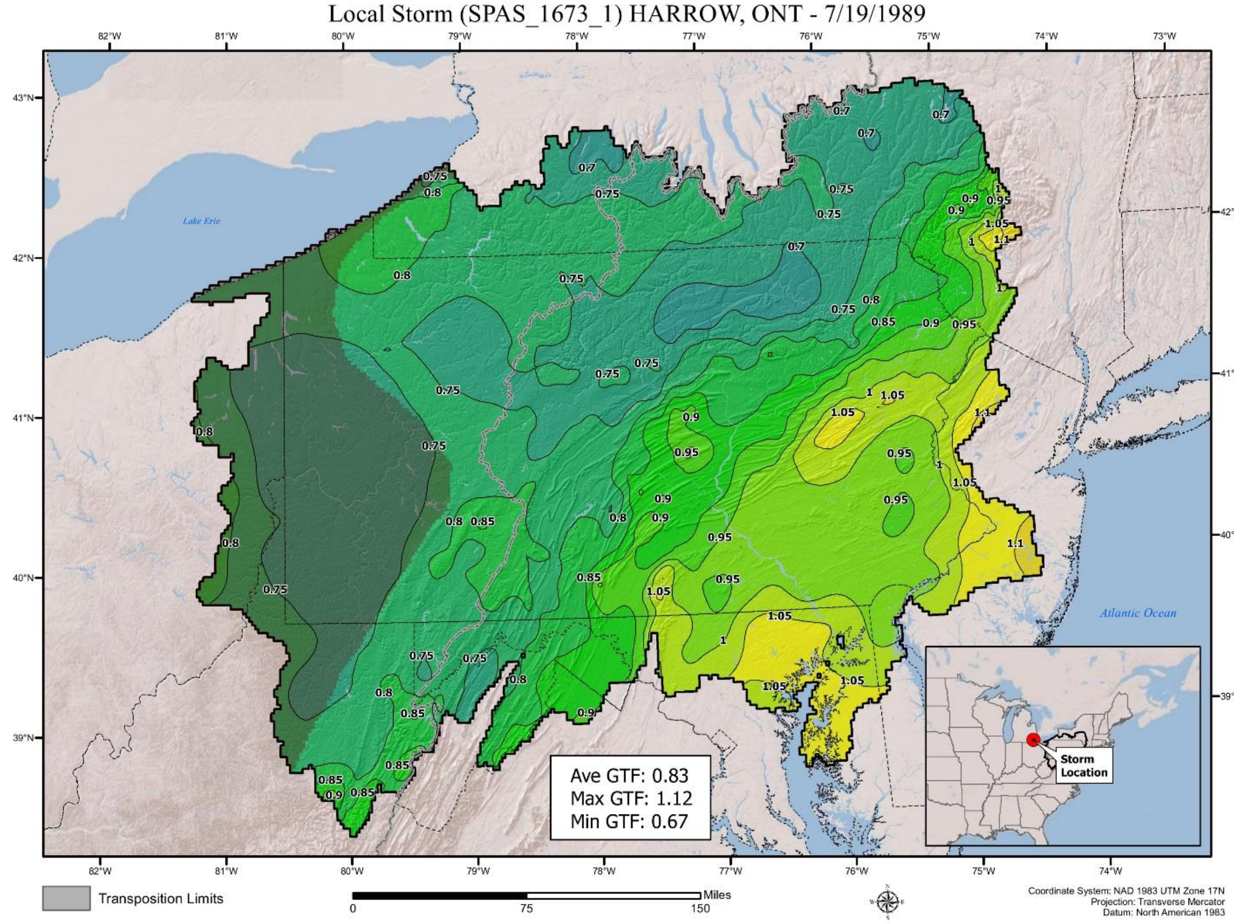
Geographic Transposition Factor
Local Storm (SPAS_1550_1) JOHNSTOWN, PA - 7/18/1977



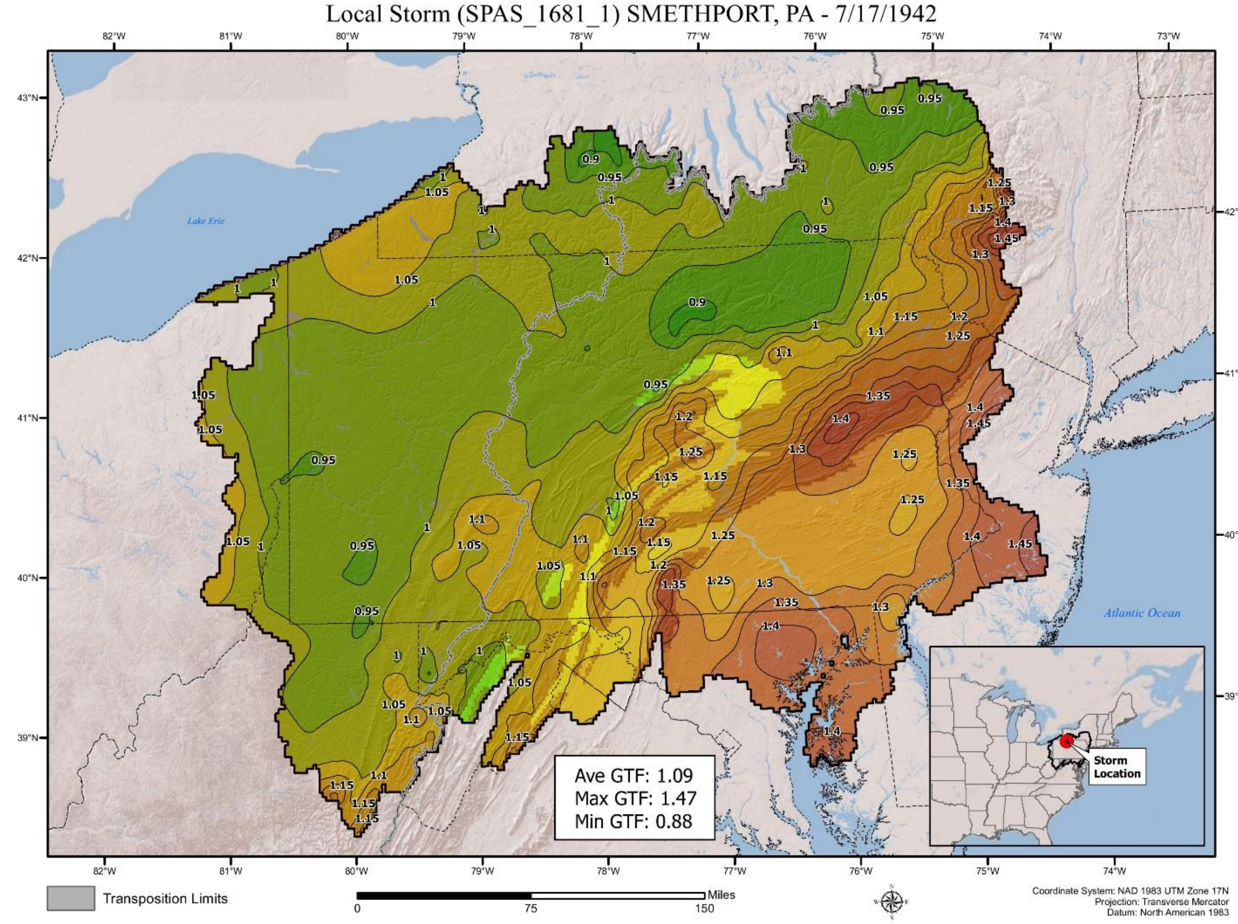
Geographic Transposition Factor
Local Storm (SPAS_1629_1_LOC) HECTOR, NY - 7/6/1935



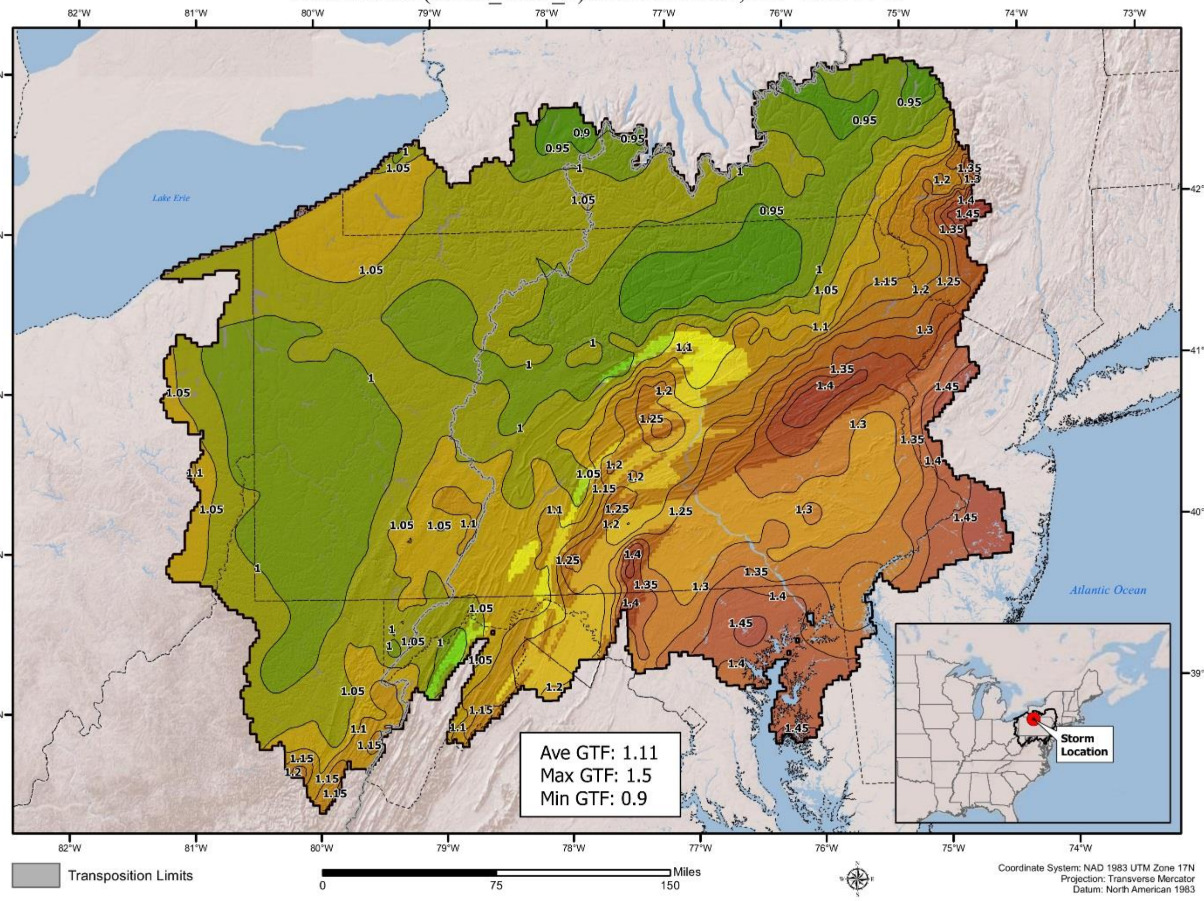
Geographic Transposition Factor
Local Storm (SPAS_1673_1) HARROW, ONT - 7/19/1989



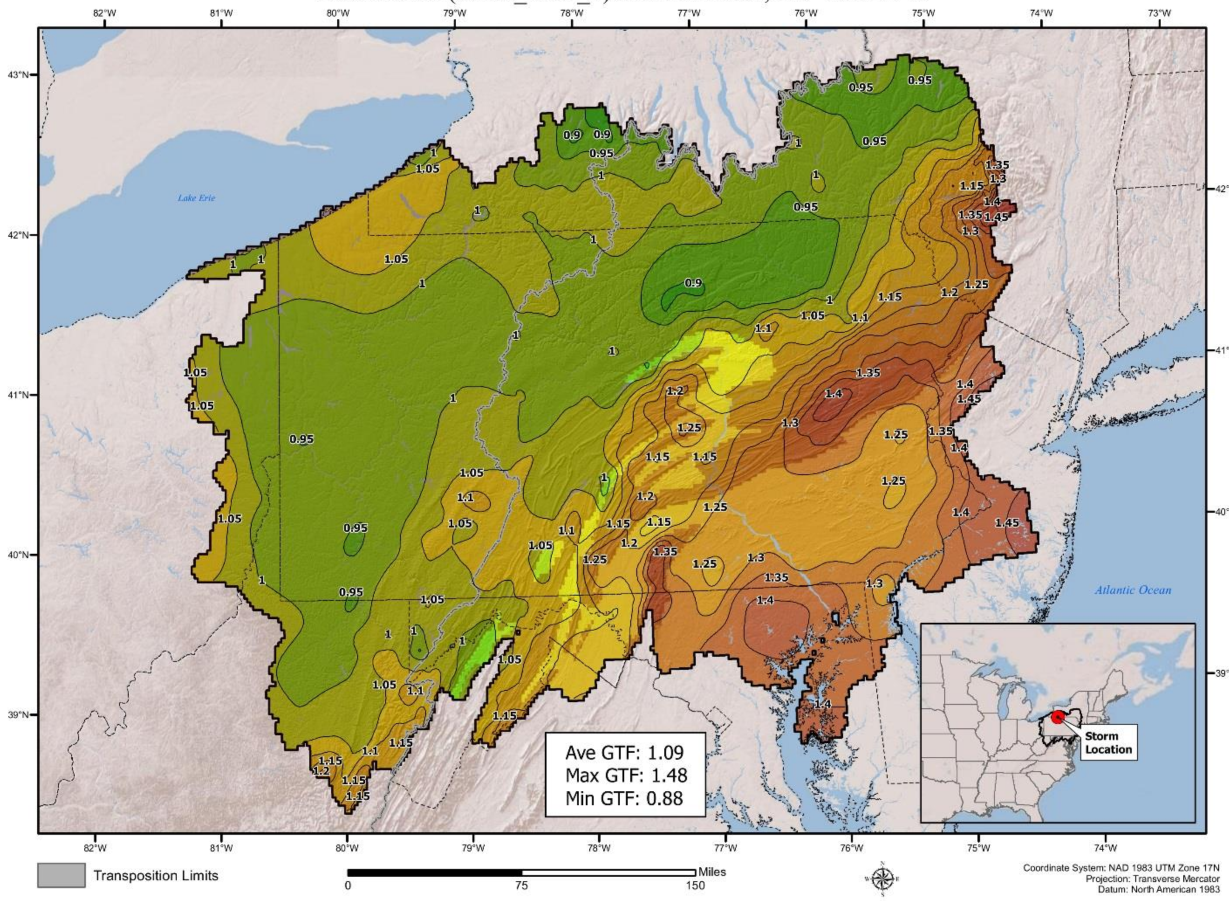
Geographic Transposition Factor
Local Storm (SPAS_1681_1) SMETHPORT, PA - 7/17/1942



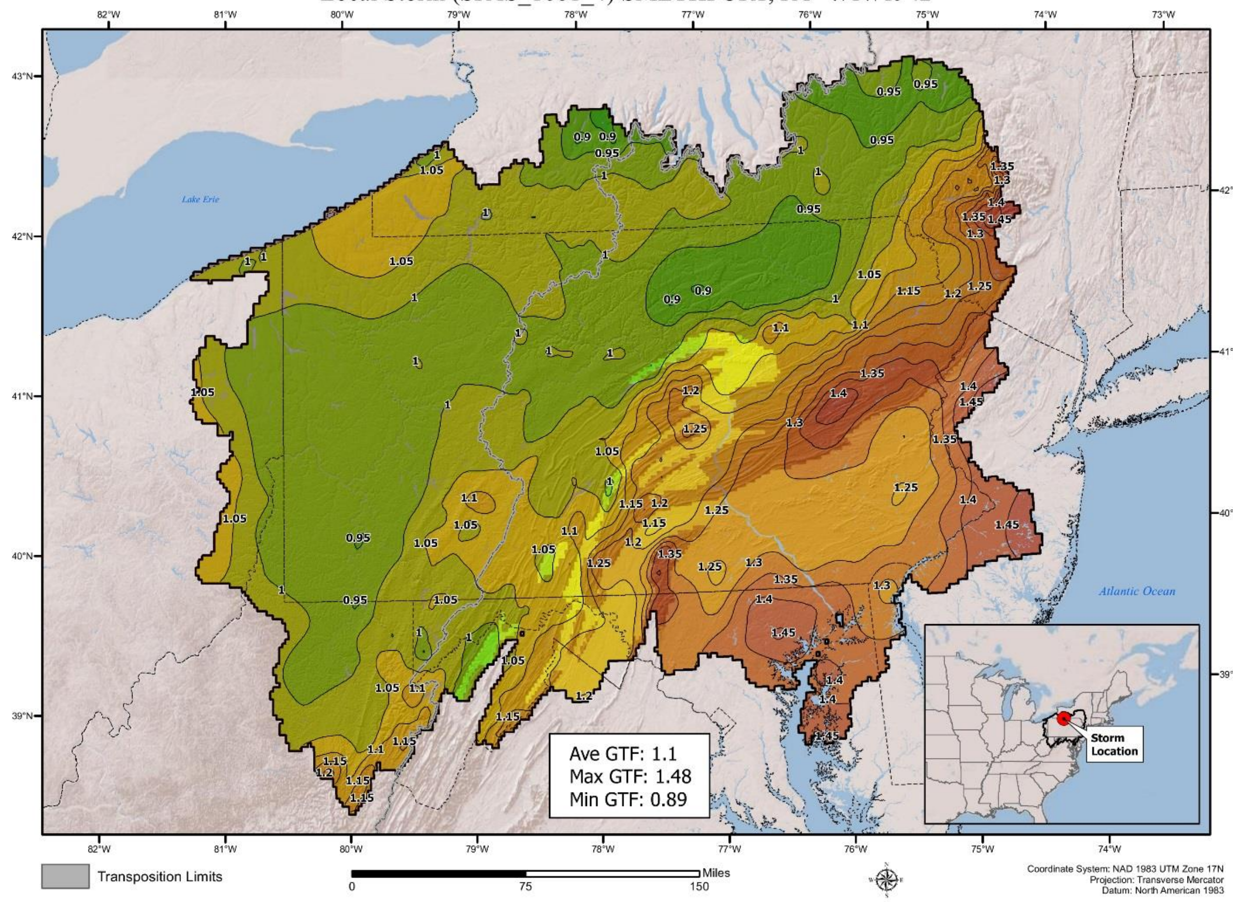
Geographic Transposition Factor
Local Storm (SPAS_1681_2) SMETHPORT, PA - 7/17/1942



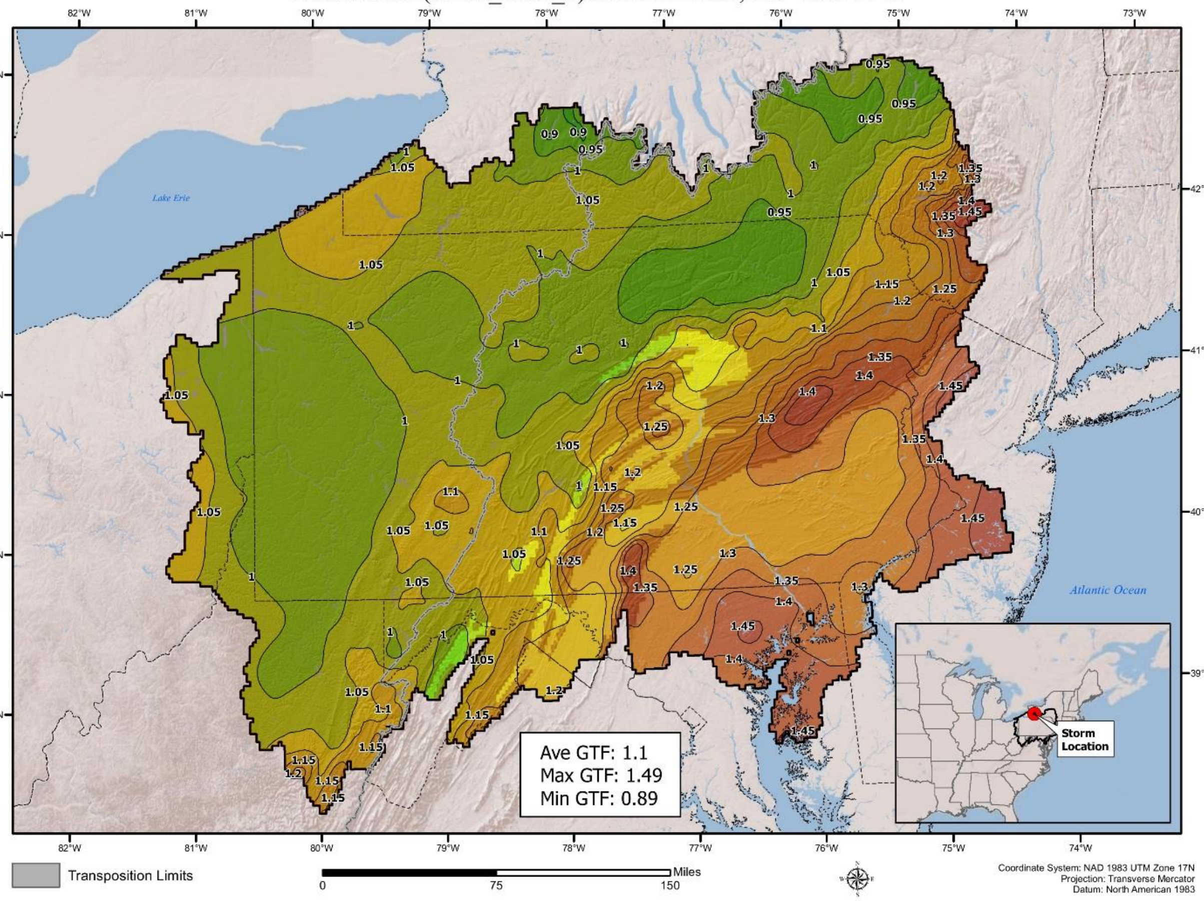
Geographic Transposition Factor
Local Storm (SPAS_1681_3) SMETHPORT, PA - 7/17/1942



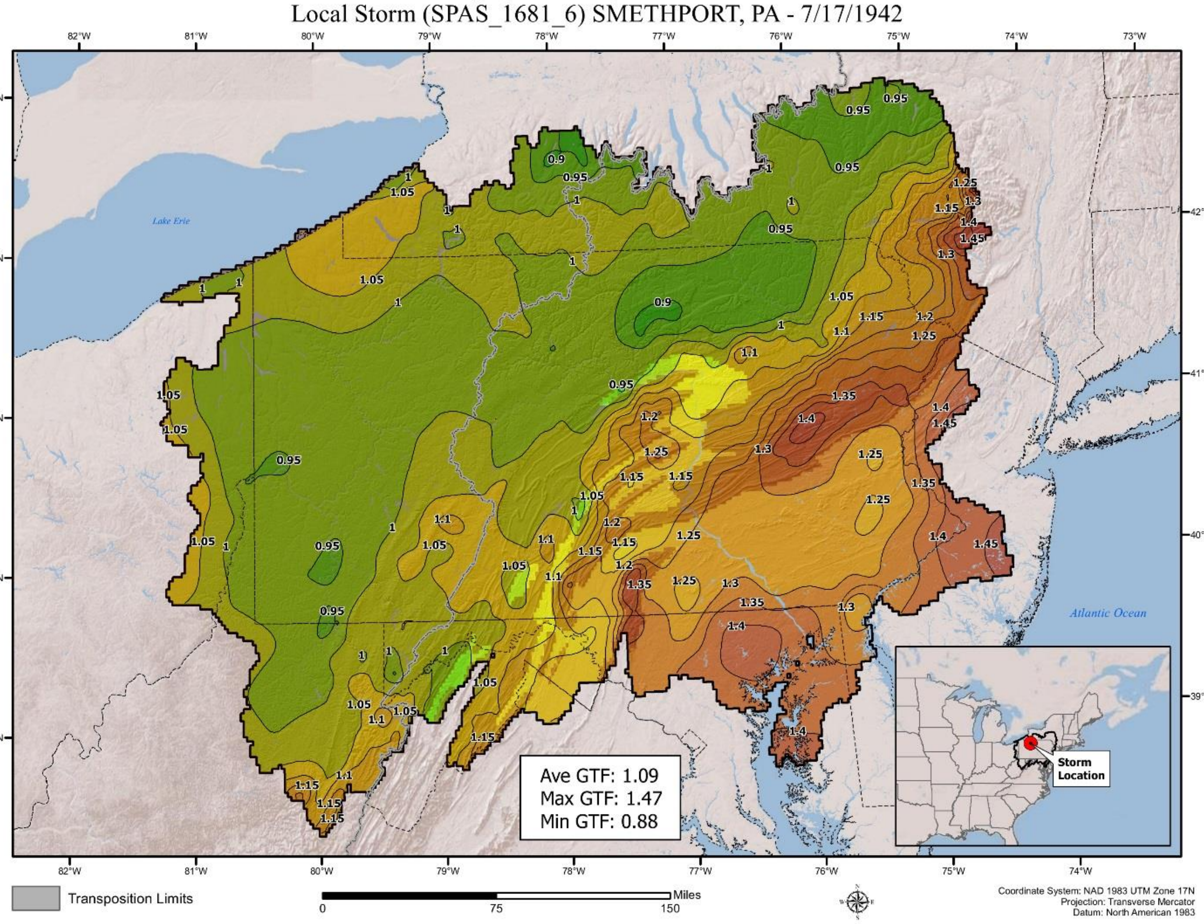
Geographic Transposition Factor
Local Storm (SPAS_1681_4) SMETHPORT, PA - 7/17/1942



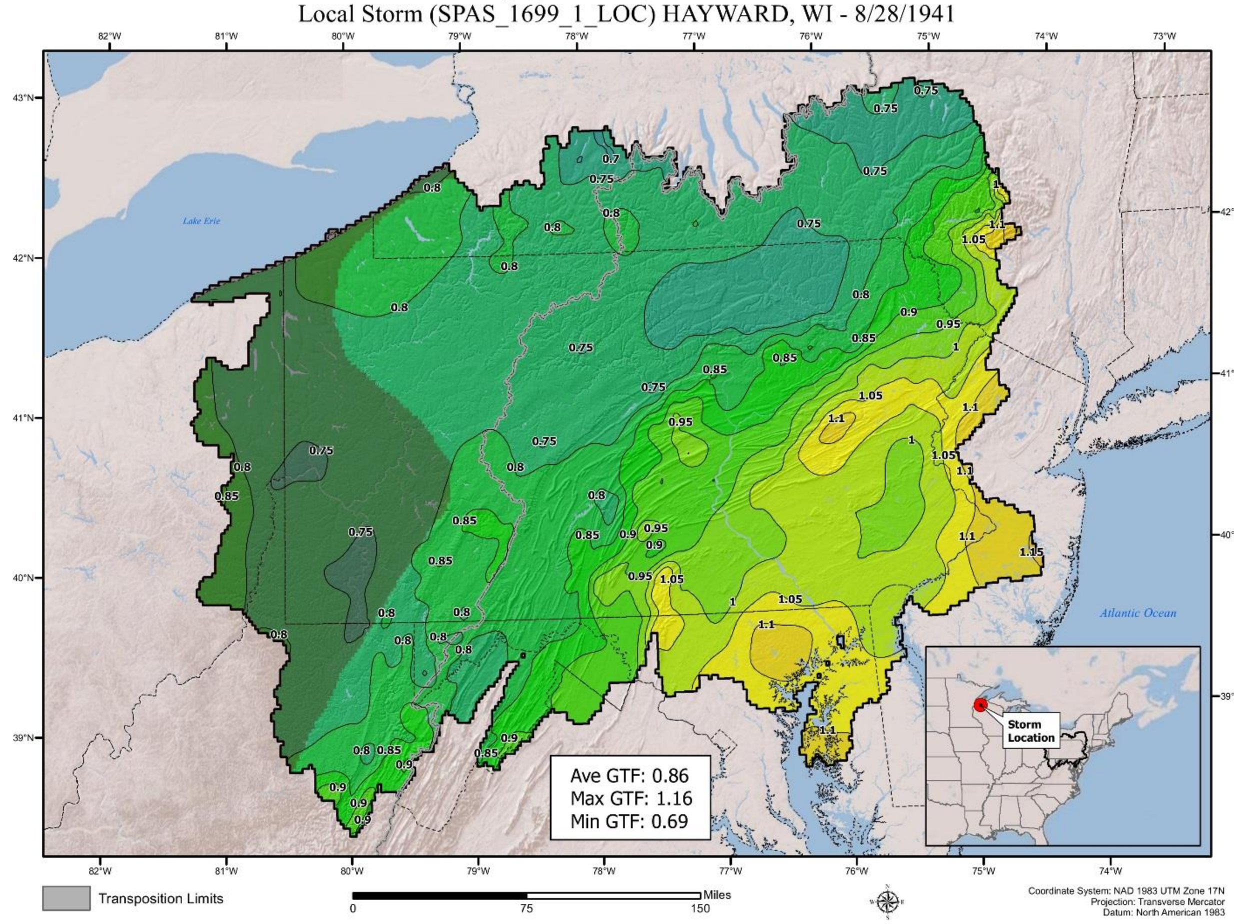
Geographic Transposition Factor
Local Storm (SPAS_1681_5) SMETHPORT, PA - 7/17/1942



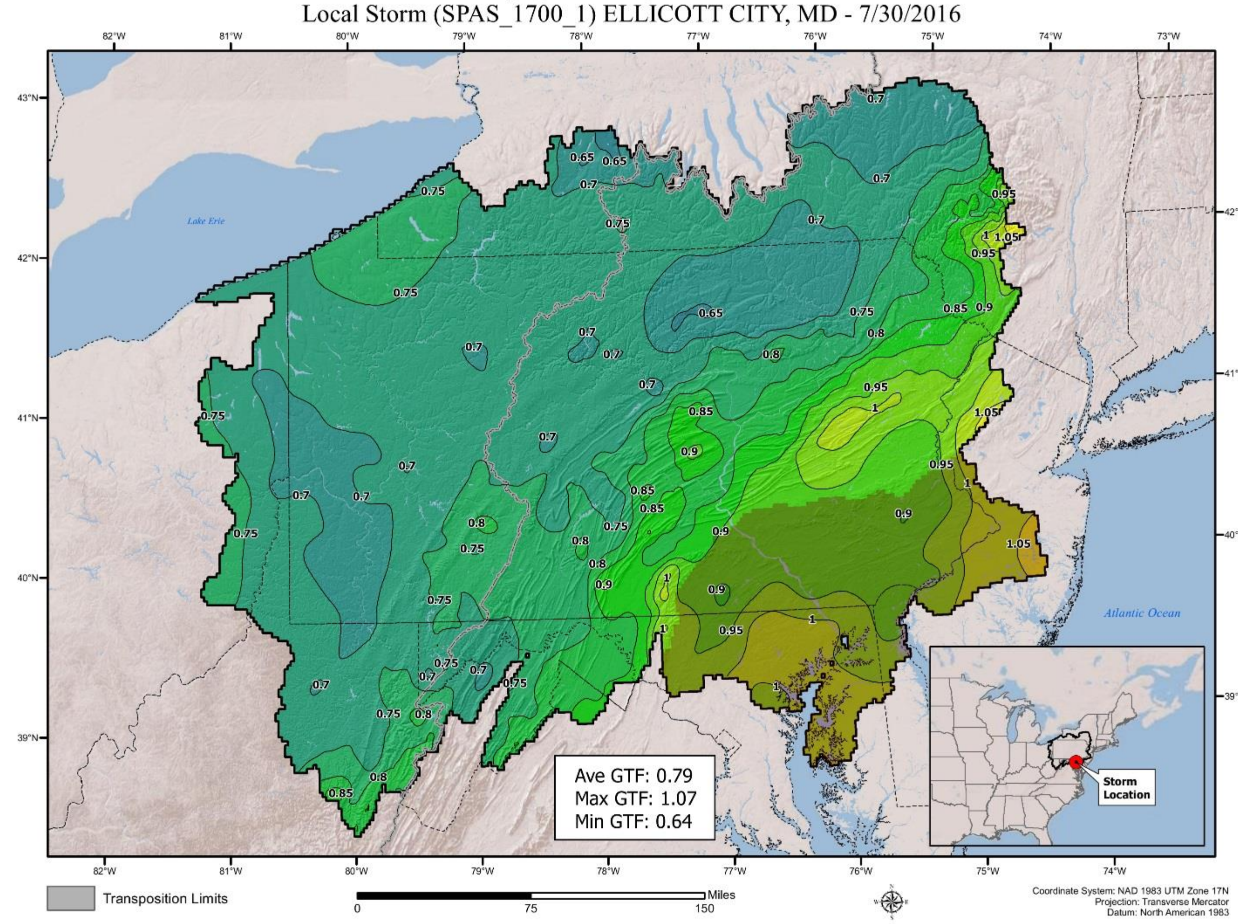
Geographic Transposition Factor
Local Storm (SPAS_1681_6) SMETHPORT, PA - 7/17/1942



Geographic Transposition Factor
Local Storm (SPAS_1699_1_LOC) HAYWARD, WI - 8/28/1941

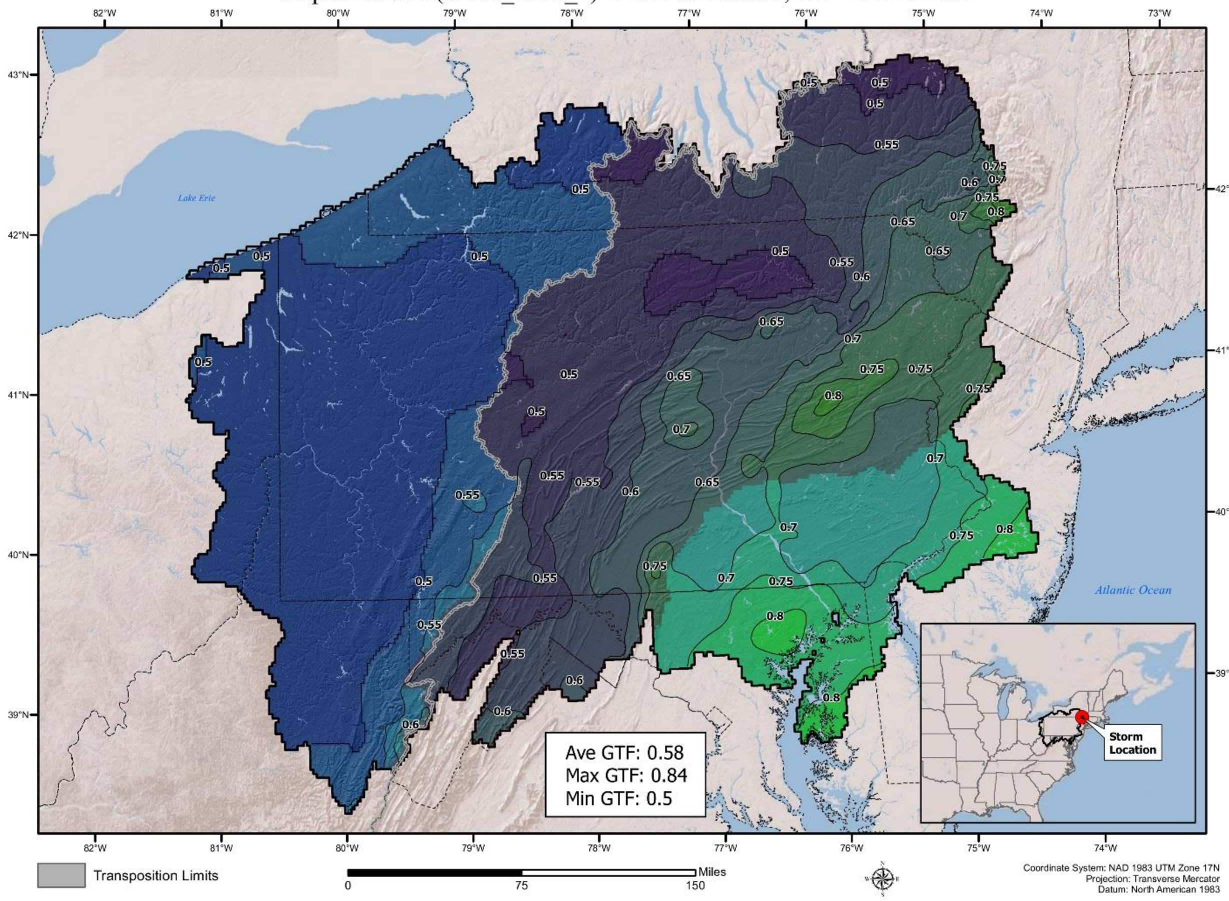


Geographic Transposition Factor
Local Storm (SPAS_1700_1) ELLICOTT CITY, MD - 7/30/2016

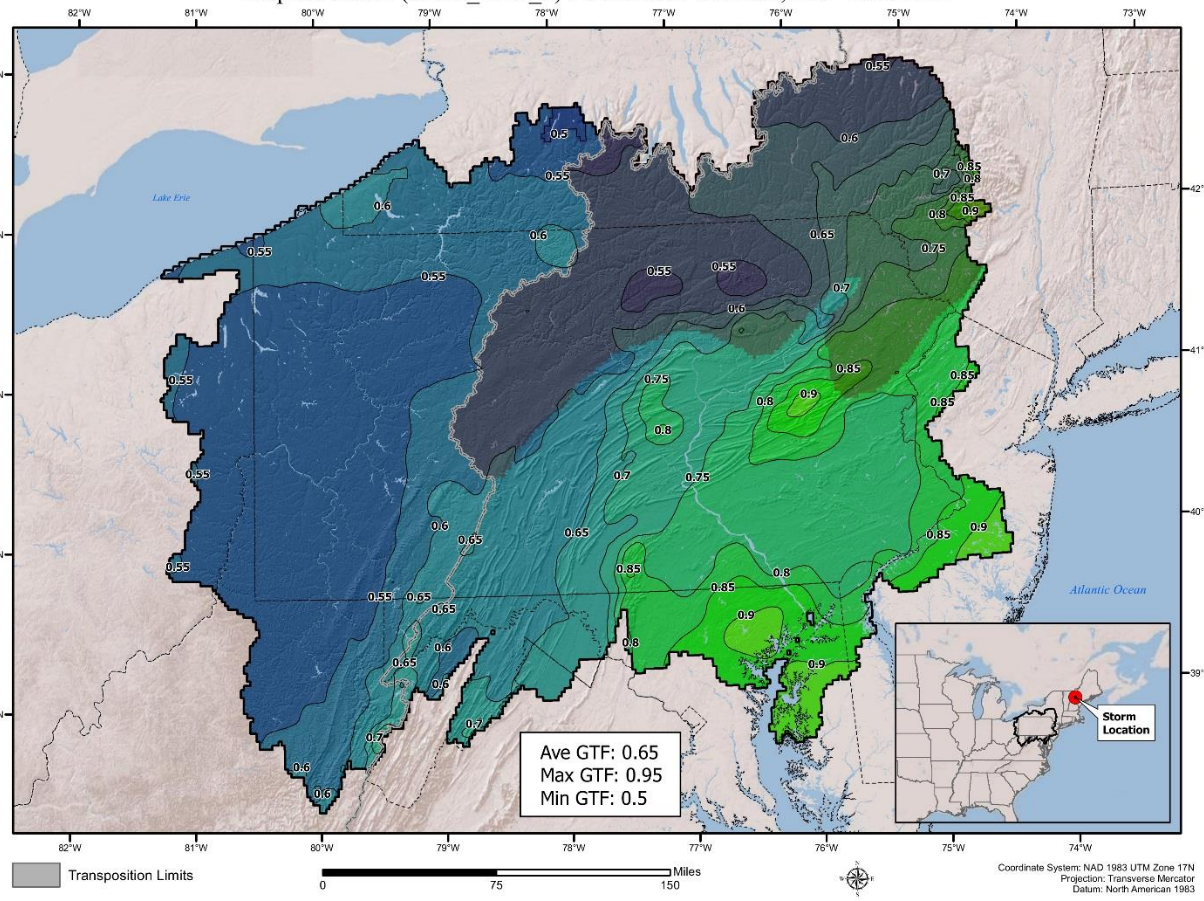


Tropical Storms

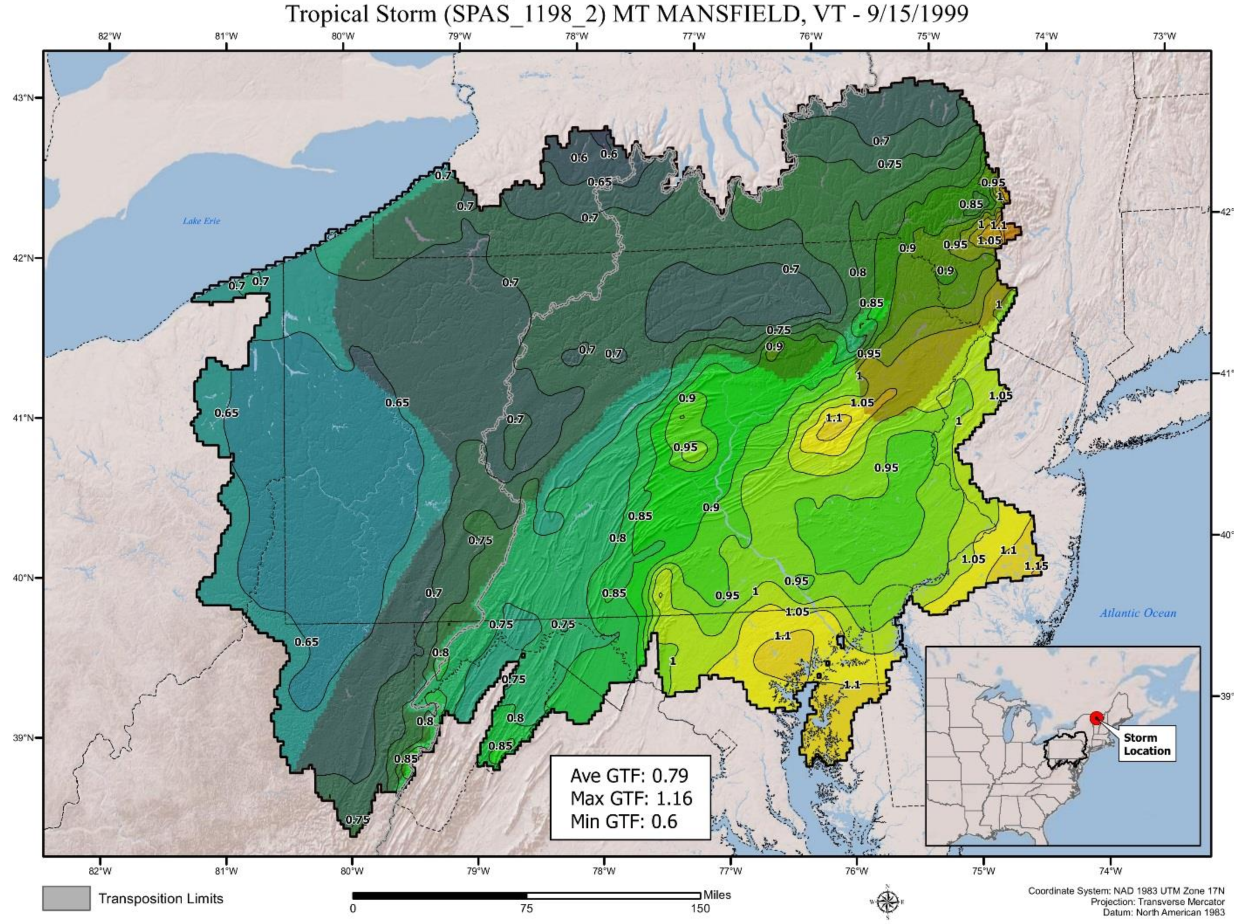
Geographic Transposition Factor
Tropical Storm (SPAS_1006_1) WEST SHOKAN, NY - 10/14/1955



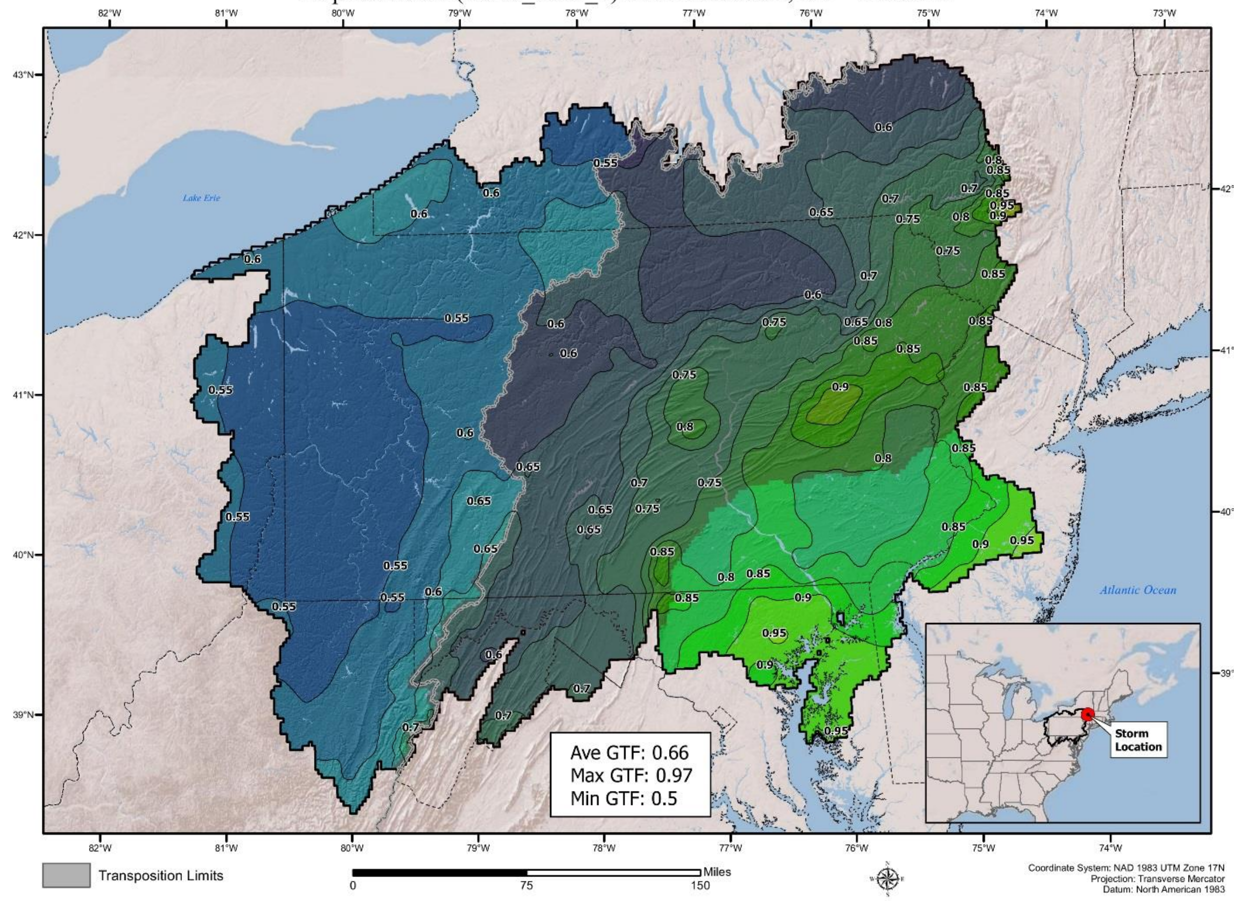
Geographic Transposition Factor
Tropical Storm (SPAS_1198_1) PINKHAM NOTCH, NH - 9/15/1999



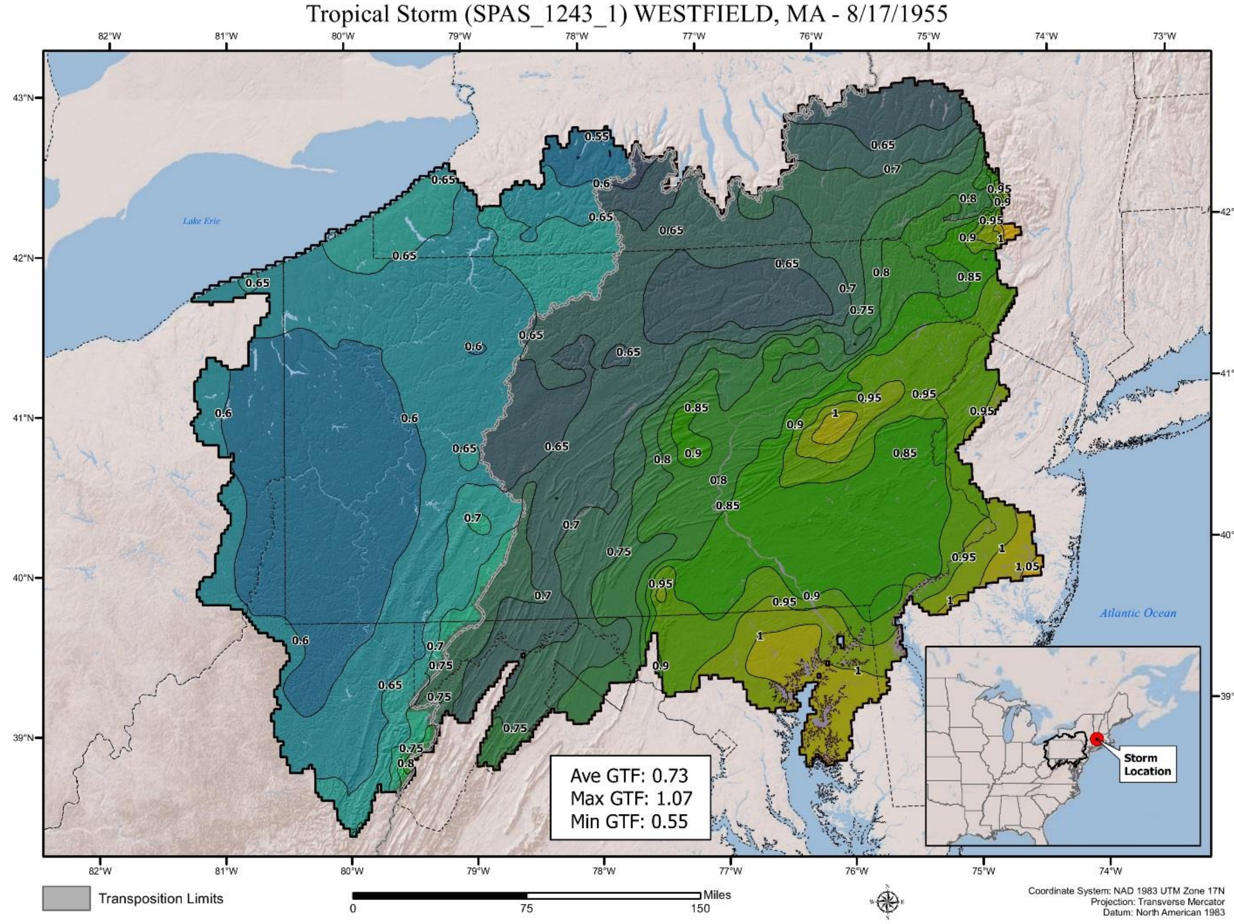
Geographic Transposition Factor
Tropical Storm (SPAS_1198_2) MT MANSFIELD, VT - 9/15/1999



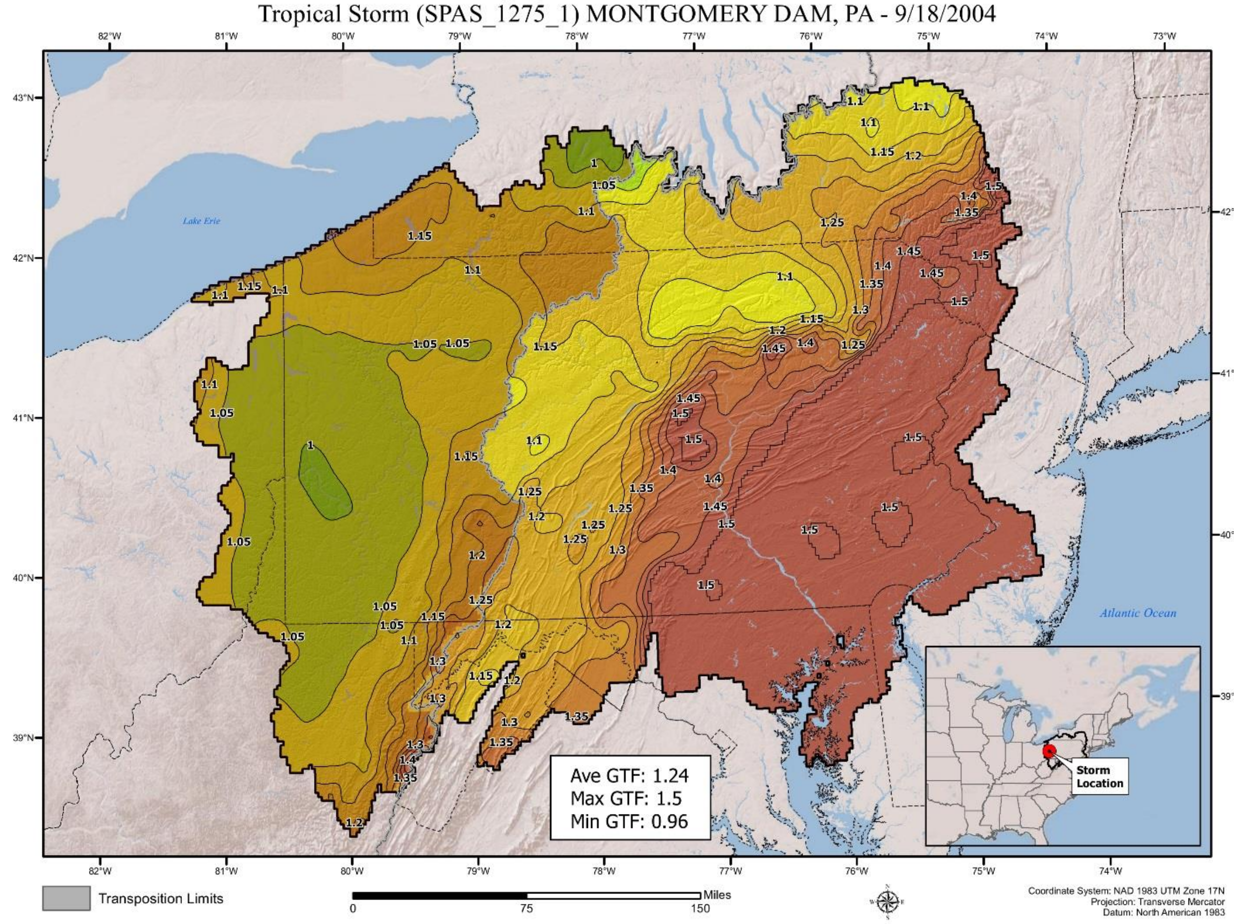
Geographic Transposition Factor
Tropical Storm (SPAS_1224_1) MAPLECREST, NY - 8/27/2011



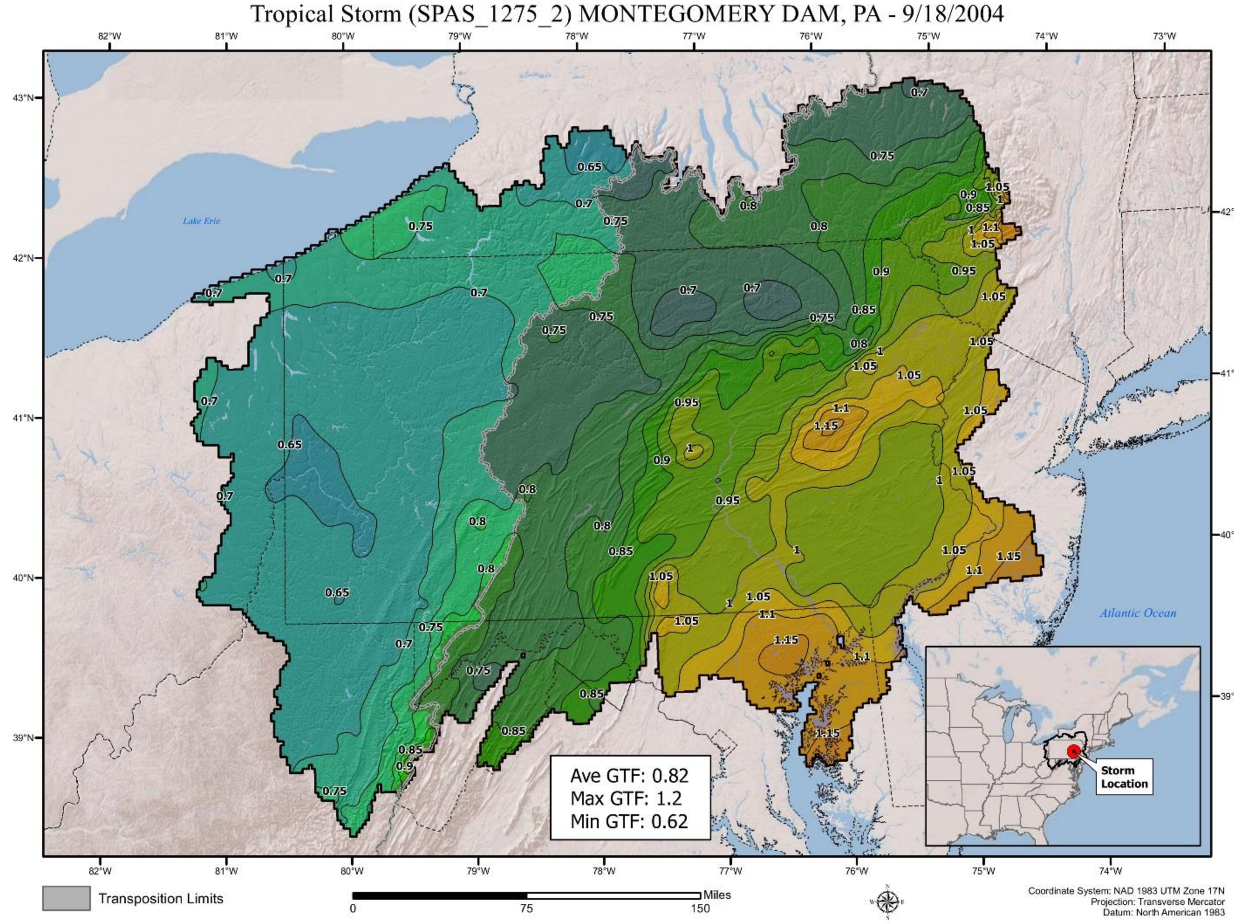
Geographic Transposition Factor
Tropical Storm (SPAS_1243_1) WESTFIELD, MA - 8/17/1955



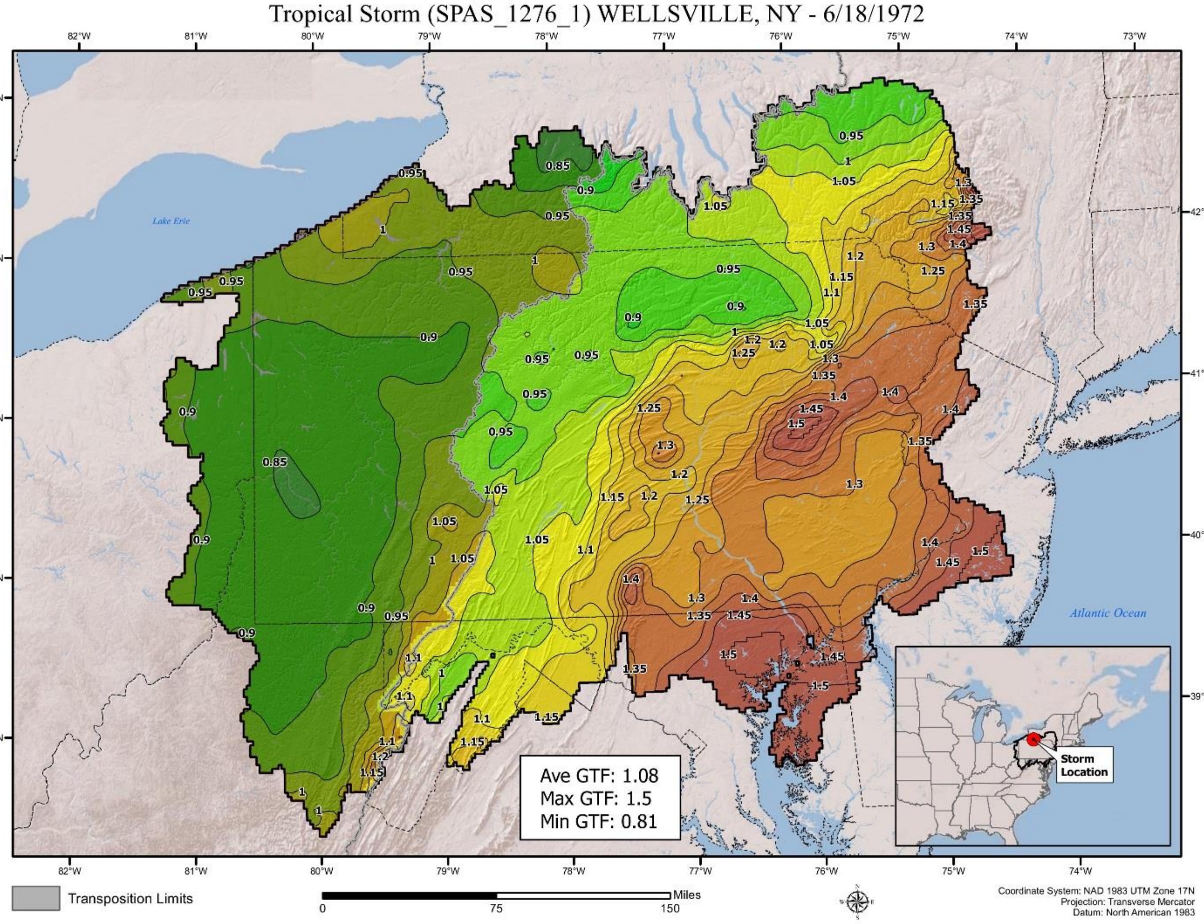
Geographic Transposition Factor
Tropical Storm (SPAS_1275_1) MONTGOMERY DAM, PA - 9/18/2004



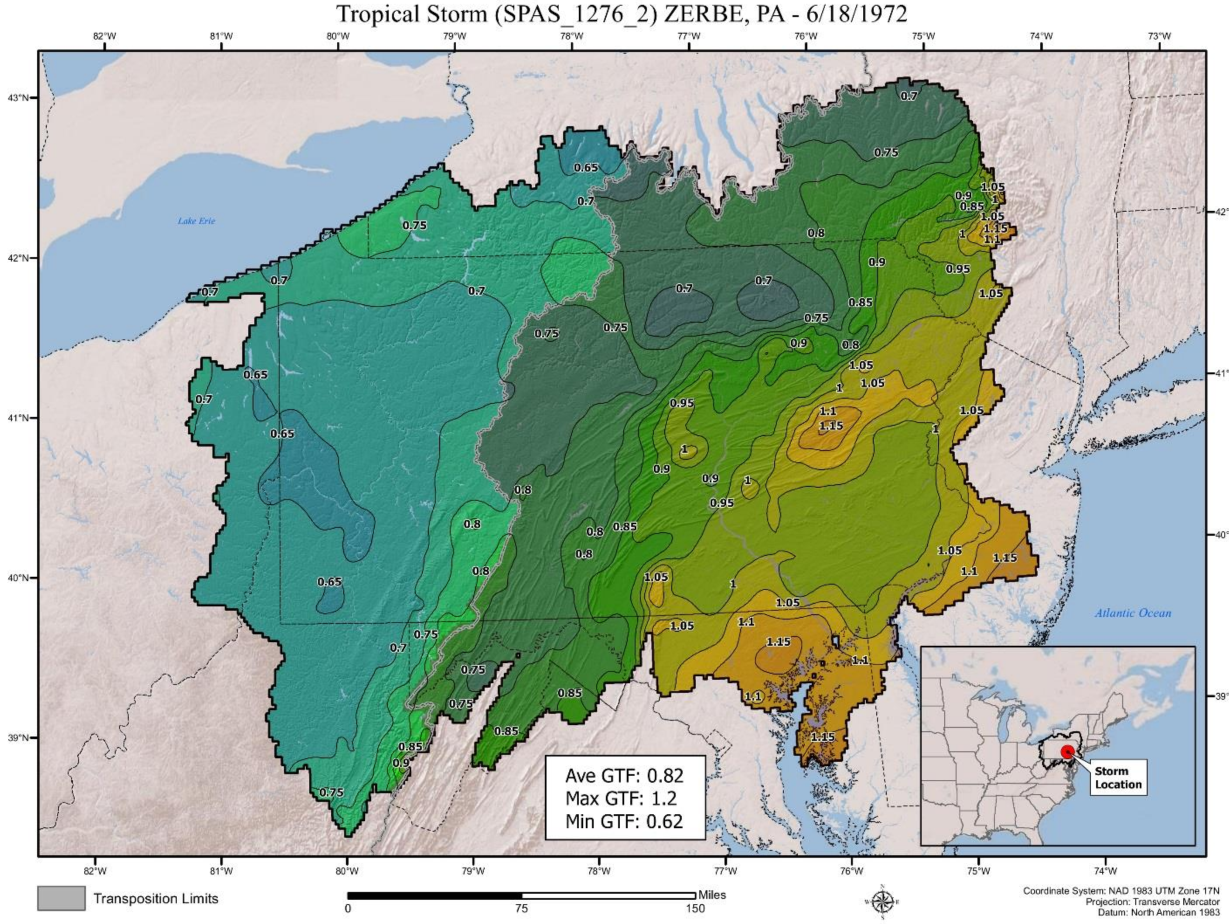
Geographic Transposition Factor
Tropical Storm (SPAS_1275_2) MONTEGOMERY DAM, PA - 9/18/2004



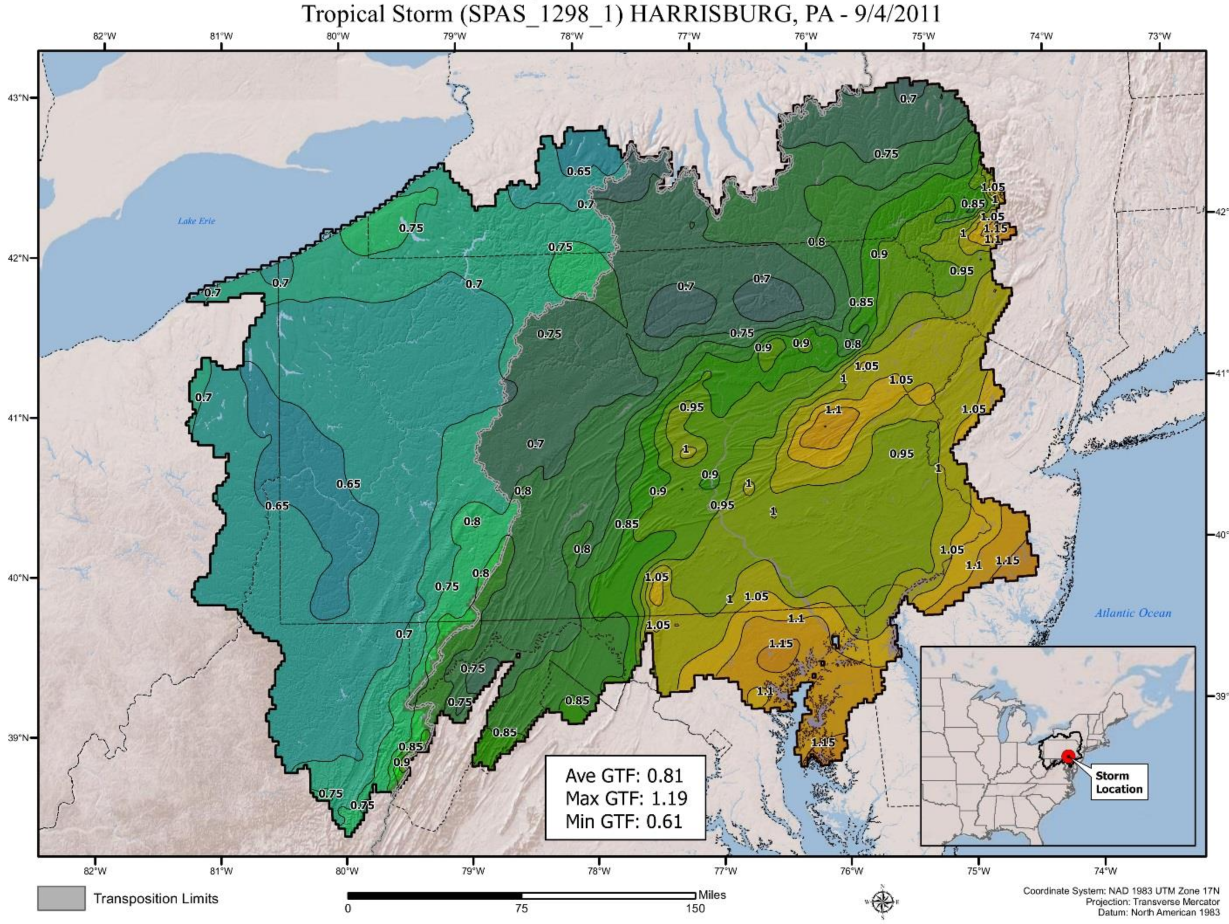
Geographic Transposition Factor
Tropical Storm (SPAS_1276_1) WELLSVILLE, NY - 6/18/1972



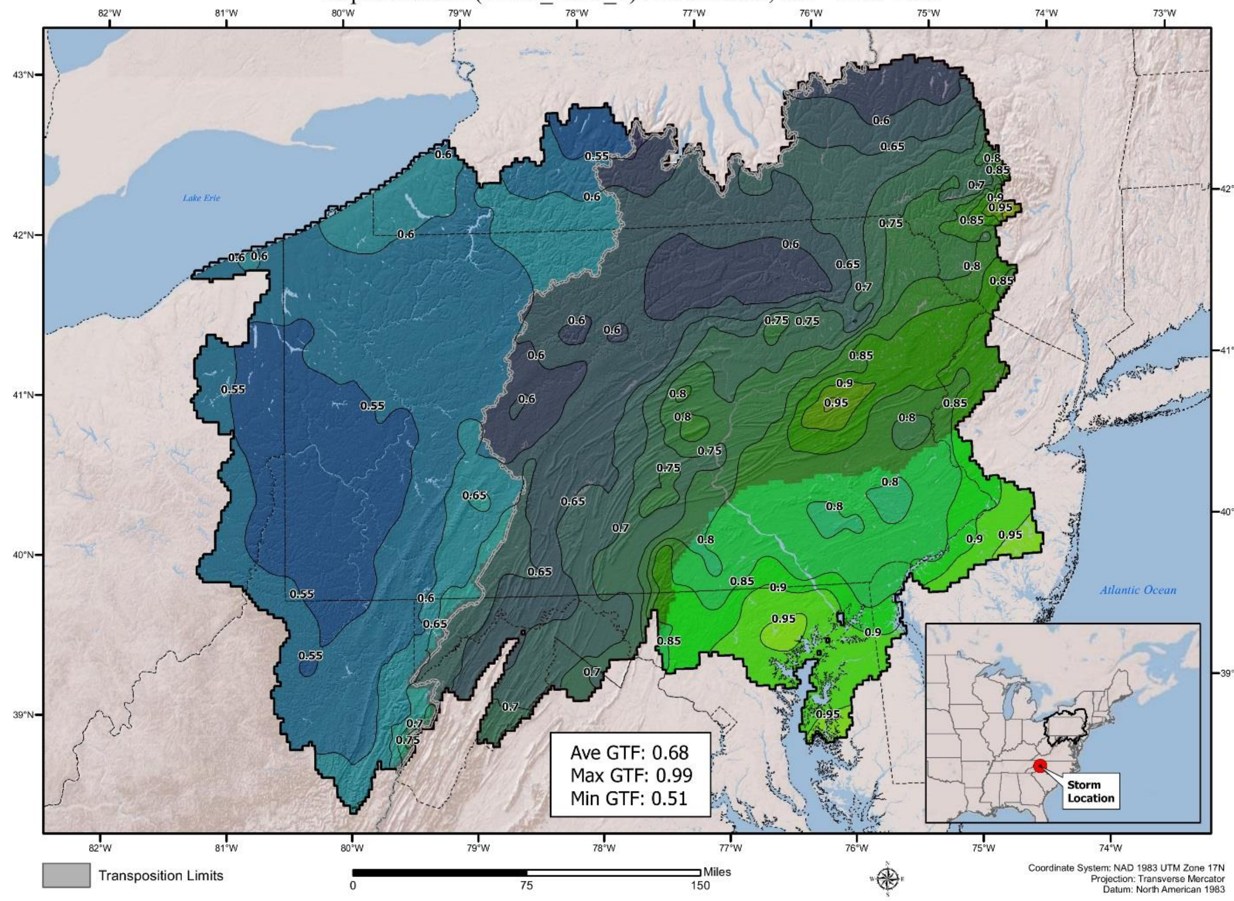
Geographic Transposition Factor
Tropical Storm (SPAS_1276_2) ZERBE, PA - 6/18/1972



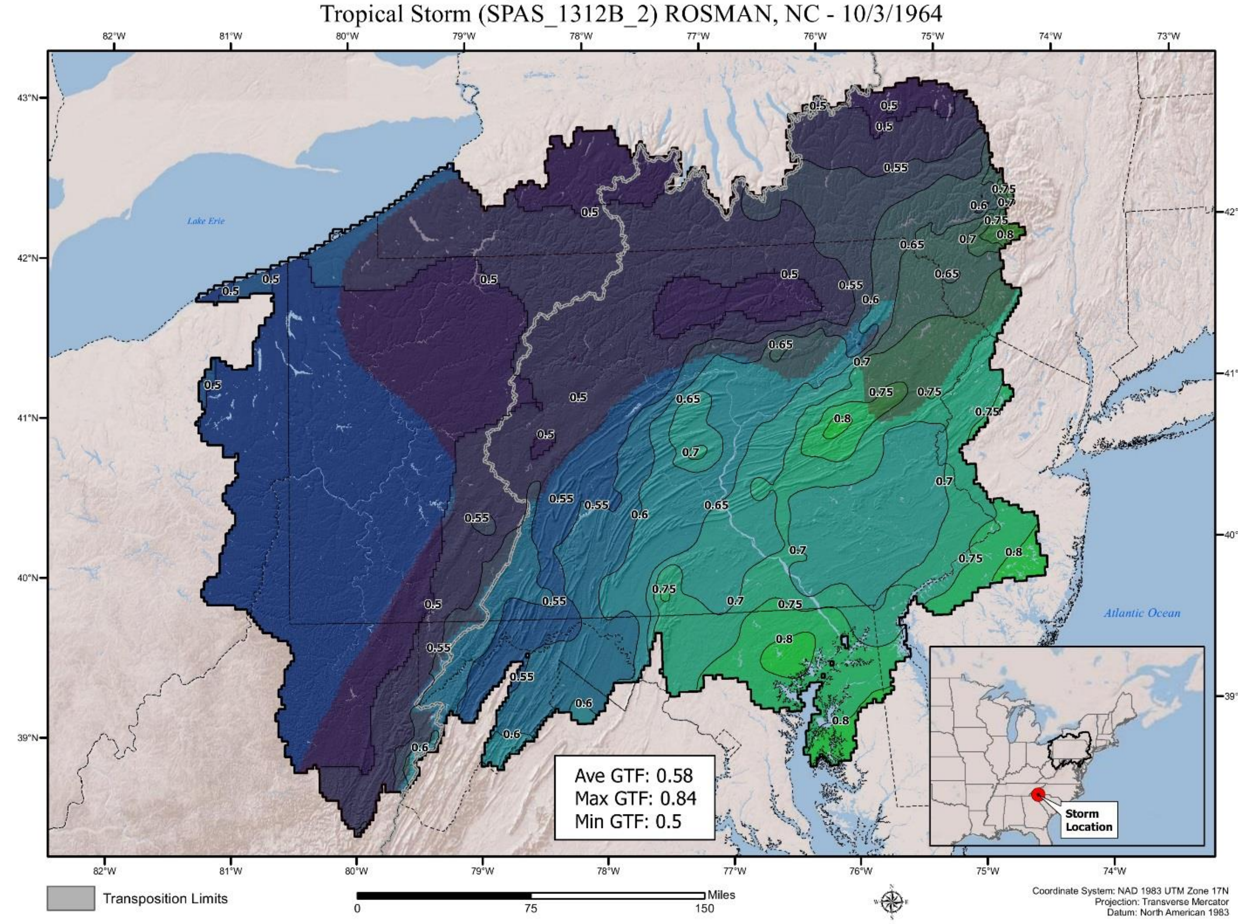
Geographic Transposition Factor
Tropical Storm (SPAS_1298_1) HARRISBURG, PA - 9/4/2011



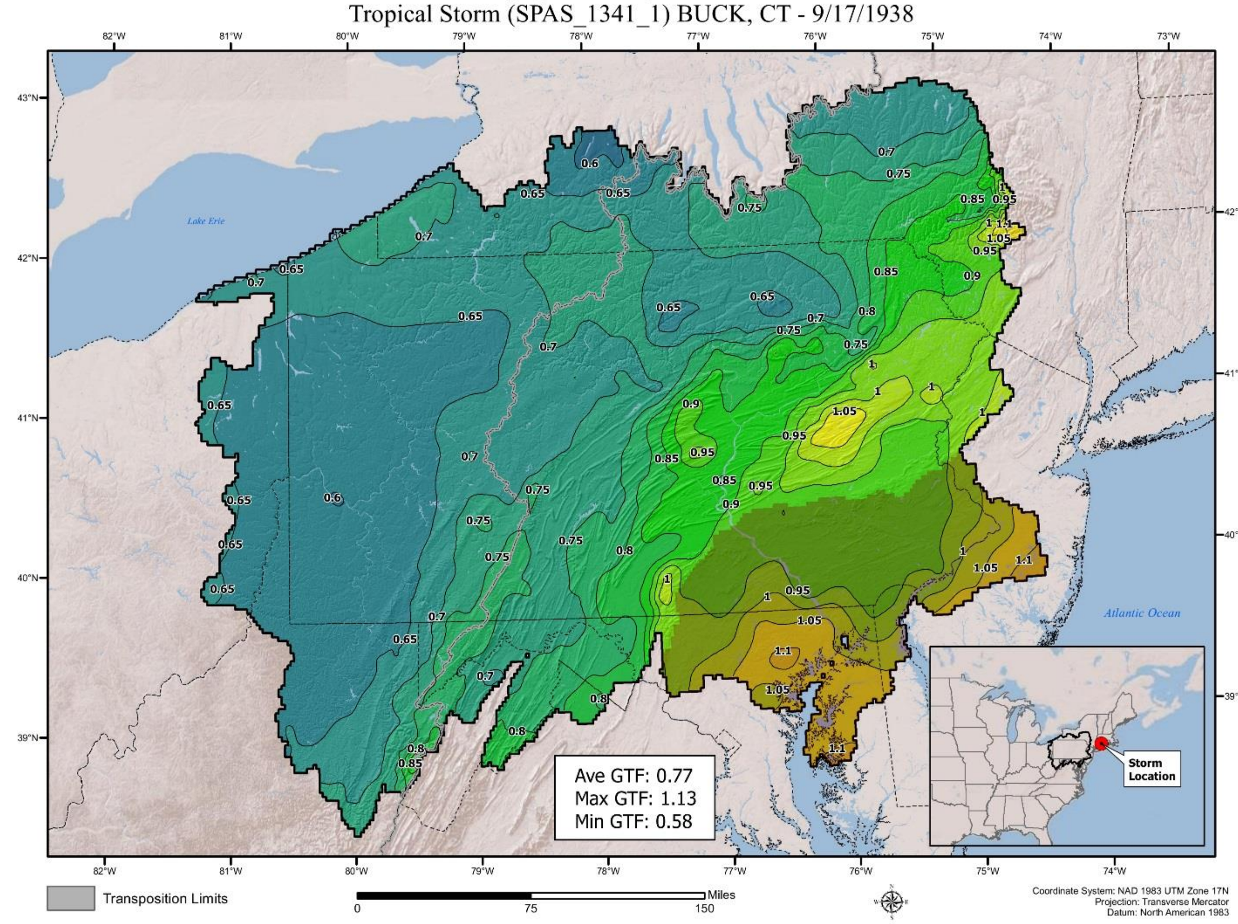
Geographic Transposition Factor
Tropical Storm (SPAS_1299_1) ALTA PASS, NC - 7/13/1916



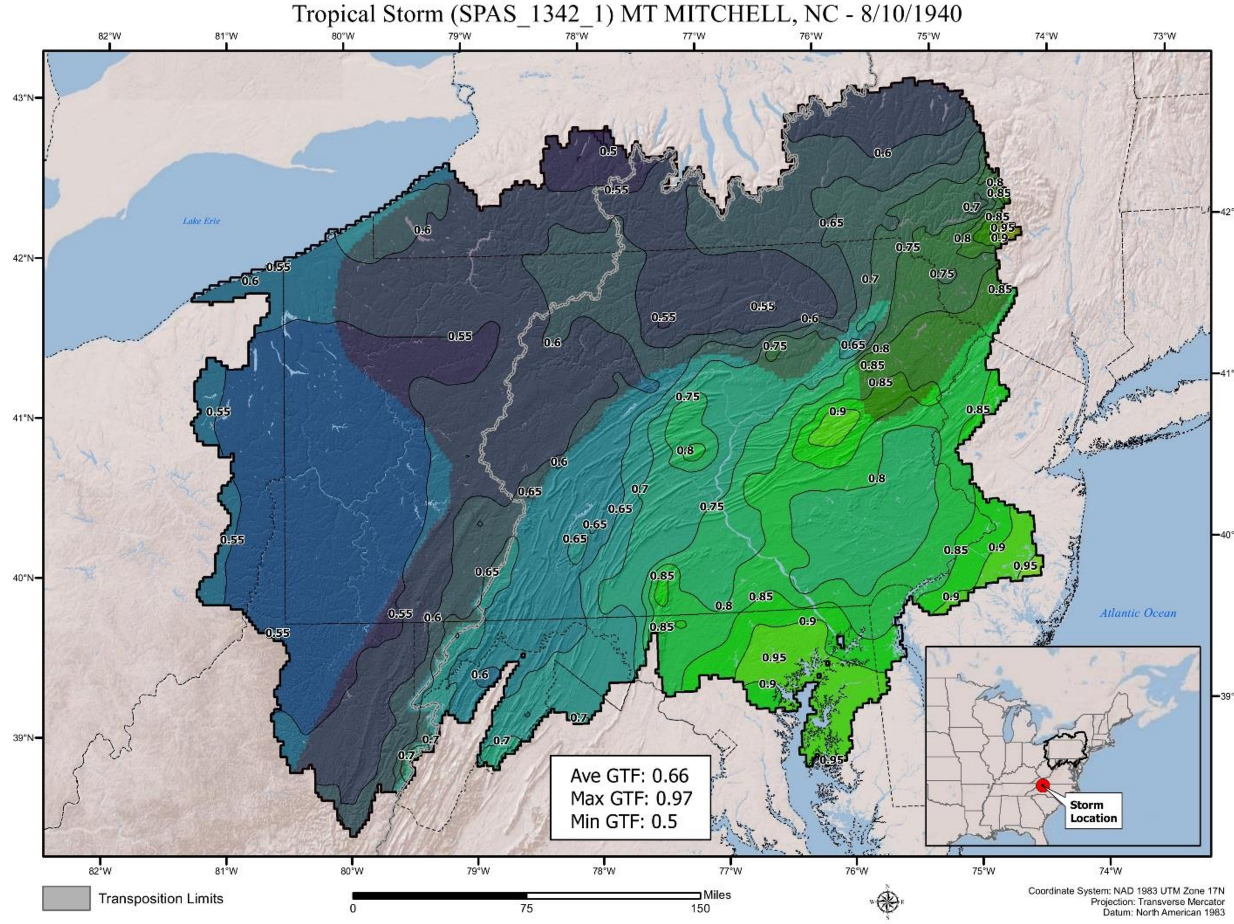
Geographic Transposition Factor
Tropical Storm (SPAS_1312B_2) ROSMAN, NC - 10/3/1964



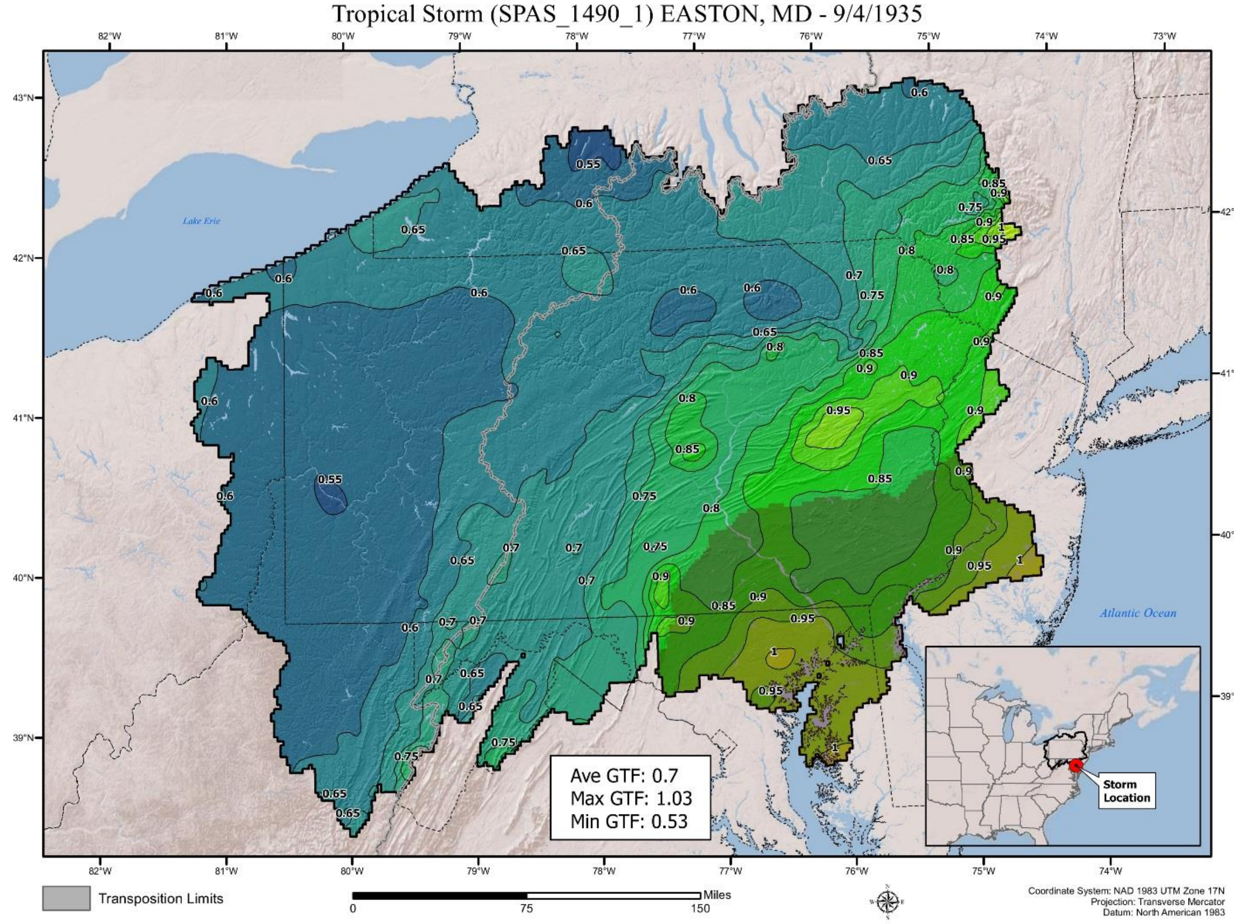
Geographic Transposition Factor
Tropical Storm (SPAS_1341_1) BUCK, CT - 9/17/1938



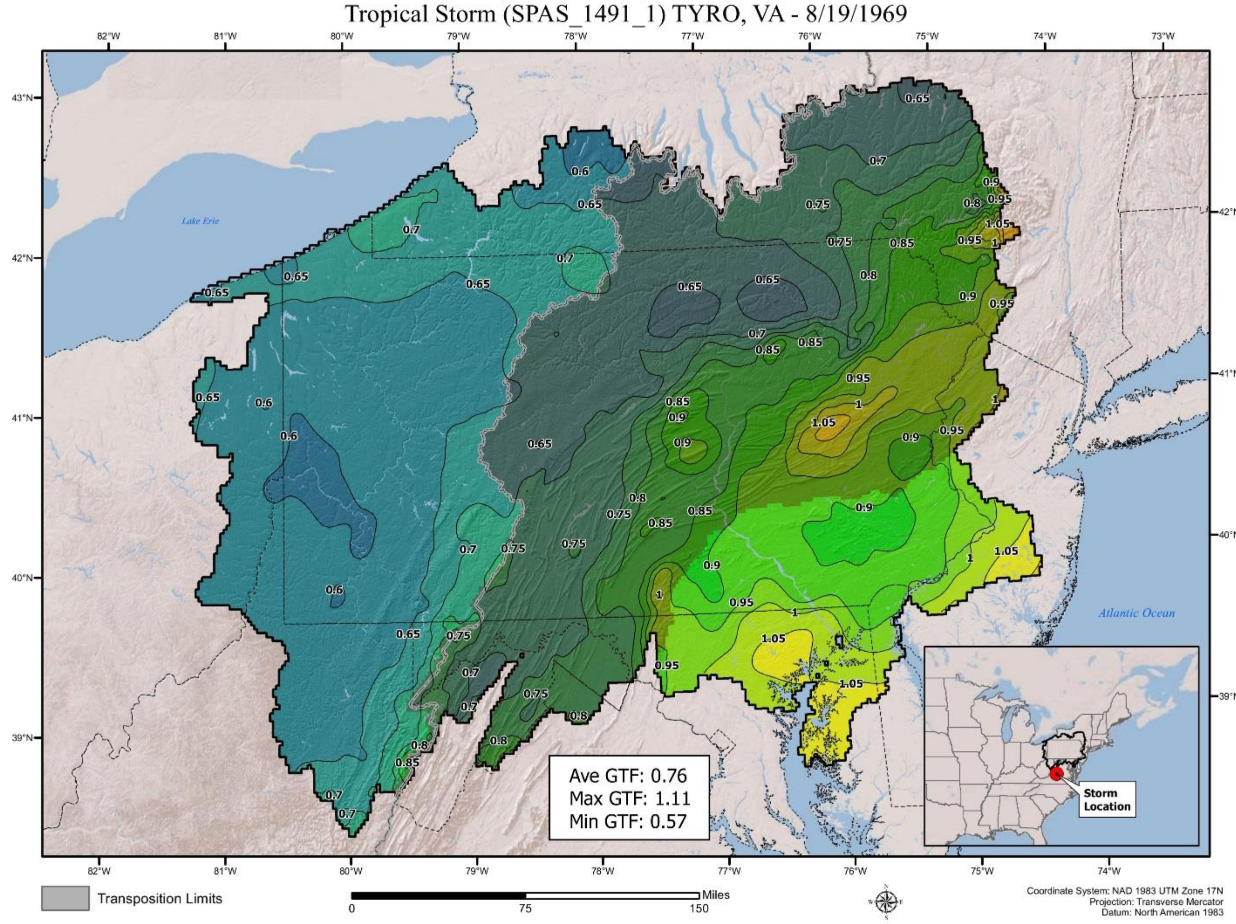
Geographic Transposition Factor
Tropical Storm (SPAS_1342_1) MT MITCHELL, NC - 8/10/1940



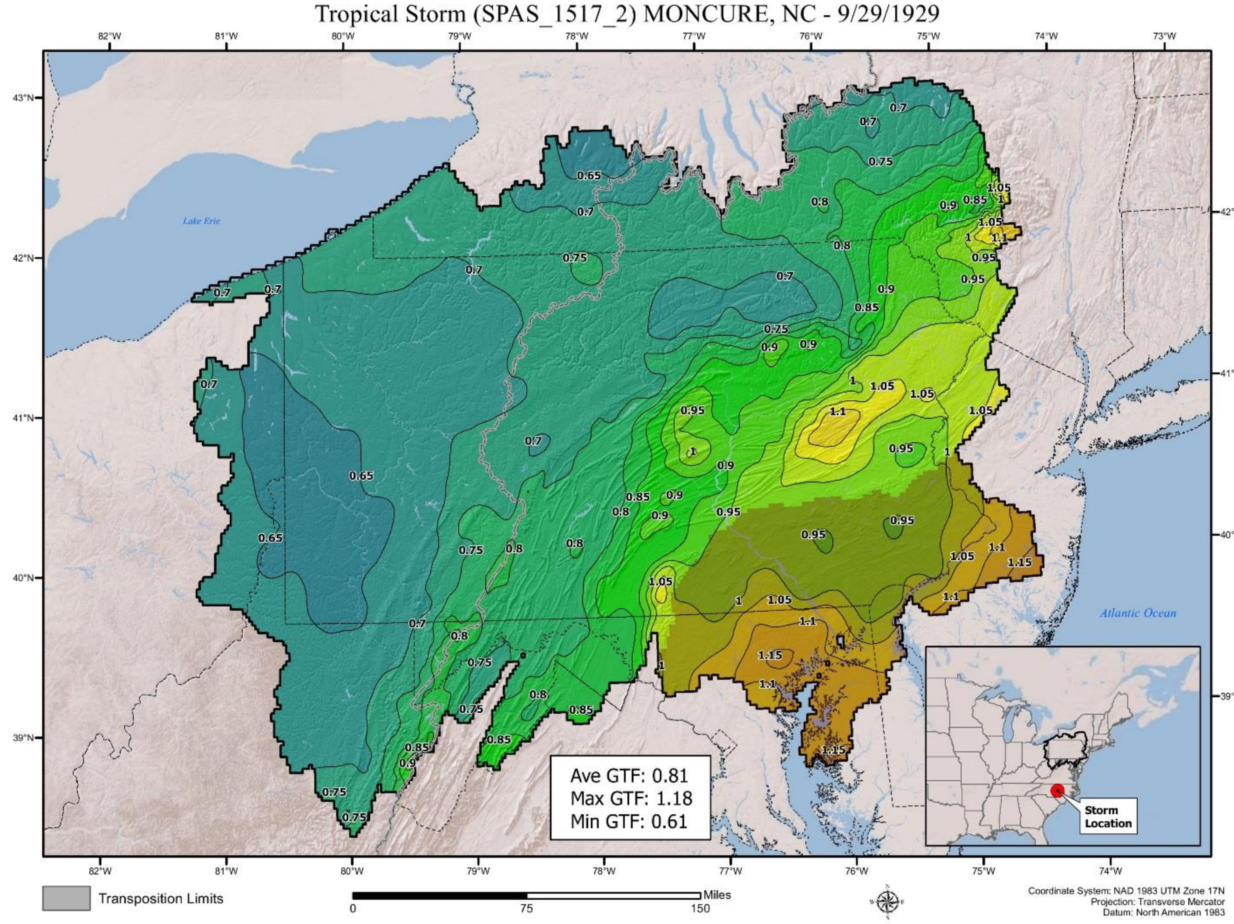
Geographic Transposition Factor
Tropical Storm (SPAS_1490_1) EASTON, MD - 9/4/1935



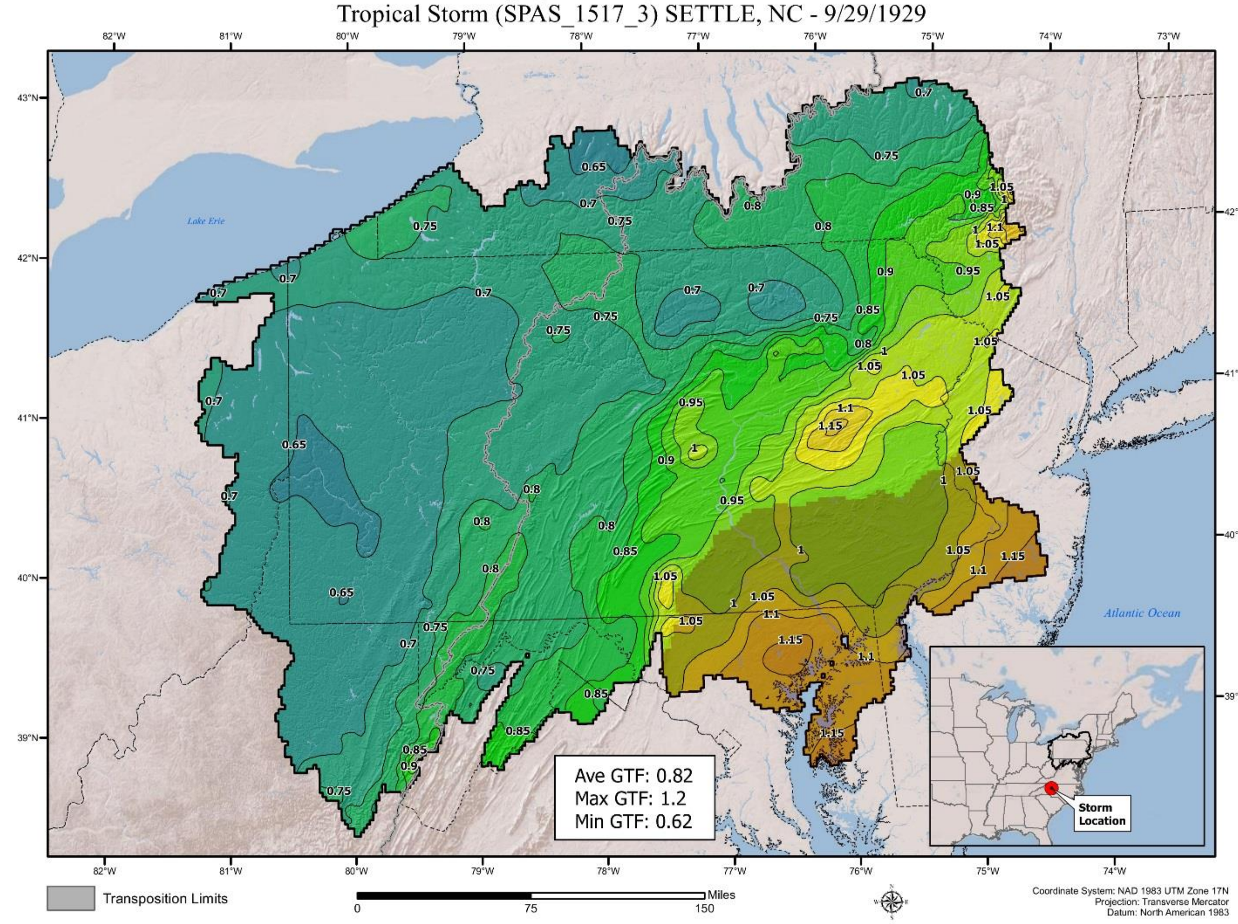
Geographic Transposition Factor
Tropical Storm (SPAS_1491_1) TYRO, VA - 8/19/1969



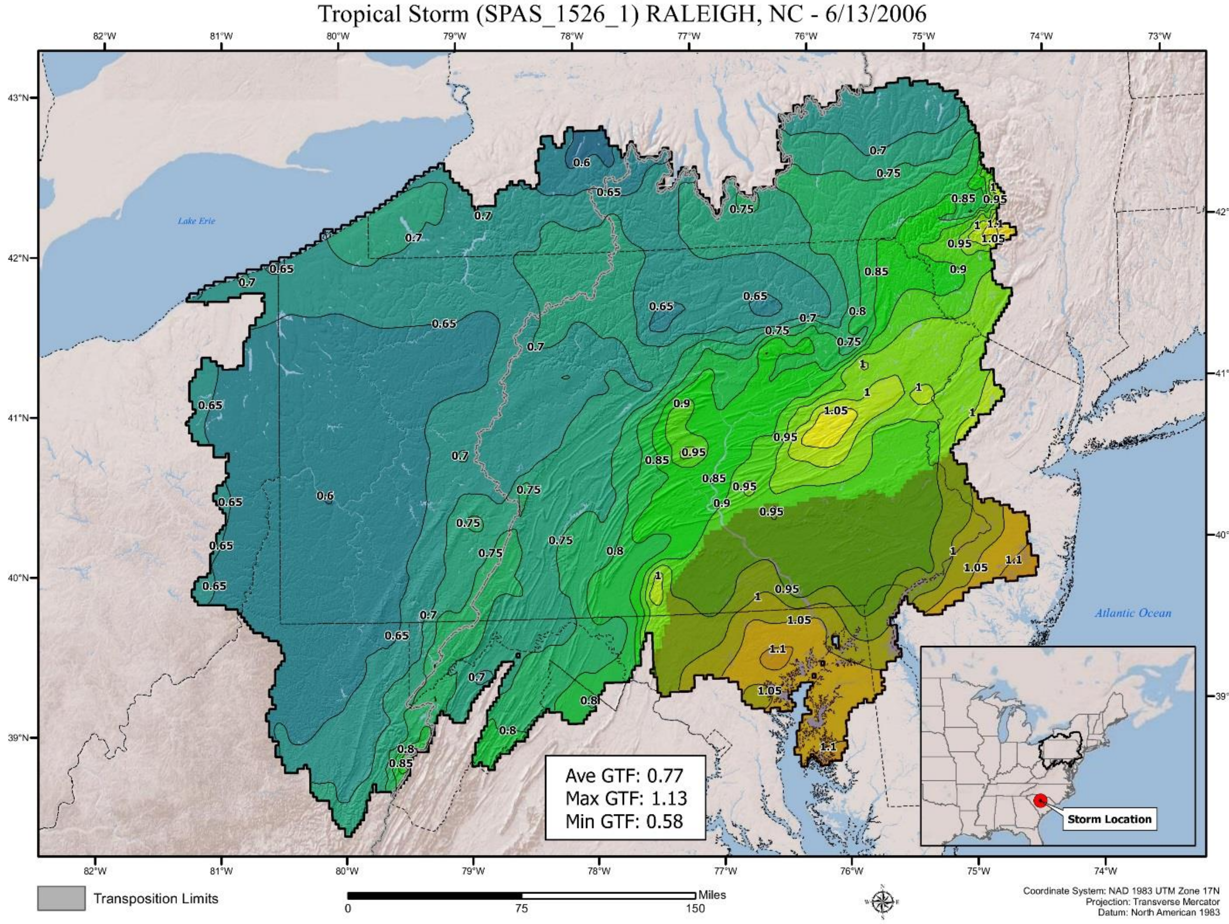
Geographic Transposition Factor
Tropical Storm (SPAS_1517_2) MONCURE, NC - 9/29/1929



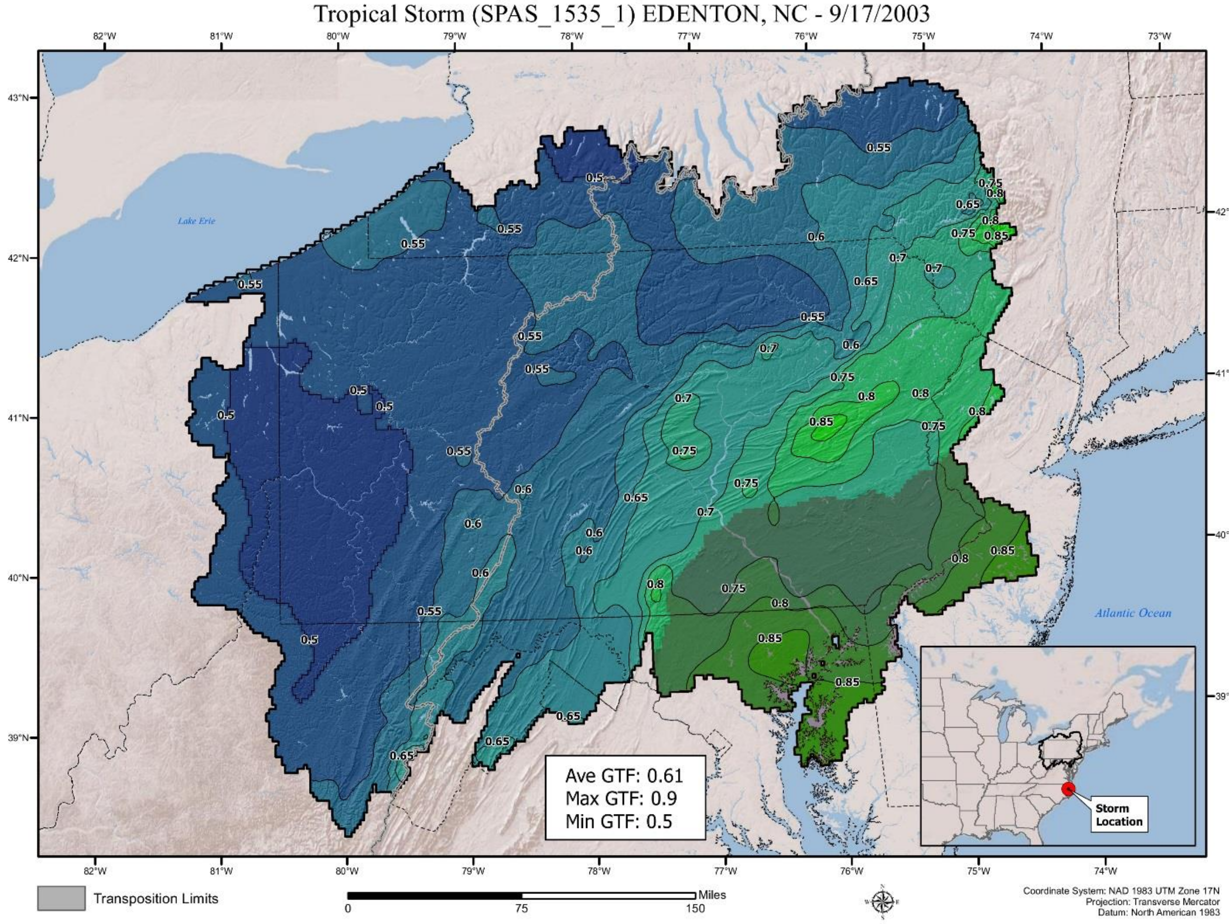
Geographic Transposition Factor
Tropical Storm (SPAS_1517_3) SETTLE, NC - 9/29/1929



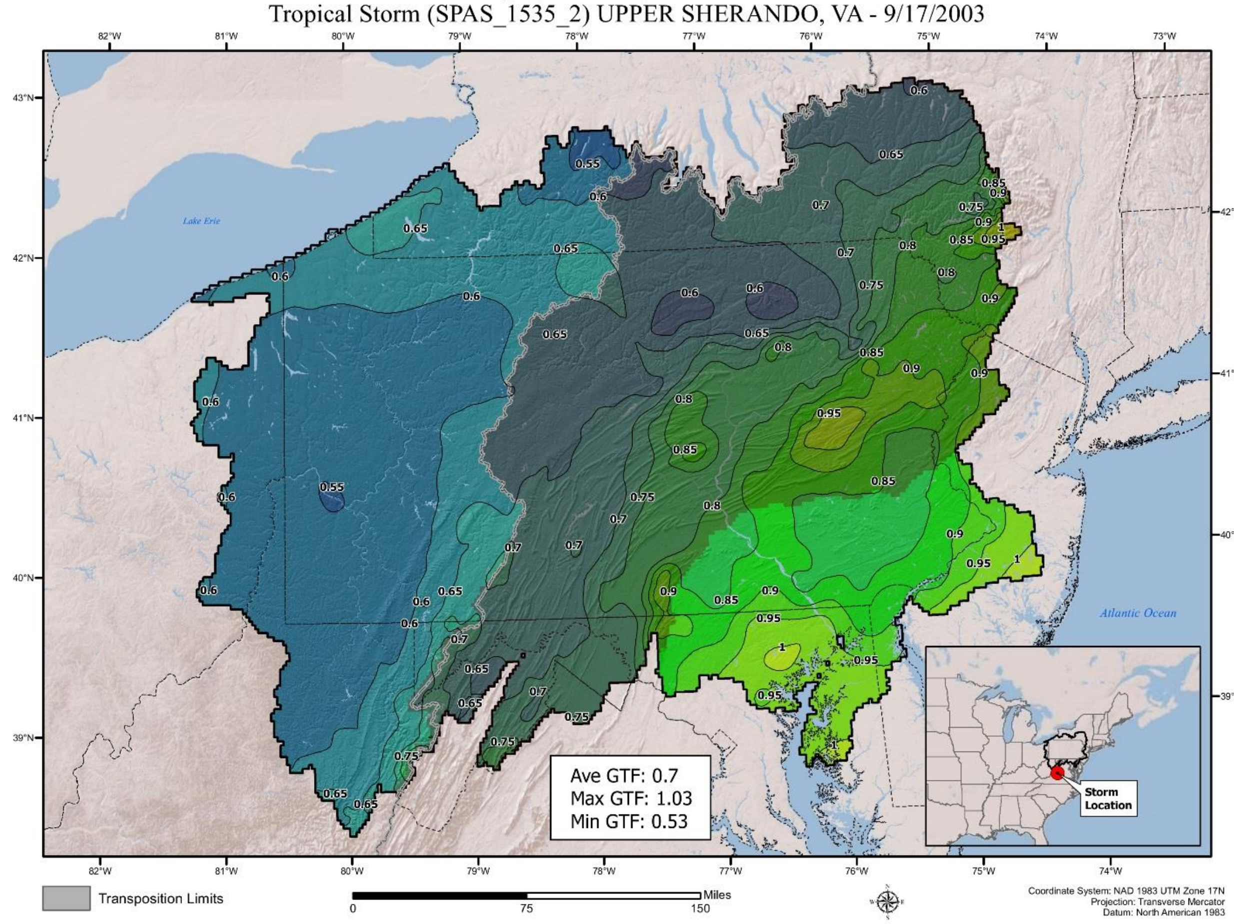
Geographic Transposition Factor
Tropical Storm (SPAS_1526_1) RALEIGH, NC - 6/13/2006



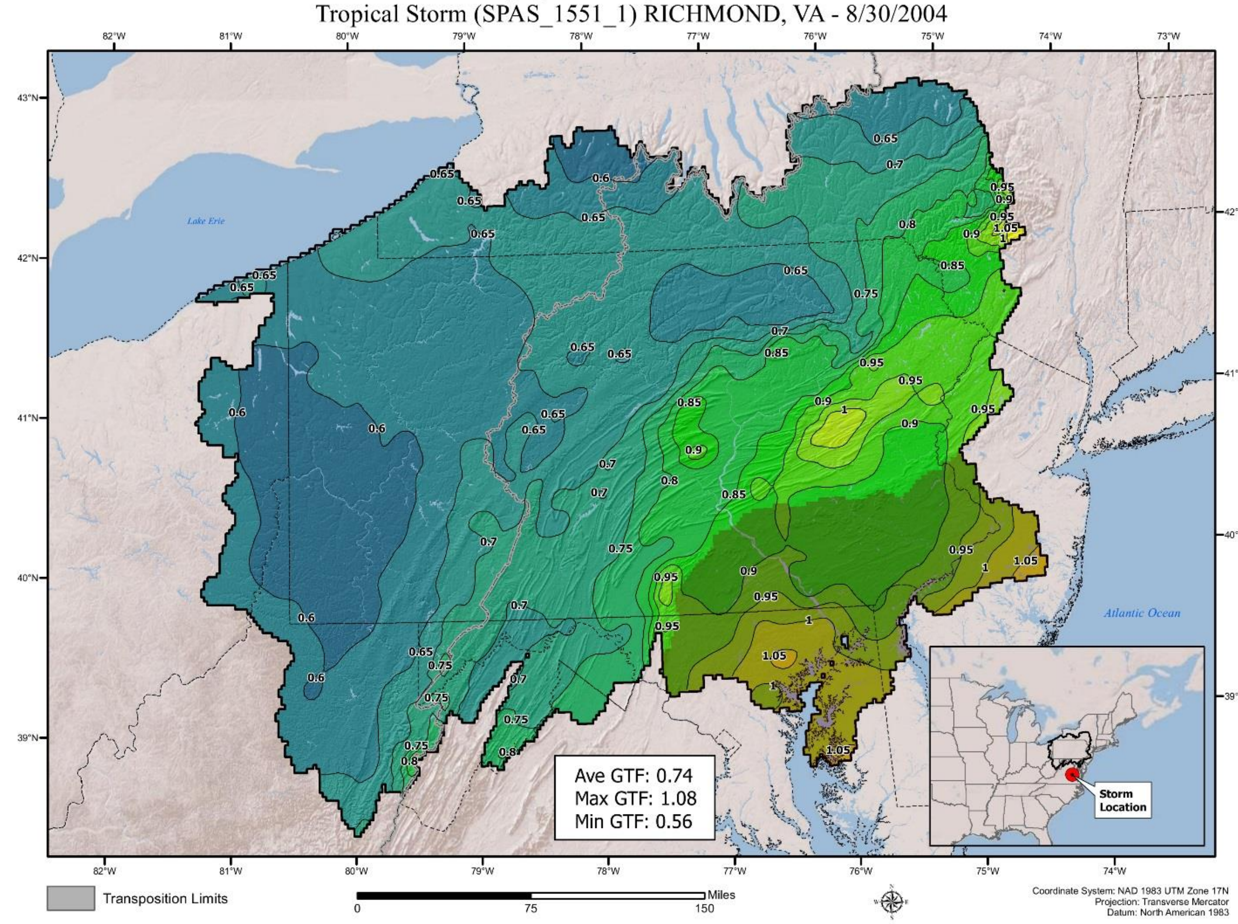
Geographic Transposition Factor
Tropical Storm (SPAS_1535_1) EDENTON, NC - 9/17/2003



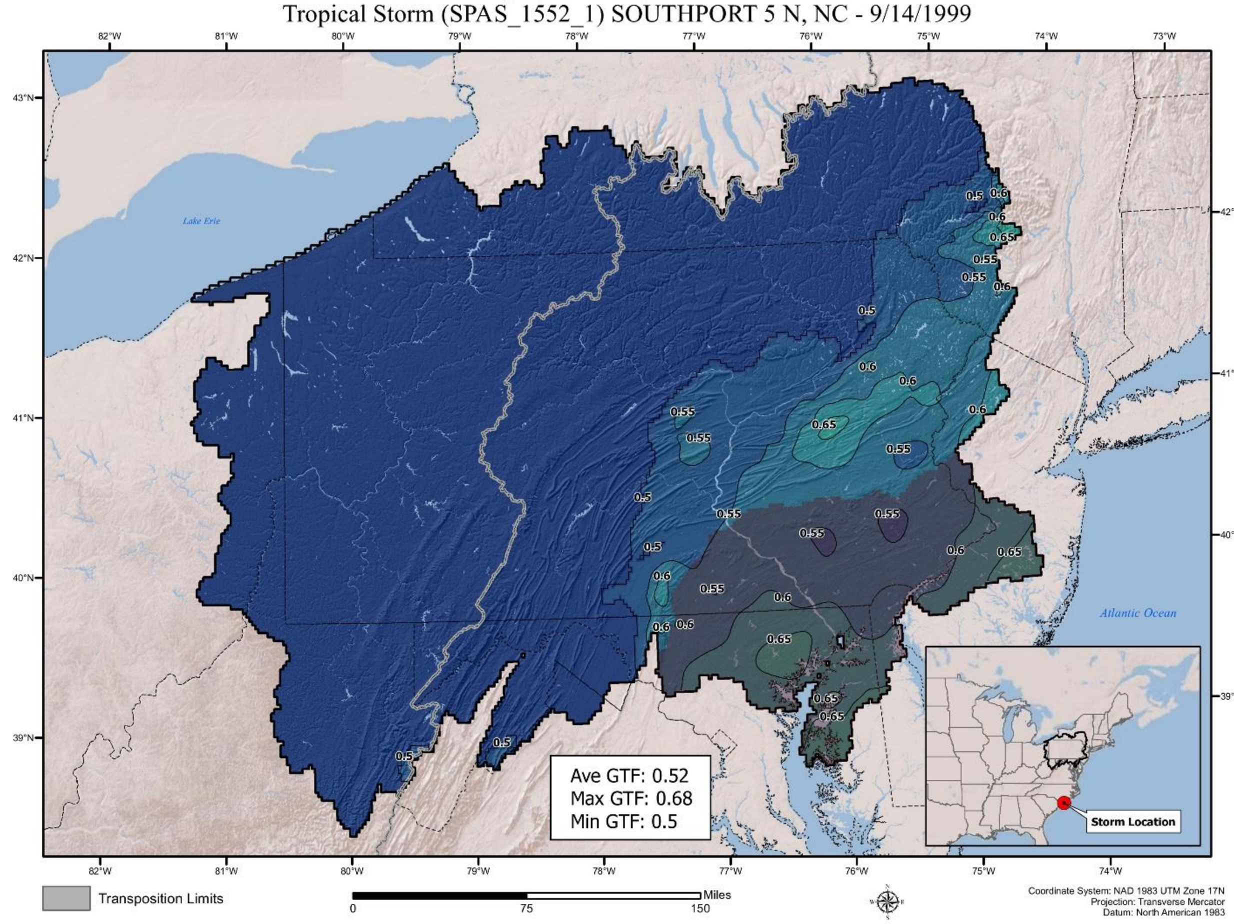
Geographic Transposition Factor
Tropical Storm (SPAS_1535_2) UPPER SHERANDO, VA - 9/17/2003



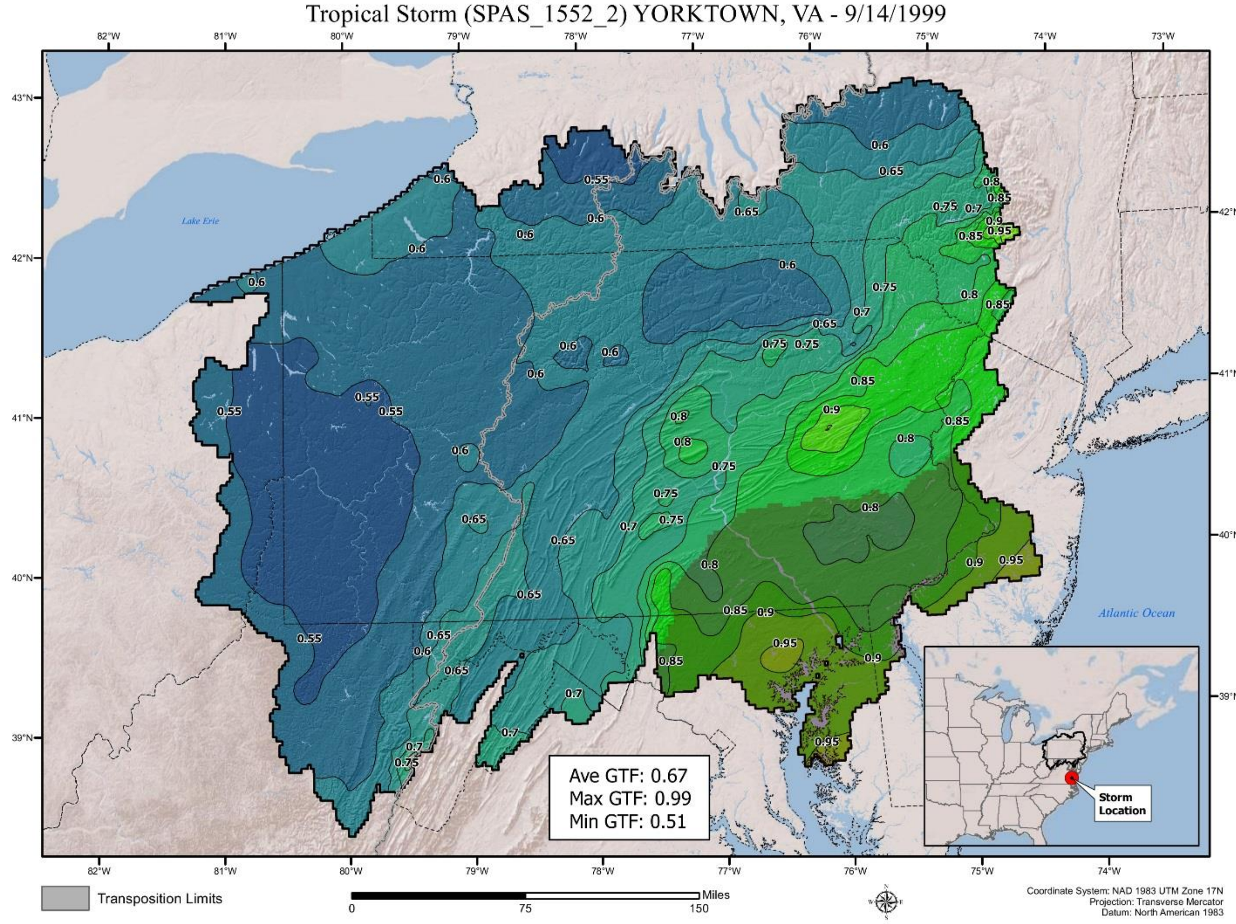
Geographic Transposition Factor
Tropical Storm (SPAS_1551_1) RICHMOND, VA - 8/30/2004



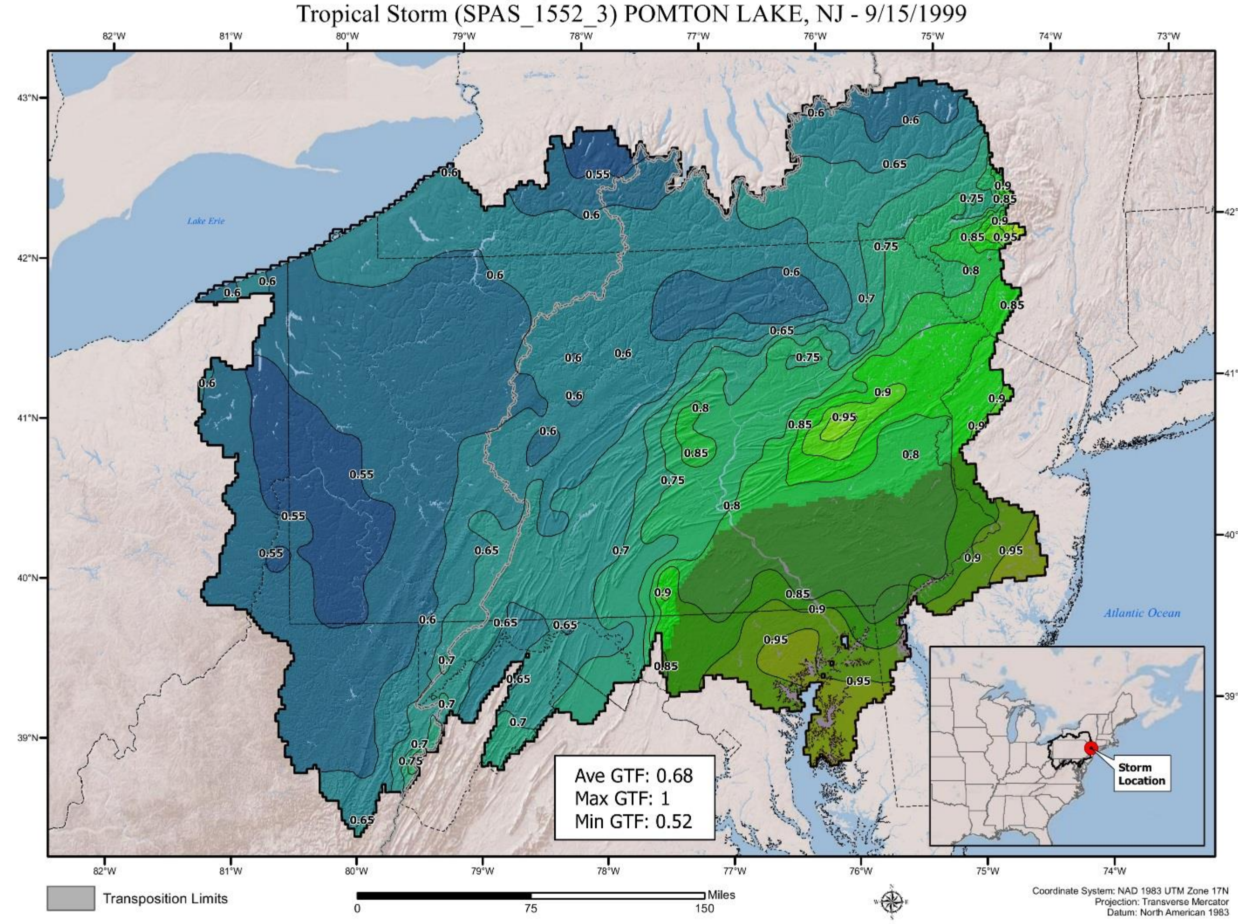
Geographic Transposition Factor
Tropical Storm (SPAS_1552_1) SOUTHPORT 5 N, NC - 9/14/1999



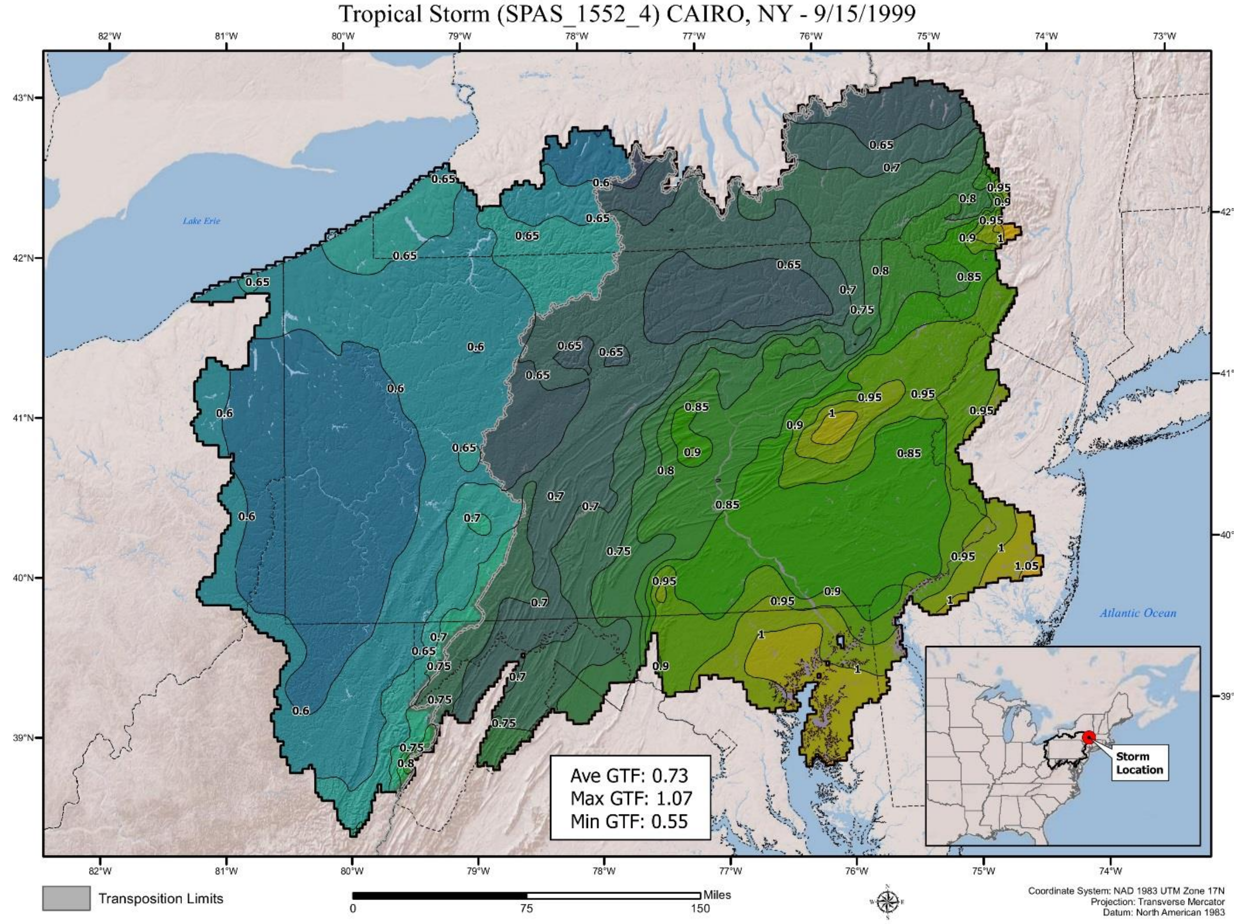
Geographic Transposition Factor
Tropical Storm (SPAS_1552_2) YORKTOWN, VA - 9/14/1999



Geographic Transposition Factor
Tropical Storm (SPAS_1552_3) POMTON LAKE, NJ - 9/15/1999



Geographic Transposition Factor
Tropical Storm (SPAS_1552_4) CAIRO, NY - 9/15/1999



Geographic Transposition Factor
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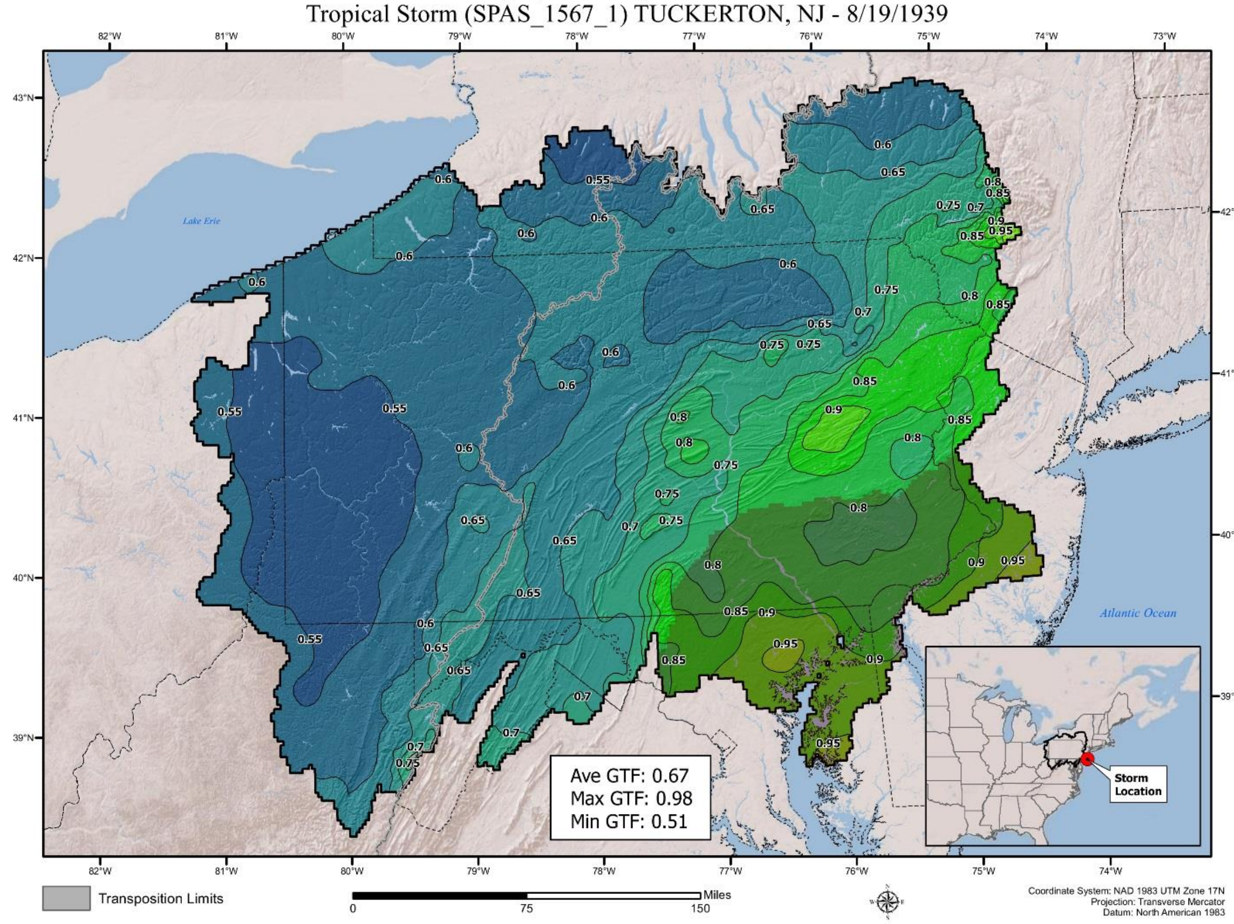
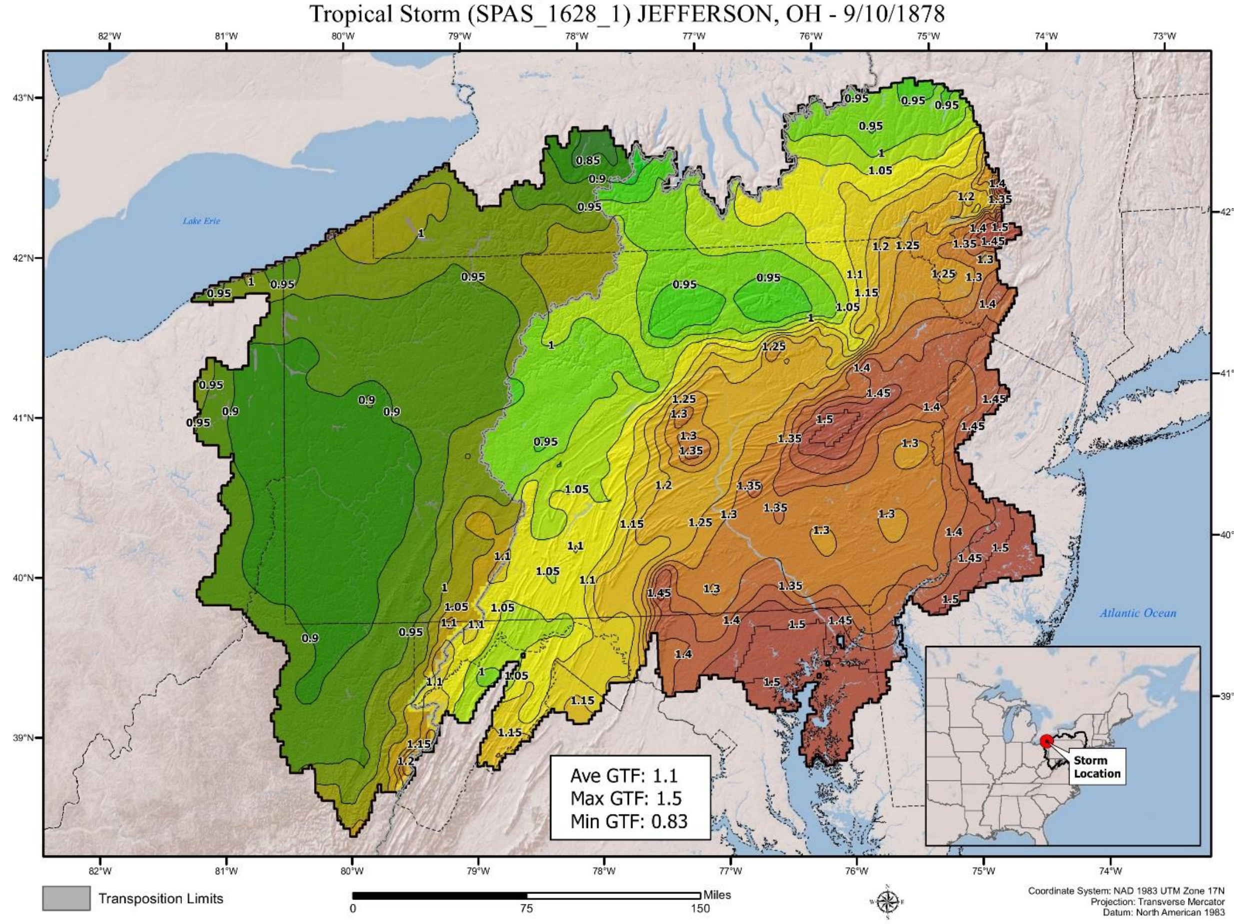
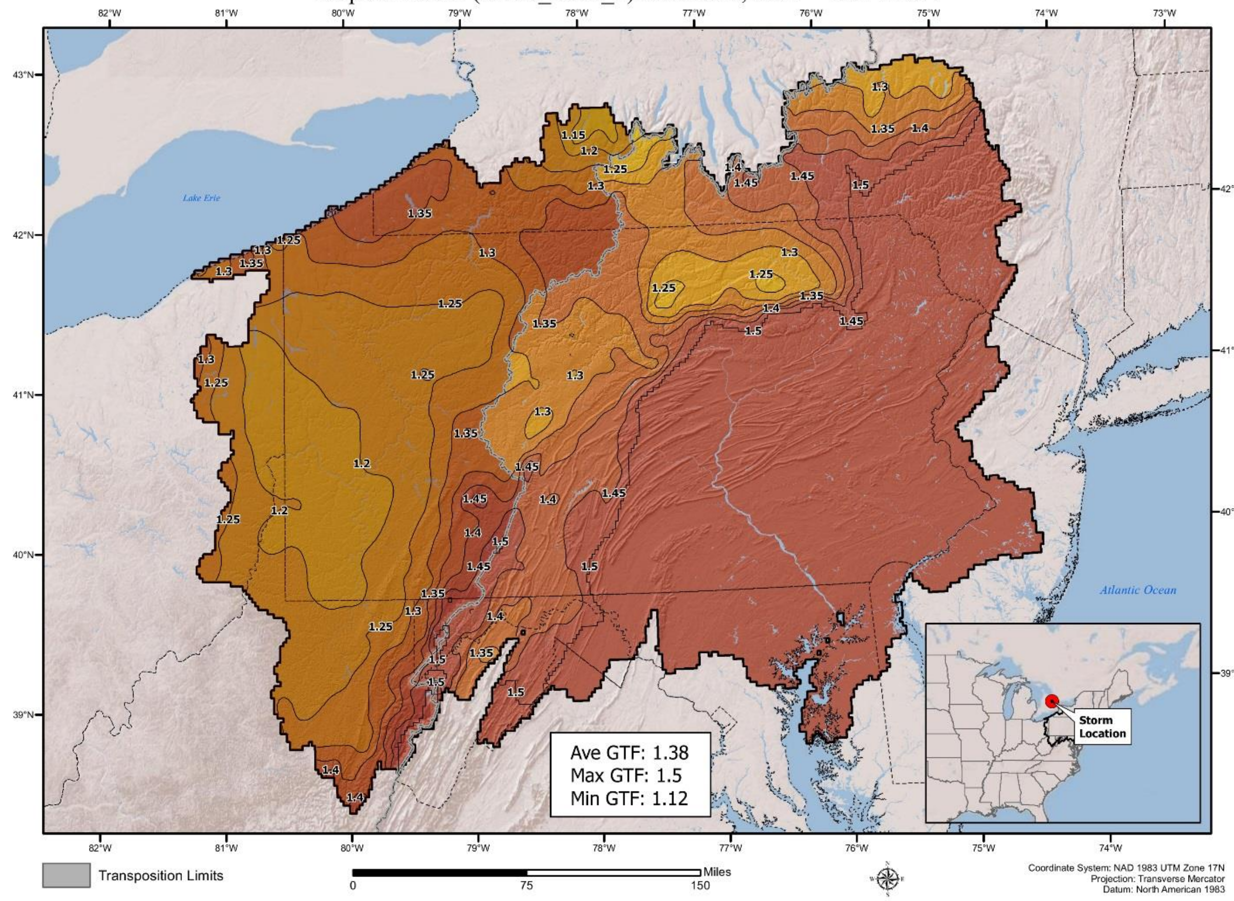


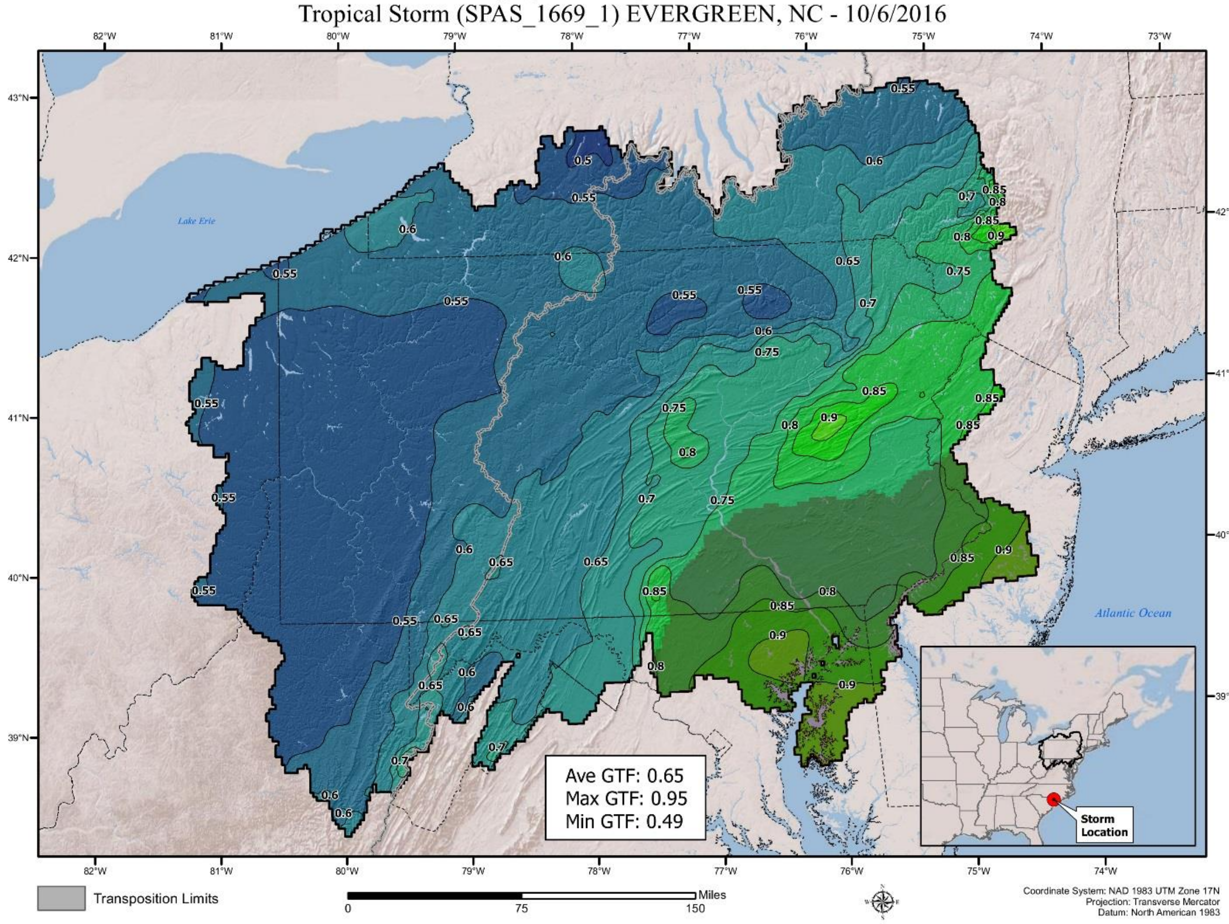
Geographic Transposition Factor
Tropical Storm (SPAS_1628_1) JEFFERSON, OH - 9/10/1878



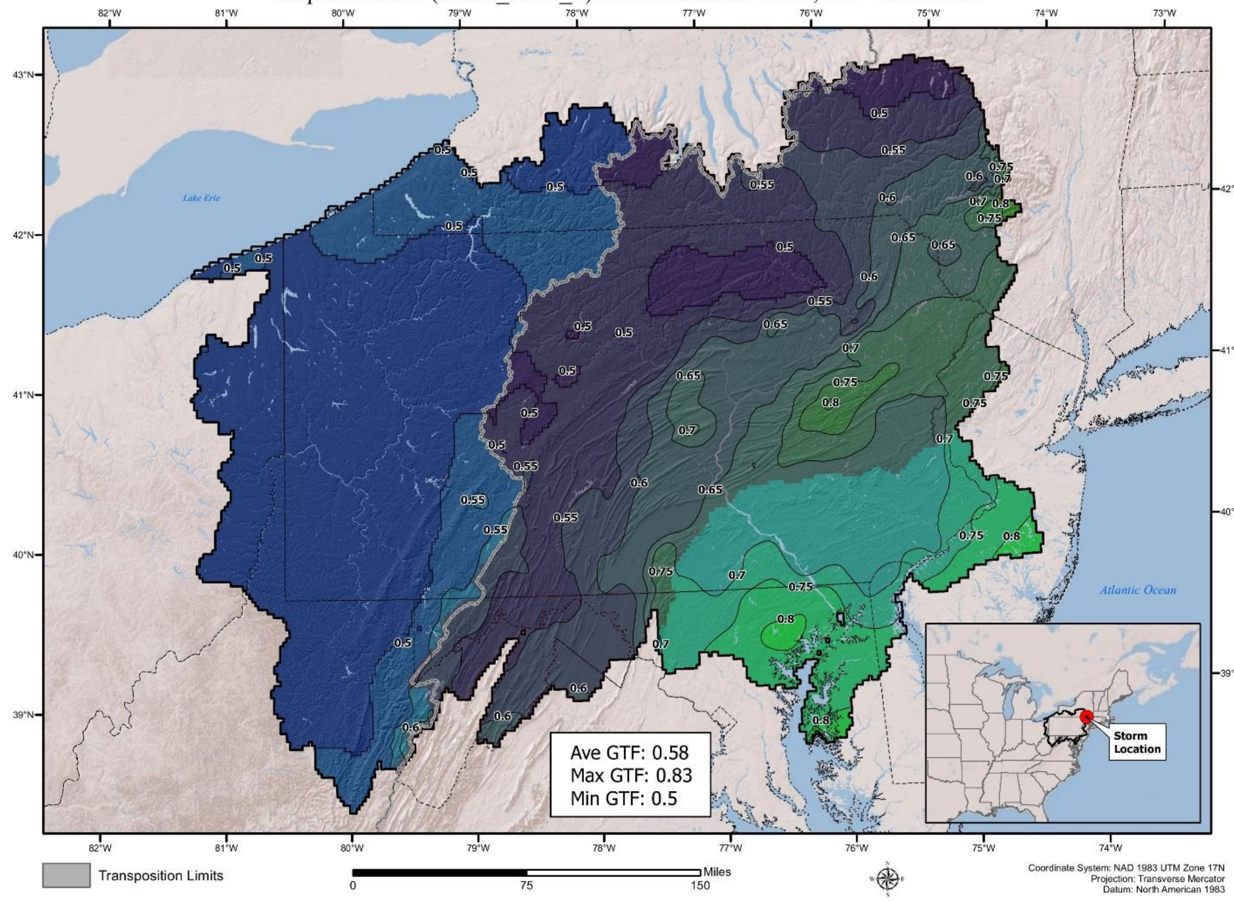
Geographic Transposition Factor
Tropical Storm (SPAS_1630_1) BOLTON, ONT - 10/14/1954



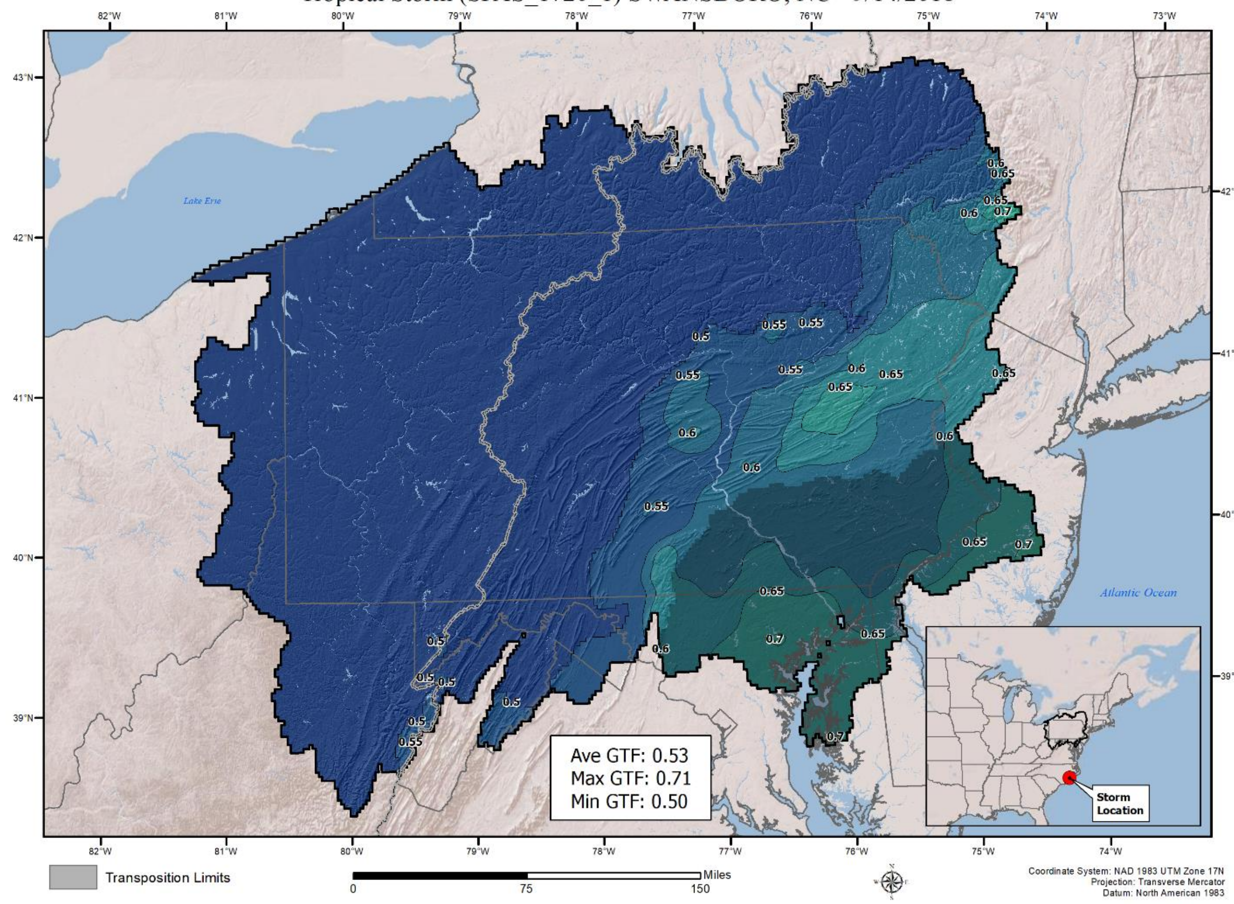
Geographic Transposition Factor
Tropical Storm (SPAS_1669_1) EVERGREEN, NC - 10/6/2016



Geographic Transposition Factor
Tropical Storm (SPAS_1679_1) SLIDE MOUNTAIN, NY - 8/11/1955



Geographic Transposition Factor
Tropical Storm (SPAS_1720_1) SWANSBORO, NC - 9/14/2018

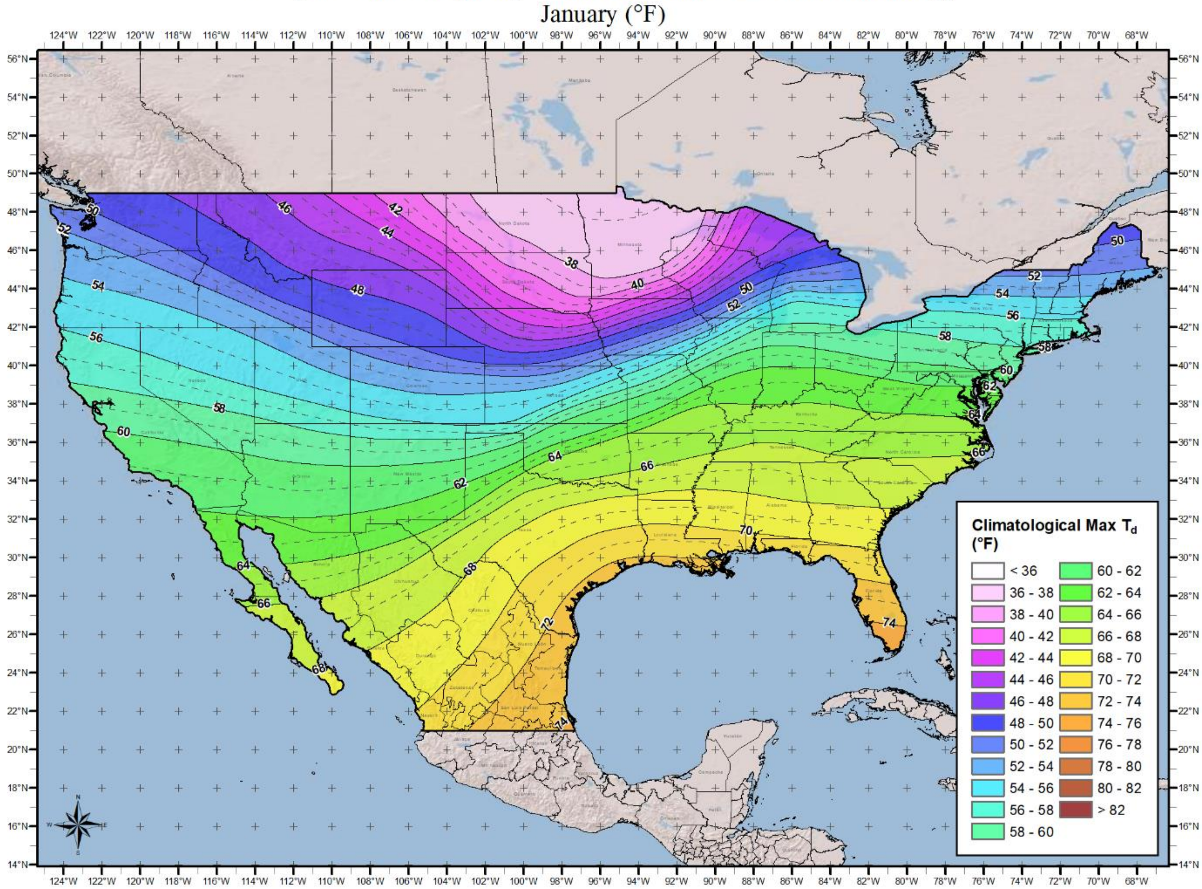


Appendix C

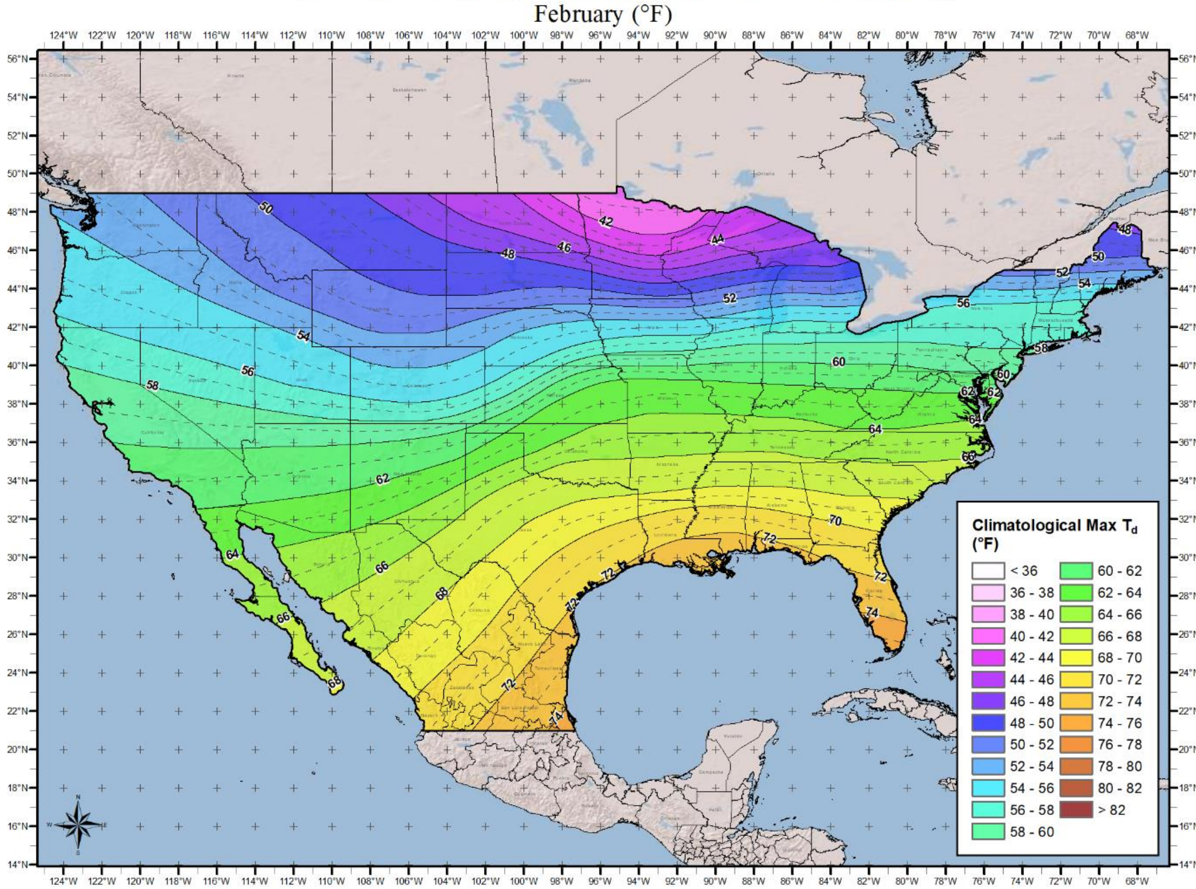
100-year Return Frequency Maximum Average Dew Point Temperature Climatology Maps

6-hour 1000mb Dew Point Maps

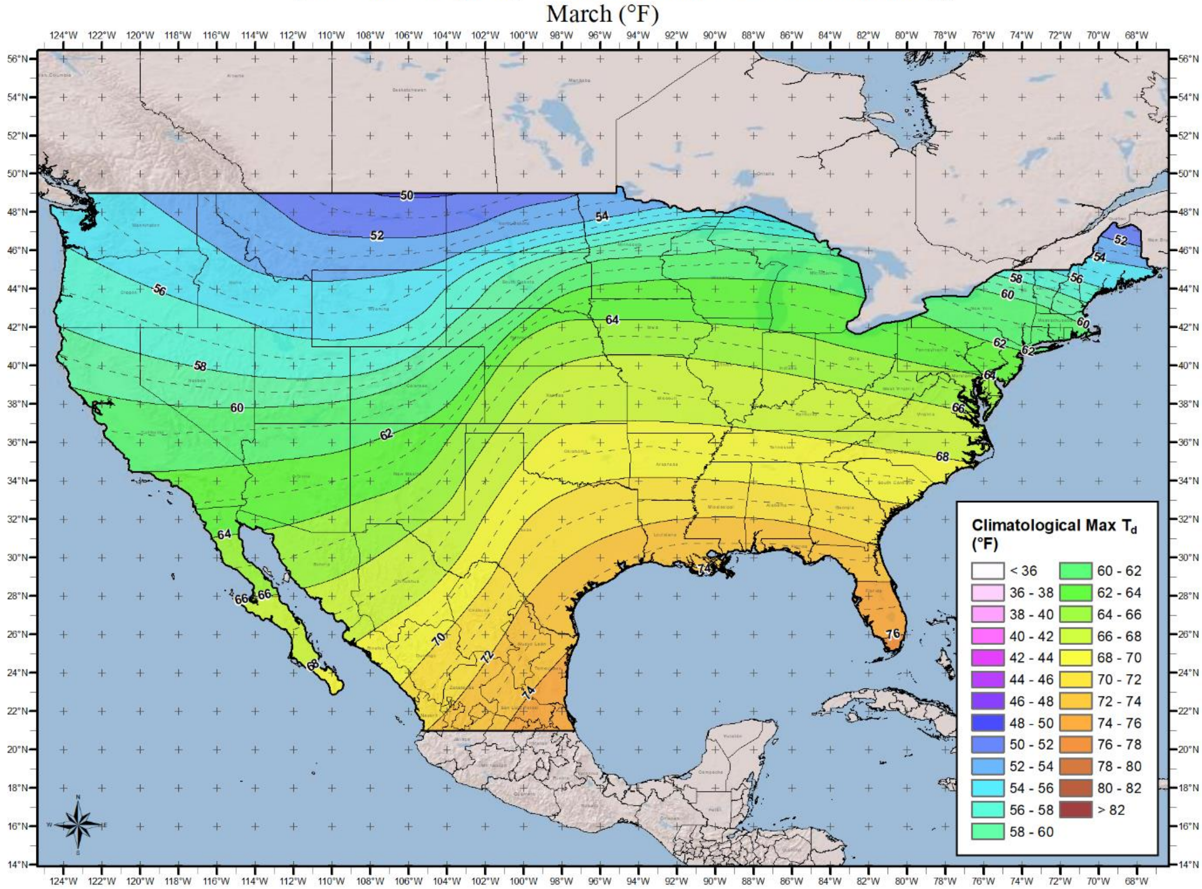
100-year Return Frequency 6-hour Maximum Dew Point Climatology
January (°F)



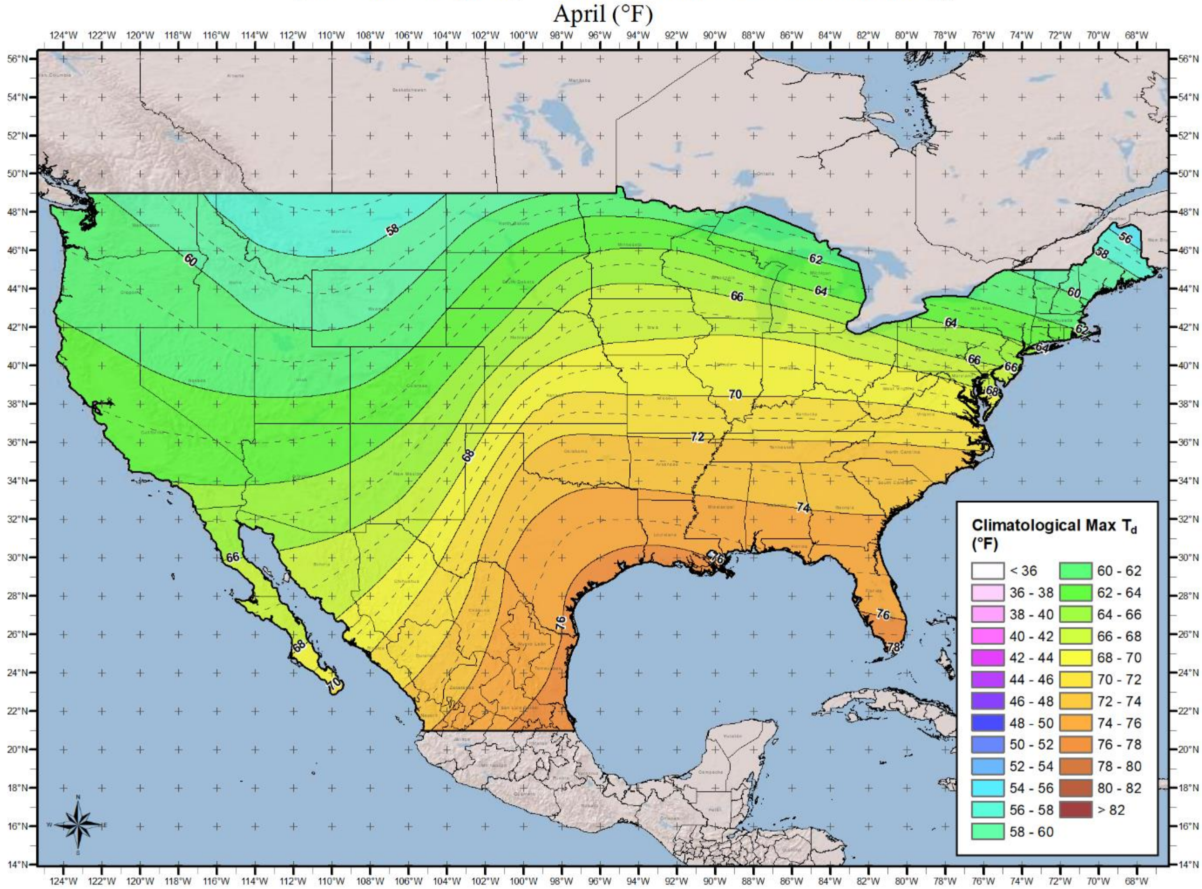
100-year Return Frequency 6-hour Maximum Dew Point Climatology
February (°F)



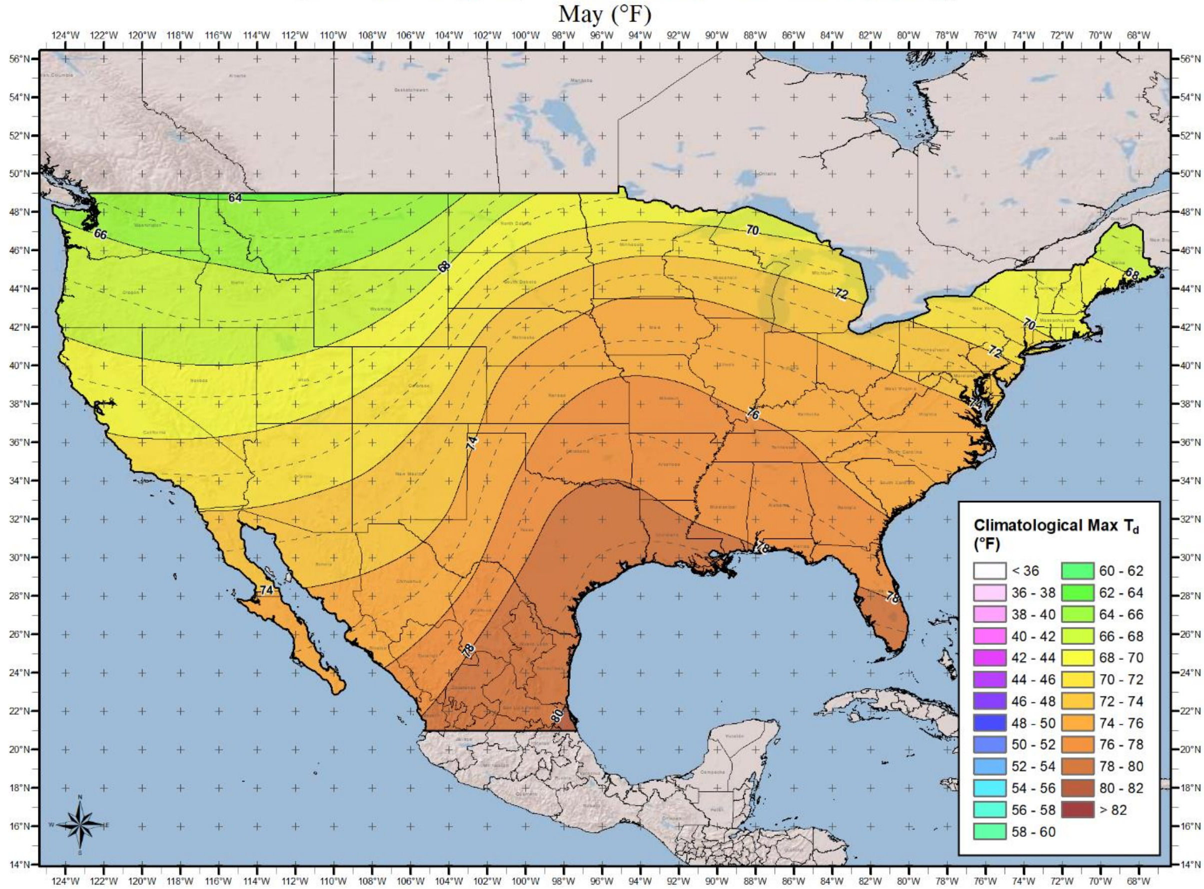
100-year Return Frequency 6-hour Maximum Dew Point Climatology
March (°F)



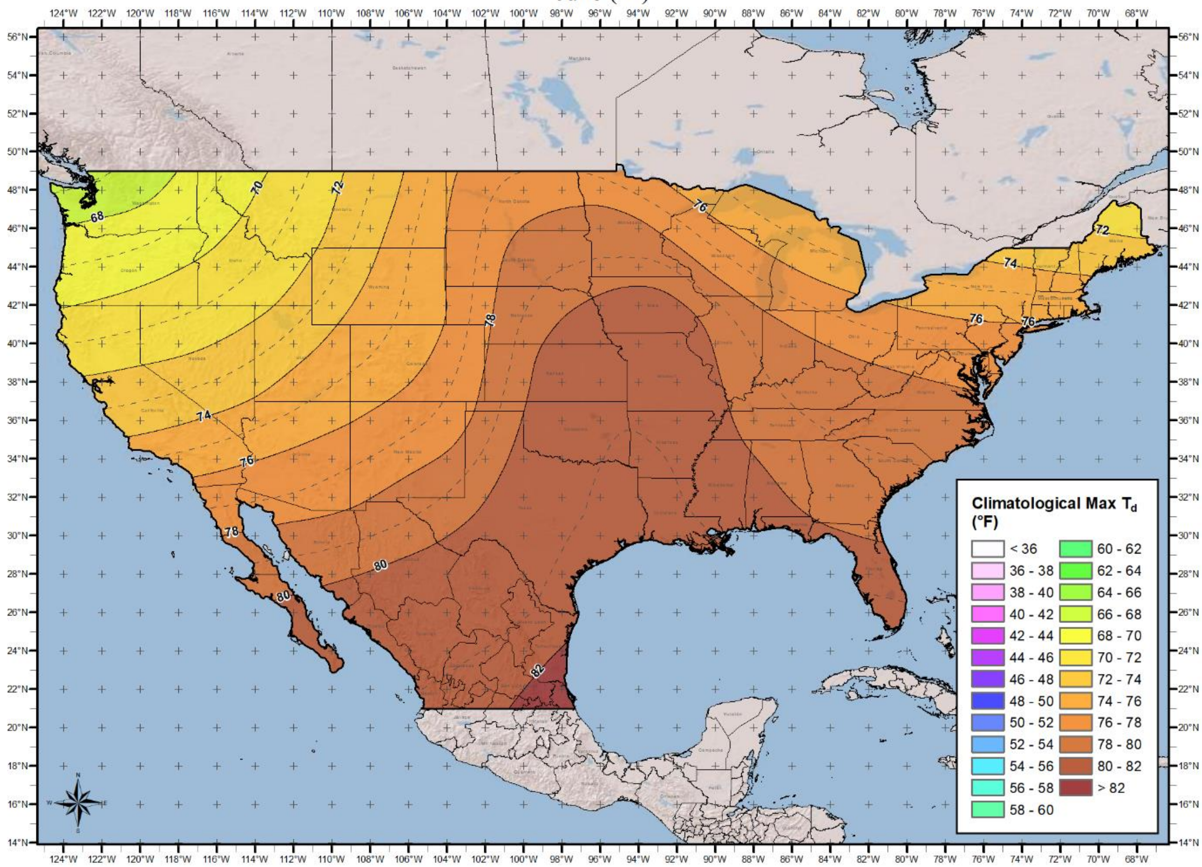
100-year Return Frequency 6-hour Maximum Dew Point Climatology
April (°F)



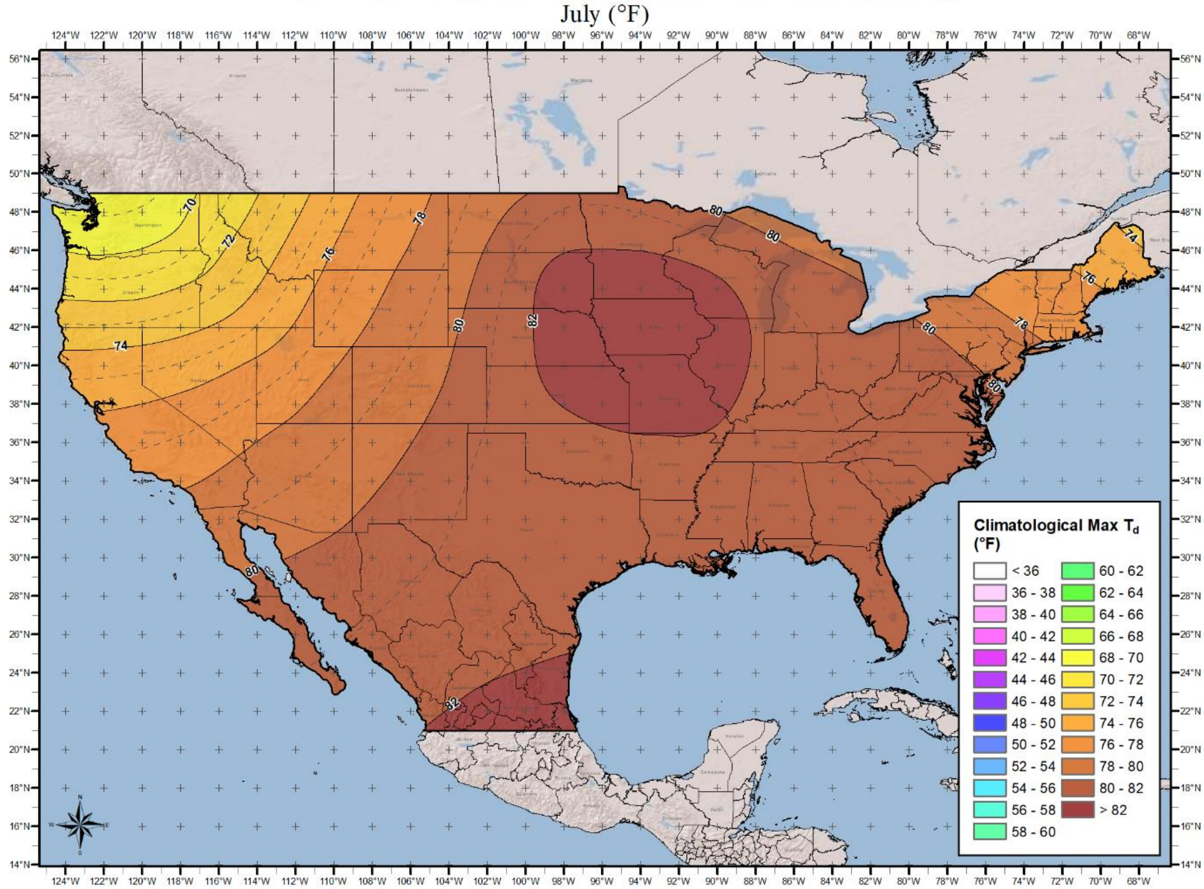
100-year Return Frequency 6-hour Maximum Dew Point Climatology
May (°F)



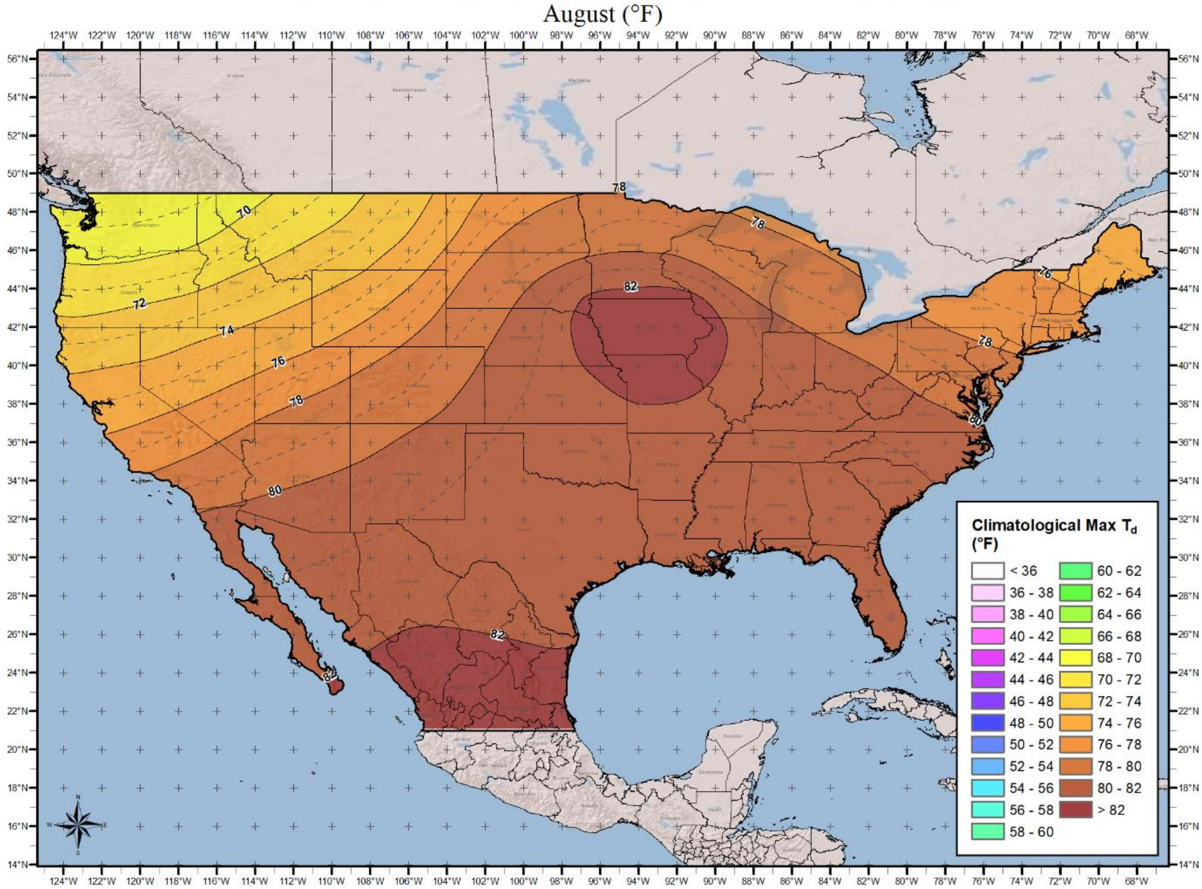
100-year Return Frequency 6-hour Maximum Dew Point Climatology
June (°F)



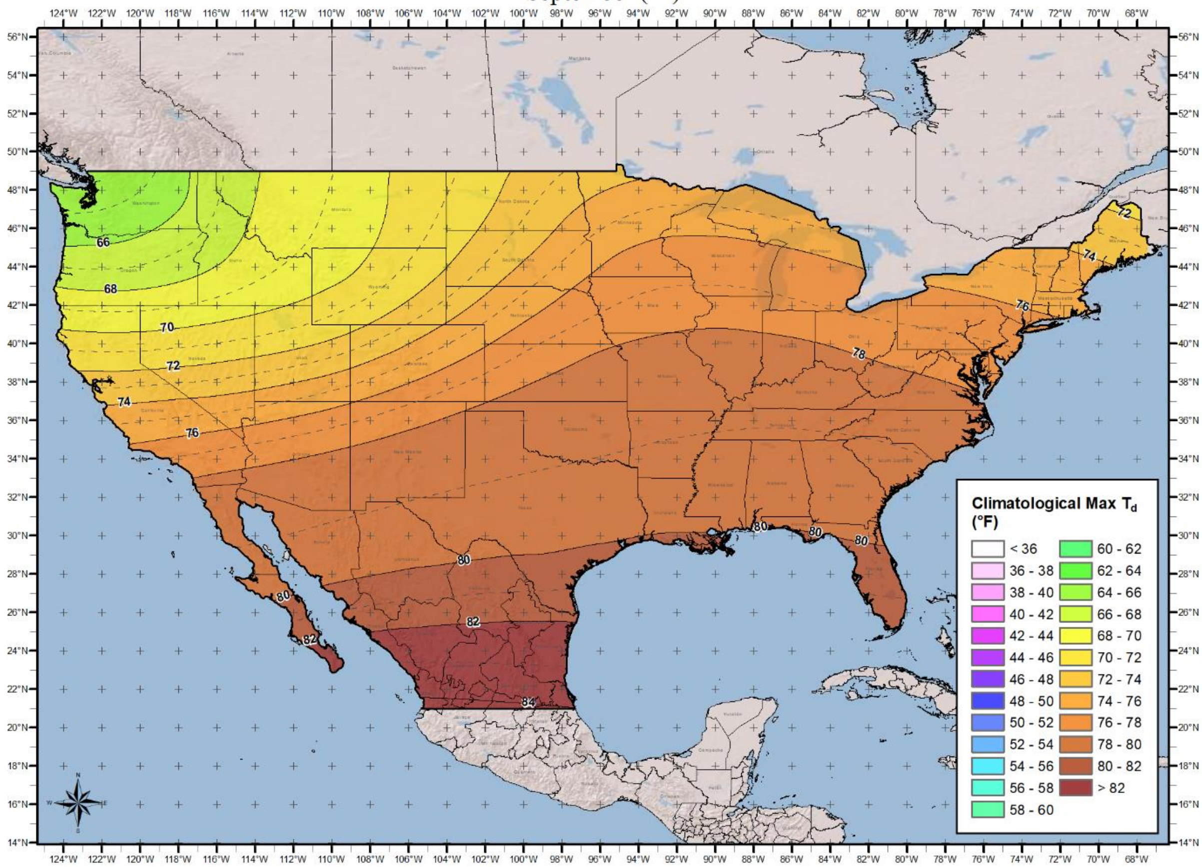
100-year Return Frequency 6-hour Maximum Dew Point Climatology
July (°F)

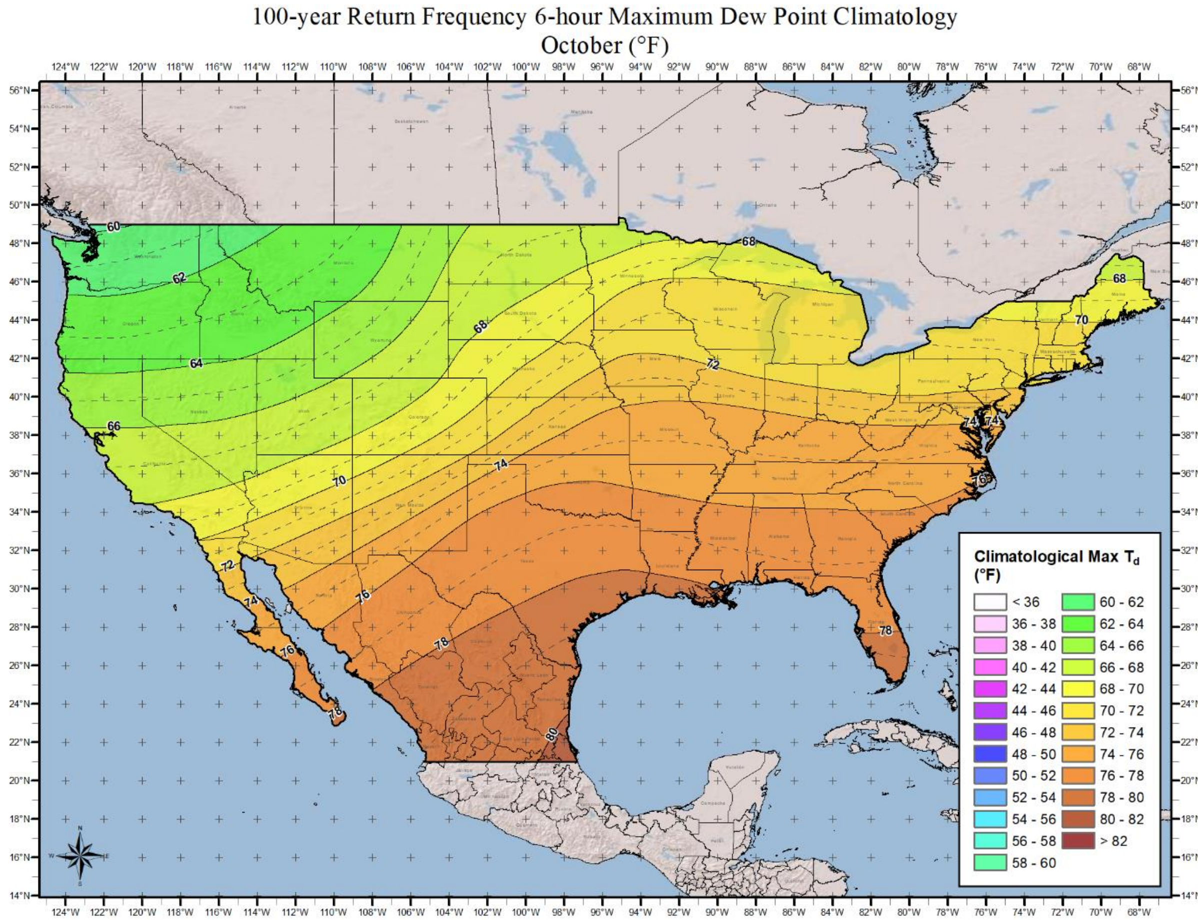


100-year Return Frequency 6-hour Maximum Dew Point Climatology
August (°F)

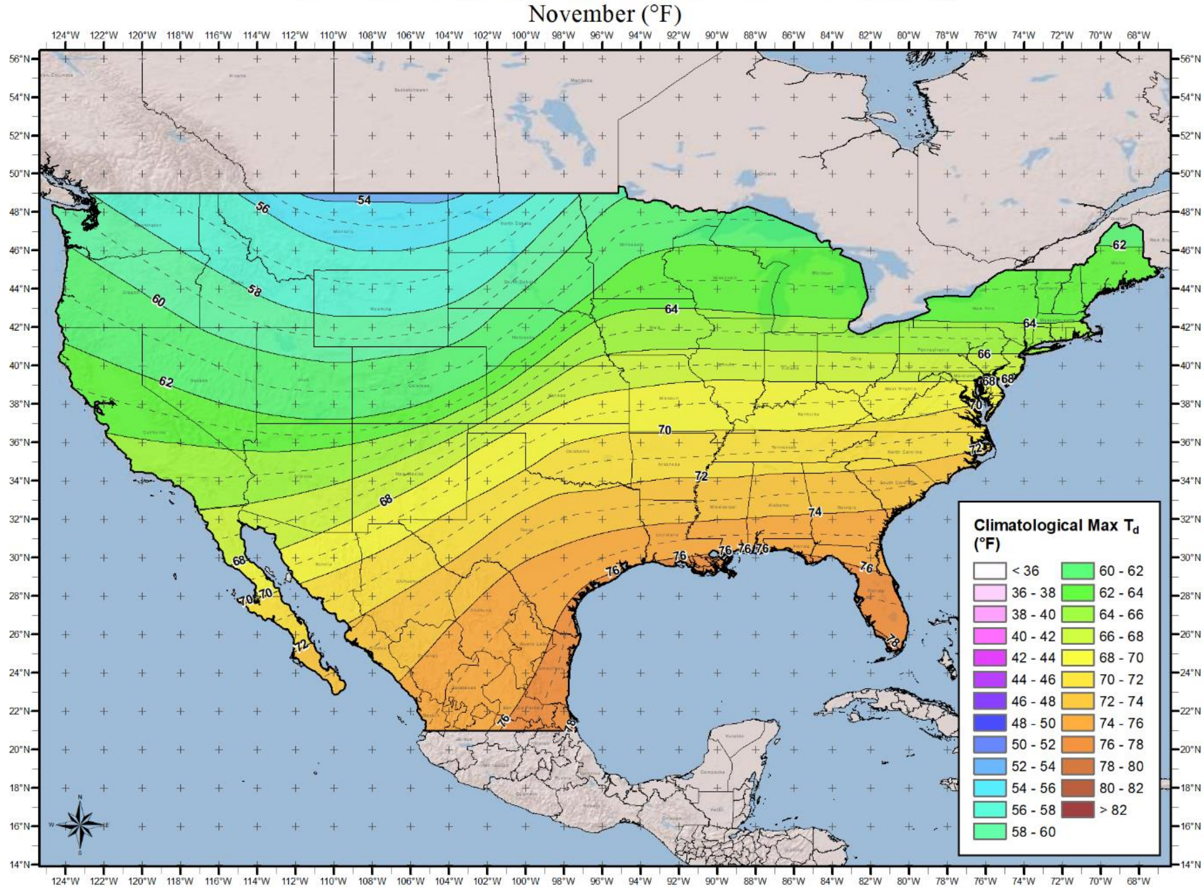


100-year Return Frequency 6-hour Maximum Dew Point Climatology
September (°F)

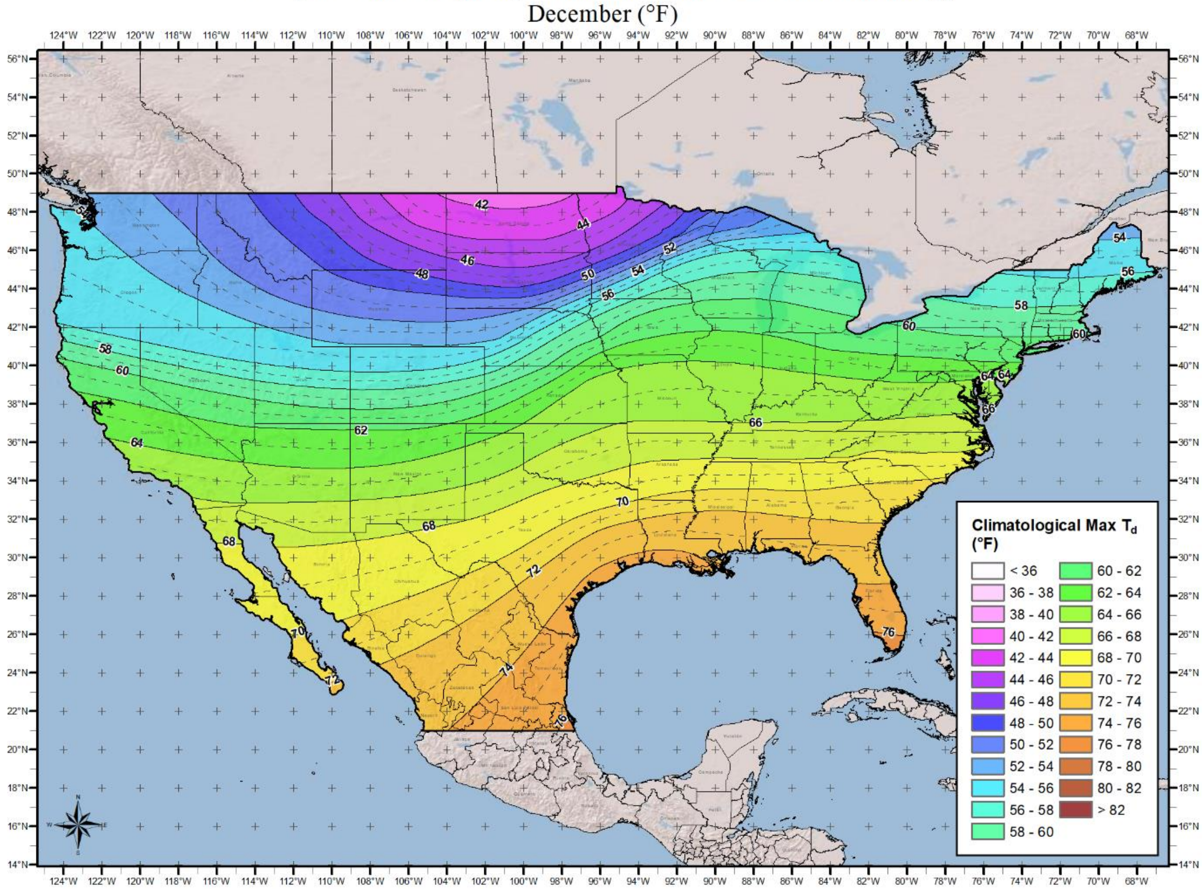



100-year Return Frequency 6-hour Maximum Dew Point Climatology
October (°F)
Climatological Max T_d (°F)
< 36
36 - 38
38 - 40
40 - 42
42 - 44
44 - 46
46 - 48
48 - 50
50 - 52
52 - 54
54 - 56
56 - 58
58 - 60
60 - 62
62 - 64
64 - 66
66 - 68
68 - 70
70 - 72
72 - 74
74 - 76
76 - 78
78 - 80
80 - 82
> 82

100-year Return Frequency 6-hour Maximum Dew Point Climatology
November (°F)

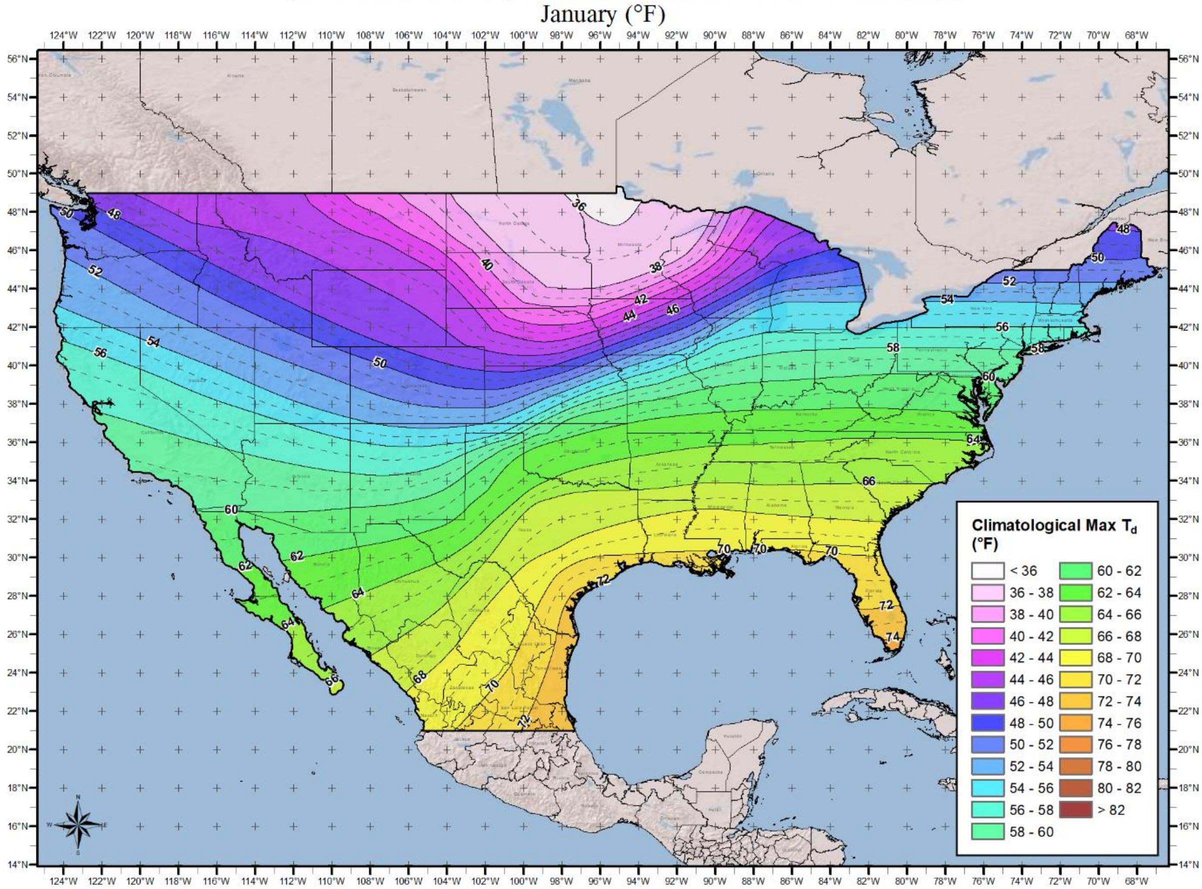


100-year Return Frequency 6-hour Maximum Dew Point Climatology
December (°F)

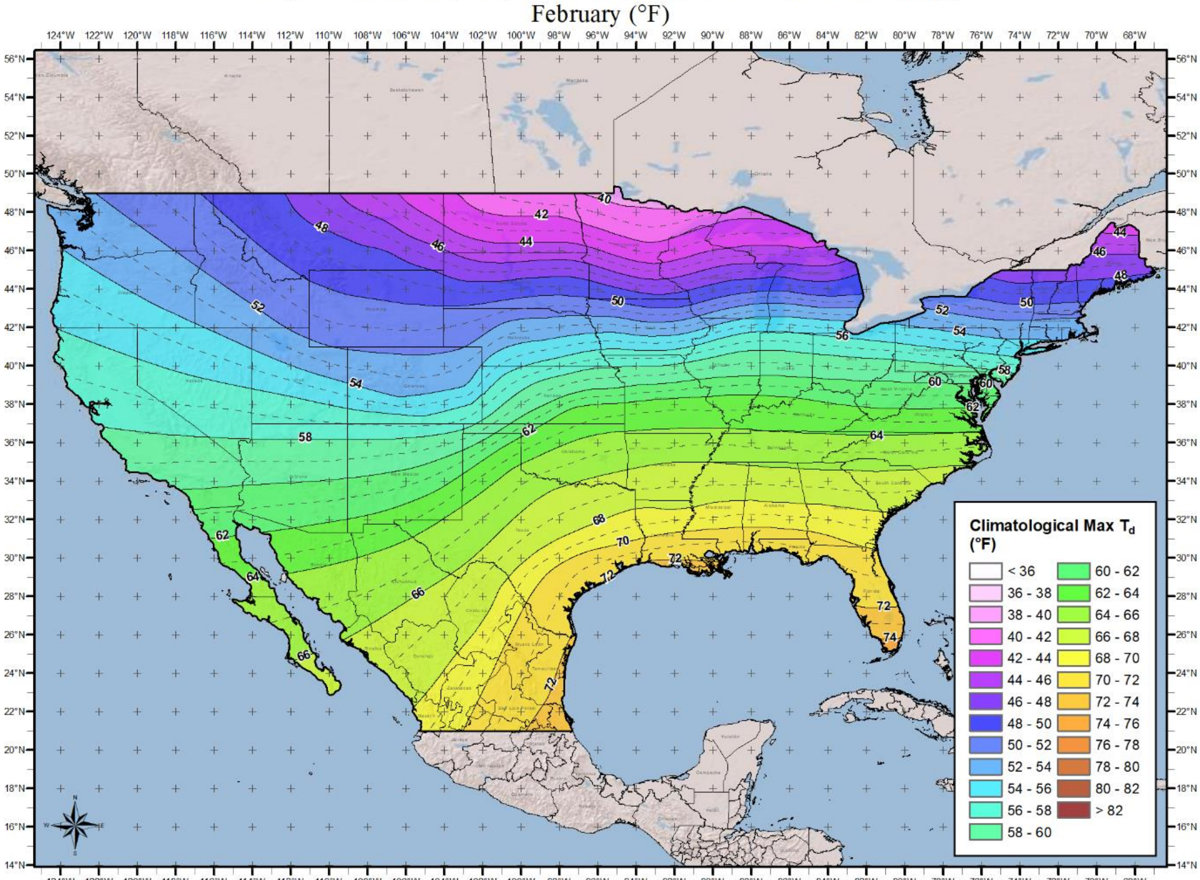


12-hour 1000mb Dew Point Maps

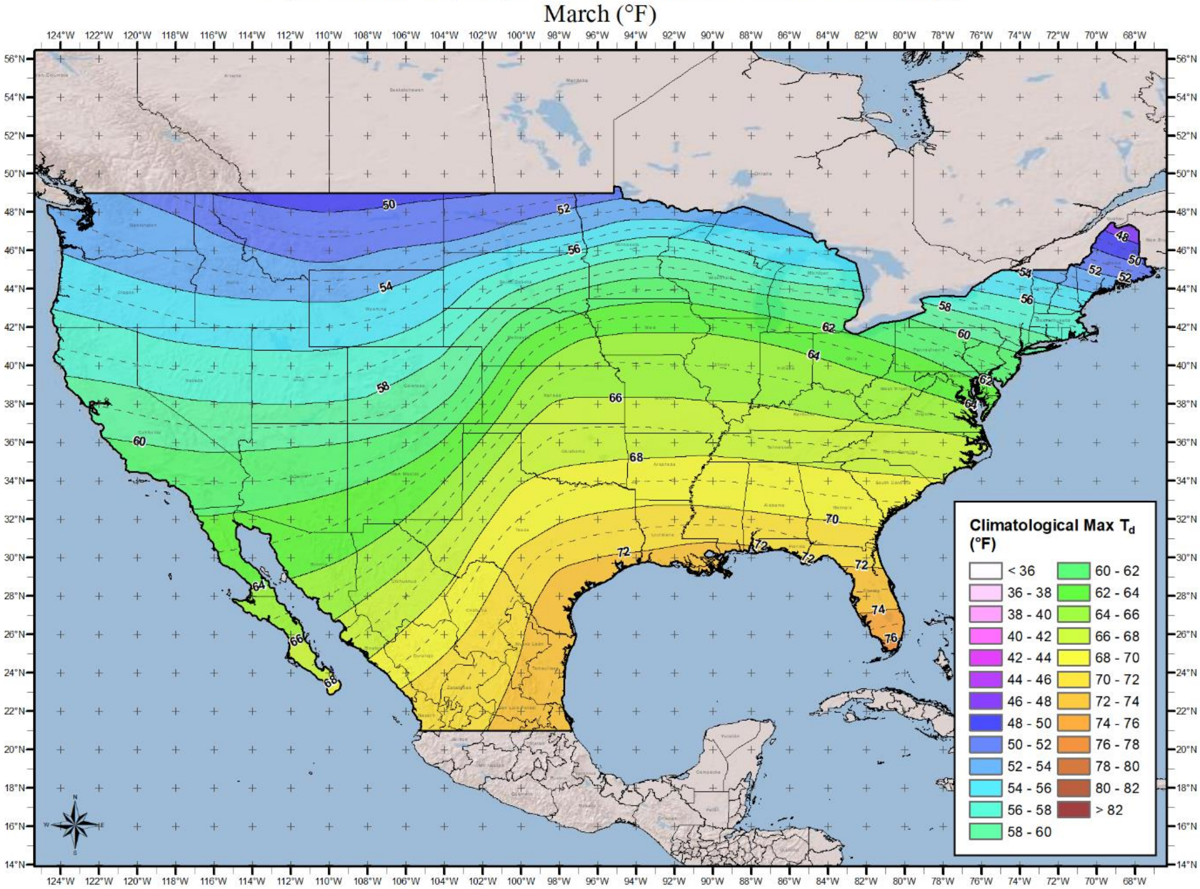
100-year Return Frequency 12-hour Maximum Dew Point Climatology
January (°F)



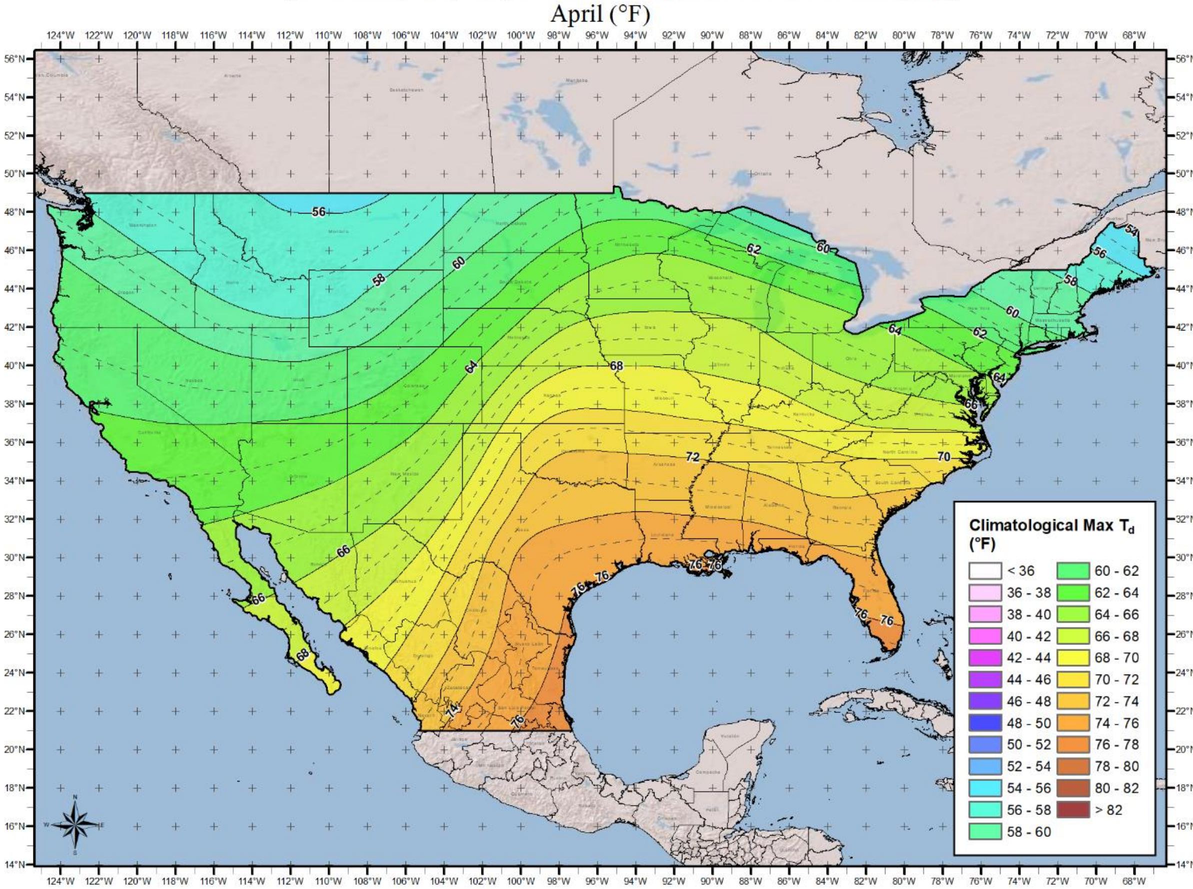
100-year Return Frequency 12-hour Maximum Dew Point Climatology
February (°F)



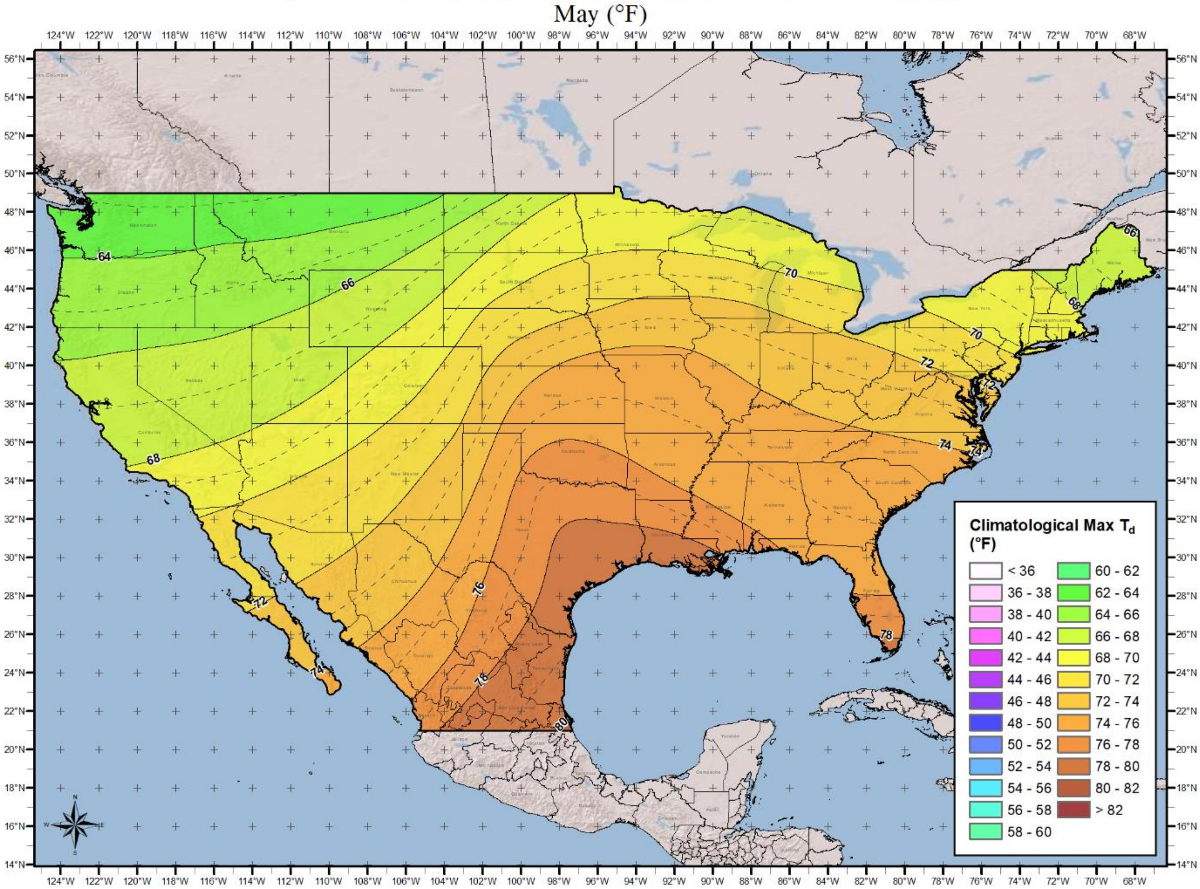
100-year Return Frequency 12-hour Maximum Dew Point Climatology
March (°F)



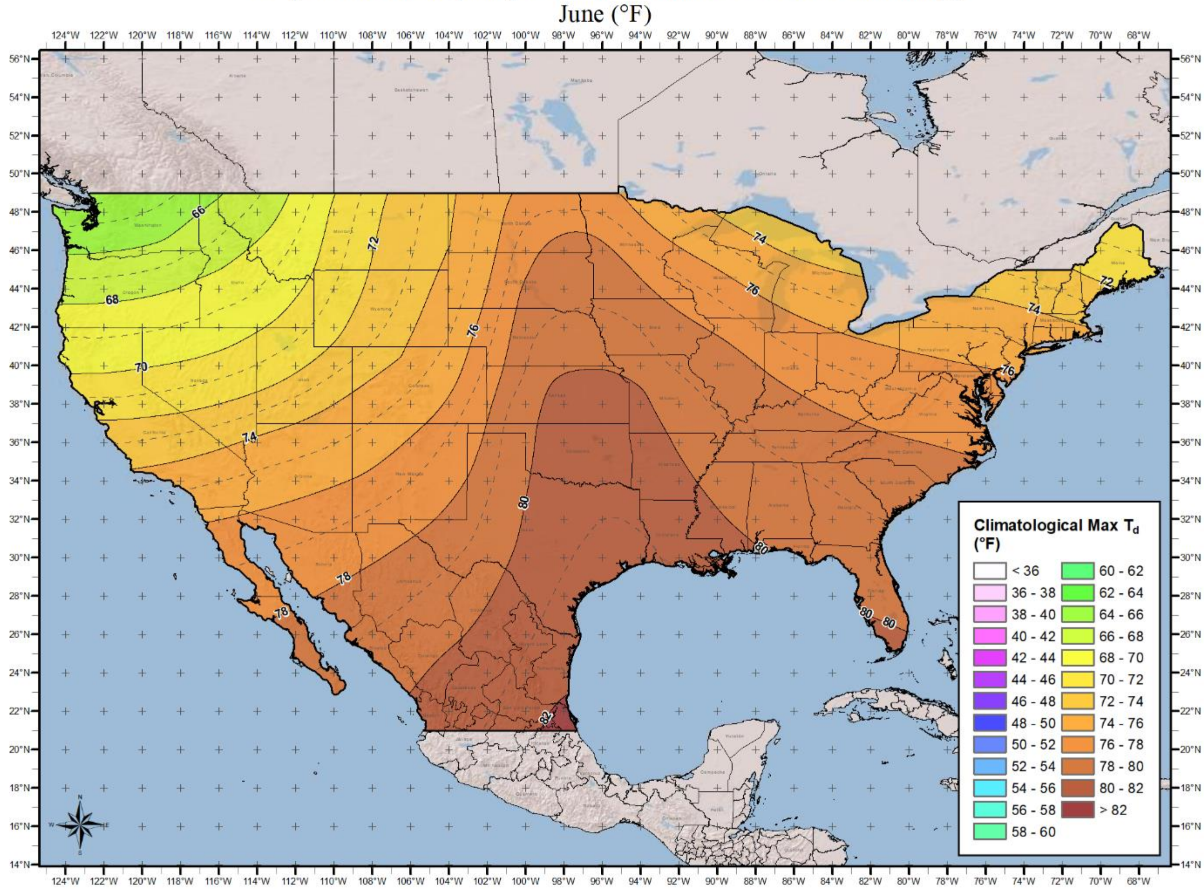
100-year Return Frequency 12-hour Maximum Dew Point Climatology
April (°F)



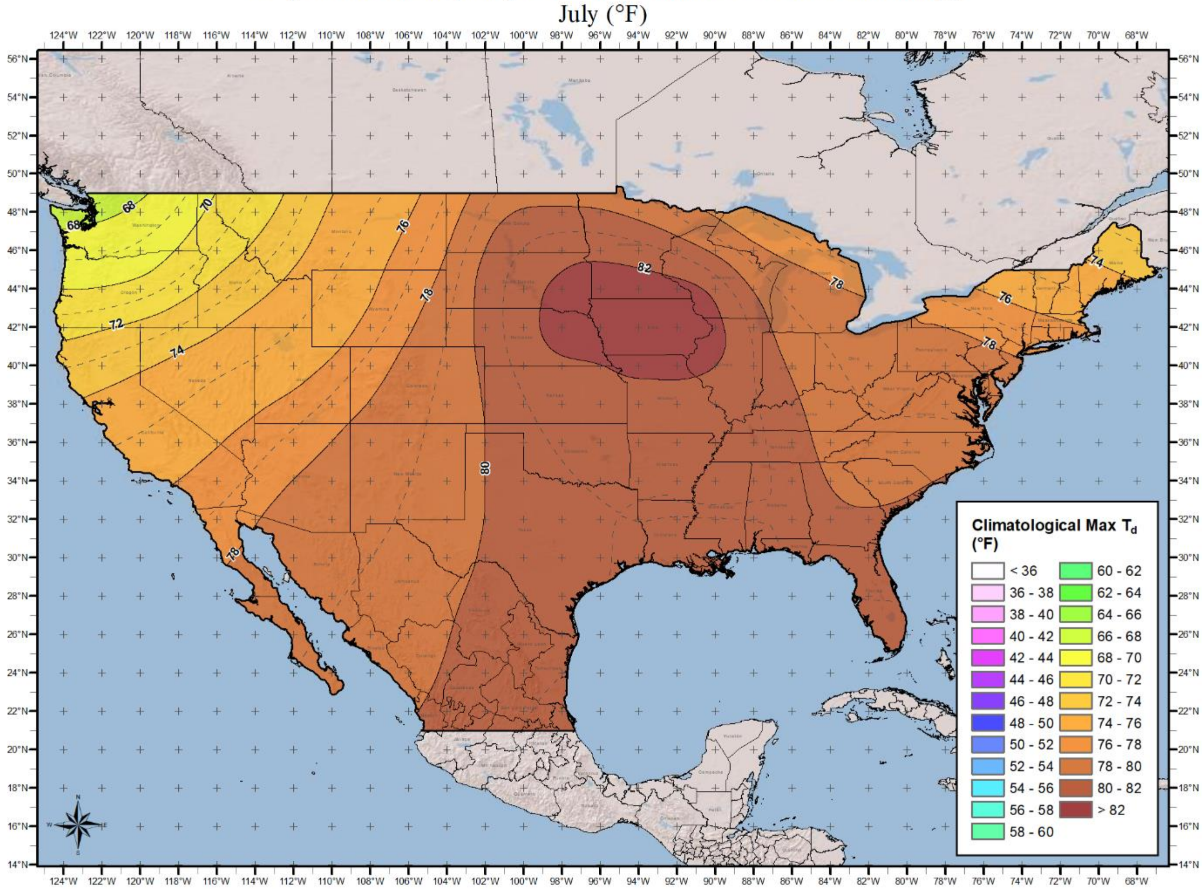
100-year Return Frequency 12-hour Maximum Dew Point Climatology
May (°F)



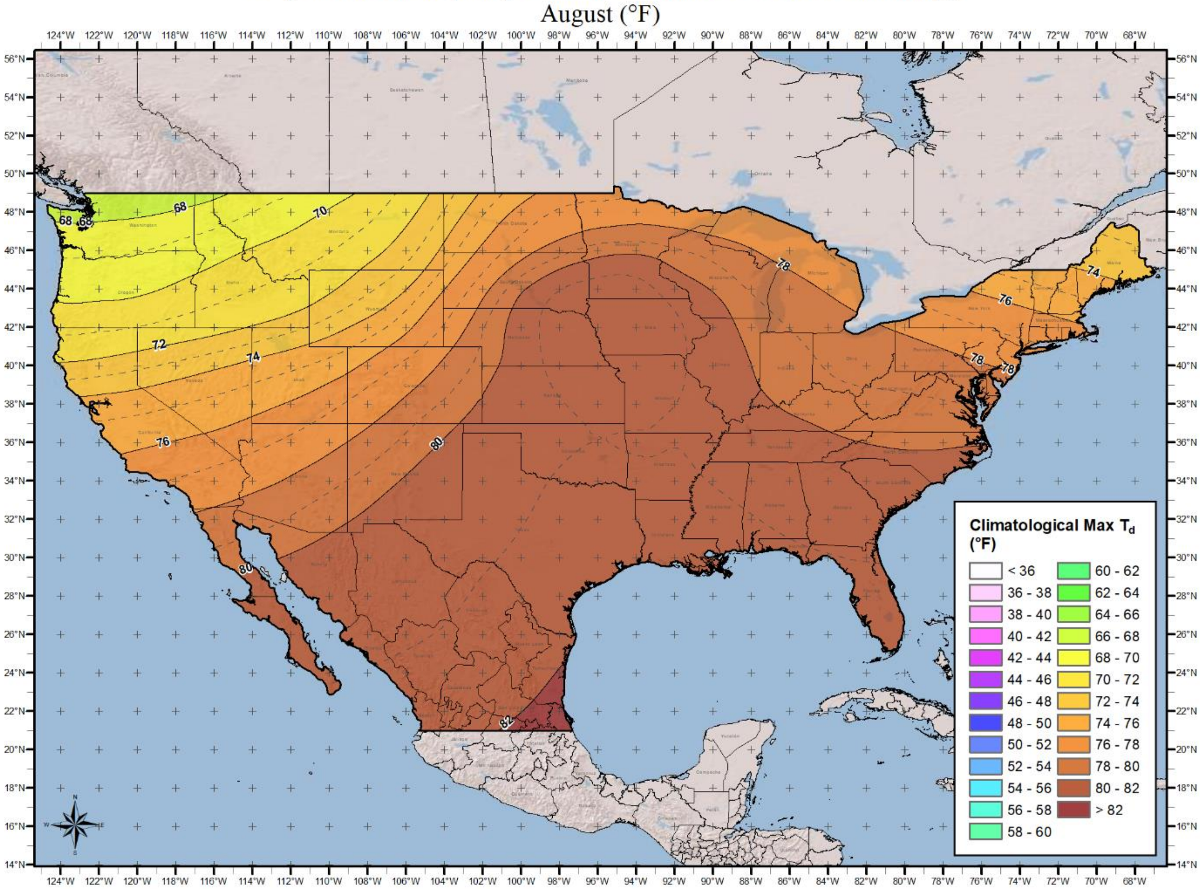
100-year Return Frequency 12-hour Maximum Dew Point Climatology
June (°F)



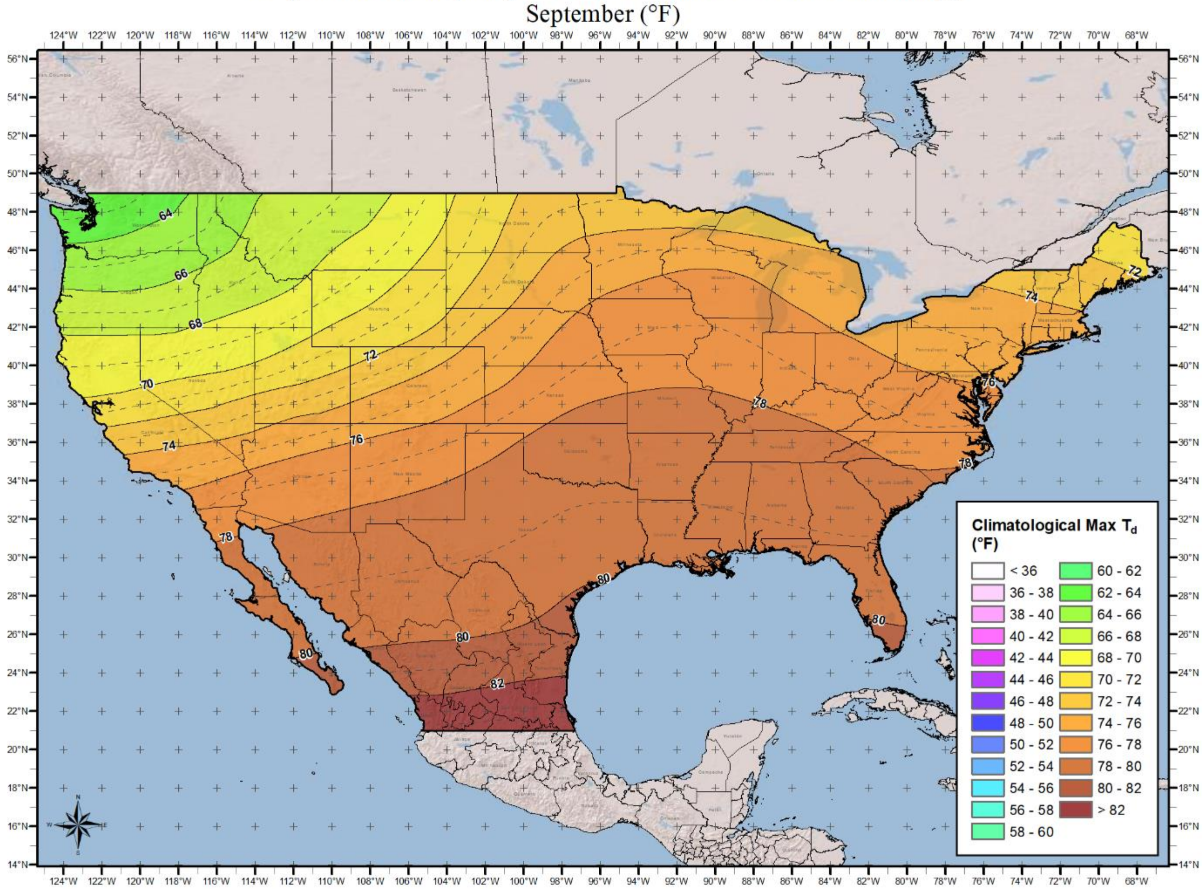
100-year Return Frequency 12-hour Maximum Dew Point Climatology
July (°F)



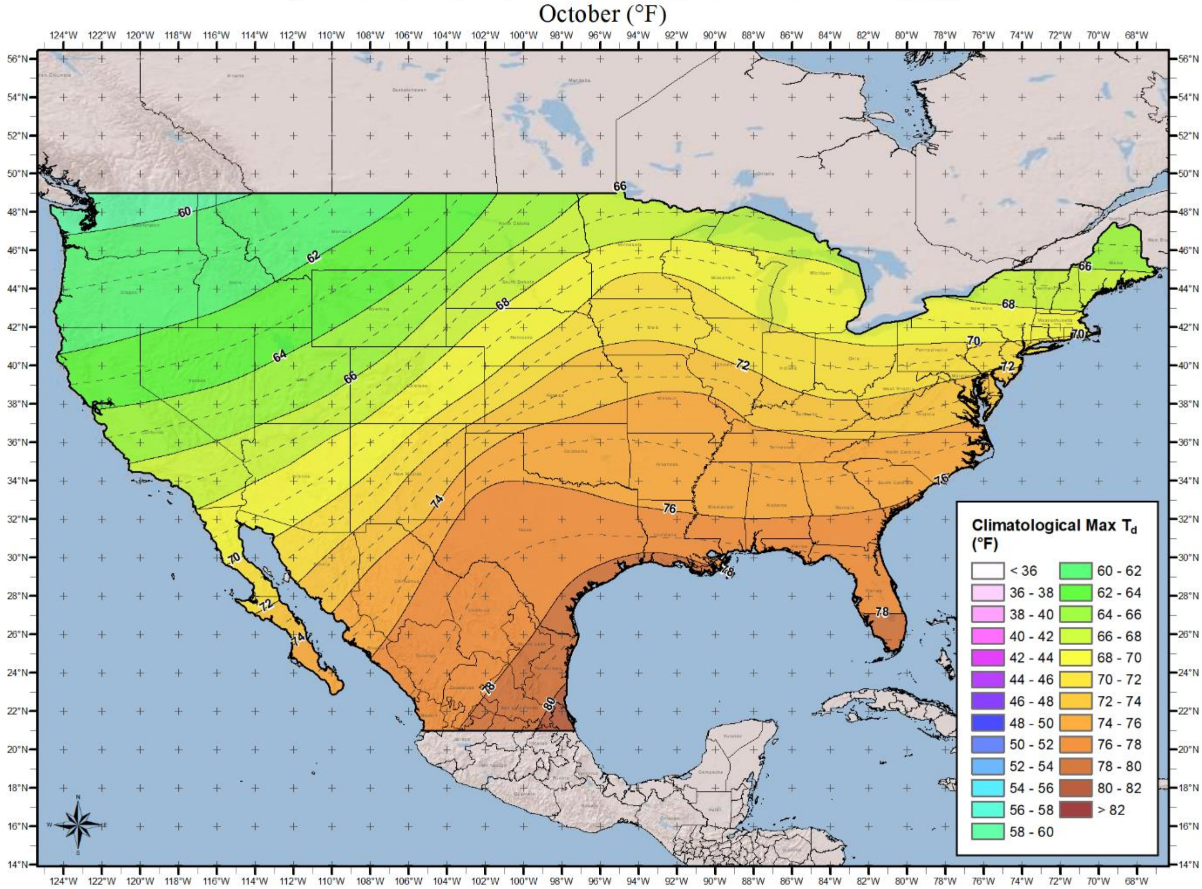
100-year Return Frequency 12-hour Maximum Dew Point Climatology
August (°F)



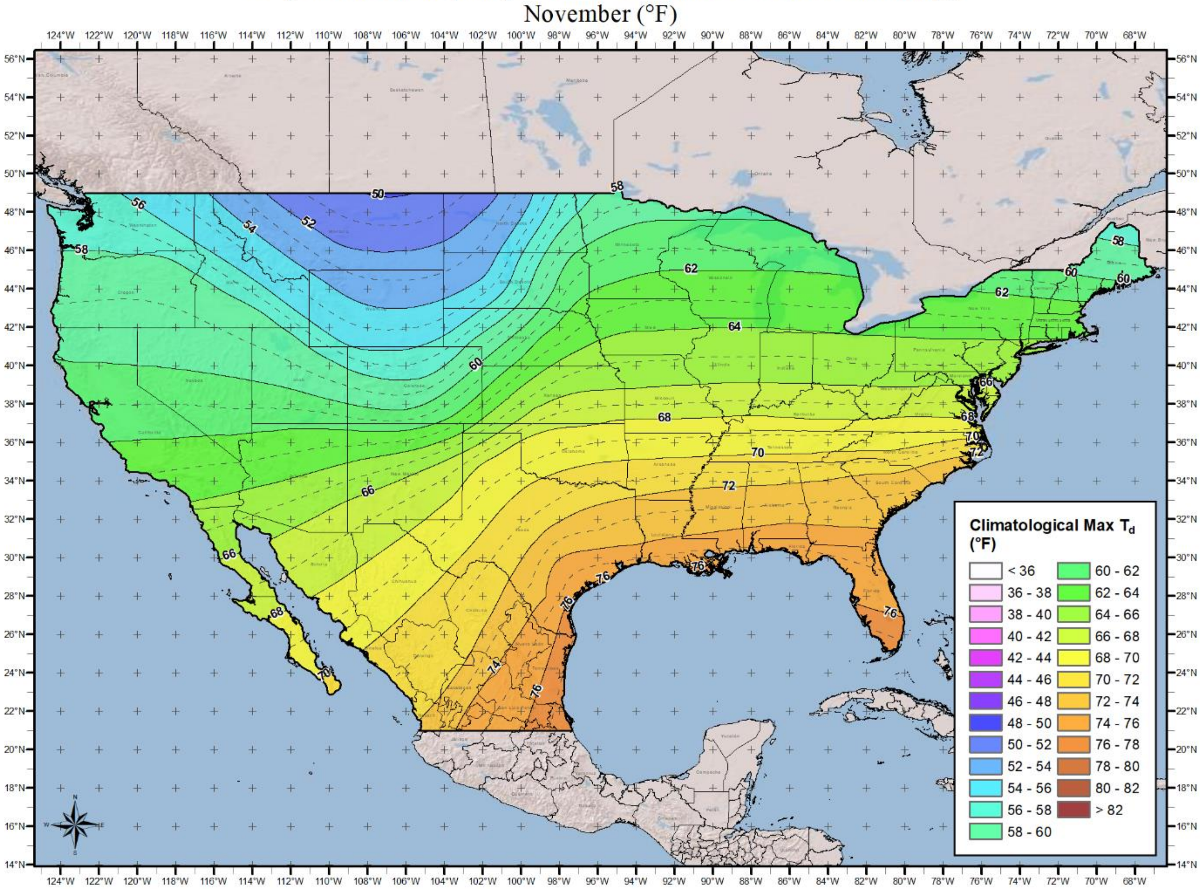
100-year Return Frequency 12-hour Maximum Dew Point Climatology
September (°F)



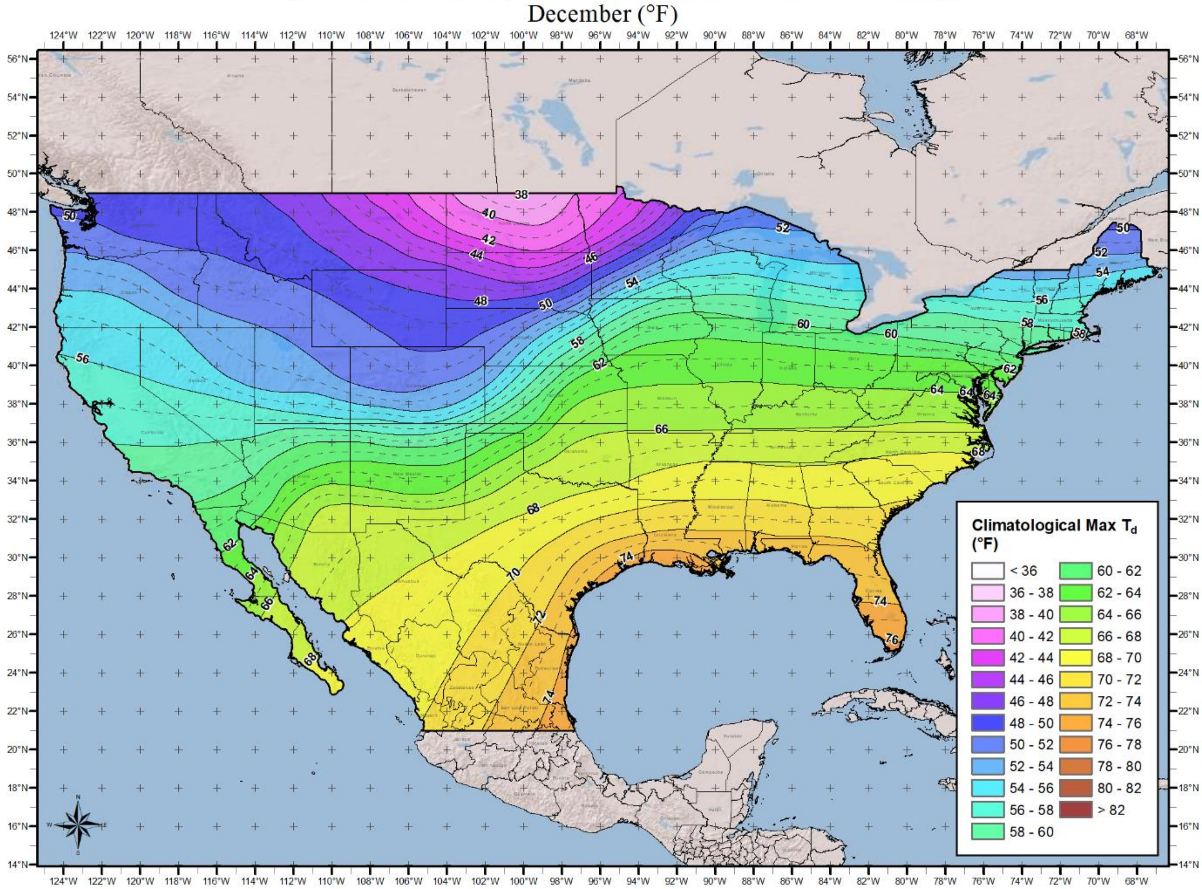
100-year Return Frequency 12-hour Maximum Dew Point Climatology
October (°F)



100-year Return Frequency 12-hour Maximum Dew Point Climatology
November (°F)

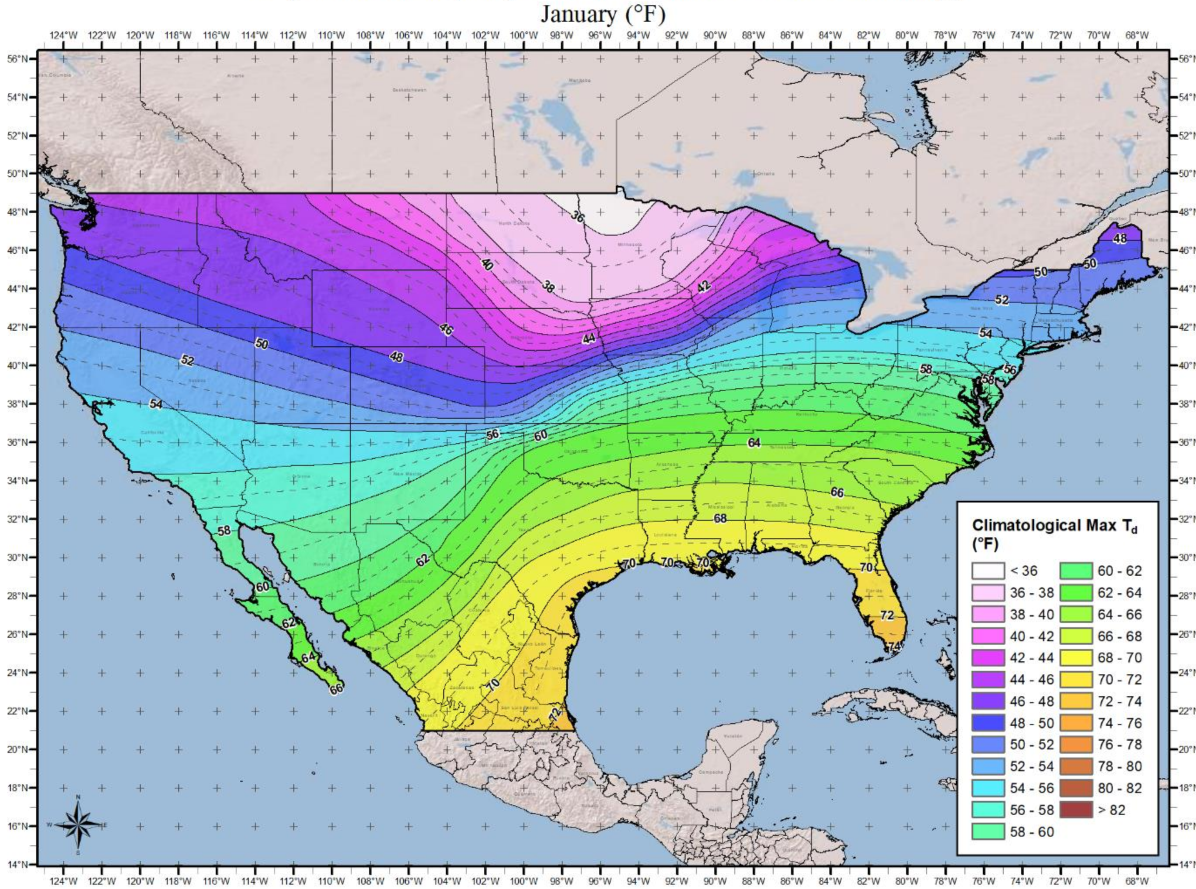


100-year Return Frequency 12-hour Maximum Dew Point Climatology
December (°F)

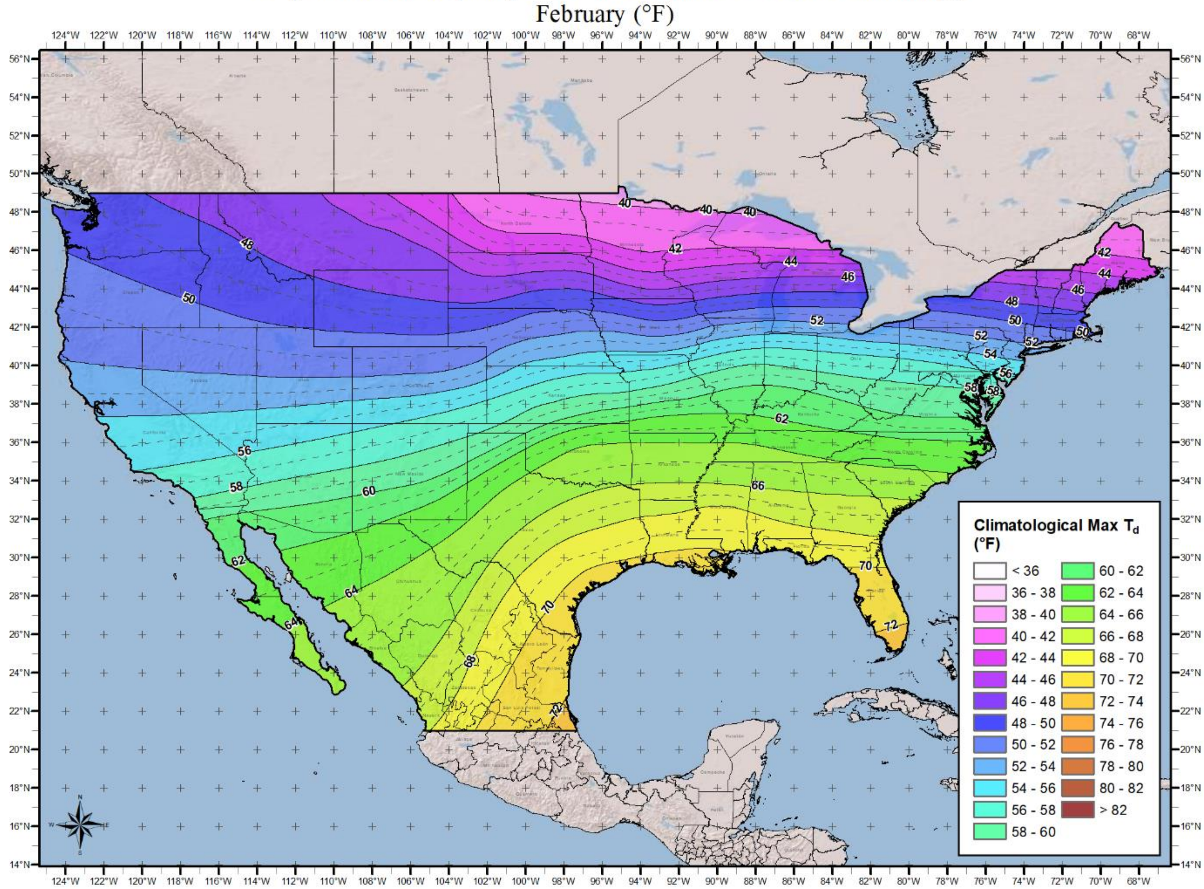


24-hour 1000mb Dew Point Maps

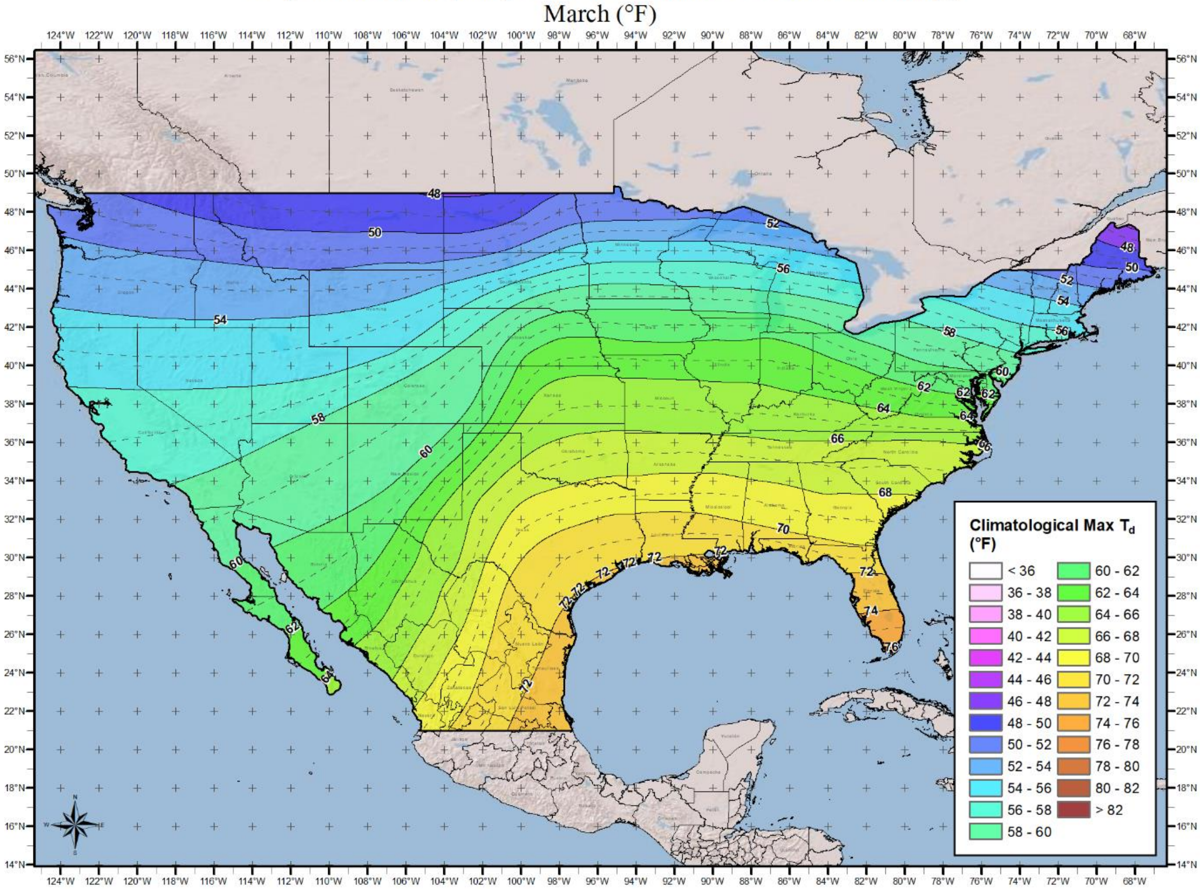
100-year Return Frequency 24-hour Maximum Dew Point Climatology
January (°F)



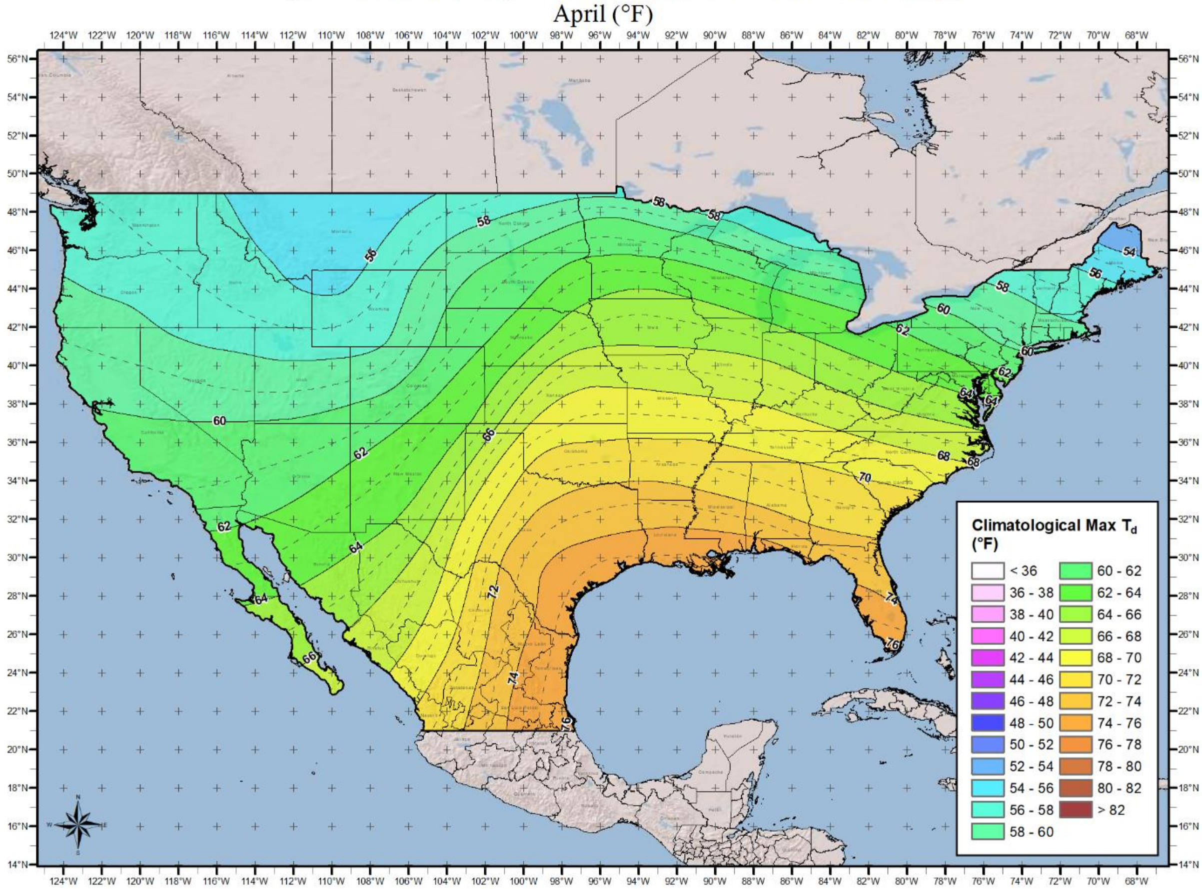
100-year Return Frequency 24-hour Maximum Dew Point Climatology
February (°F)



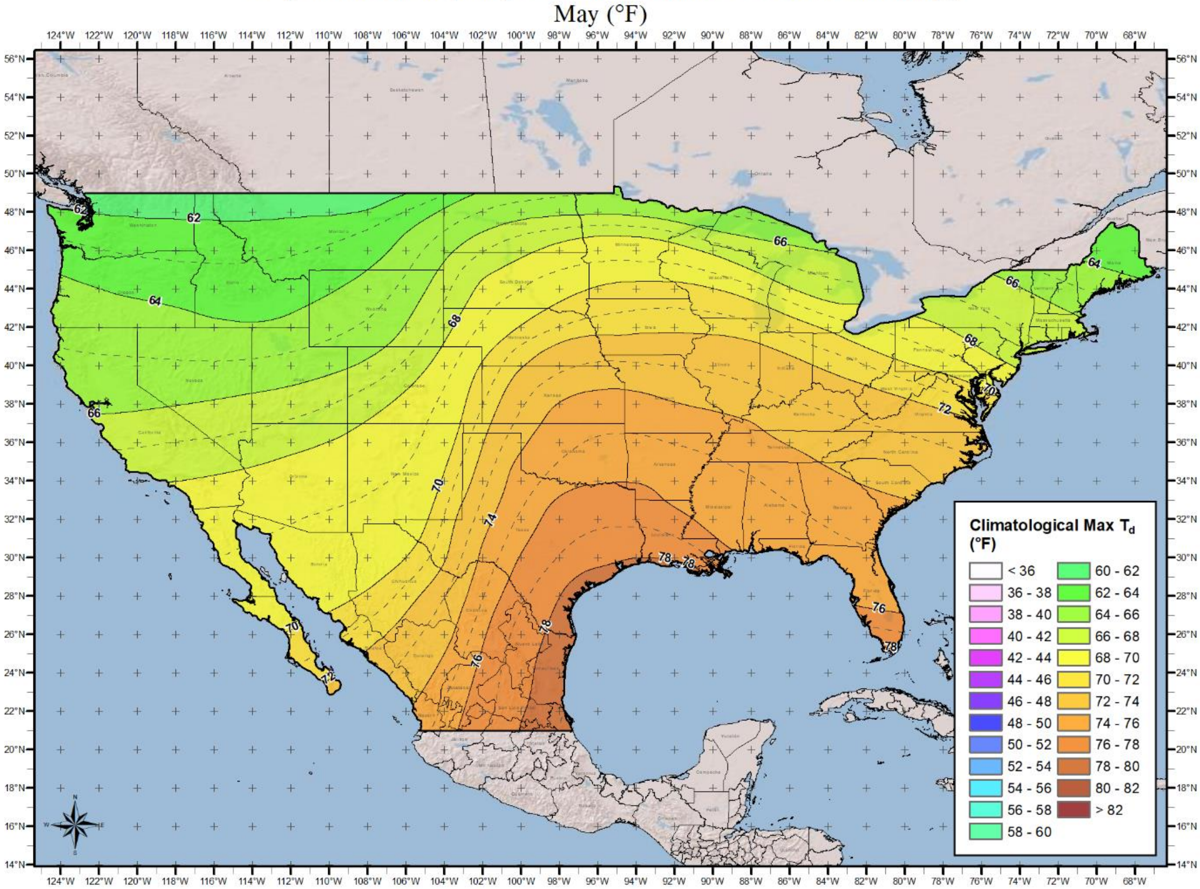
100-year Return Frequency 24-hour Maximum Dew Point Climatology
March (°F)



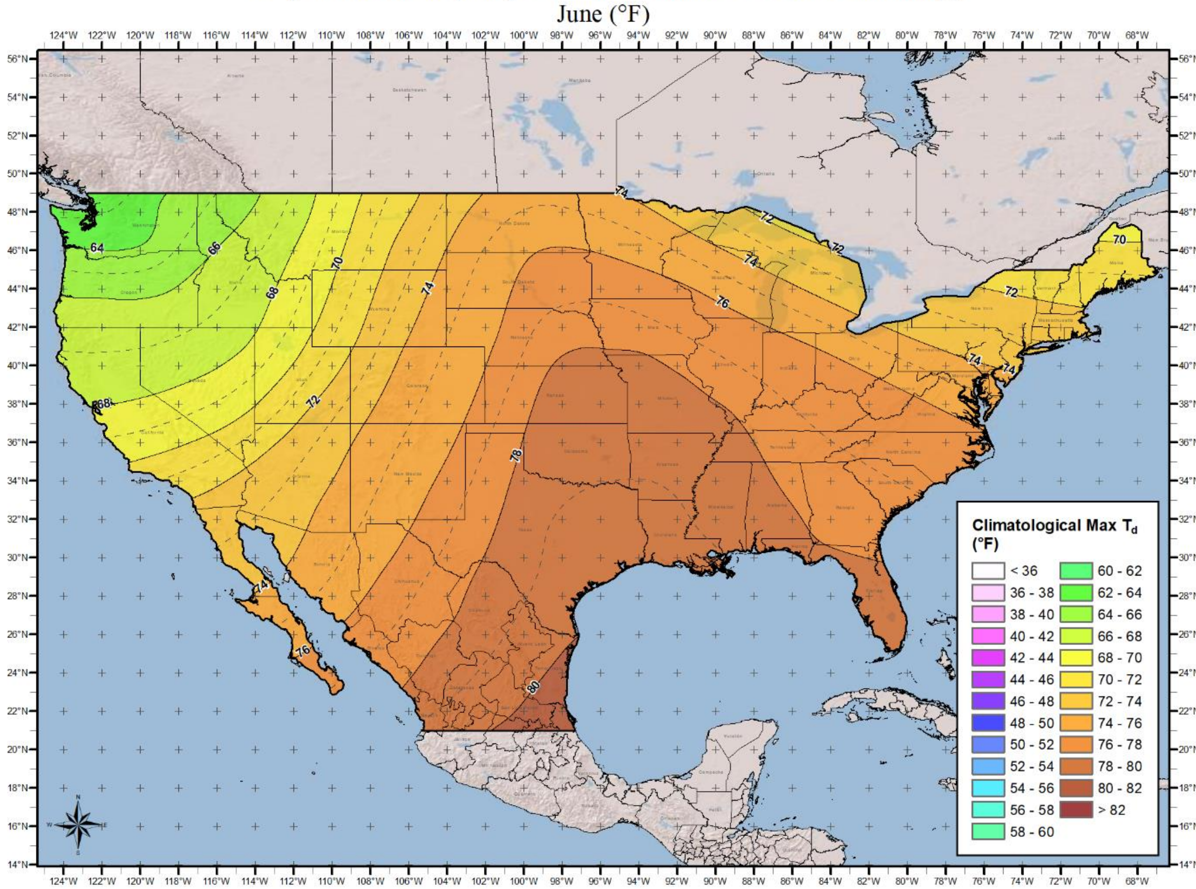
100-year Return Frequency 24-hour Maximum Dew Point Climatology
April (°F)



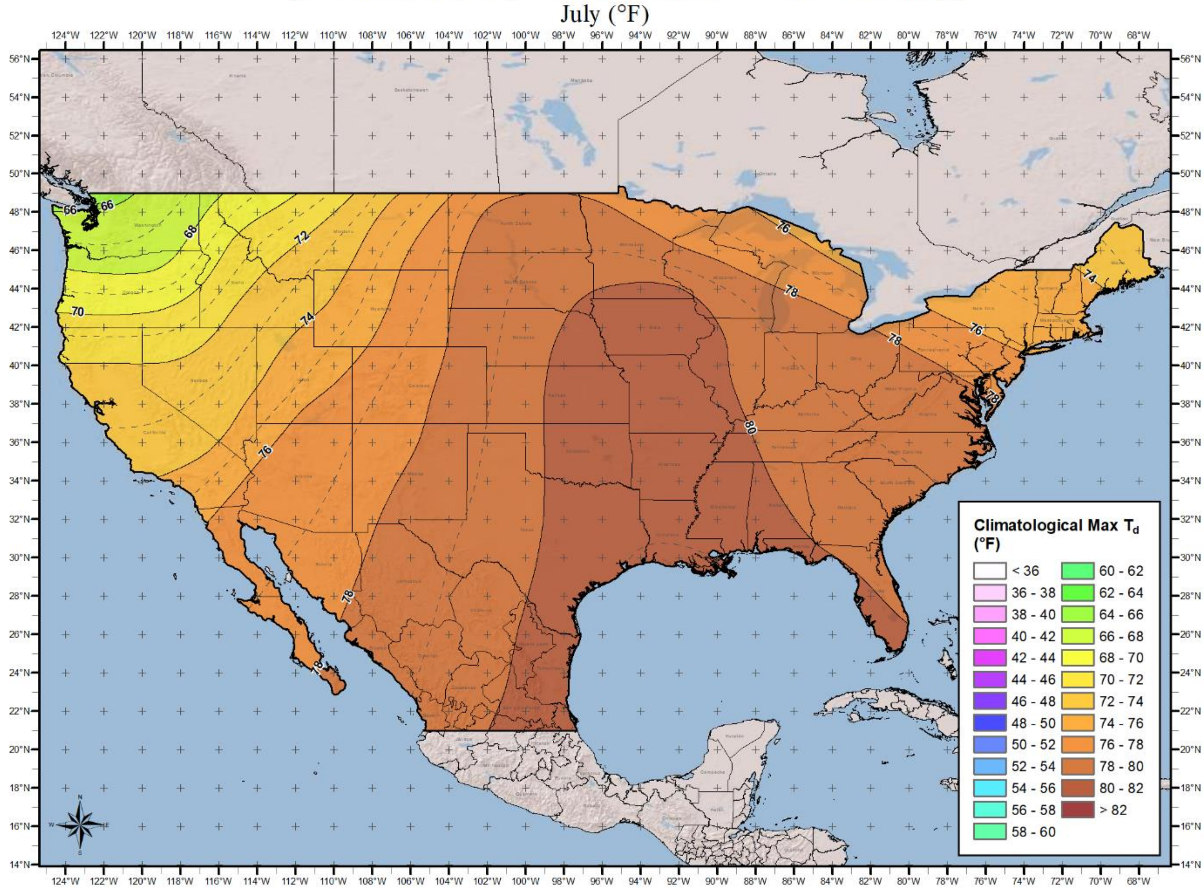
100-year Return Frequency 24-hour Maximum Dew Point Climatology
May (°F)



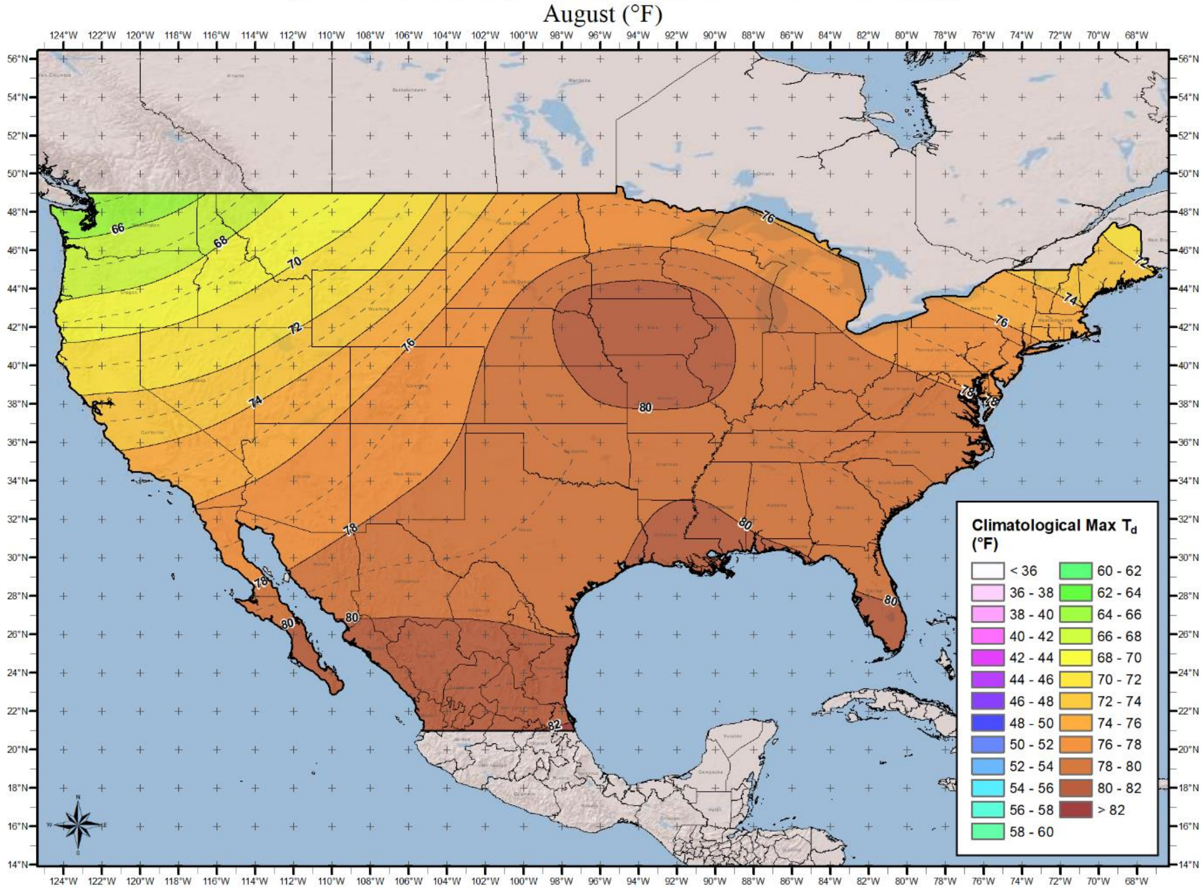
100-year Return Frequency 24-hour Maximum Dew Point Climatology
June (°F)



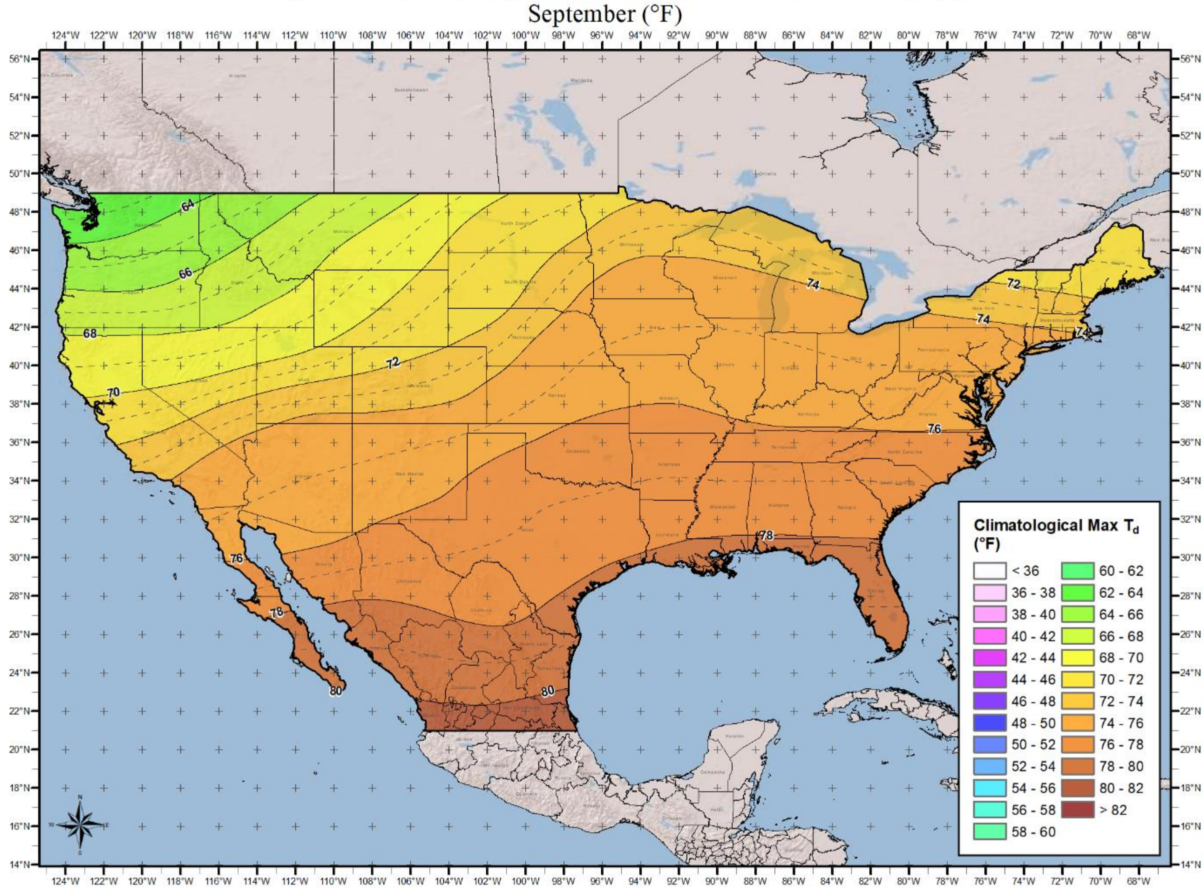
100-year Return Frequency 24-hour Maximum Dew Point Climatology
July (°F)



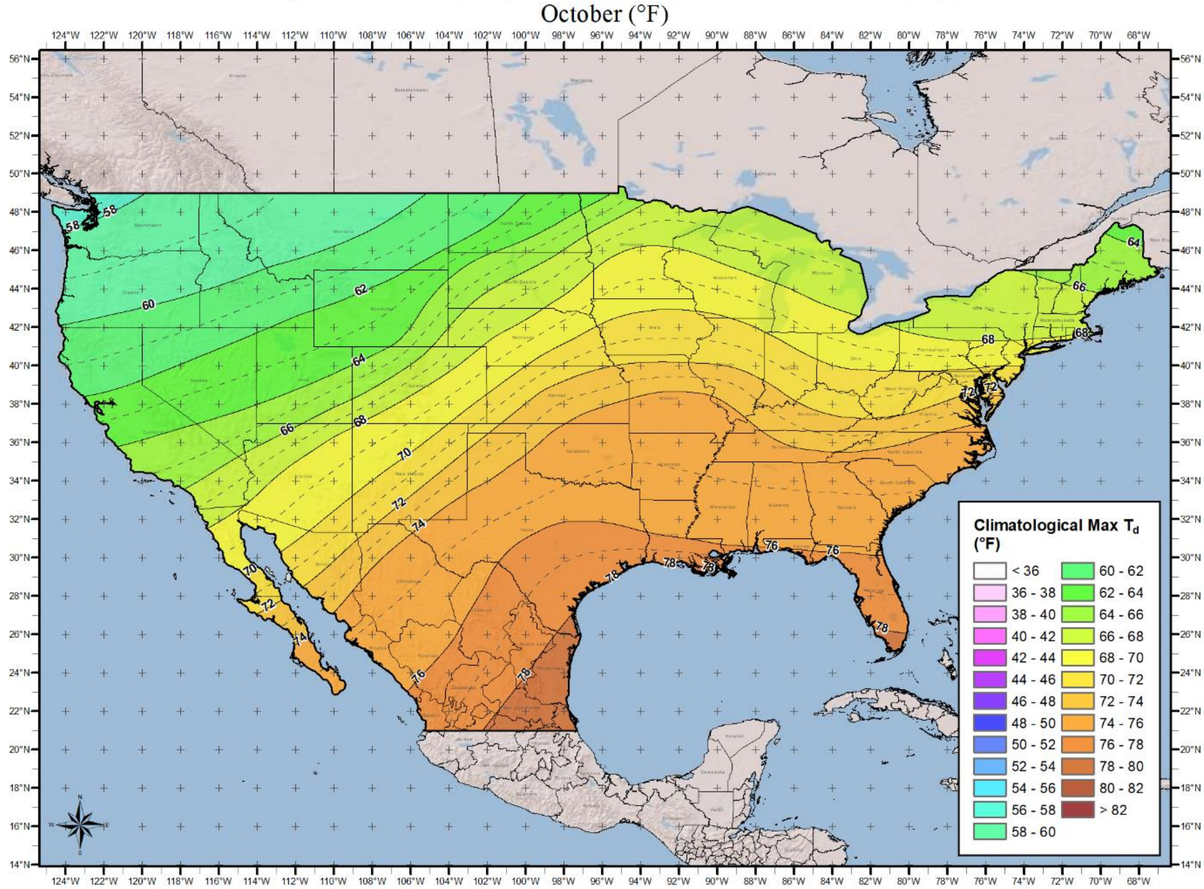
100-year Return Frequency 24-hour Maximum Dew Point Climatology
August (°F)



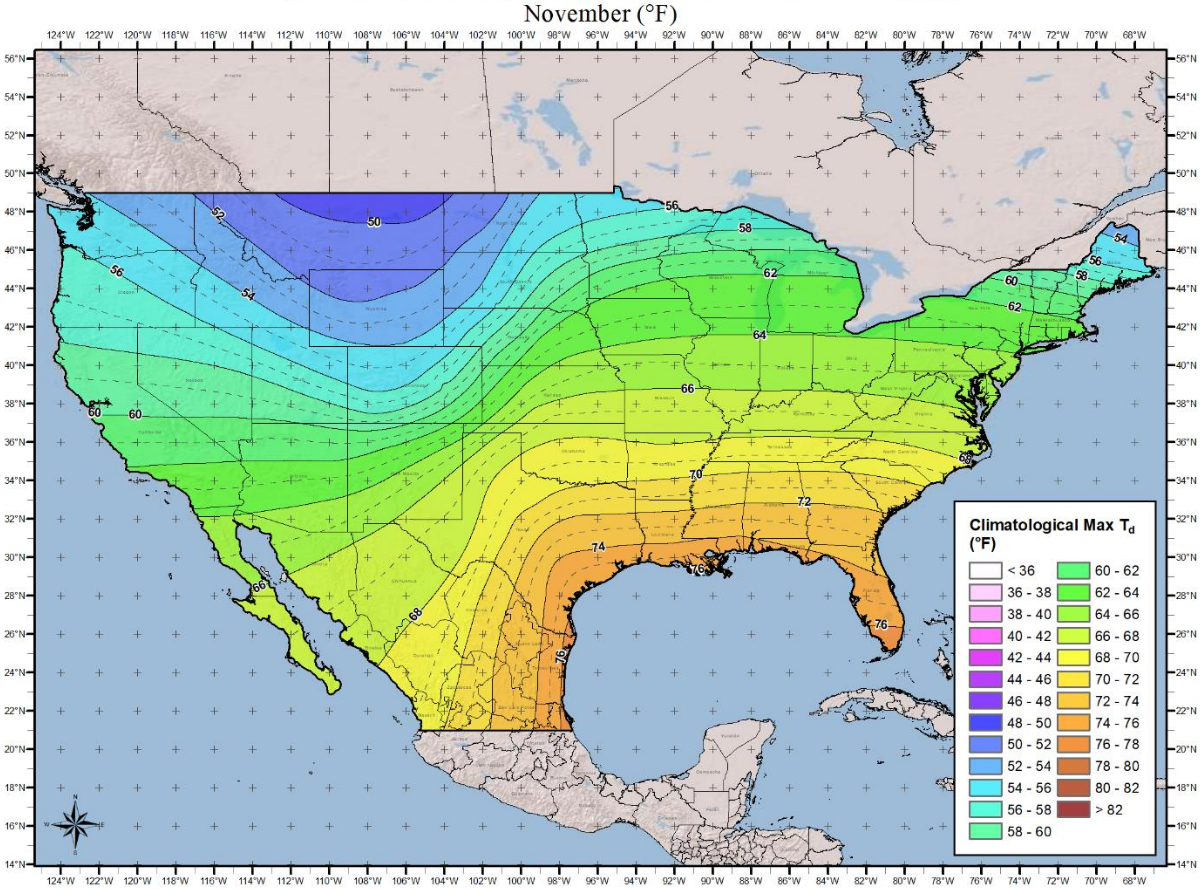
100-year Return Frequency 24-hour Maximum Dew Point Climatology
September (°F)



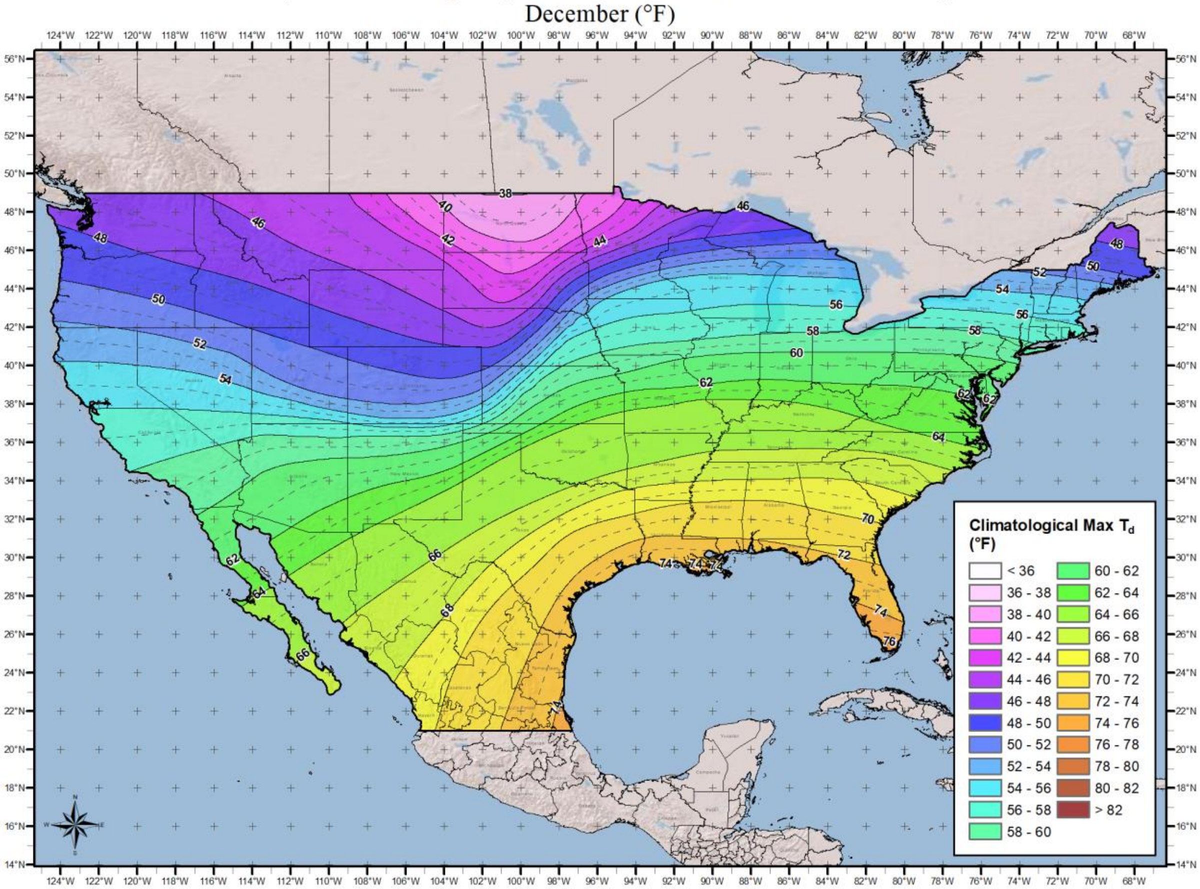
100-year Return Frequency 24-hour Maximum Dew Point Climatology
October (°F)



100-year Return Frequency 24-hour Maximum Dew Point Climatology
November (°F)

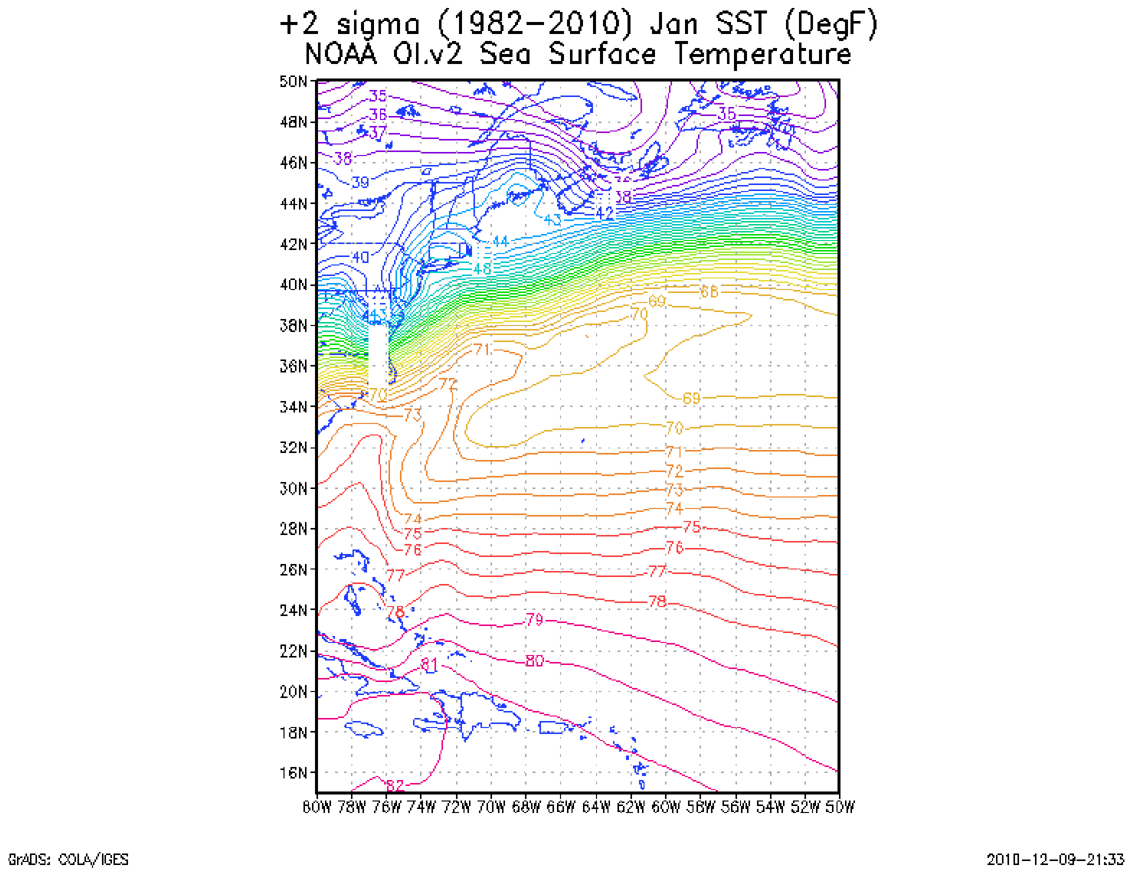


100-year Return Frequency 24-hour Maximum Dew Point Climatology
December (°F)

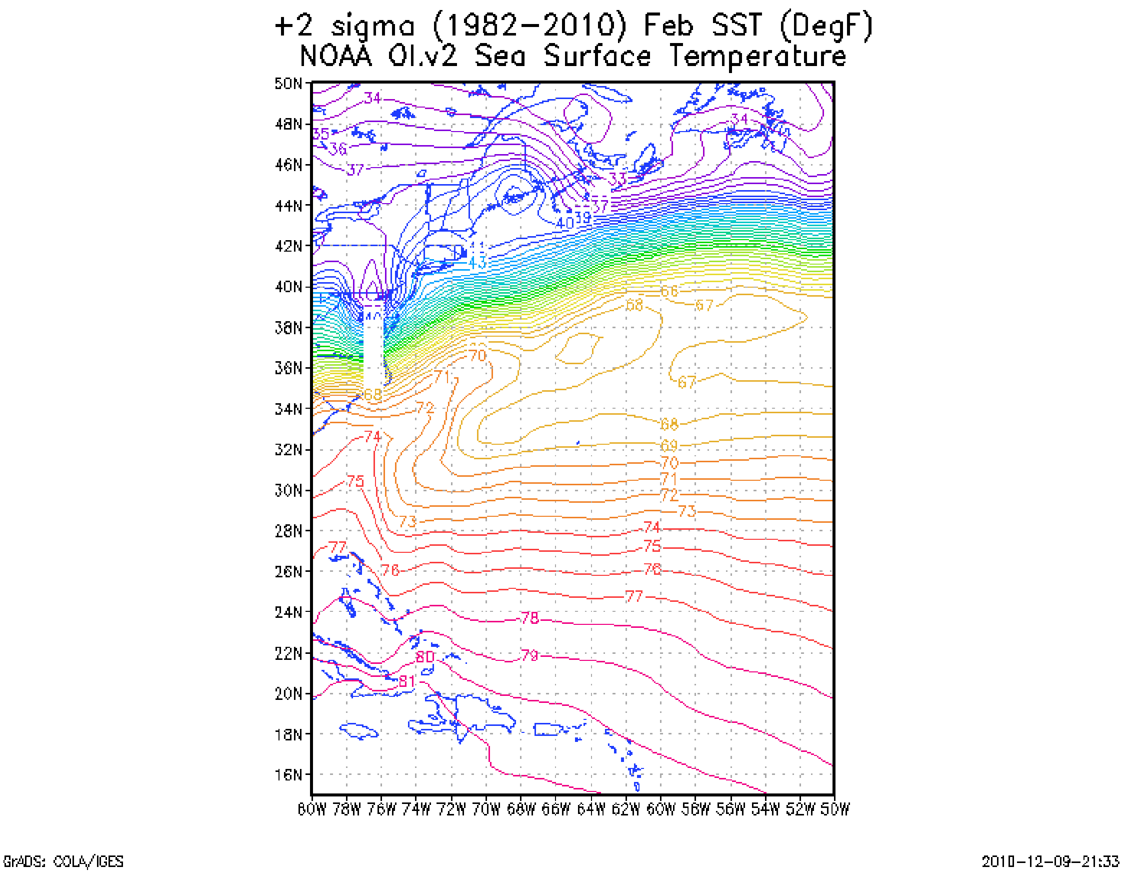


Appendix D
Sea Surface Temperature (SST) Climatology Maps

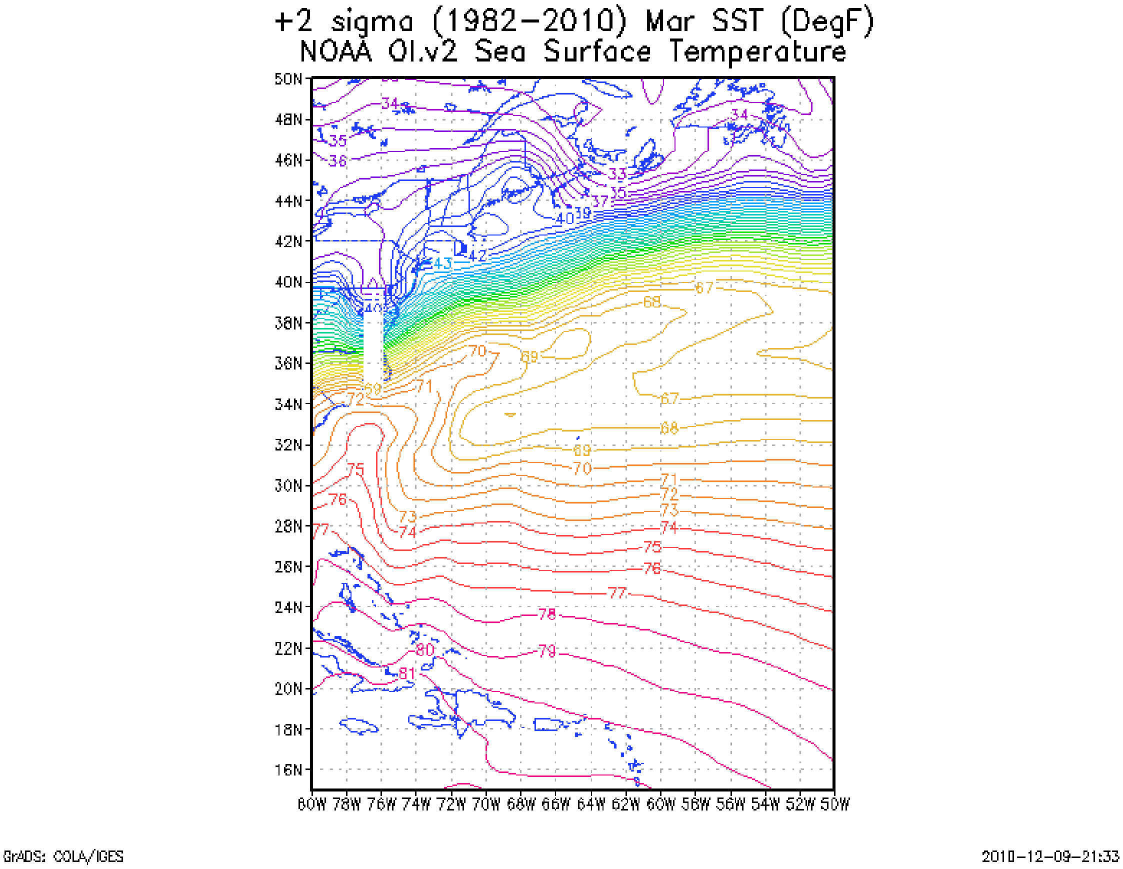
2-Sigma Sea Surface Temperature Maps



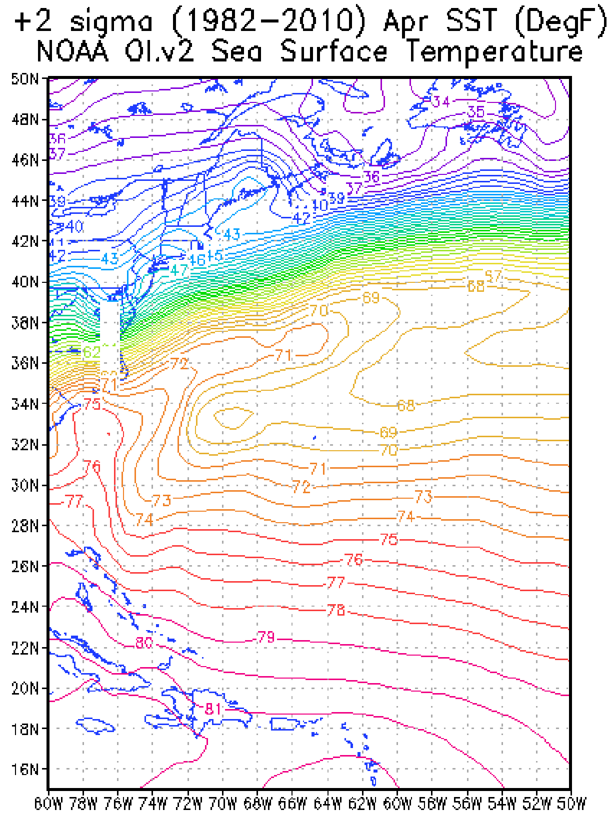
January +2 sigma SST climatology-western Atlantic Ocean



February +2 sigma SST climatology-western Atlantic Ocean

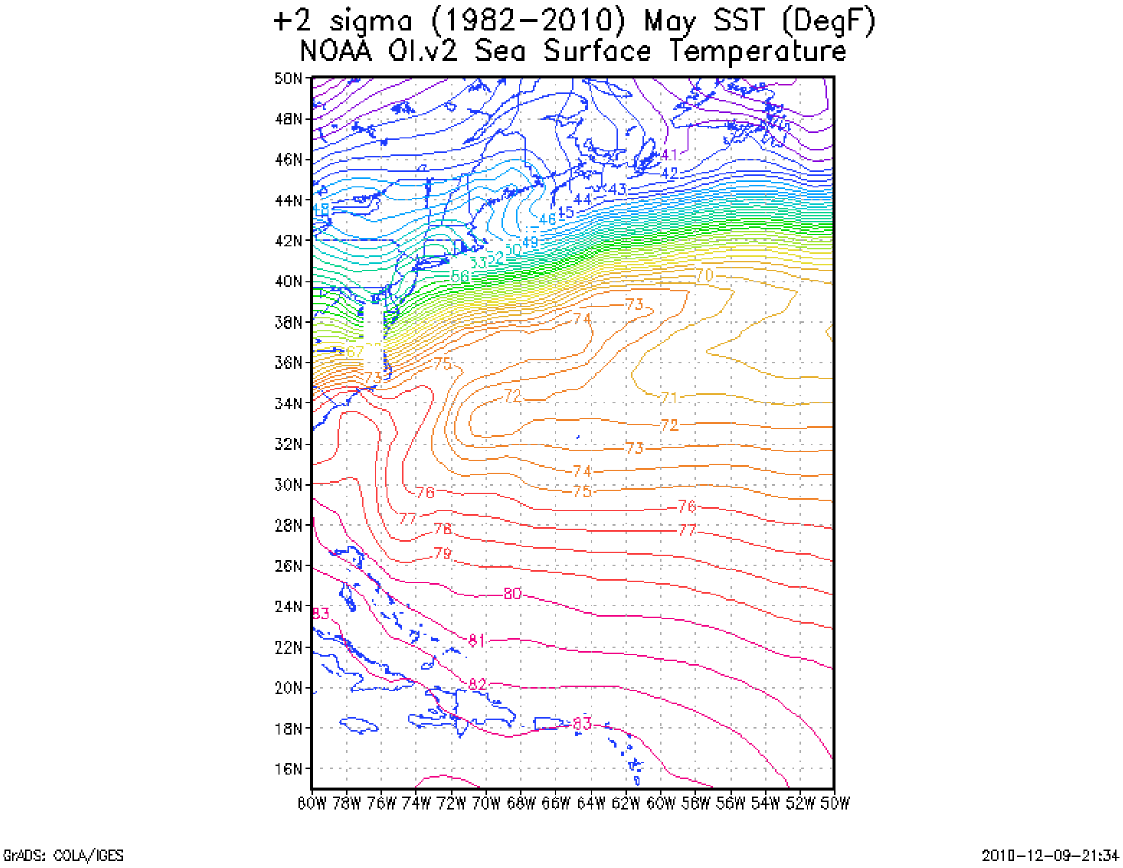


March +2 sigma SST climatology-western Atlantic Ocean

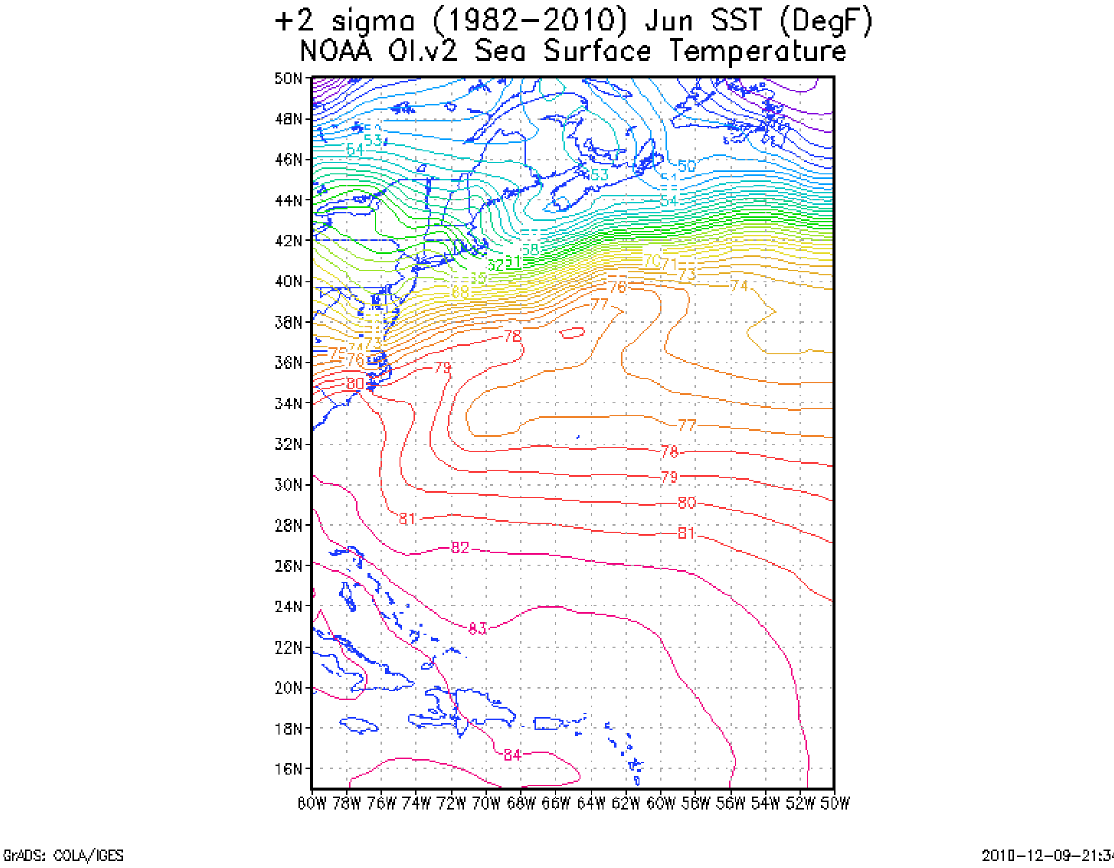


GrADS: COLA/IGES 2010-12-09-21:33

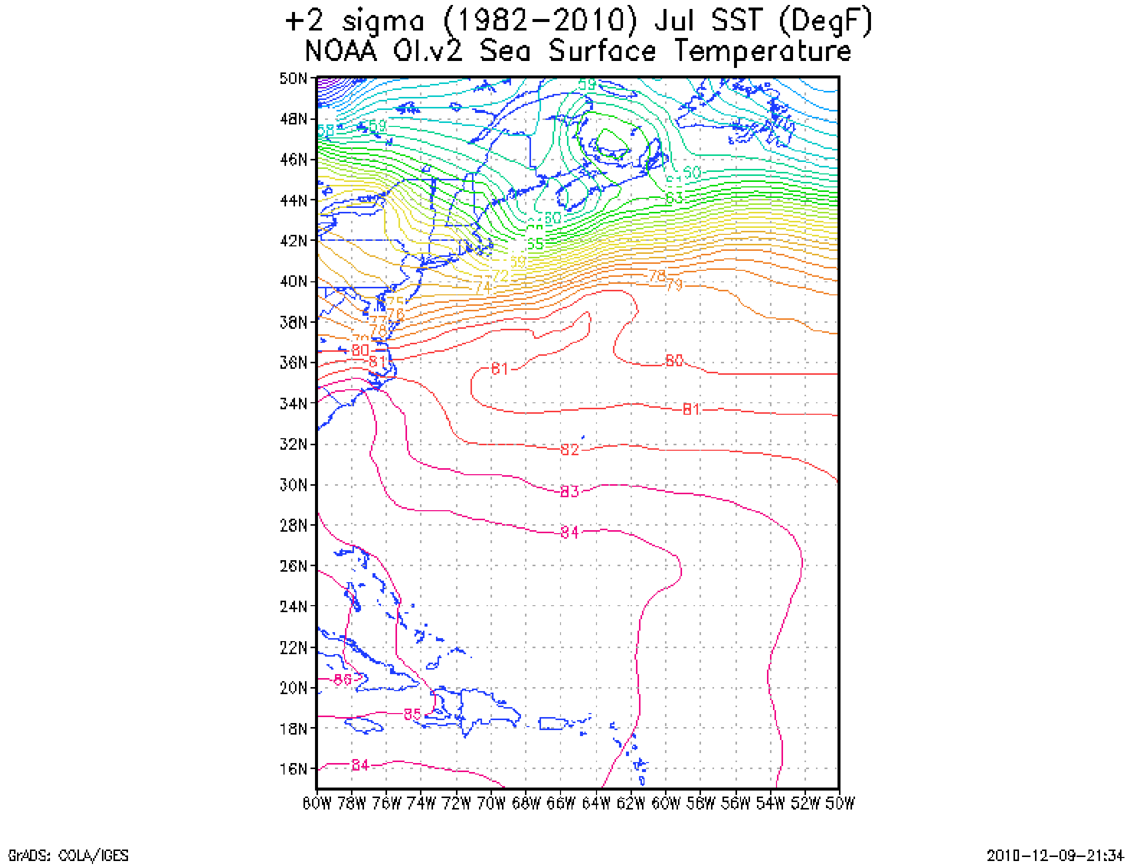
April +2 sigma SST climatology-western Atlantic Ocean



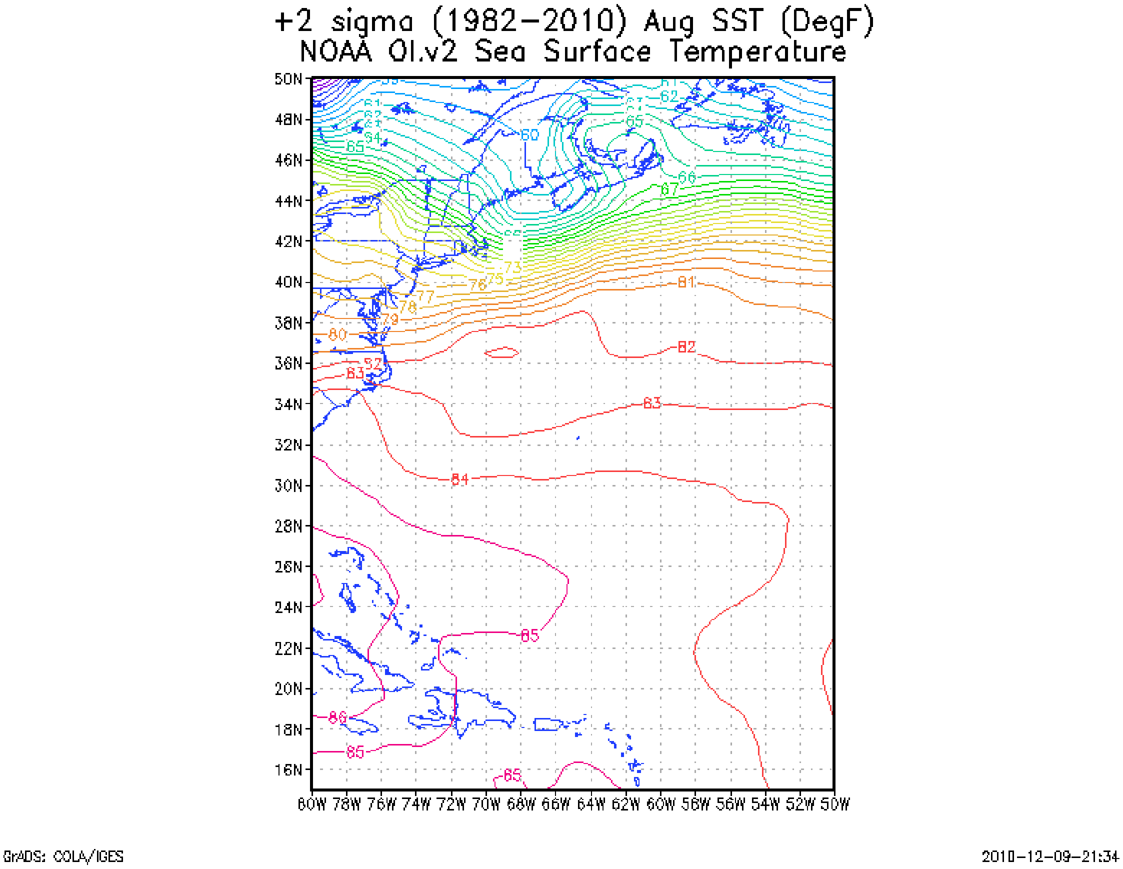
May +2 sigma SST climatology-western Atlantic Ocean



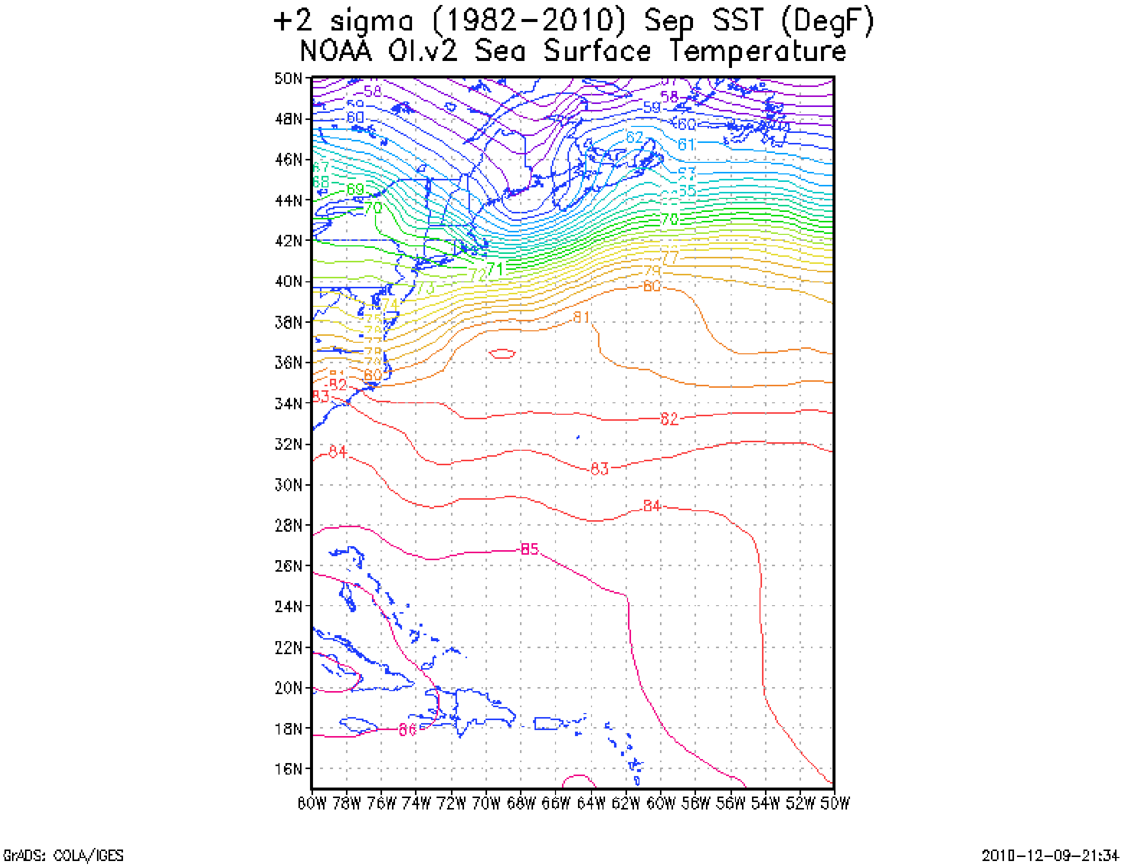
June +2 sigma SST climatology-western Atlantic Ocean



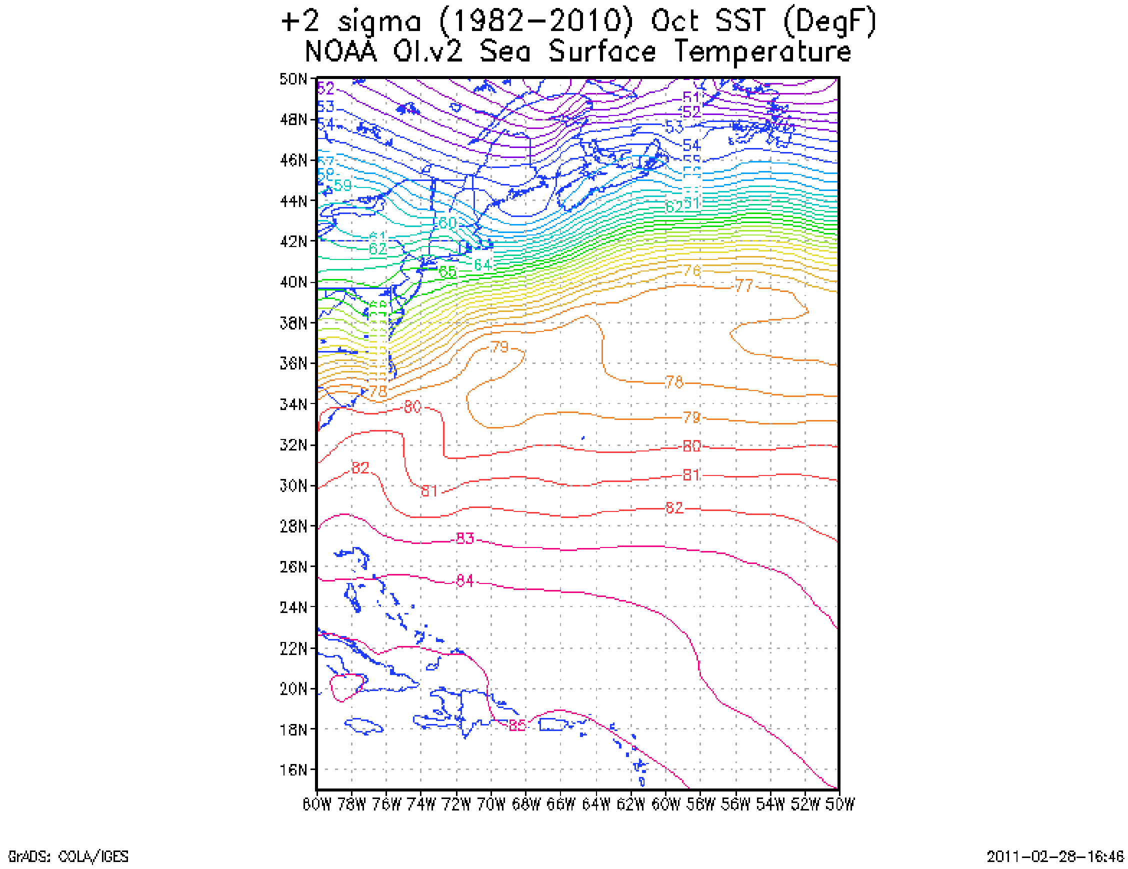
July +2 sigma SST climatology-western Atlantic Ocean



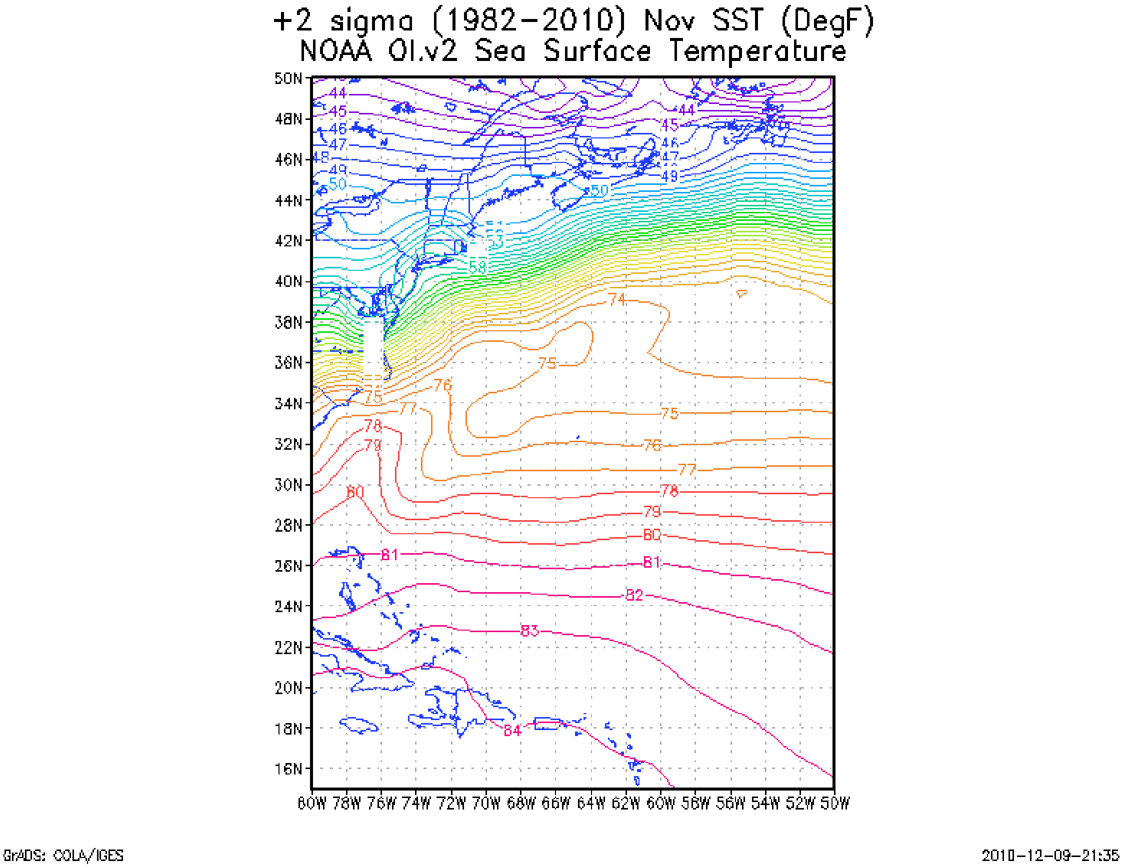
August +2 sigma SST climatology-western Atlantic Ocean



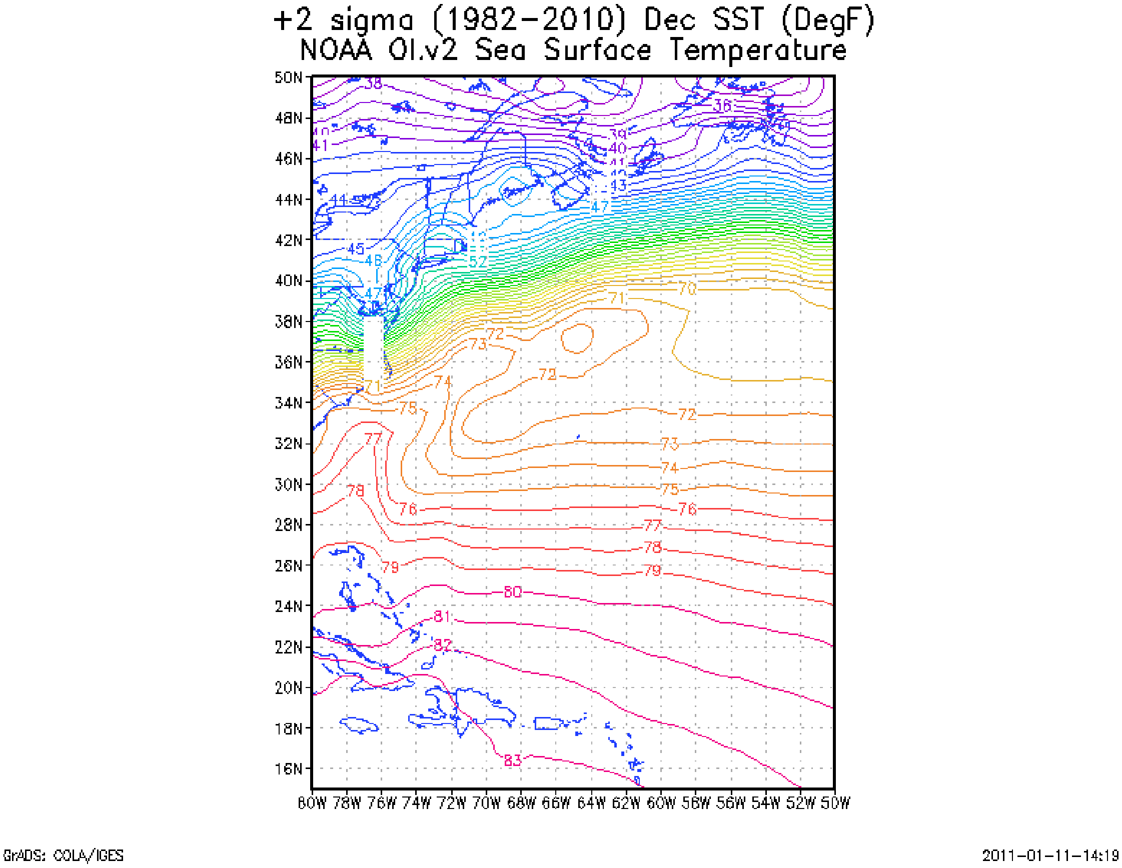
September +2 sigma SST climatology-western Atlantic Ocean



October +2 sigma SST climatology-western Atlantic Ocean



November +2 sigma SST climatology-western Atlantic Ocean



December +2 sigma SST climatology-western Atlantic Ocean

Appendix E
Storm Precipitation Analysis System (SPAS) 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. To date (March 2015 SPAS has 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 and 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 is shown in flow chart in Figure E.1.

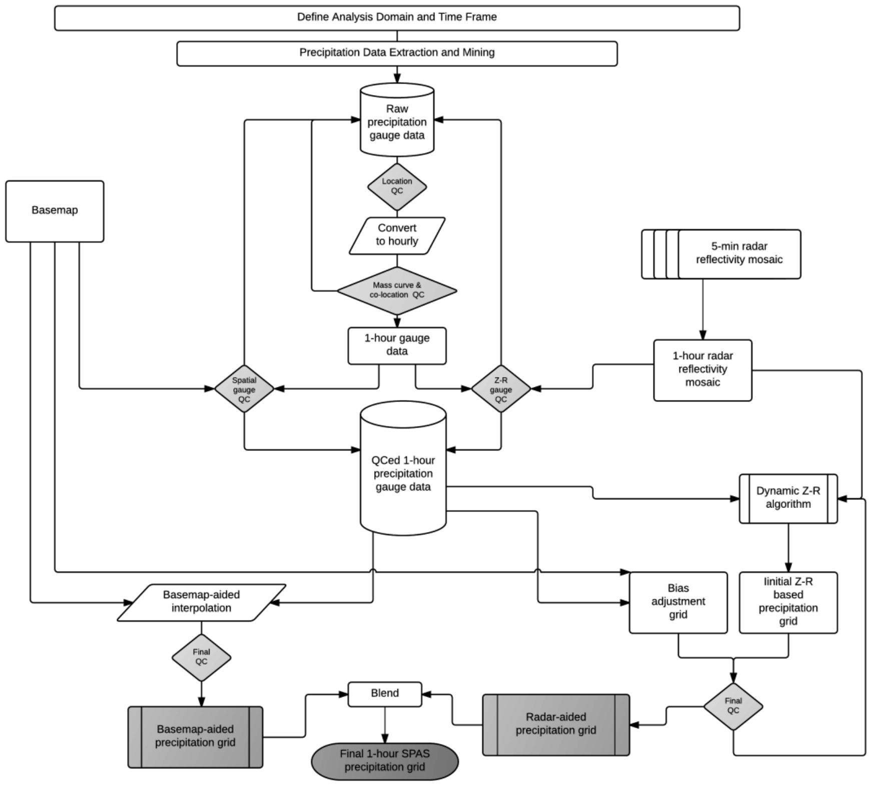


Figure E.1: SPAS flow chart

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 E.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 data 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 large proportion of official data, but also includes data from unofficial gauges.

Table E.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.)
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.

Perhaps the most important source 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) 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 E.2a) or Hydrometeorological Design Studies Center precipitation frequency grids (Figure E.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 the small terrain forced precipitation gradients. Therefore, basemaps for SPAS analyses in flat terrain are often developed from pre-existing (hand-drawn) isohyetal patterns (Figure E.2c), composite radar imagery or a blend of both.

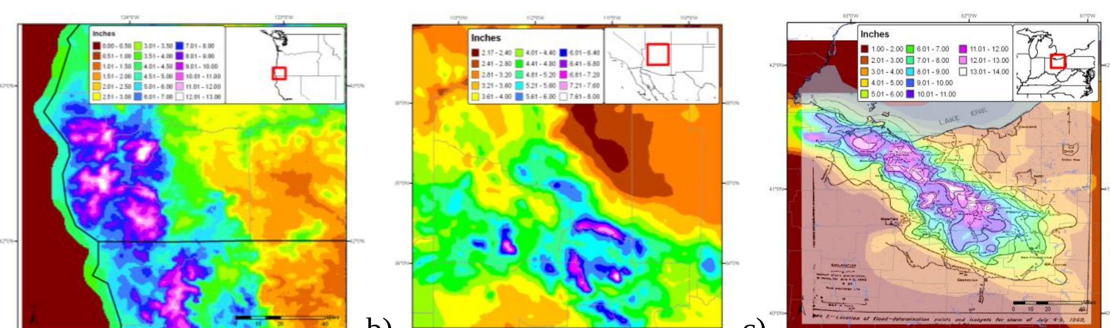

a) b) c)

Figure E.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 E.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.

NEXRAD Coverage Below 10,000 Feet AGL

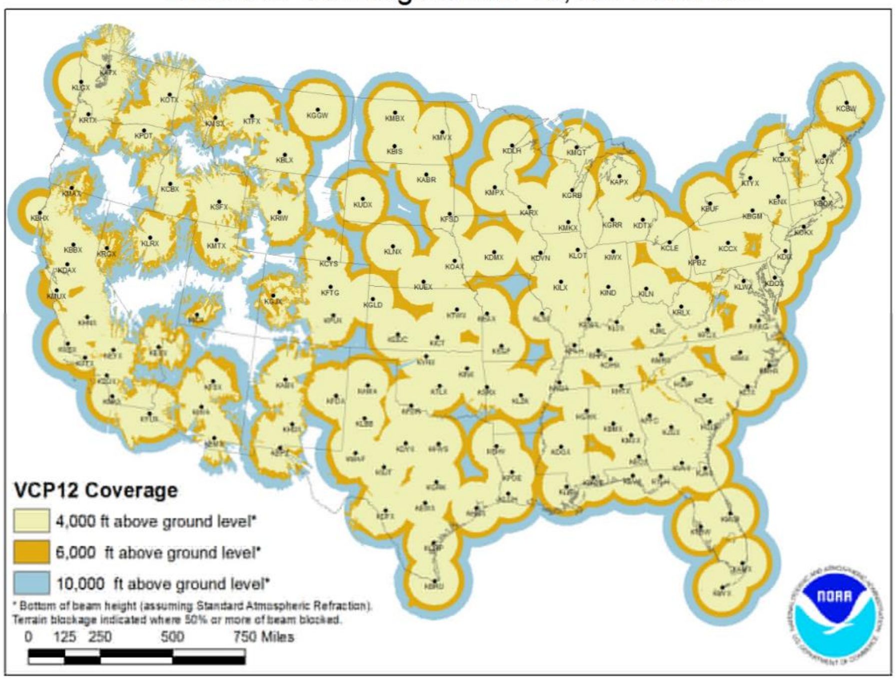


Figure E.3: U.S. radar locations and their radial extents of coverage below 10,000 feet above ground level (AGL). Each U.S. radar covers an approximate 285 mile radial extent over which the radar can detect precipitation.

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, and 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 DEM 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 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 E.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 E.4(b) 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 ~1/3rdmi^2 for processing in SPAS.

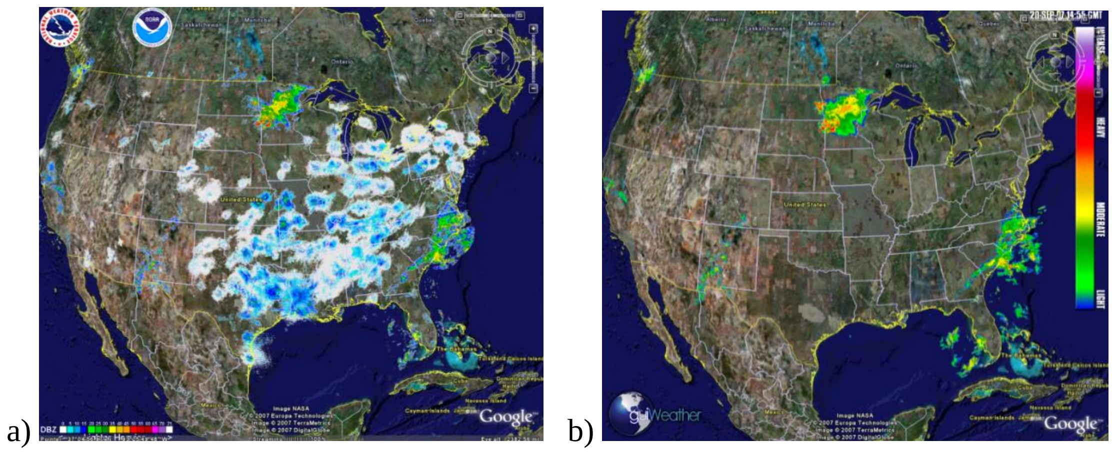


Figure E.4: (a) Level-II radar mosaic of CONUS radar with no quality control, (b) WDT quality controlled Level-II radar mosaic

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 E.5.

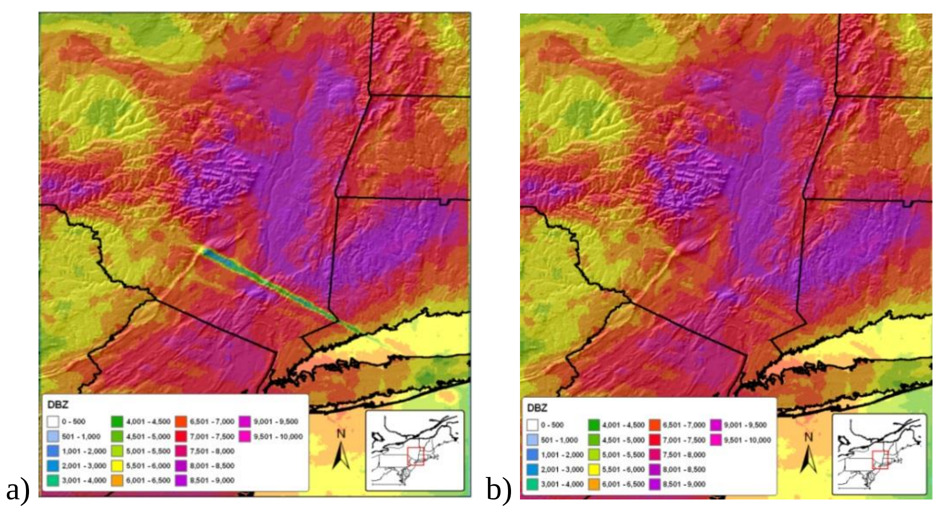


Figure E.5: Illustration of SPAS-beam blockage infilling where (a) is raw, blocked radar and (b) is filled for a 42-hour storm event

Methodology

Daily and Supplemental Precipitation to Hourly

To obtain one hour temporal resolutions and utilize all gauge data, it is necessary to disaggregate 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. Hourly Pseudo stations add additional detail on the timing of rainfall, either from COOP forms, radar reflectivity timing, and/or bucket survey reports with time increments. Hourly Pseudo stations are used only for the timing surrounding daily and supplemental stations and not for the magnitude. The limitations of Hourly Pseudo stations is that they are based on surrogate information, the quality of the information can be highly questionable (based on source) thus the importance of the station QC procedures are extremely important. 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 E.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 E.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 E.7 for an example.

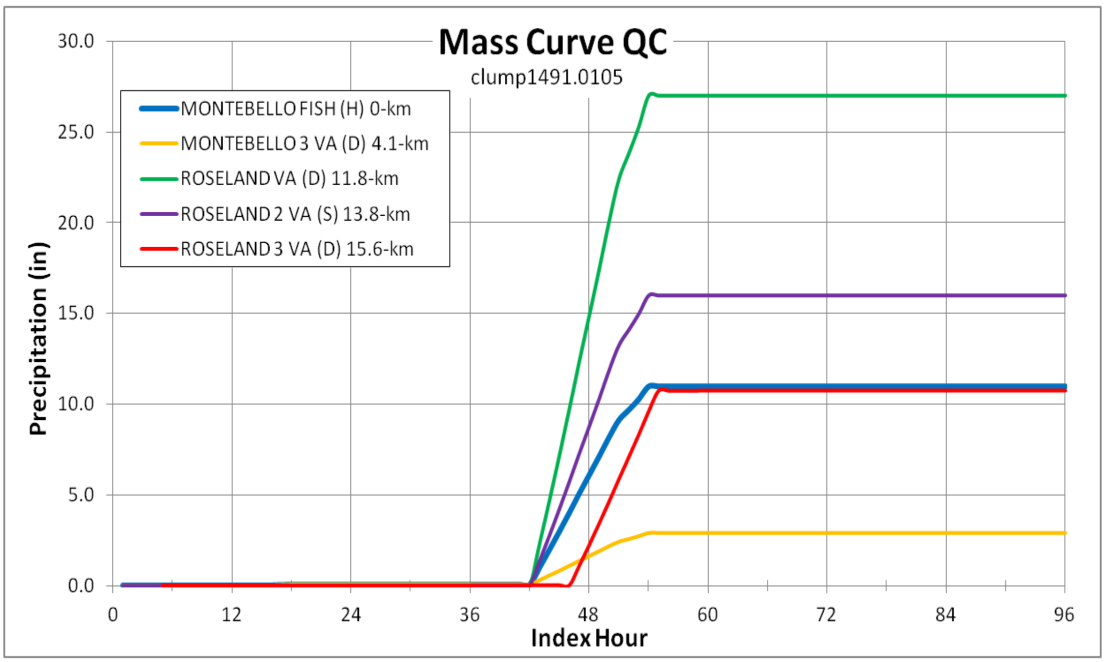


Figure E.7: Sample mass curve plot depicting a precipitation gauge with an erroneous observation time (red line). X-axis is the SPAS index hour and the y-axis is inches. The statistics in the upper left denote gauge type, and distance from target gauge (in km). In this example, the daily gauge (red line) was found to have an observation error/shift of 6-hours.

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 DEM 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 E.8 depicts the results of each spatial interpolation methodology based on the same precipitation gauge data.

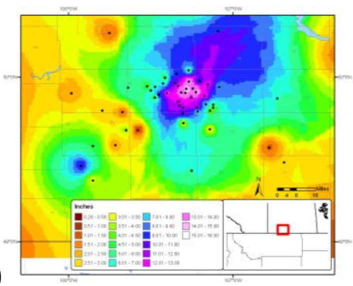
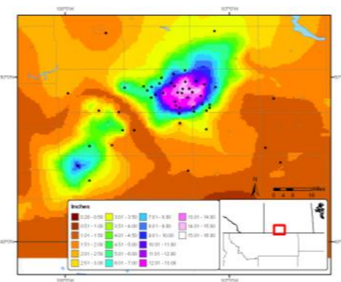
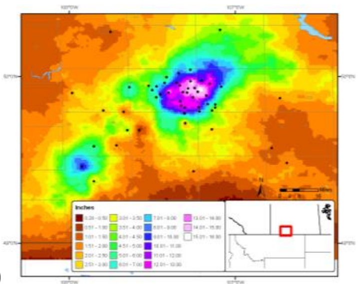
a) 
b) 
c) 

Figure E.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. The SPAS general code is where the daily and supplemental station are timed to hourly data. Therefore, to get the correct timing of daily and supplemental stations, SPAS general needs to be run. The timed hourly data are used as input into SPAS-NEXRAD to derive the dynamic ZR relationship each hour.

Basemaps are only used to aid in the spatial interpolation. In regards to SPAS-NEXRAD, a basemap is used to interpolate the radar residuals (bias adjustments).

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 E.9).

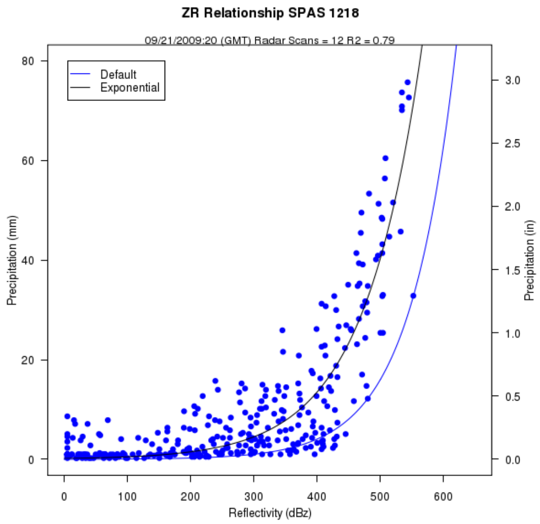


Figure E.9: Example SPAS (denoted as "Exponential") vs. default Z-R relationship (SPAS #1218, Georgia September 2009)

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 E.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 E.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 E.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.

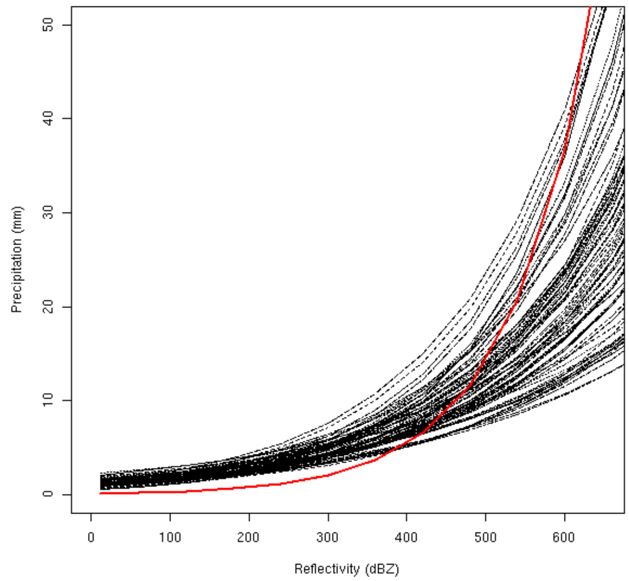


Figure E.11: Comparison of the SPAS optimized hourly Z-R relationships (black lines) versus a default Z=75R2.0 Z-R relationship (red line) for a period of 99 hours for a storm over southern California.

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 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 E.12 illustrates the evolution of final precipitation from radar reflectivity in an area of complex terrain in southern California.

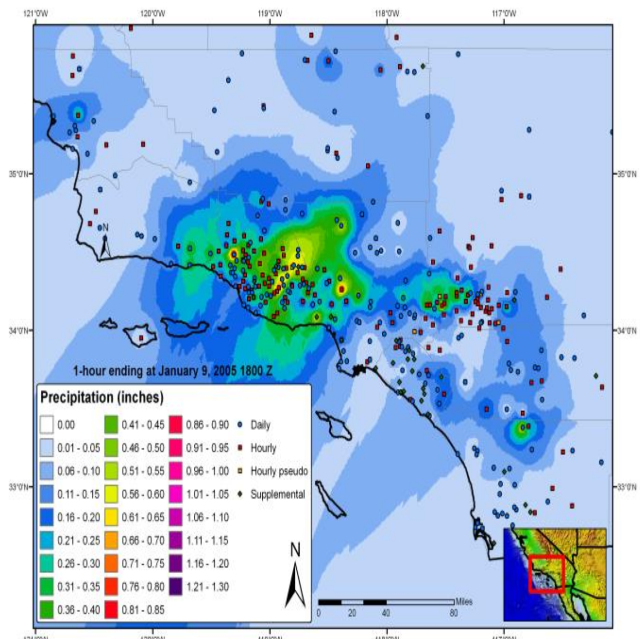


Figure E.12a: Map depicting 1-hour of precipitation utilizing inverse distance weighting of gauge precipitation for a January 2005 storm in southern California, USA

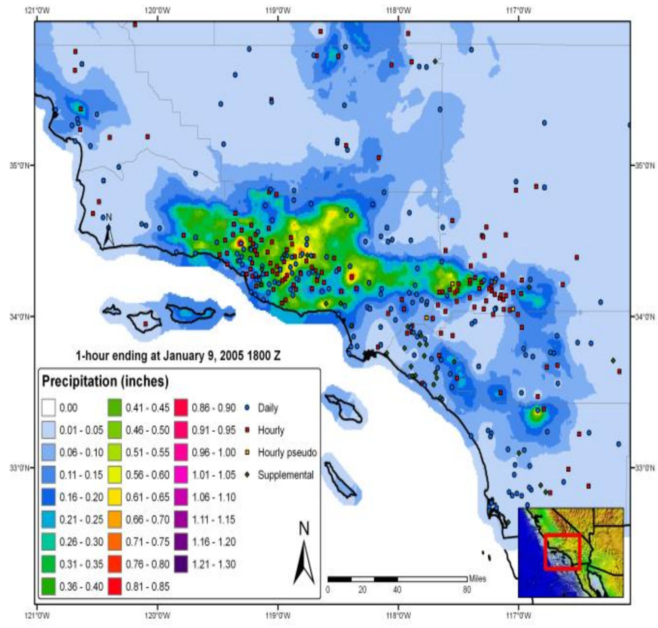


Figure E.12b: Map depicting 1-hour of precipitation utilizing gauge data together with a climatologically-aided interpolation scheme for a January 2005 storm in southern California, USA

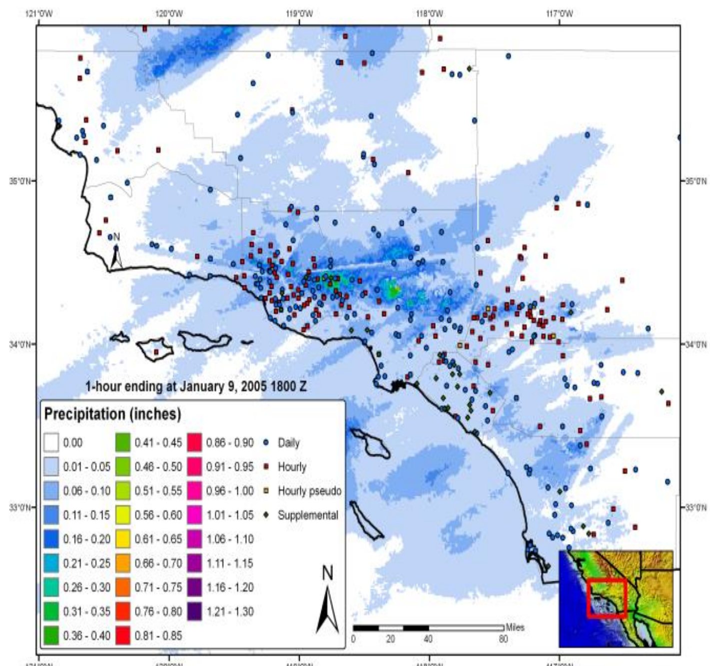


Figure E.12c: Map depicting 1-hour of precipitation utilizing default Z-R radar-estimated interpolation (no gauge correction) for a January 2005 storm in southern California, USA

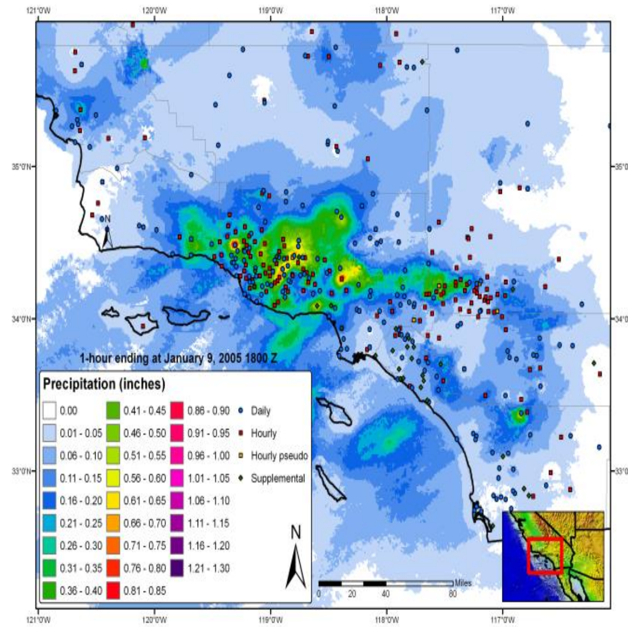


Figure E.12d: Map depicting 1-hour of precipitation utilizing SPAS precipitation for a January 2005 storm in southern California, USA

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).

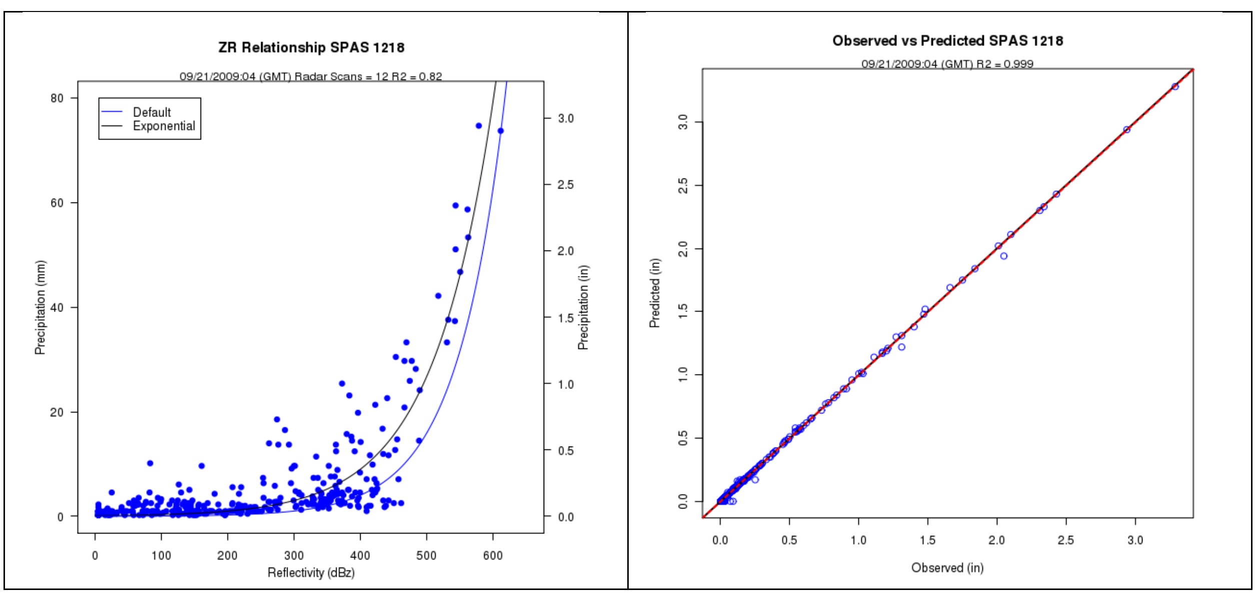


Figure E.13: Z-R plot (a), where the blue line is the SPAS derived Z-R and the black line is the default Z-R, and the (b) associated observed versus SPAS scatter plot at gauge locations.

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 E.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 km^2, whereas a standard rain gauge has an opening 8 inches in diameter, hence it only samples approximately $8.0x10^{-9}$ km^2. Furthermore, the radar data represent an average reflectivity (Z) over the grid cell, when in fact the reflectivity can vary across the 1 km^2 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 R_{spas} using the default Z-R relationship $Z=300R^{1.4}$. Higher calibration errors will result in higher R_{spas} 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 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 E.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.

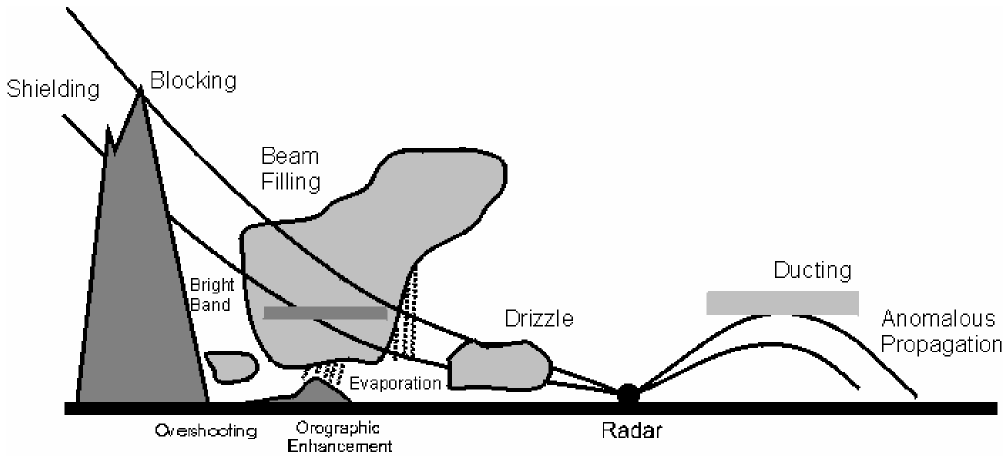


Figure E.14: Depiction of radar artifacts. (Source: Wikipedia)

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 grid-cell 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 grid-cell 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 grid-cell. In general, when the gauge and grid-cell 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 grid-cell value equal to the observed value. Sometimes simply shifting the gauge location to an adjacent grid-cell resolves the problems. Regardless, a large gauge versus grid-cell 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 E.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 mi^2)

    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 mi^2)

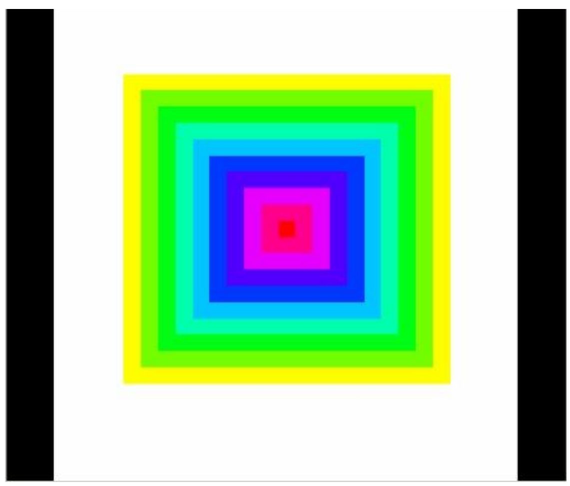


Figure E.15: "Pyramidville” Total precipitation. Center = 1.00”, Outside edge = 0.10”

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 E.16).

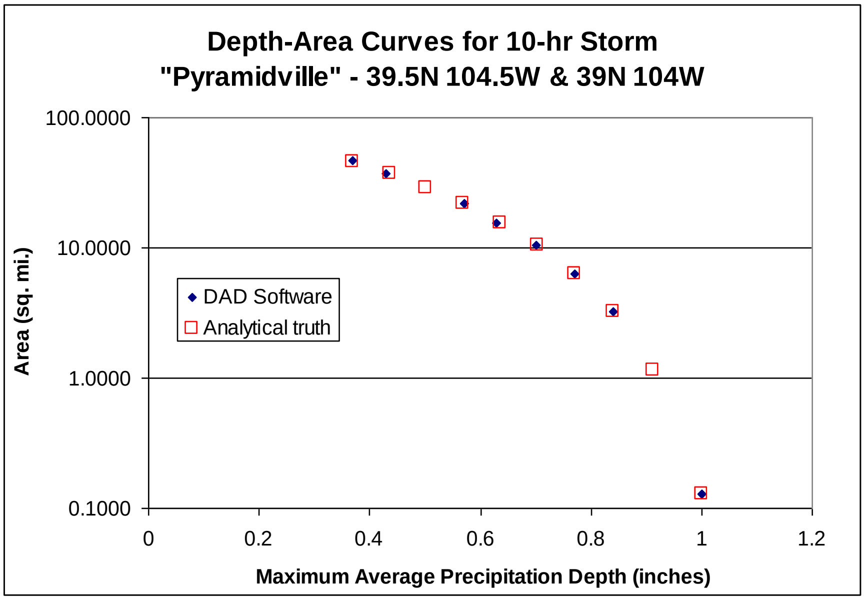


Figure E.16: 10-hour DA results for "Pyramidville"; truth vs. output from DAD software

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 E.2).

Table E.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 E.3).

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

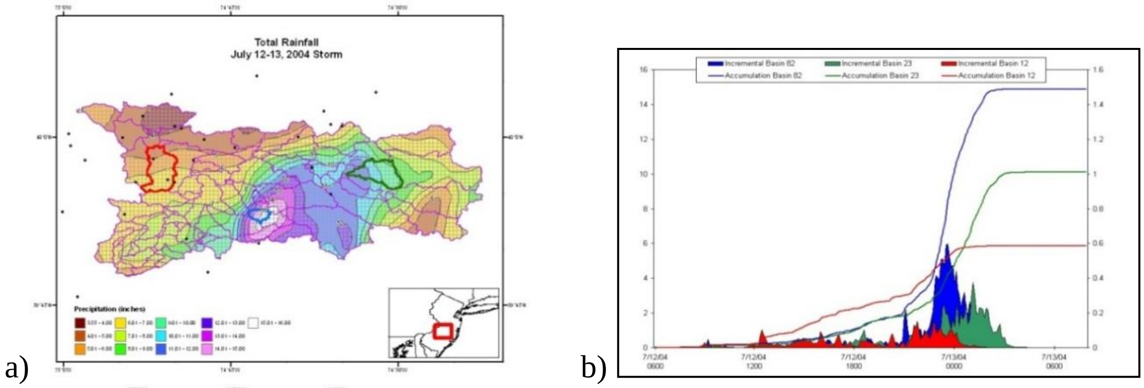
% Difference

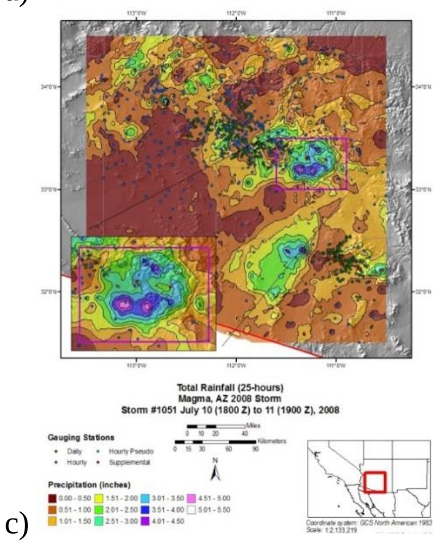
	Duration (hours)							
Area (sq. mi.)		6	12	24	36	48	60	total
10		2%	3%	0%	1%	-1%	0%	2%
100		-5%	2%	4%	-2%	-6%	-4%	-3%
200		-6%	1%	1%	-4%	-7%	-5%	-5%
1000		-4%	-2%	1%	-6%	-7%	-6%	-3%
5000		3%	2%	-3%	-3%	-5%	-5%	0%
10000		4%	9%	-5%	-4%	-7%	-5%	1%
20000		7%	12%	-6%	-3%	-4%	-3%	3%

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 E.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 E.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).





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	2.45	4.77	7.85	11.89	14.88	17.31	17.55	18.19	18.26	18.26
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

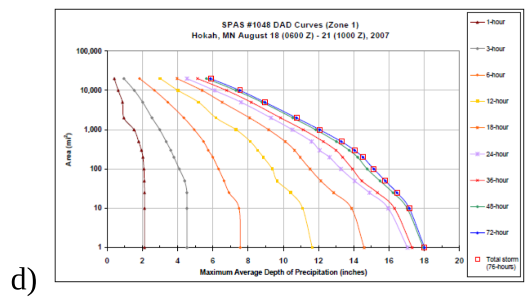


Figure E.17: Various examples of SPAS output, including (a) total storm map and its associated (b) basin average precipitation time series, (c) total storm precipitation map, (d) depth-area-duration (DAD) table and plot

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 F
Storm Data (Separate Binding)

Appendix G
Hydrologic Validation of July 1942 Smethport Flood

Commonwealth of Pennsylvania
Probable Maximum Precipitation Study

Watershed Analysis and Flood Validation of the July 1942 Smethport Extreme Rainfall Event

Technical Report

Revision 1
April 5, 2019

Supporting

Applied Weather Associates, LLC
appliedweatherassociates.com

Prepared by

Aterra Solutions, LLC
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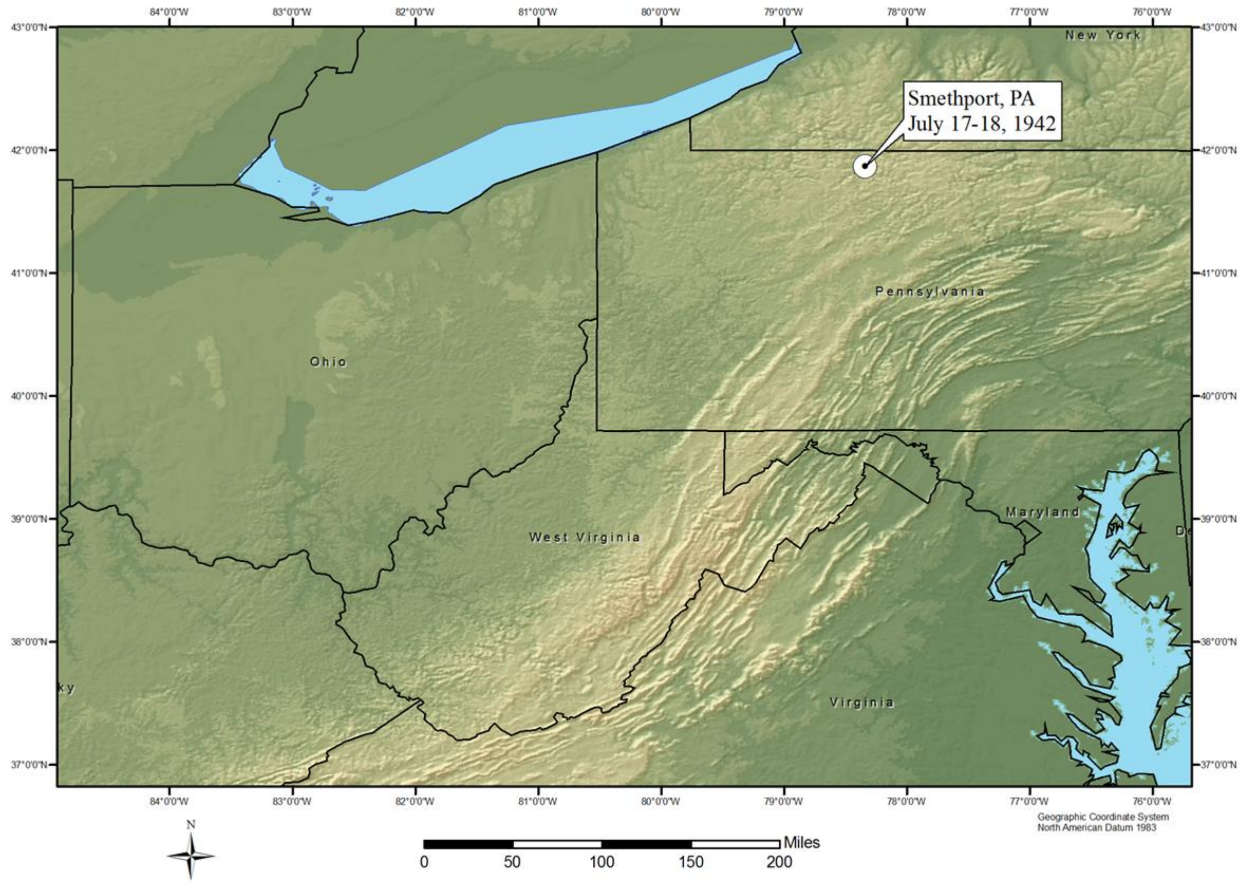
1 Purpose and Background

The Division of Dam Safety, Pennsylvania Department of Environmental Protection (PA DEP), sponsored a Probable Maximum Precipitation (PMP) Study for the Commonwealth of Pennsylvania, led by Applied Weather Associates (AWA). Without an updated study, PMP data are typically obtained from one or more of a series of Hydrometeorological Reports (HMRs) prepared by the National Weather Service (NWS). Areas of the United States east of the 105th meridian are covered by HMR 51 (Schreiner, 1978), which provides generalized depth-area-duration PMP data; with additional generalized temporal and spatial formation in HMR 52 (Hansen, 1982). The outcome of the updated PMP study will enable users in Pennsylvania, many of whom are dam owners, to access site-specific hourly PMP data for areas as small as 1 km^2 to evaluate the impact of the Probable Maximum Flood (PMF) on critical infrastructure (existing or planned), particularly high-hazard dams. The Pennsylvania PMP study uses a storm-based method to transposition and maximize extreme rainfall events in the region to create an envelope of depth-area-duration relationships unique to specific locations in the Commonwealth. Because it is storm-based, PMP depths for Pennsylvania, and much of the larger region covered by HMR 51, are greatly influenced by the exceptional magnitude of a storm that occurred on July 18, 1942 in the region of McKean County (PA), Potter County (PA), and Cattaraugus County (NY). The storm-center occurred in the Smethport/Port Allegany region McKean County, PA. See Figure 1.

Figure 1. Location of July 1942 Storm Center



According to the National Oceanic and Atmospheric Administration (NOAA), the "Smethport" Storm of July 18, 1942, was a world-record setting event for the 3- and 4.5-hour durations at 28.5 and 30.8 inches, respectively (National Oceanic and Atmospheric Administration, 2017). See Figure 2. A significant number of rainfall observations were reported; however, most were unofficial "bucket surveys" (Eisenlohr, 1952) that have uncertainties in the total reported rainfall and limited temporal information. See Figure 3 for the locations of the hourly gauges in the storm region and Figure 4 for all of the observation points (including bucket surveys) in the study area and vicinity of the storm center. As shown in Figure 5 through Figure 7, the hourly gauges in the areas surrounding the storm center near Smethport and Port Allegany show an initial intense burst of rain near midnight of July 18, 1942 followed by lower intense rainfall then a second significant rainfall period. (Note that midnight of July 18, 1942 corresponds to the end of Index Hour 47 on the hyetographs.) While significant number of total rainfall depths were recorded, including the "bucket surveys", only the scattered hourly gauges shown in Figure 3 and Figure 4 were available to provide temporal information.

Figure 2. Greatest Observed Point Precipitation Values for the World (National Oceanic and Atmospheric Administration, 2017)

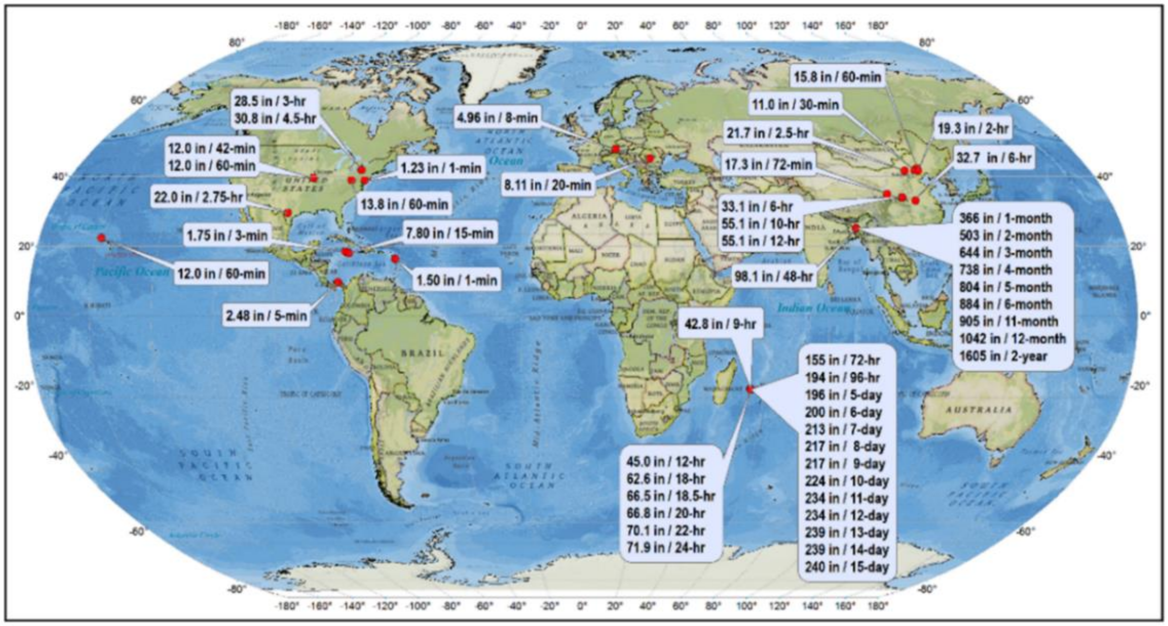


Figure 3. Location of Hourly Rain Gauges in Storm Region New York/Pennsylvania Border

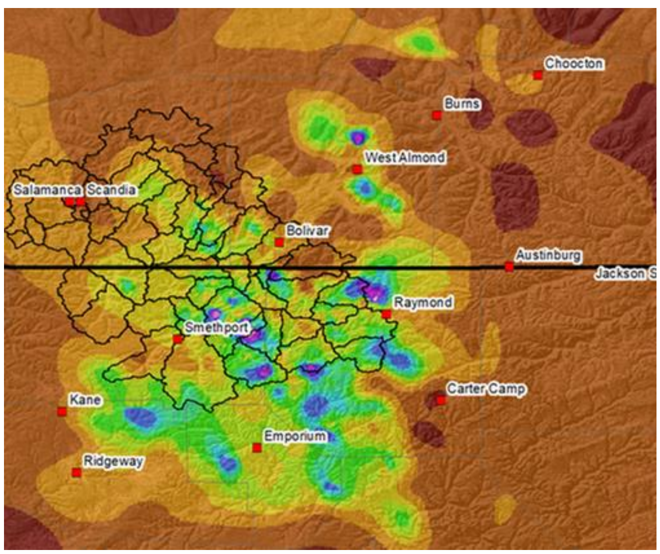


Figure 4. All Rain Gauges in Study Area and Vicinity of Storm Center

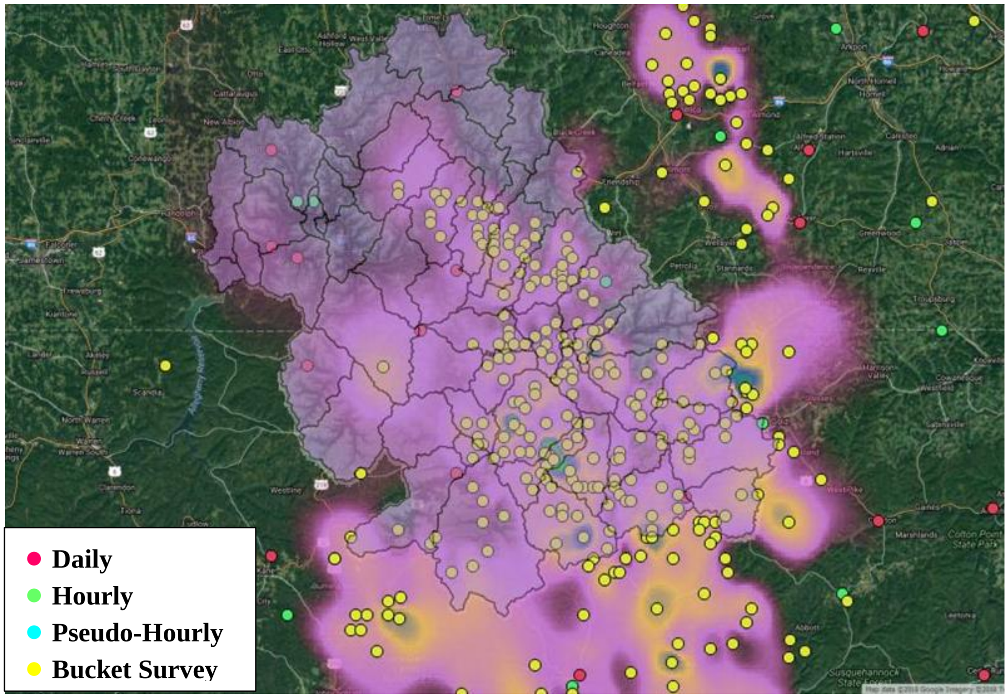


Figure 5. Rainfall Hyetograph at Smethport Hourly Gauge

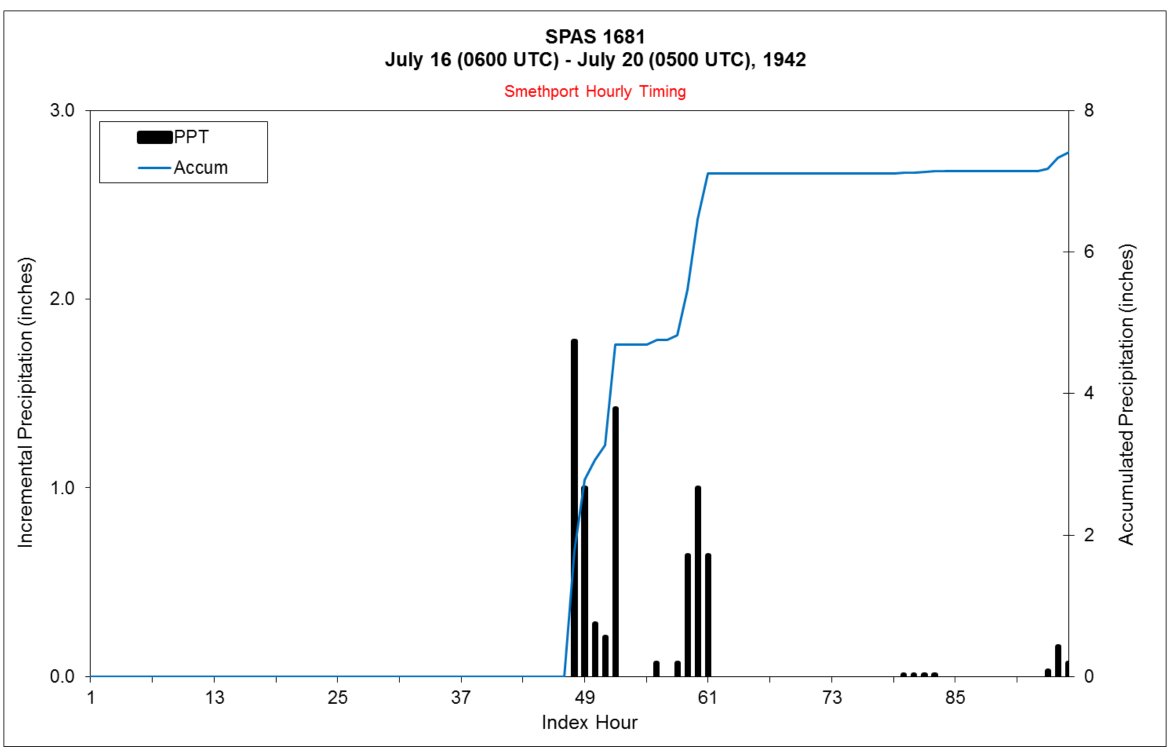


Figure 6. Rainfall Hyetograph at Bolivar Hourly Gauge

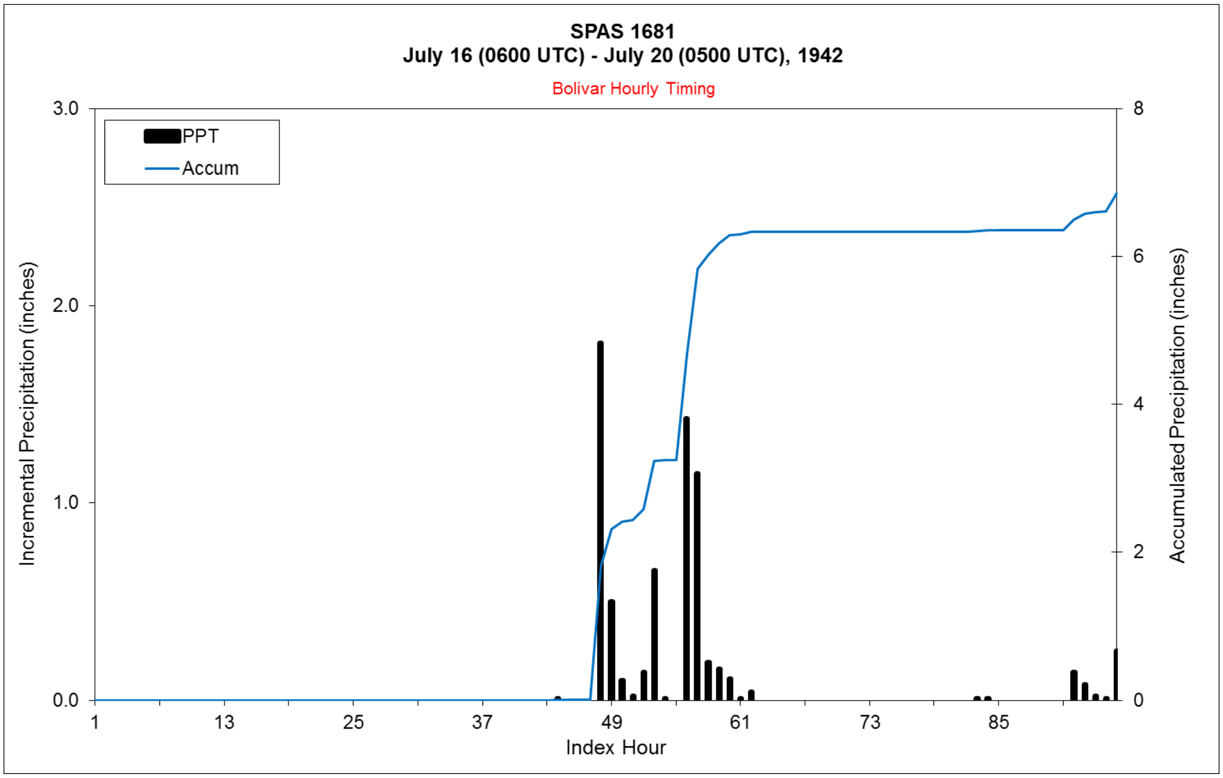
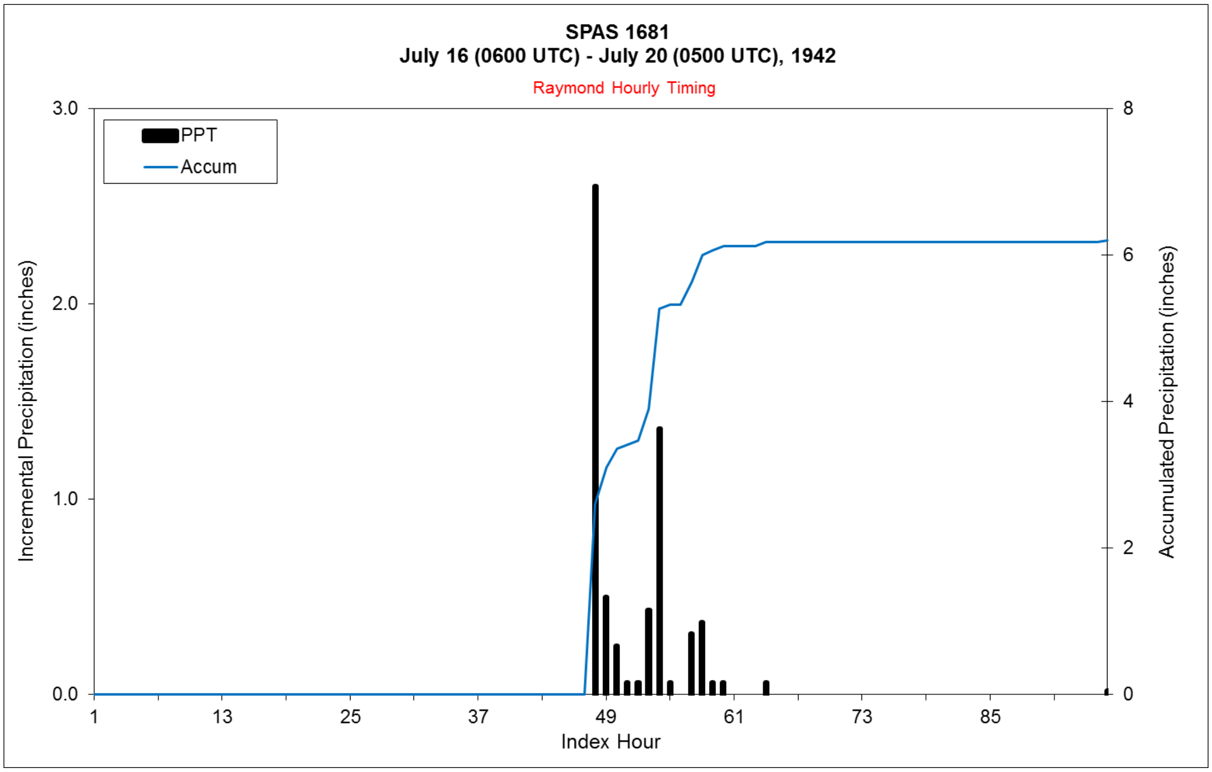


Figure 7. Rainfall Hyetograph at Raymond Hourly Gauge



The focus of this study was on the characteristics of the July 1942 storm and the flood analysis that provided additional insights on the storm's rainfall accumulation patterns and magnitude, utilizing the immense amount of rain gauge observational data and post-flood high-water and peak flow measurements. As discussed previously, many of the rainfall observations are from unofficial "bucket survey" sources, which lack spatial coverage and temporal accumulation information, especially at the hourly level. The hydrologic information provides a way to back-calculate many of the of the unknown rainfall accumulation characteristics that are not captured by the rainfall observations, which were analyzed using AWA's Storm Precipitation Analysis System (SPAS). The outcome of the flood analysis was to substantiate the recorded rainfall or identify, isolate, and quantify observational uncertainties in the recorded rainfall and develop rainfall depth, spatial, and/or temporal patterns that better match observed flood data. The quality and accuracy of the rainfall data was not pre-judged; the flood analysis was conducted to be unbiased and reveal areas where improved accuracy to rainfall magnitude, temporal, and/or spatial patterns can be achieved. The ultimate result of this improved rainfall analysis would be a more accurate representation of the July 1942 rainfall in time, space, and magnitude. This would result in a more accurate estimation of PMP depths and PMF analyses.

2 Flood Model

2.1 Domain

The location of the heaviest rainfall (the storm center) during the July 1942 storm is located in the Upper Allegheny River Watershed, just upstream of the Allegheny Reservoir. The heaviest and most intense rainfall occurred over the Borough of Port Allegany, PA. The storm produced the largest discharges on record at several locations in the upper portions of the Allegheny River, Clarion River, and Sinnemahoning Creek watersheds; shown by the Hydrologic Unit Code Level 8 (HUC-8) watershed boundaries on Figure 8. Discharges diminished in the lower reaches of major streams. See peak flow summary in Table 1 and Figure 9 through Figure 14.

The domain of the flood models focused on the drainage area affected by Port Allegany and surrounding areas and is defined by the Allegheny River 1,780 mi^2 watershed at Red House, NY (discontinued gauge number 03011500). See Figure 15. The location of the Red House gauge moved in October 1964 to its current location in Salamanca, NY, with a gauge number 03011020. The current gauge 03011020 maintains the systematic record prior to October 1964. Review of streamflow gauge records in the region indicate that the July 1942 flood was particularly significant for watersheds less than 500 mi^2, approximately corresponding to the Borough of Eldred, PA and USGS gauge number 03010500 along the Upper Allegheny River.

Figure 8. HUC-8 Watersheds

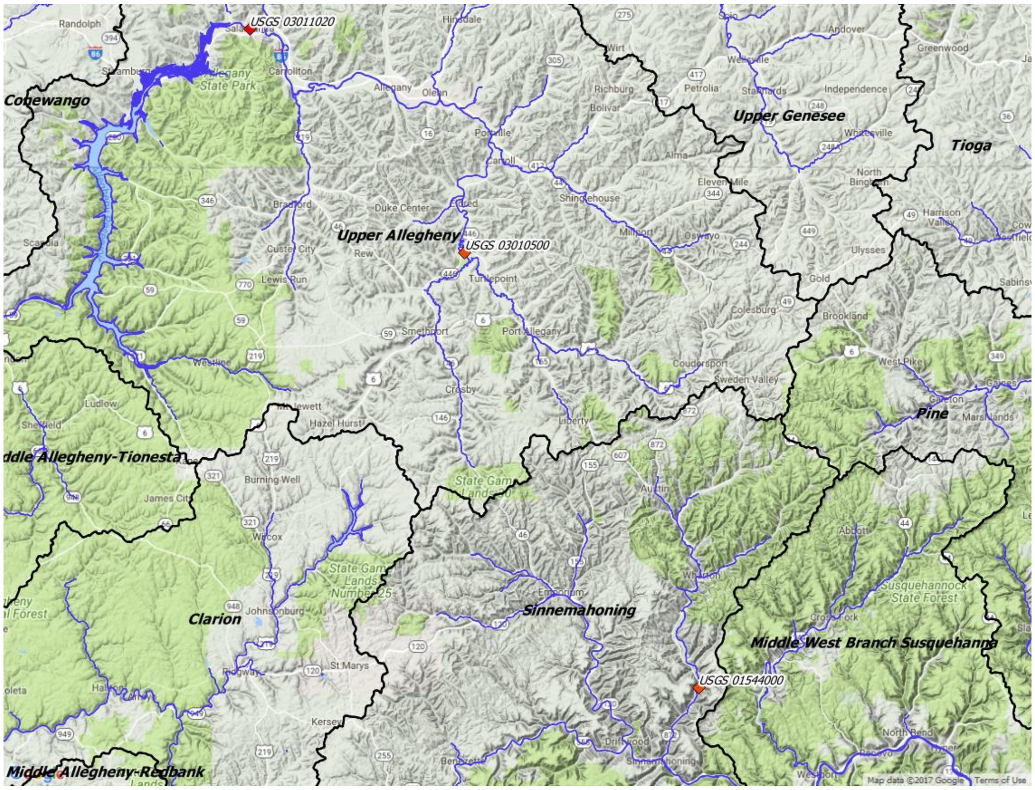


Figure 9. USGS 03011020 Allegheny River at Salamanca, NY (1,608 mi²)

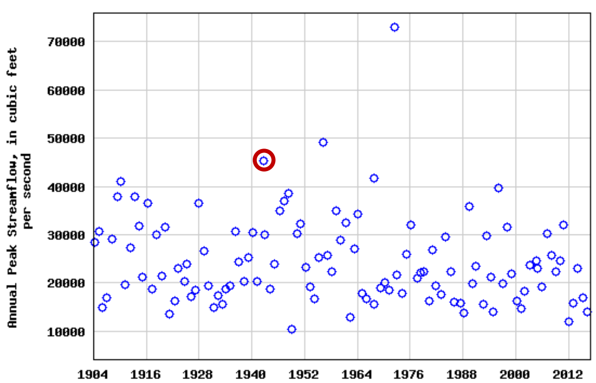


Figure 11. USGS 03010500 Allegheny River at Eldred, PA (550 mi²)

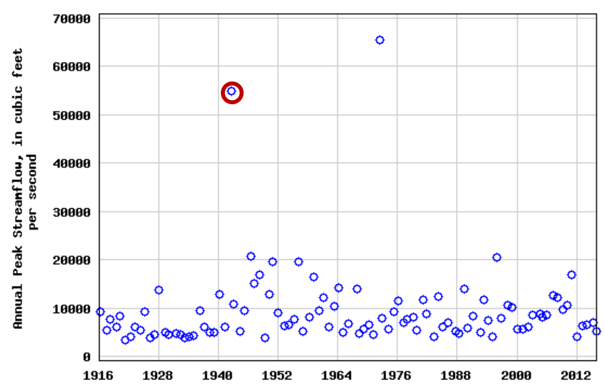


Figure 10. USGS 01543500 Sinnemahoning Creek at Sinnemahoning, PA (685 mi²)

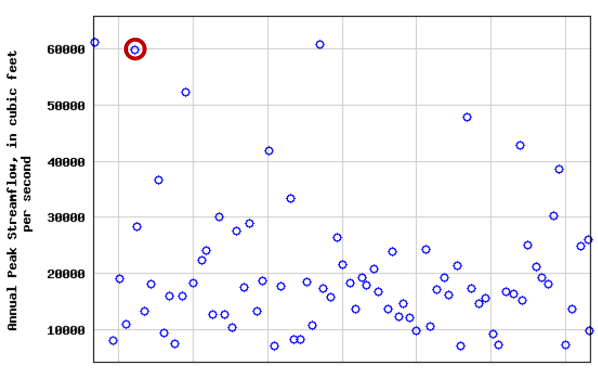


Figure 12. USGS 01543000 Driftwood Bridge Sinnemahoning Creek at Sterling Run, PA (272 mi²)

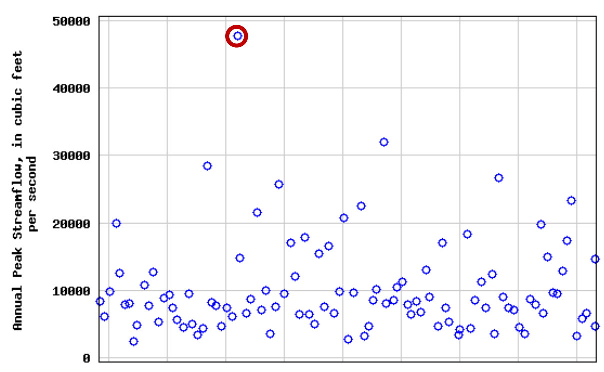


Figure 13. USGS 01544000 1st Fork Sinnemahoning Creek near Sinnemahoning, PA (245 mi^2)

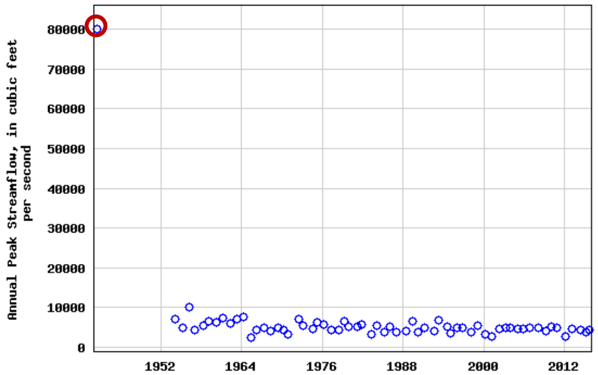


Figure 14. USGS 03007800 Allegheny River at Port Allegany, PA (248 mi^2)

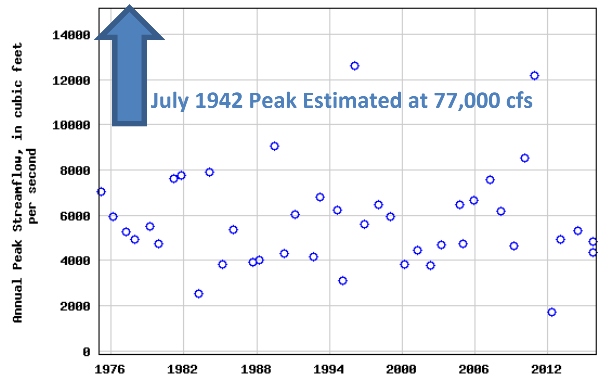
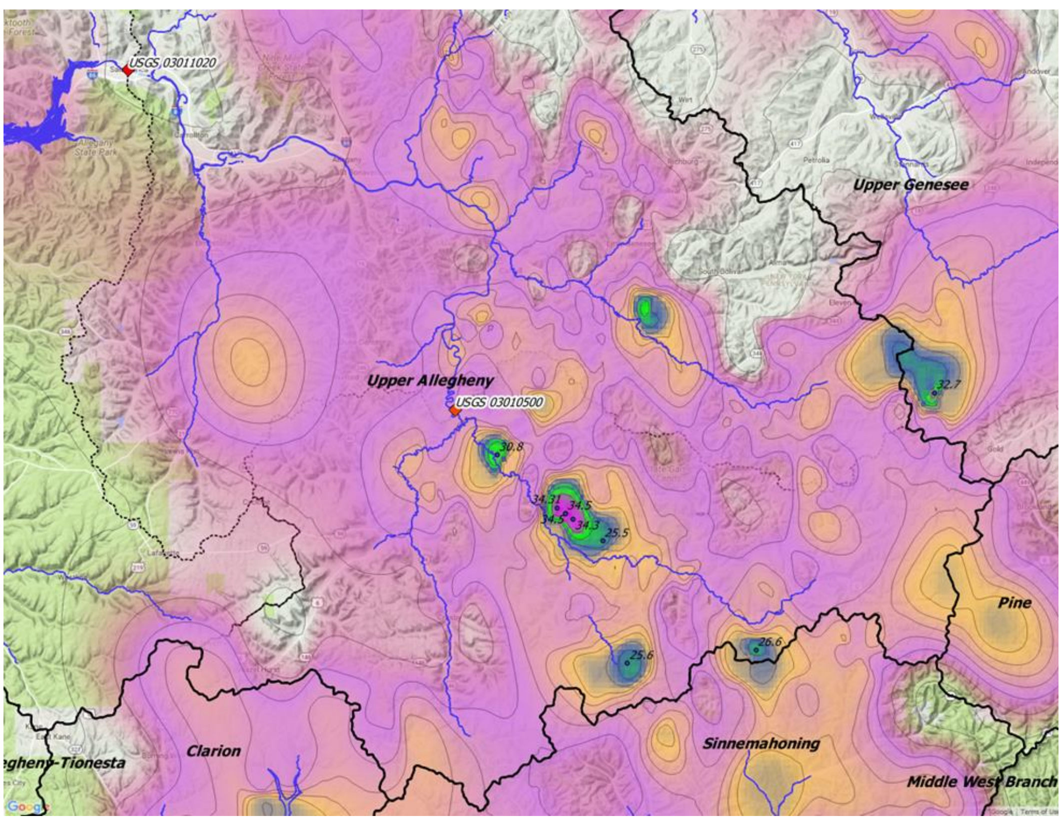


Table 1. Peak Flow Summary

Location	Drainage Area (mi^2)	Peak Flow (cfs)	Unit Peak Flow (cfs/mi^2)
Port Allegany, PA	251	77,000	307
Eldred, PA	549	55,000	100
Olean, NY	1,167	44,000	38
Red House, NY	1,780	45,300	25

Figure 15. July 1942 Storm Pattern and Flood Model Domain



2.2 Description

The flooding analysis of the 1,780 mi^2 watershed was accomplished using complementary models designed to make optimal use of current computational capacity. The entire study domain, to Red House, NY, was modeled with the USACE's HEC-HMS Version 4.2 software using the Runoff Curve Number (RCN) approach for loss/retention estimation and the Snyder Unit Hydrograph for runoff transformation. As part of the calibration process, the Unit Hydrograph in the HEC-HMS model was adjusted to reconcile the hydrograph from the 2D hydrologic/hydraulic models (discussed further below) and account for a non-linear watershed response in the calibration events. Distributed, 2-dimensional (2D) watershed models were developed for three (3) sub-watersheds within the study domain: Upper Allegheny River watershed Port Allegany, PA (250 mi^2); Oswayo Creek watershed to its confluence with the Allegheny River (248 mi^2); and Tunungwant Creek watershed to its confluence with the Allegheny River (169 mi^2). These are the sub-watersheds, particularly the watershed to Port Allegany, where the most extreme rainfall measurements were recorded. A distributed 2D modeling approach has advantages over conventional lumped and semi-distributed hydrologic models. The distributed 2D modeling approach is more physically-based, making it flexible in modeling hydrologic and hydraulic responses to rainfall events of various magnitudes, intensities, spatial distributions, and temporal distributions. The 2D approach was chosen where the more concentrated rainfall occurred. Another important consideration in using the 2D approach is it reduces concerns over the application of generic non-linearity Unit Hydrograph adjustments in the HEC-HMS model, which introduces an unknown level of inaccuracy. Saghafian (Saghafian, 2006) provides additional discussion regarding non-linearity characteristics of Unit Hydrographs. Mesh sizes were kept relatively small (25 ft to 60 ft, with an average distance between the mesh nodes of 46 ft) to maintain accuracy, particularly to limit artificial retention of runoff in the watershed. This mesh size limitation made the 2D model computationally impractical for the entire 1,780 mi^2 watershed.

The computer software chosen to provide the distributed 2D watershed simulation was RiverFlow2D, developed by Hydronia, LLC. As stated in the Reference Manual, RiverFlow2D is a "combined hydrologic and hydraulic, mobile bed and pollutant transport finite-volume model for rivers, estuaries and floodplains. The model can integrate hydraulic structures such as culverts, weirs, bridges, gates and internal rating tables. The hydrologic capabilities include spatially distributed rainfall, evaporation, and infiltration." RiverFlow2D solves the shallow water equations (depth averaged/vertical integration of the Navier-Stokes equation) using a finite-volume scheme and, therefore, does not rely on the lumped unit hydrograph approach to estimate flow rates over time (hydrographs). Each triangulated mesh element is assigned individual parameters (rather than homogenous parameters for each sub-basin). Bed stresses use Manning friction law; turbulence and energy losses are implicit in the Manning n-value. Hydrologic capabilities include spatially distributed rainfall, evaporation, and infiltration.

Downstream of Port Allegany PA, 2D hydraulic modeling was also performed along the main-stem Allegheny River using USACE HEC-RAS (Version 5.0.5). The HEC-RAS2D model extended upstream along unnamed and named Allegheny River tributaries, including Potato Creek, Cole Creek, Oswayo Creek, Olean Creek, and Tunungwant Creek, to account for the effects of backwater on flood attenuation. Outflow hydrographs from each HEC-HMS sub-watershed were directly linked, via the HEC-HMS DSS file, to the HEC-RAS2D model along external inflow boundaries with one exception; the outflow hydrograph from the Upper Allegheny RiverFlow2D model (at Port Allegany) was a manual input to HEC-RAS2D at the upstream inflow boundary. HEC-HMS parameters, specifically RCN and Snyder Parameters, were adjusted in the Oswayo Creek and Tunungwant Creek watershed models to achieve a good hydrologic match with RiverFlow2D. The HEC-RAS2D model provided the ability to more accurately account for river and floodplain attenuation and flood profile data for comparison with high-water observations. See Figure 16 and Figure 17 for an illustration on how the HEC-HMS and 2D models relate to cover the watershed.

Figure 18 and Figure 19 show the land use and hydrologic soil groups in the model domain, respectively. Note the apparent discrepancy in hydrologic soil groups (HSG) between PA and NY shown in Figure 19. This is addressed further in Section 2.4.1. Table 2 summarizes the input data collected for the models.

Figure 16. HEC-HMS Model Schematic

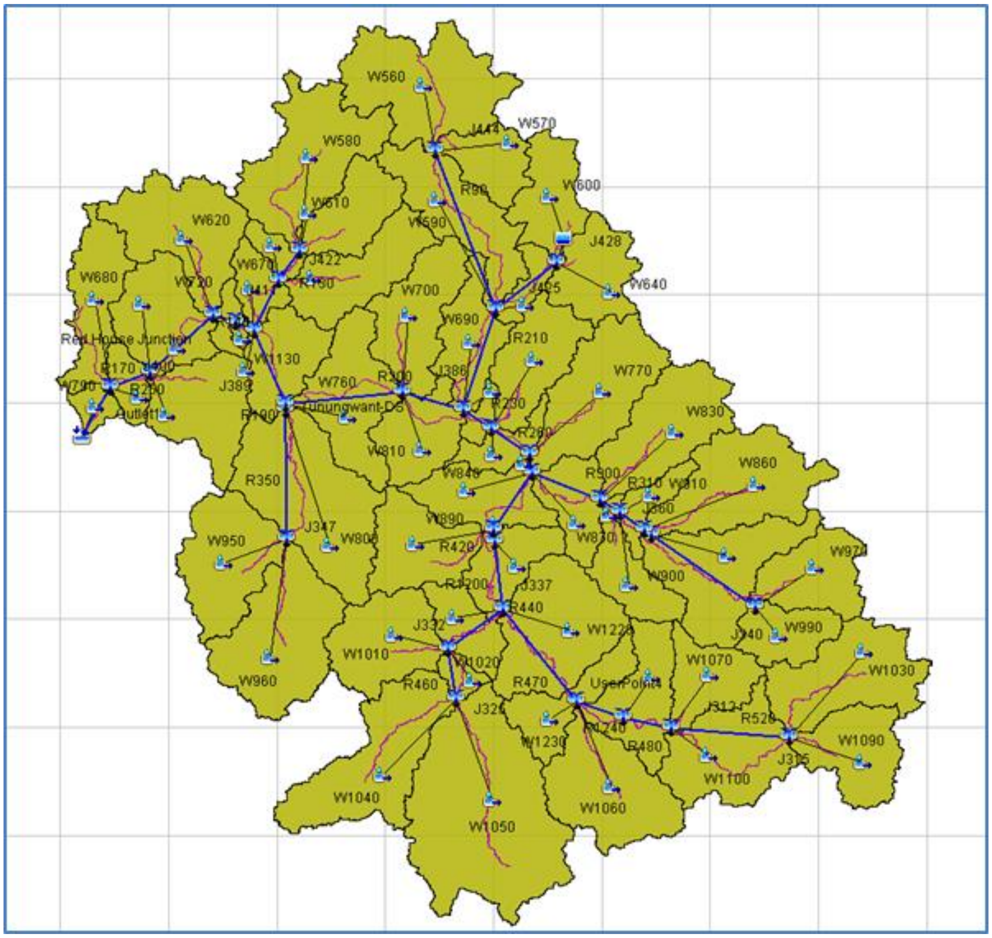


Figure 17. Areas Covered by 2D Models

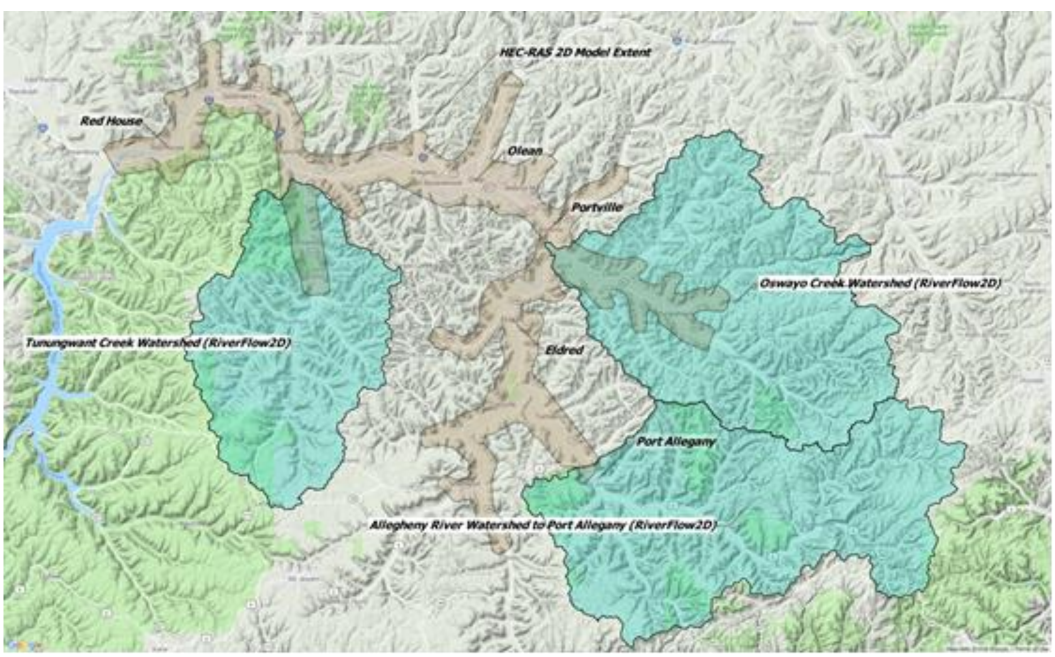


Figure 18. Overview of Land Use

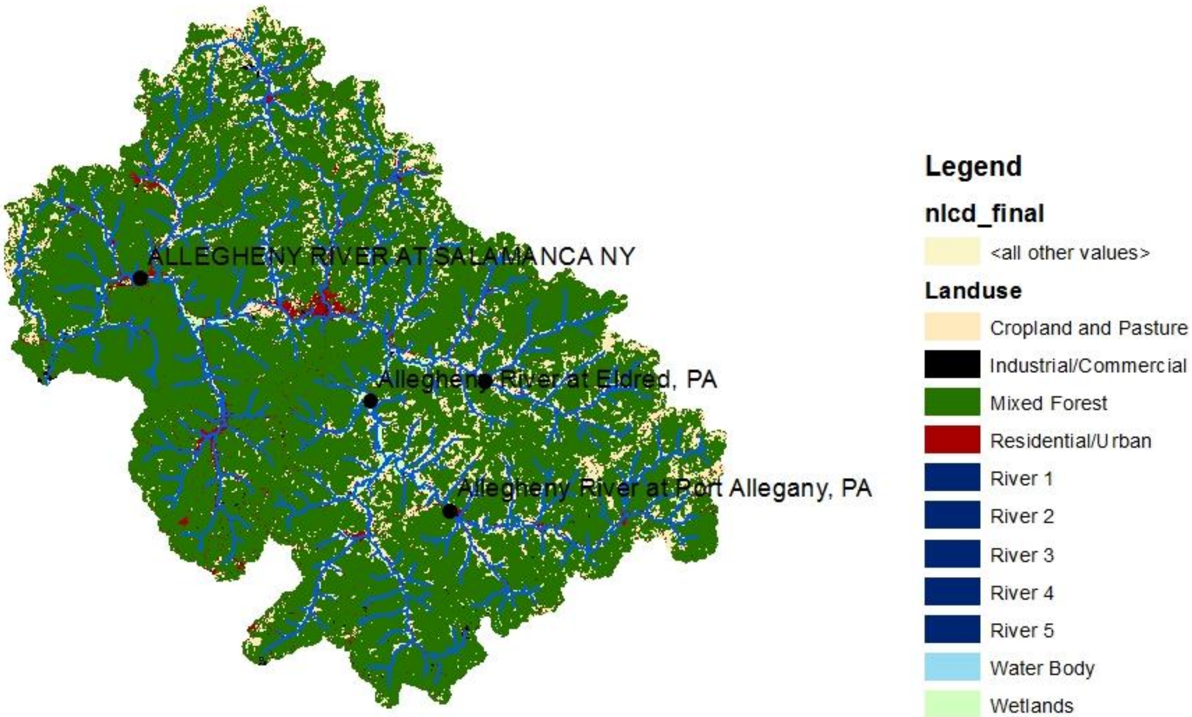


Figure 19. Hydrologic Soil Groups

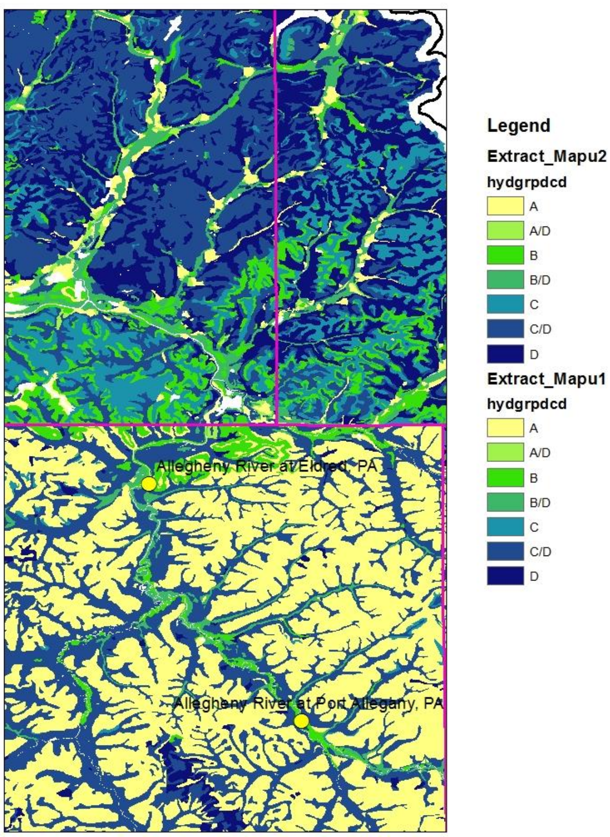


Table 2. Input Data for the Hydrologic Models

NED elevation data	https://nationalmap.gov/3dep_prodserv.html	Primarily NY DEM
Lidar (PA only)	www.pasda.psu.edu	DEM for PA
1m DEM	LiDAR (PA) and NED (NY)	this is a composite data set of LiDAR and resampled NED from NY.
Buffer of watershed for clipping	HUC 10 plus buffer	Primarily reference
Historical land use (poly)	https://water.usgs.gov/GIS/dsdl/ds240/index.html	Will be used for Agnes storm modeling
NLCD land cover	https://www.mrlc.gov/nlcd2011.php	Ivan storm modeling
HUC 10 & 8 watershed boundaries	https://datagateway.nrcs.usda.gov/	Primarily reference
NHD Streams	https://nhd.usgs.gov/data.html	Primarily reference
Streamgage data - U.S.	water.usgs.gov	Primarily reference
gssurgo data	https://datagateway.nrcs.usda.gov/	Soils Data for Curve Number
Current aerial photographs	www.pasda.psu.edu	For final mapping
Current aerial photographs	https://orthos.dhses.ny.gov/	For final mapping
Historical aerial photographs	www.pasda.psu.edu	For final mapping

2.3 Calibration

The 2D and HEC-HMS models were calibrated using three warm-season flood events in months with full vegetative growth to simulate canopy coverage comparable to July 1942. The September 2004 “Ivan” flood and June 2014 storms were selected as warm-season candidates and run through AWA’s SPAS program to produce the hourly gridded rainfall data. Using post-1996 storm events allows the use of the NEXRAD data, providing a more reliable and comprehensive understanding of the spatial and temporal distribution for the calibration storms. Combining the NEXRAD data with the stream gauge data from these events, processed through SPAS (in 1-hour 1 km2 gridded format), reduces uncertainty and improves the quality of the input data for the 2D and HEC-HMS models. In addition to post-1996 floods, the 1972 “Tropical Storm Agnes” flood was selected for calibration due to its significant effect on the region and availability of a substantial amount of reliable precipitation and flood data. Note that the June 2014 storm was only significant to Port Allegany and, thus, only used to validate the RiverFlow2D model. The results of the June 2014 analysis were similar to the September 2004 “Ivan” analysis and, therefore, are not provided in this report. As indicated in Table 3 and Table 4, all other post-1996 annual peaks occurred in months with potential rain/snowmelt combinations and/or periods with limited or no vegetation canopy.

Once the judgement was made that the RiverFlow2D model was reasonably reliable in hydrologically simulating watershed response, parameters were adjusted in the HEC-HMS model (particularly Curve Number and Snyder Unit Hydrograph (UH) parameters) to establish a match with RiverFlow2D. The rainfall patterns and calibration results for the 1972 (Agnes) and 2004 (Ivan) floods are provided in Figure 20 through Figure 28. Additional tabulation of observed and model data for the 1972 Agnes Flood is provided in Table 5.

It should be noted that, in calibrating the HEC-HMS model to the June 1972 "Agnes" flood, a discrepancy was identified between the USGS's and USACE's estimation of the actual peak flows at the Eldred PA gauge. The USGS's streamflow records (page 283 of the USGS Hurricane Agnes Report (USGS, 1975)) show a peak flow rate of 65,400 cfs, whereas the USACE reported a peak flow rate of 30,300 cfs in Table 2 of their 1974 Report (USACE, 1974). The USACE updated this flow to 35,500 cfs, as reported by FEMA in Section 2.3 of the Effective Flood Insurance Study (FIS) for McKean County PA (FEMA, 2016), which cites a 1976 report from the USACE (USACE, December 1976). It appears the USACE updated the original estimate of 30,300 cfs to 35,500 cfs based on a HEC-2 model developed for the FEMA FIS. Figure 24 shows the recorded USGS flows and approximated hydrograph from the USACE 1976 estimated peak flow. Iterations of the HEC-HMS model indicate that the USACE peak flow estimate is more plausible since a runoff volume estimated using the USGS streamflows exceed the rainfall volume estimate. Therefore, it was concluded that the HEC-HMS calibration should be based on a comparison with an estimated hydrograph that corresponds to the USACE peak flow of 35,500 cfs. See Figure 24 for the approximated hydrograph and HEC-HMS model hydrograph. Figure 24 also shows the hydrograph generated from a "profile line" created at the Eldred gauge in the HEC-RAS2D model, which shows a hydrograph that deviates from the approximated and HEC-HMS hydrographs. Hydrographs generated at selected locations in HEC-RAS2D generally compare well with observed at other locations. Therefore, given the uncertainties surrounding the streamflow estimates at the Eldred gauge, the discrepancies at the Eldred gauge were accepted for the purpose of this study. It is possible that the measured and modelled flows at Eldred are affected by backwater from the confluence between the Allegheny River and Cole Creek, located just downstream of the gauge and the Route 346 bridge.

Table 3. Annual Maximum Streamflow @ USGS 03007800, Allegheny R @ Pt Allegany, PA (248 mi^2)

Date	Annual Peak Discharge (cfs)
12/1/2010	12,200
1/26/2010	8,530
3/15/2007	7,560
11/30/2005	6,650
1/9/1998	6,480
9/18/2004	6,460
2/7/2008	6,170
1/24/1999	5,940
6/26/2014	5,300
1/31/2013	4,920
9/30/2015	4,820
1/14/2005	4,730
3/22/2003	4,670
3/9/2009	4,660
4/10/2001	4,460
10/1/2015	4,370
2/28/2000	3,840
5/14/2002	3,760
5/8/2012	1,740

Table 4. Annual Maximum Streamflow @ USGS 03010500, Allegheny R @ Eldred, PA (550 mi^2)

Date	Annual Peak Discharge (cfs)
12/2/2010	17,000
3/16/2007	12,600
2/8/2008	12,200
1/10/1998	10,700
1/27/2010	10,500
1/26/1999	10,100
3/11/2009	9,670
9/19/2004	8,800
3/23/2003	8,610
12/1/2005	8,560
1/15/2005	8,110
4/11/2015	6,890
12/23/2013	6,650
2/2/2013	6,330
5/15/2002	6,030
2/29/2000	5,730
4/11/2001	5,640
12/29/2015	5,270
1/28/2012	4,010

Figure 20. Precipitation Patterns for the June 1972 (Agnes) and September 2004 (Ivan) Floods

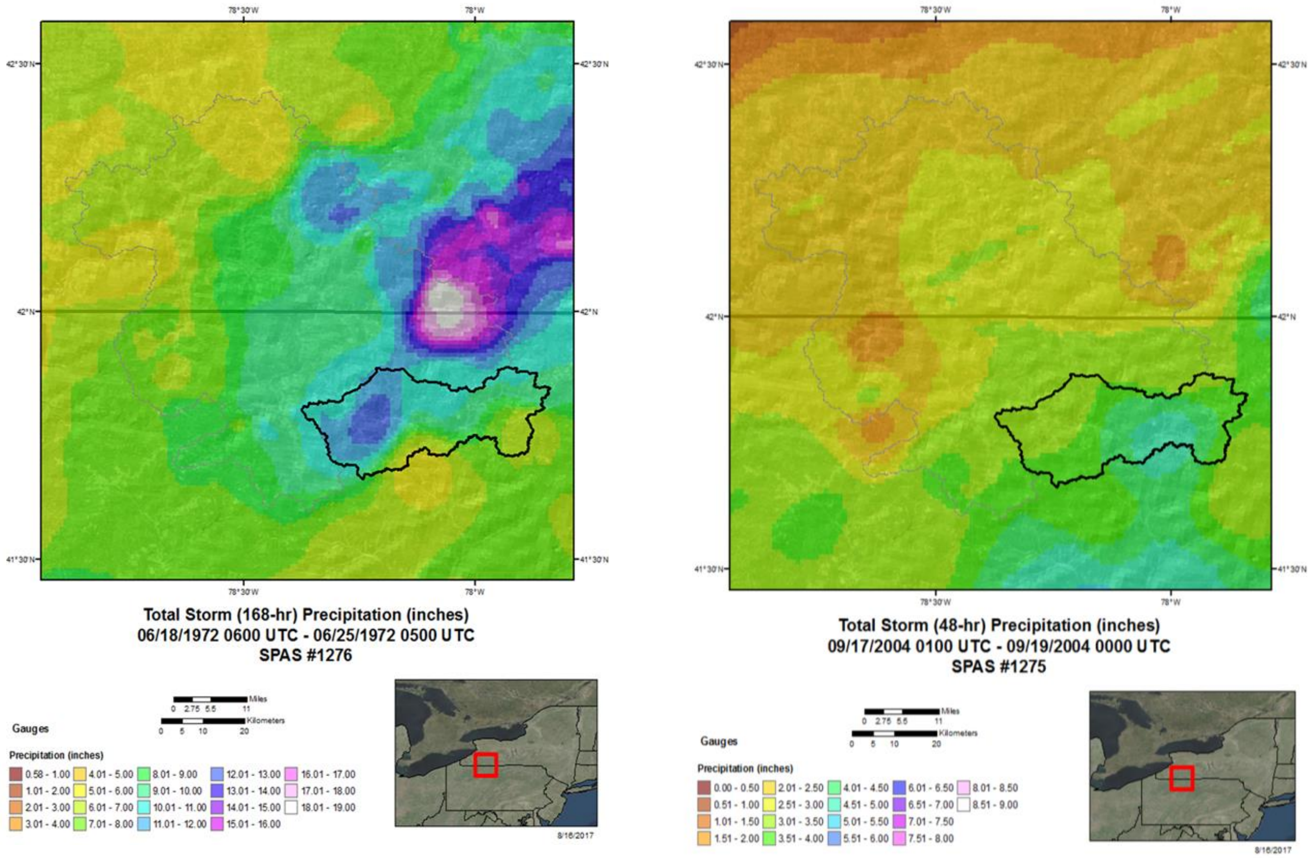


Table 5. Model Calibration Results for the June 1972 (Agnes) Flood

River Mile[3]	Location	Observed			Model[4]			
		Date/Time	Peak Discharge (cfs)	Peak WSEL (ft, NGVD29)	Date/Time	Peak Discharge (cfs)	Peak WSEL (ft, NAVD88)	Peak WSEL (ft, NGVD29)
	Coudersport (US Rt 6 Br)		5,790	1653.1	6/23/72 12:00 AM	6,348	1655.0	1655.4
	Coudersport (Mill Creek)		3,490			2,865		
298.3	Roulette (Fishing Cr Rd Br)			1527.6			1529.2	1529.7
295.1	Burtville PA (Kim Hill Rd Br)			1509.7			1510.7	1511.2
289.6	Port Allegany (Rte 155 Bridge)			1478.9			1478.4	1478.9
288.9	Port Allegany (W Mill St Br)[2]	6/22/72 9:00 PM	22,000	1475.2	6/22/72 9:00 PM	21,083	1476.6	1477.1
288.0	Port Allegany (Rte 6 Bridge)[2]	6/22/72 9:00 PM		1472.3	6/22/72 9:00 PM	21,325	1473.1	1473.6
269.0	Eldred PA[1,5]	6/23/72 9:00 PM	35,000	1445.5	6/23/72 8:00 AM	35,540	1443.1	1443.6
	Olean NY[1]		59,000	1426.0	6/23/72 9:30 AM	65,143	1427.1	1427.6
233.7	Salamanca NY[1]	6/23/72 1:00 PM	73,000	1381.5	6/23/72 12:45 PM	80,797	1379.2	1379.7

1 Observed peak discharge value obtained from the FEMA Flood Insurance Study for McKean County (FEMA, 2016), which cites a 1976 USACE study (USACE, December 1976).
2 Estimated to be 24 hours before the peak at Eldred (6/23/72 9:00 PM at USGS Eldred Gauge), from the HEC-HMS model.
3 River Miles from USGS report vary from the USACE profile for Agnes.
4 Results from the 2D model are shown at and upstream of Port Allegany. Results from the HEC-HMS model are shown downstream of Port Allegany.
5 The "peak discharge" reported in the HEC-HMS model of 32,913 cfs at 8:30 AM on June 23, 1972, appears to be an anomaly. The actual peak appears to be occurring at the magnitude and time shown in the table.

Figure 21. June 1972 (Agnes) HEC-HMS Hydrographs – Allegheny River at Coudersport (Compared to 2D Model)

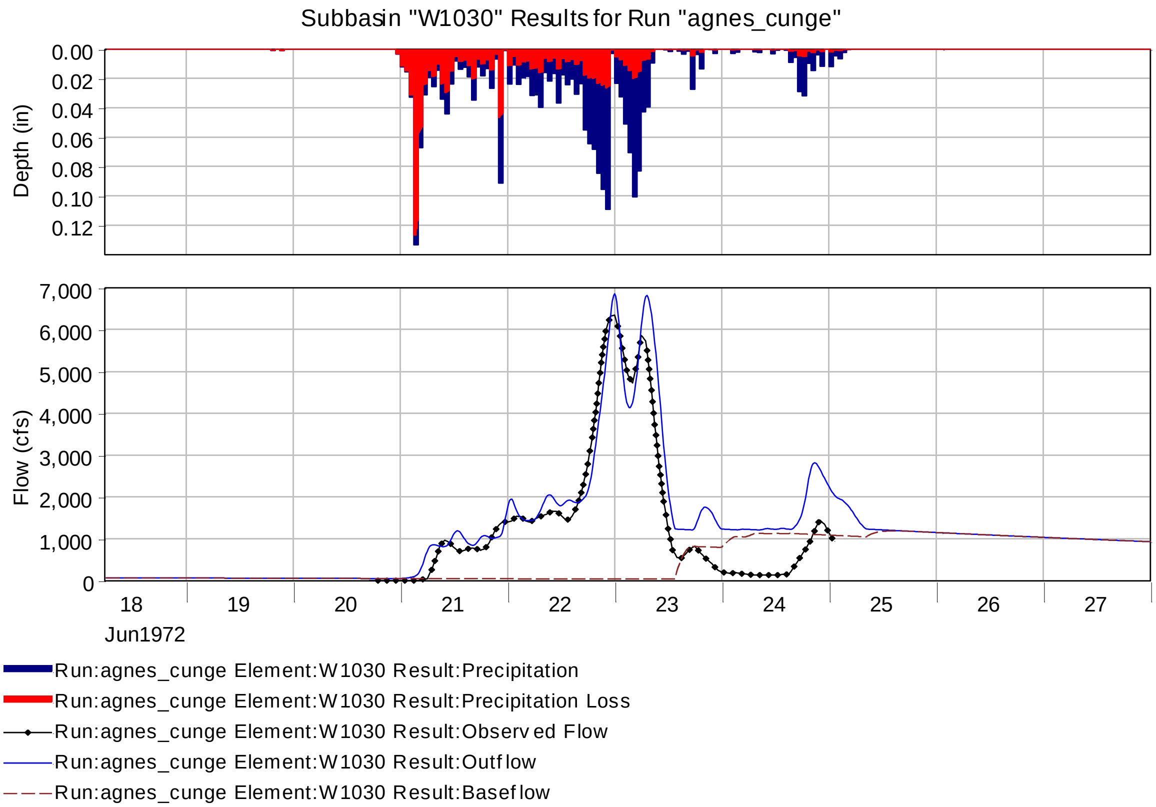


Figure 22. June 1972 (Agnes) HEC-HMS Hydrographs – Mill Creek at Coudersport (Compared to 2D Model)

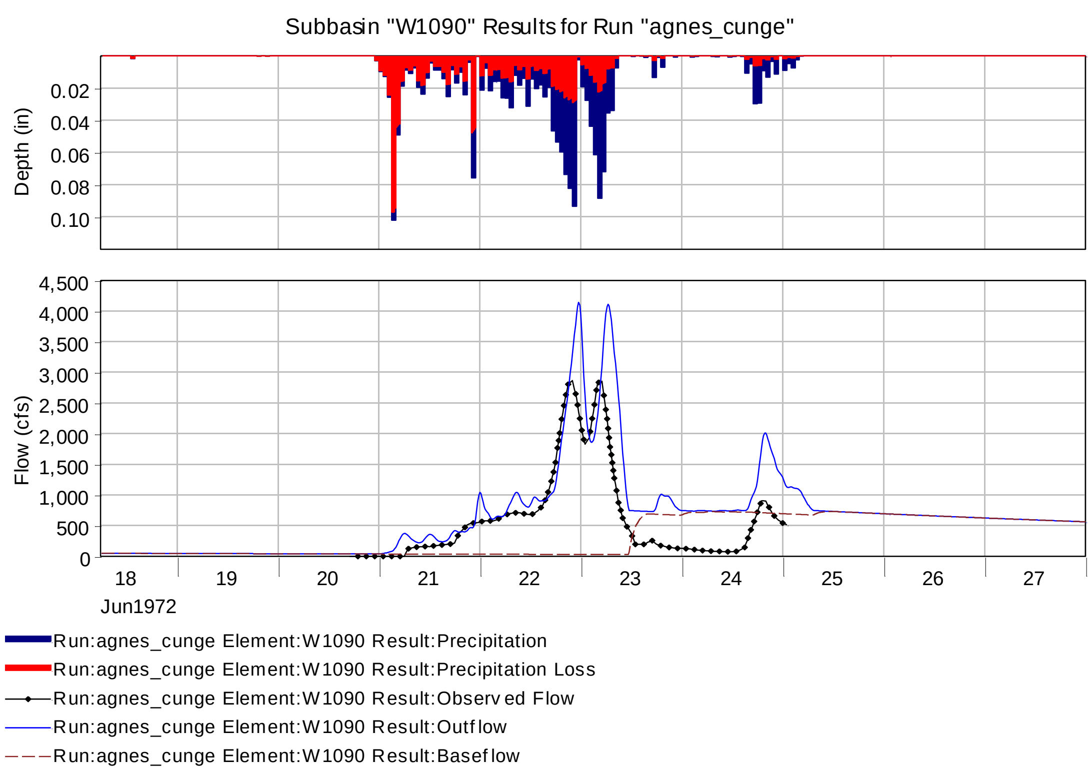


Figure 23. June 1972 (Agnes) HEC-HMS Hydrographs – Allegheny River at Port Allegany (Compared to 2D Model)

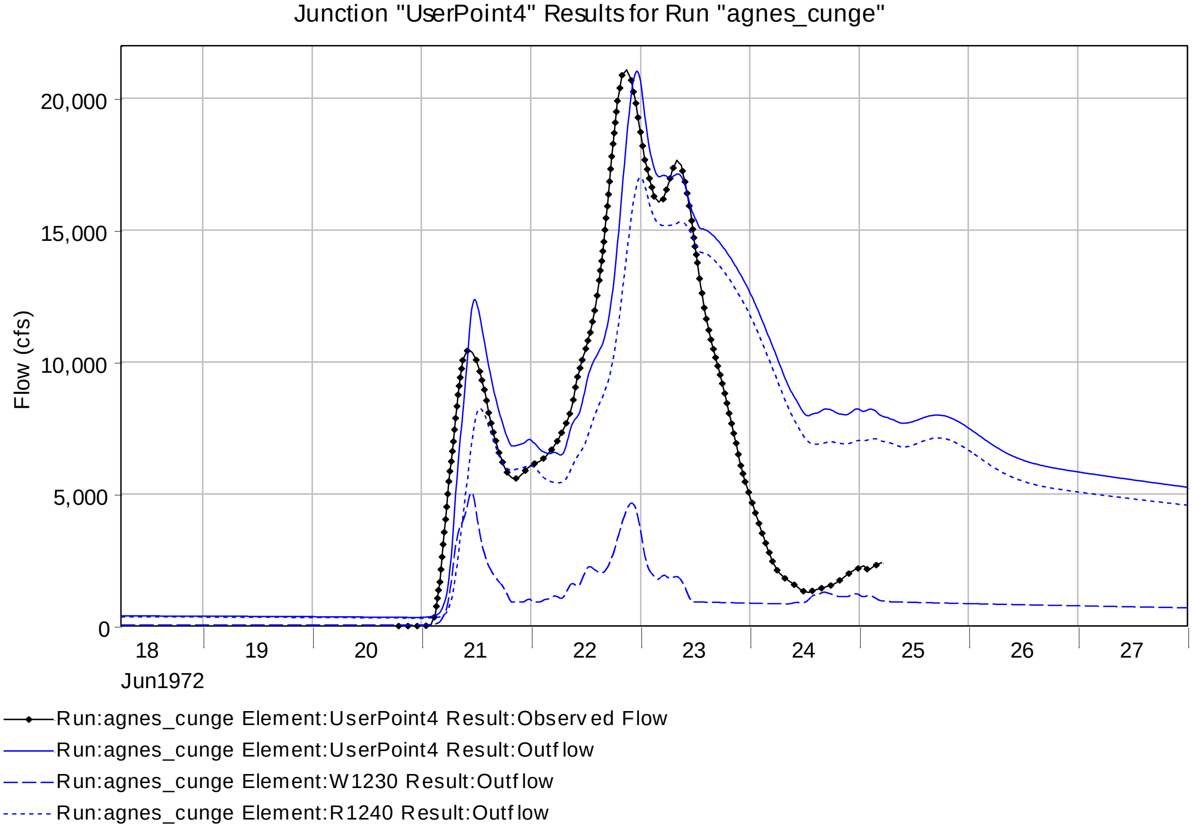


Figure 24. June 1972 (Agnes) HEC-HMS Hydrographs – Allegheny River at Eldred (Streamflow data above 20,000 cfs is approximated based on 35,500 cfs USACE peak flow estimate)

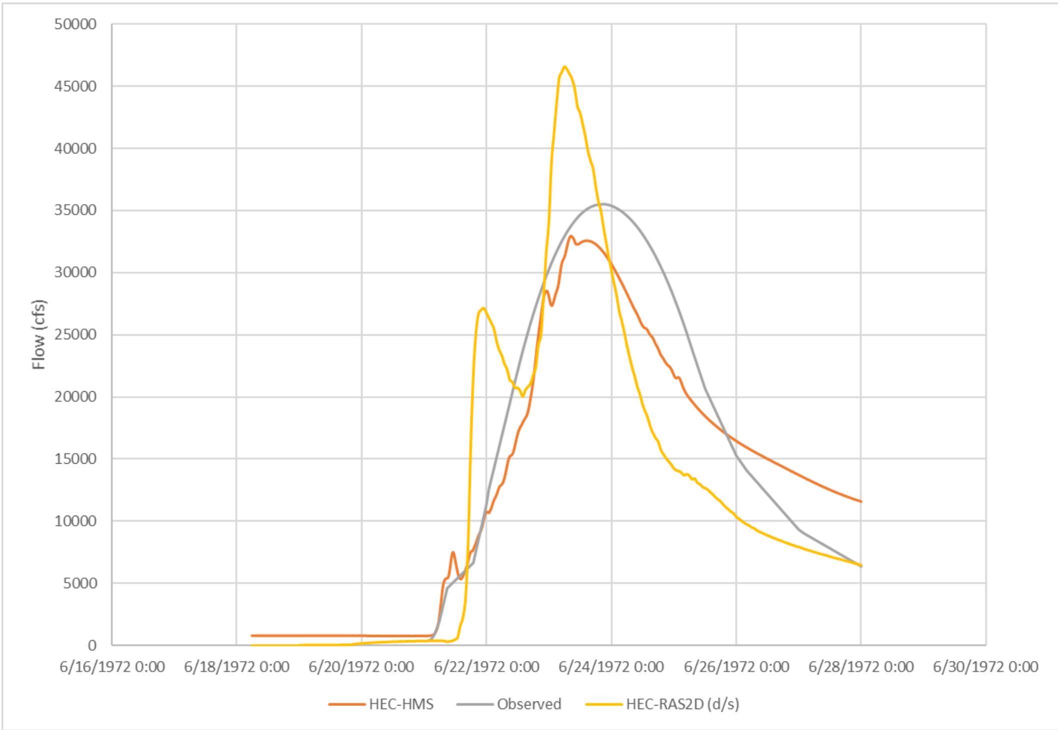


Figure 25. June 1972 (Agnes) Hydrographs – Allegheny River at Olean (Streamflow data approximated from NOAA Report 73-1, page 24)

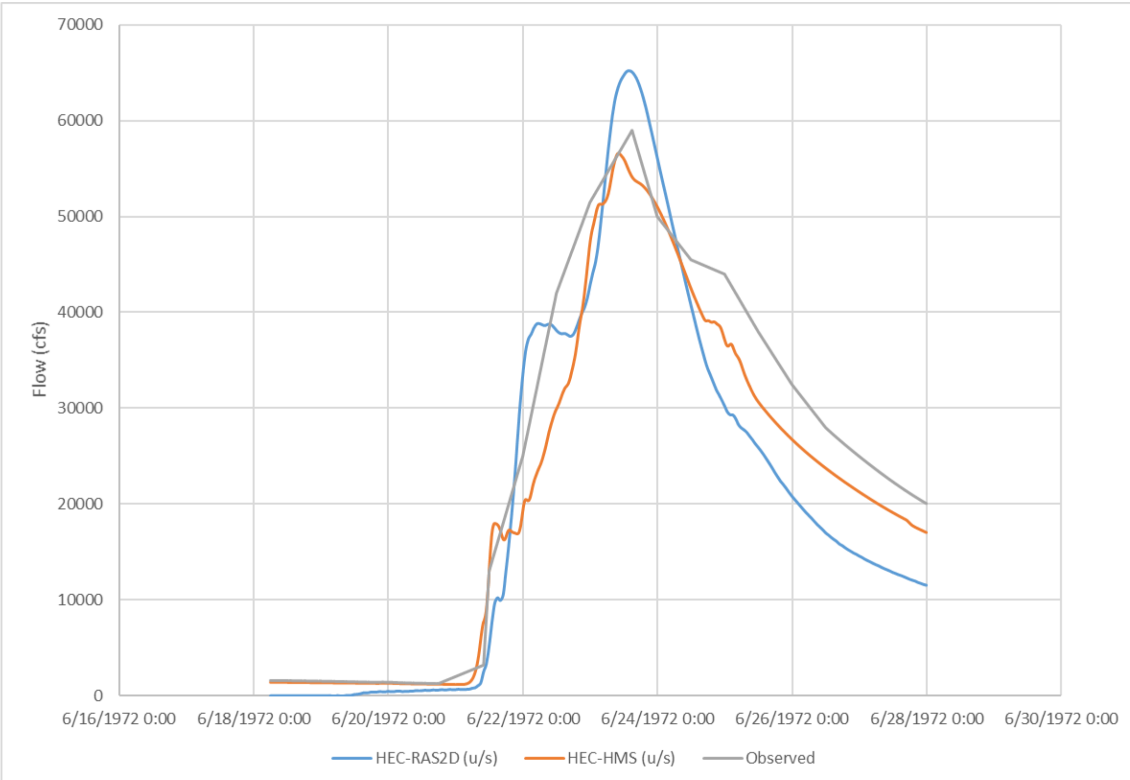


Figure 26. HEC-HMS Model Run for the September 2004 (Ivan) Flood at Port Allegany

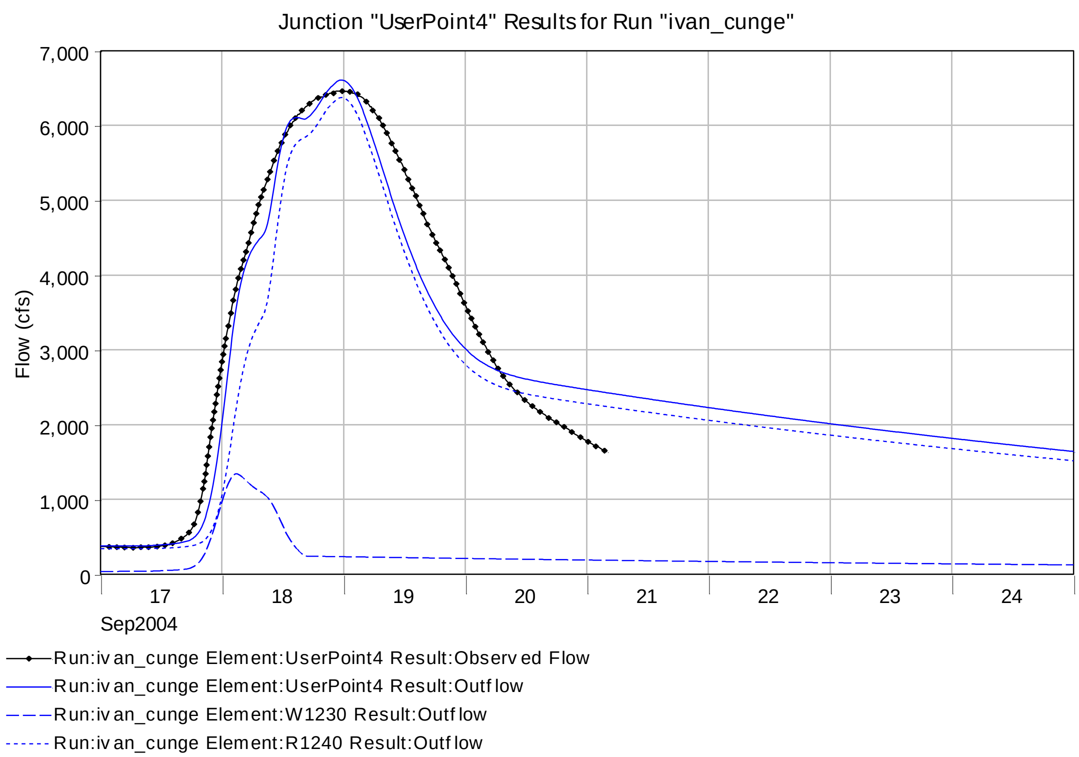


Figure 27. HEC-HMS Model Run for the September 2004 (Ivan) Flood at Eldred

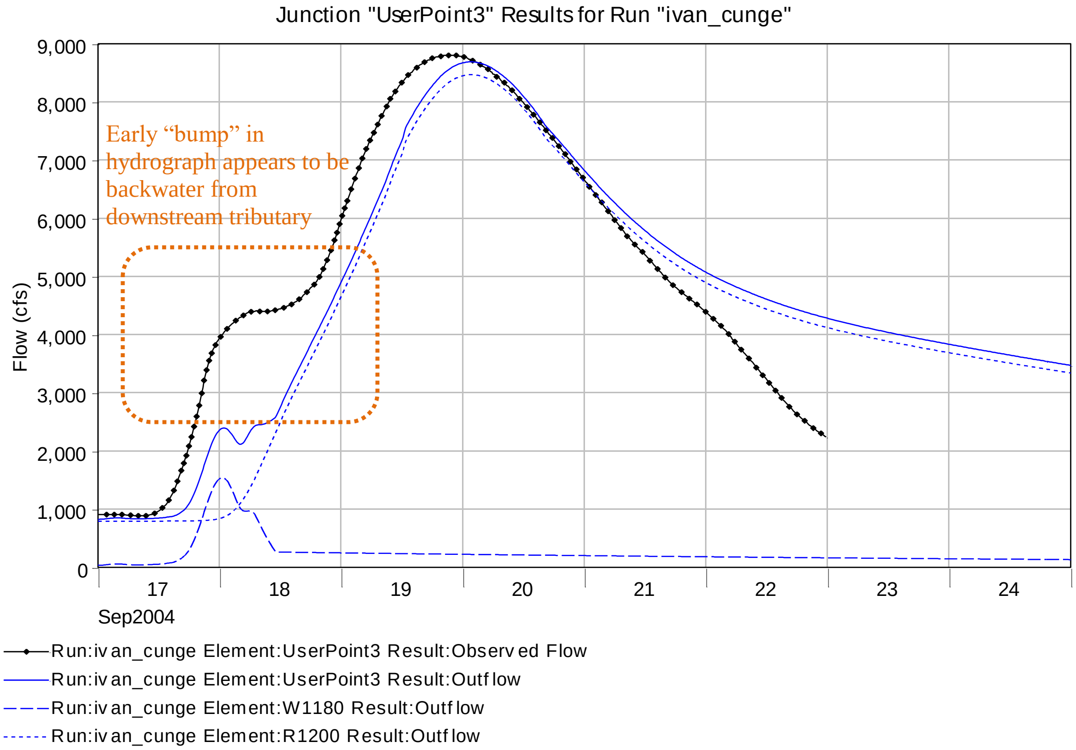
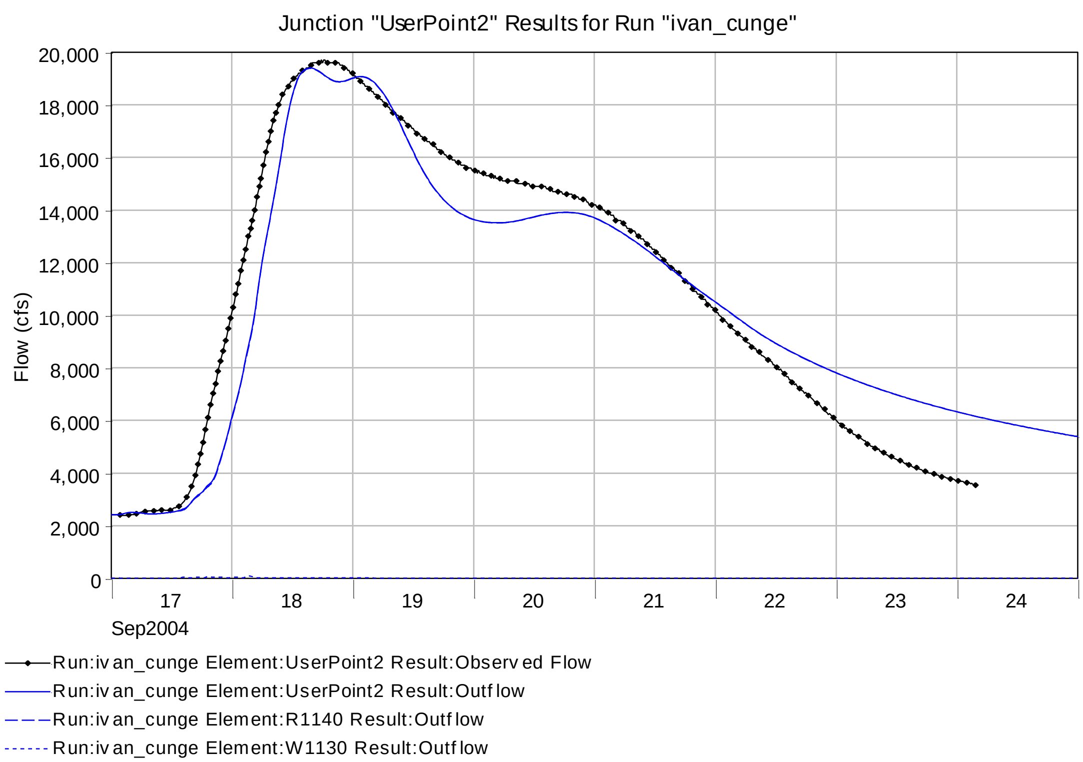


Figure 28. HEC-HMS Model Run for the September 2004 (Ivan) Flood at Salamanca



2.4 Parameters

2.4.1 HEC-HMS Model Parameters

The HEC-HMS model was developed using the following components:

- Loss Method – SCS (Runoff Curve Number)
- Transformation Method – Snyder Unit Hydrograph
- Reach Routing Method – Muskingum-Cunge
- Baseflow Method – Recession

Similar to the 2D model, RCNs were developed based on cover type, hydrologic conditions, and hydrologic soil groups (HSG) obtained from various sources, as described in Section 2.2. The RCN and initial abstraction values were adjusted as part of the calibration process to provide a good fit of the modeled hydrograph with the observed data. Given the homogenous watershed characteristics, the calibration focused on the mixed forest (HSG A) land use type. Table 6 provides the calibrated RCNs and Initial Abstraction for each sub-basin. In developing the HEC-HMS model, discontinuities in the NRCS's HSG Classifications were discovered along the PA-NY border. (See Figure 19.) The majority of the model domain in PA has a "Mixed Forest" land cover with HSG A. Much of the apparent discontinuity is in the PA HSG A and NY HSG C or HSG C/D. Similar to the 2D Model RCN calibration, the HEC-HMS Model calibration produced RCNs in HSG A, "Mixed Forest", areas of PA that correspond closer to HSG B or HSG C.

Table 6. Final HEC-HMS Runoff Curve Numbers

Sub-Basin	Initial Abstraction (inches)	Curve Number	Impervious (%)
W1000	0.5	79.5	5
W1010	0.5	79.2	5
W1020	0.5	79.7	5
W1030	0.5	64.0	5
W1040	0.5	79.0	5
W1050	0.5	78.8	5
W1060	0.5	62.0	5
W1070	0.5	67.6	5
W1080	0.5	65.0	5
W1090	0.5	64.0	5
W1100	0.5	67.5	5
W1120	0.5	68.5	5
W1130	0.5	66.1	5
W1170	0.5	59.6	5
W1180	0.5	78.3	5
W1220	0.5	76.2	5
W1230	0.5	70.0	5
W560	0.5	76.9	5
W570	0.5	78.3	5
W580	0.5	77.0	5
W590	0.5	77.3	5

Sub-Basin	Initial Abstraction (inches)	Curve Number	Impervious (%)
W600	0.5	78.6	5
W610	0.5	77.5	5
W620	0.5	74.4	5
W630	0.5	72.0	5
W640	0.5	78.4	5
W650	0.5	77.8	5
W660	0.5	77.0	5
W670	0.5	72.0	5
W680	0.5	74.9	5
W690	0.2	78.3	7
W700	0.5	75.6	7
W720	0.5	70.7	5
W730	0.5	70.3	5
W740	0.5	72.9	5
W750	0.5	71.6	5
W760	0.5	78.1	7
W770	0.5	75.0	5
W780	0.5	77.1	7
W790	0.5	70.0	5
W800	0.5	70.0	5
W810	0.5	78.1	7
W820	0.5	85.1	7
W830	0.5	72.9	5
W840	0.5	72.0	5
W850	0.5	72.2	5
W860	0.5	73.8	5
W870	0.5	75.1	5
W880	0.5	80.2	5
W890	0.5	72.1	5
W900	0.5	76.1	5
W910	0.5	73.8	5
W920	0.5	60.0	5
W940	0.5	77.6	5
W950	0.5	75.0	5
W960	0.5	75.0	5
W970	0.5	50.0	2
W990	0.5	50.0	2

The Muskingum-Cunge modeling technique was used to simulate attenuation in the hydrographs due to river channel and floodplain storage. The technique is based on a finite difference solution of a combination of the continuity equation and simplified (diffusion-form) of the momentum equation. The model inputs include an 8-point cross-section configuration, reach length, roughness (n-value) coefficients, and energy slope. The initial value for energy slope was determined from the LiDAR representation of the channel bottom (which is the base-flow water surface at the time LiDAR data was collected). Early calibration runs of the HEC-HMS model, particularly for the June 1972 "Agnes" flood, showed significant attenuation in the hydrographs that was not represented by observed streamflow data. Typically, velocities and bottom shear increases, resulting in steepening of the energy slope, as flow increases. Therefore, the energy slope was gradually increased to achieve good agreement in the hydrograph peak flow and timing for the "Agnes" flood model.

The Snyder Unit Hydrograph method for runoff transformation consists of two key parameters: Lag Time (t_p) and Peaking Coefficient (C_p). Equation 34 from the HEC-HMS Technical Reference Manual (USACE, 2000) provides the equation for t_p:

$$t_p = CC_t(LL_c)^{0.3}$$

where,

- C = 1 (for English Units)
- C_t = Basin Coefficient
- L = Length of the main stream from the outlet to the divide
- L_c = Length along the main stream from the outlet to a point nearest to the watershed centroid

Citing Bedient and Huber (1992), the HEC-HMS Technical Reference Manual states that C_t typically ranges between 1.8 and 2.2, although lower values have been found in mountainous regions (0.4). For each sub-basin, an initial value for t_p was calculated using a C_t of 2.0. L and L_c were estimated for each sub-basin using GIS. The initial values for Lag Time (t_p) were adjusted to achieve good agreement between the observed and model hydrographs at the Port Allegany, Eldred, and Salamanca streamflow gauges for the September 2004 (Ivan) flood. The Peaking Coefficient (C_p) is reported in the HEC-HMS Technical Reference Manual to range between 0.4 and 0.8. An initial C_P value of 0.6 was selected for each sub-basin, which were then adjusted higher to achieve a good match for the September 2004 (Ivan) hydrographs.

Unit Hydrographs, commonly used to transform runoff volume to a runoff hydrograph, inherently assume that "discharge at any time is proportional to the volume of runoff and that the time factors affecting hydrograph shape are constant" (USDA-NRCS, 2007). This linearity assumption is not strictly true when a Unit Hydrograph is applied to a storm of much higher magnitude than the calibration storm, even when calibrated at a gauged location. As discussed previously, the non-linearity property of lumped Unit Hydrographs was a significant consideration in using a 2D distributed model for part of the study area.

The non-linearity unit hydrograph issue became evident in applying an "Ivan" calibrated HEC-HMS model to the June 1972 "Agnes" storm. Additional adjustments to the "Ivan-calibrated" Snyder Unit Hydrograph parameters were required to achieve an acceptable level of agreement at Coudersport, Port Allegany, Eldred, and Olean for the "Agnes" calibration. Because the June 1972 "Agnes" flood was much larger in magnitude than the September 2004 "Ivan" flood, the "Agnes" calibrated Snyder Unit Hydrograph parameters were initially applied to the July 1942 storm in the HEC-HMS model. The "Ivan-Calibrated" RCNs were reduced by between 0% and 30% to achieve good runoff volume agreement for the "Agnes" flood. HEC-HMS model parameters were adjusted to provide good agreement with both streamflow gauge data and the three calibrated RiverFlow2D models for the "Agnes" flood. Calibration of the RiverFlow2D models also involved adjustments to Manning n-values to provide good agreement with the "Agnes" runoff responses and flood profiles provided by the USACE in their 1974 report (USACE, 1974).

Another "check" in the HEC-HMS model was at the critical location of Port Allegany. An observed hydrograph at Port Allegany was not available for the 1972 "Agnes" flood. However, as discussed in the previous section, available peak water surface profiles, flows, and timing information was available for the 1972 "Agnes" flood (USACE, 1974), for validating the RiverFlow2D model within the domain at and upstream of Port Allegany, which showed good agreement in the RiverFlow2D model for the 1972 "Agnes" flood. Therefore, the Snyder Unit Hydrograph Lag Times were further reduced by 50% for all sub-basins in HEC-HMS, from the "Ivan" calibrated Lag Times, to achieve good agreement with the RiverFlow2D model at Port Allegany and Coudersport. Table 7 shows the evolution in the development of the Snyder Unit Hydrograph parameters. See also Section 2.3 for the results of the "Agnes" and "Ivan" HEC-HMS calibrations, respectively.

Table 7. HEC-HMS Snyder Unit Hydrograph Parameters

Basin Parameters					Ivan			Agnes	
Sub-Basin ID	Longest Flowline (ft)	Centroidal Length (ft)	HMS Drainage Area (mi^2)	Calculated Lag Time (hrs)	Lag Time (t_p), hr	Ratio of Calc/Final Lag Time	Peaking Coef (C_p)	Lag Time (t_p), hr (½ x t_p^{Ivan})	Peaking Coef (C_p)
W1000	47,226	22,492	18.37	5.96	2.62	0.44	0.80	1.31	0.80
W1010	64,798	30,268	37.02	7.16	2.23	0.31	0.80	1.12	0.80
W1020	37,354	20,747	6.03	5.42	1.88	0.35	0.80	0.94	0.80
W1030	88,123	43,038	47.01	8.73	4.95	0.57	0.60	2.48	0.60
W1040	112,665	48,121	55.61	9.72	4.31	0.44	0.80	2.16	0.80
W1050	129,619	57,755	106.23	10.71	5.32	0.50	0.80	2.66	0.80
W1060	90,953	45,255	47.76	8.95	6.00	0.67	0.60	3.00	0.60
W1070	56,054	29,965	24.49	6.84	3.60	0.53	0.60	1.80	0.60
W1080	77,440	40,094	32.22	8.22	6.07	0.74	0.60	3.04	0.60
W1090	57,353	26,237	31.49	6.62	3.21	0.49	0.60	1.61	0.60
W1100	91,356	25,828	44.02	7.57	6.26	0.83	0.60	3.13	0.60
W1120	26,071	5,016	6.30	3.18	2.52	0.79	0.60	1.26	0.60
W1130	12,748	5,753	1.54	2.67	0.72	0.27	0.80	0.36	0.80
W1170	3,697	2,573	0.10	1.45	0.80	0.55	0.40	0.40	0.40
W1180	59,289	18,866	21.95	6.05	3.06	0.51	0.80	1.53	0.80
W1220	100,241	41,697	53.68	8.99	4.91	0.55	0.80	2.46	0.80
W1230	49,373	5,120	23.59	3.88	4.00	1.03	0.60	2.00	0.60
W560	103,008	32,583	58.88	8.42	6.00	0.71	0.60	3.00	0.60
W570	53,288	31,715	19.88	6.85	3.18	0.46	0.80	1.59	0.80
W580	108,732	51,228	54.61	9.80	8.00	0.82	0.80	4.00	0.80
W590	105,448	48,877	41.01	9.57	6.00	0.63	0.80	3.00	0.80
W600	69,734	31,940	26.59	7.44	2.00	0.27	0.80	1.00	0.80
W610	58,036	31,924	26.12	7.04	4.00	0.57	0.80	2.00	0.80
W620	84,296	41,496	47.07	8.52	4.75	0.56	0.60	2.38	0.60
W630	35,403	16,209	7.36	4.96	1.50	0.30	0.80	0.75	0.80
W640	47,053	14,301	27.63	5.20	2.63	0.51	0.80	1.32	0.80
W650	46,287	20,491	9.15	5.76	1.50	0.26	0.80	0.75	0.80
W660	80,449	36,979	35.01	8.12	4.00	0.49	0.80	2.00	0.80
W670	43,169	22,584	12.72	5.81	2.00	0.34	0.80	1.00	0.80
W680	91,656	42,243	30.59	8.79	8.20	0.93	0.60	4.10	0.60
W690	72,740	34,077	26.84	7.69	4.00	0.52	0.80	2.00	0.80
W700	83,642	34,308	37.60	8.03	3.00	0.37	0.80	1.50	0.80
W720	68,843	38,612	35.61	7.85	4.57	0.58	0.60	2.29	0.60
W730	50,810	24,442	26.52	6.25	3.00	0.48	0.80	1.50	0.80

Basin Parameters					**Ivan**			**Agnes**	
Sub-Basin ID	**Longest Flowline (ft)**	**Centroidal Length (ft)**	**HMS Drainage Area (mi²)**	**Calculated Lag Time (hrs)**	**Lag Time (t_p), hr**	**Ratio of Calc/Final Lag Time**	**Peaking Coef (C_p)**	**Lag Time (t_p), hr (½ x t_p^{Ivan})**	**Peaking Coef (C_p)**
W740	83,679	30,574	36.96	7.76	4.77	0.61	0.60	2.39	0.60
W750	23,669	5,898	10.17	3.24	1.43	0.44	0.60	0.72	0.60
W760	72,688	29,633	41.83	7.37	3.53	0.48	0.80	1.77	0.80
W770	88,261	45,497	47.50	8.88	4.79	0.54	0.80	2.40	0.80
W780	73,589	40,037	31.96	8.10	3.00	0.37	0.80	1.50	0.80
W790	29,145	13,241	6.72	4.40	2.17	0.49	0.60	1.09	0.60
W800	110,454	54,647	69.56	10.04	6.99	0.70	0.80	3.50	0.80
W810	48,121	14,919	26.66	5.30	3.00	0.57	0.80	1.50	0.80
W820	23,355	6,446	5.04	3.32	1.00	0.30	0.80	0.50	0.80
W830	86,163	46,874	43.53	8.90	4.56	0.51	0.80	2.28	0.80
W840	44,742	15,749	12.94	5.27	2.00	0.38	0.80	1.00	0.80
W850	6,482	4,192	0.27	1.98	0.25	0.13	0.80	0.13	0.80
W860	101,506	51,421	50.84	9.61	6.74	0.70	0.80	3.37	0.80
W870	62,996	32,604	21.56	7.26	4.66	0.64	0.80	2.33	0.80
W880	17,861	9,138	2.01	3.40	2.62	0.77	0.60	1.31	0.60
W890	78,277	30,155	28.67	7.57	7.22	0.95	0.80	3.61	0.80
W900	67,269	35,364	20.25	7.59	11.23	1.48	0.40	5.62	0.40
W910	48,261	20,661	11.04	5.85	3.65	0.62	0.80	1.83	0.80
W920	102,615	50,492	48.60	9.59	5.50	0.57	0.40	2.75	0.40
W940	77,800	47,691	32.99	8.68	12.92	1.49	0.40	6.46	0.40
W950	61,239	24,329	42.64	6.60	4.17	0.63	0.60	2.09	0.60
W960	84,595	42,665	57.12	8.60	5.00	0.58	0.60	2.50	0.60
W970	60,772	32,351	29.25	7.17	3.00	0.42	0.40	1.50	0.40
W990	49,269	23,011	20.64	6.08	3.00	0.49	0.40	1.50	0.40

2.4.2 2D Model Parameters

Manning's Roughness Coefficients (n-values)

To characterize surface roughness, Manning's roughness coefficients (n-values) were assigned to each land cover type. The initial values were based on Table 5-5 of Open Channel Hydraulics (Chow, 1959) and NRCS (USDA-NRCS, 2016). The values were further adjusted during the calibration process. Manning n-values from Chow's Open Channel Hydraulics are typically applied to one-dimensional flow analyses and inherently "lump" internal and surface energy losses in three-dimensions. Typically, a reduction in n-values for two-dimensional flow would be expected when compared to n-values used in the one-dimensional flow application.

For the RiverFlow2D model, which was used for coupled hydrologic and hydraulic analyses, the roughness n-values had to be increased in the overland areas to compensate for the shallow depth flow (less than one inch) with low velocities, to keep the watershed response from being too "flashy" (compared to streamflow gauge data). The approach used in RiverFlow2D was to differentiate the overland areas from the areas where greater flow depths were expected to vary depending on the storm magnitude. For example, for the June 1972 and July 1942 floods, areas with overland flow were defined as outside the FEMA delineated 500-year floodplain, whereas for the less-intense 2014 storm event the areas with land use classification other than wetlands, river, or waterbody were defined as overland flow. Based on the calibration of the model, the normal n-values were increased by a factor of six in the overland flow areas to achieve acceptable hydrologic (time distribution and magnitude of flow) agreement. Table 8 below provides a summary of the n-values used in the analysis for the respective land use types.

Table 8. Manning's Roughness Coefficients in the RiverFlow2D Model

Land Use Type	Base n-value	Assigned n-value Overland Areas
River (Alleghany River and Mill Creek)	0.04	N/A
River (Tributaries)	0.08	N/A
Water Body	0.08	N/A
Wetlands	0.1	N/A
Industrial/Commercial	0.1	0.6
Cropland and Pasture	0.15	0.9
Residential/Urban	0.2	1.2
Mixed Forest	0.6	3.6

For the HEC-RAS2D model, Manning n-values were initially based on NRCS guidance (USDA-NRCS, 2016) using land cover information from the National Land Cover Database (NLCD). These n-values lead to good agreement with the USACE peak water surface profile for the June 1972 "Agnes" flood. As discussed further in Section 2.7, "override" regions were assigned with different n-values in areas of the floodplain that experienced significant land use changes between 1942 and present-day (which is similar to the land use conditions during the June 1972 calibration flood). Most of the land use changes, primarily from cultivated farmland in 1942 to present-day and 1972 wooded conditions, occurred between Olean, NY and Port Allegany, PA. In these "override" areas, n-values were set to 0.07. The calibrated n-values used in the HEC-RAS2D model are provided in Table 9.

Table 9. Manning's Roughness Coefficients in the HEC-RAS2D Model

Land Use Type	Base n-value
Water Body (Allegheny River and tributaries)	0.04
Wetlands	0.07
Industrial/Commercial	0.15
Cropland and Pasture	0.07
Residential/Urban	0.08
Mixed Forest	0.16

Runoff Curve Number (RiverFlow2D Only)

Runoff curve numbers (RCN) were developed based on cover type, hydrologic conditions, and hydrologic soil groups (HSG) obtained from various sources, as described in Section 2.2. The RCN, along with the initial abstraction values, were adjusted as part of the calibration process to provide a good fit of the modeled hydrograph with the observed data. The watershed characteristics of the RiverFlow2D model domain are moderately homogenous, predominantly defined as mixed forest land use. The most prevalent HSG within the model domain is Type A. Given the homogenous watershed characteristics within the model domain, the calibration focused on the mixed forest (HSG A) land use type. Table 10 below provides the initial and the calibrated RCNs for each land use and HSG combination. Initial abstraction was another hydrologic parameter that was adjusted as part of the calibration process. For the 2004 storm event, the final initial abstraction value was set to 0.15, while for the Agnes and Smethport storm events it was reduced to 0.1.

Table 10. Runoff Curve Numbers

Land Use Type	HSG	Initial RCN	Calibrated RCN
River	All	100	100
Water Body	All	100	100
Wetlands	All	98	98
Industrial/Commercial	B	90	90
Industrial/Commercial	C	92	92
Industrial/Commercial	D	95	95
Cropland and Pasture	A	45	45
Cropland and Pasture	B	60	60
Cropland and Pasture	C	75	75
Cropland and Pasture	D	85	85
Residential/Urban	A	55	55
Residential/Urban	B	70	70
Residential/Urban	C	80	80
Residential/Urban	D	85	85
Mixed Forest	A	30	55
Mixed Forest	B	55	55
Mixed Forest	C	70	70
Mixed Forest	D	78	78

2.5 Floodwater Retarding Dam Considerations

Dams contained in the USACE National Inventory of Dams (NID) (USACE, 2016) database were queried to identify dams within the HEC-HMS model domain. The location of the dams is shown in Figure 29 and the summary of dam information is provided in Table 15, ordered from largest to smallest storage volumes. Due to map scale, Figure 29 does not show all the dams (some are clustered together). Most of the dams are in sub-basins that drain to the Allegheny River at and downstream of Olean, NY. NID Identification differentiated between dams constructed prior to the July 1942 flood and between the July 1942 and June 1972 "Agnes" floods (red represent dams constructed prior to the July 1942 flood and blue were constructed between the July 1942 and June 1972 floods). Three "hypothetical" dams (representing the largest dams, lumped together for modeling purposes) were incorporated into the HEC-HMS model for the June 1972 "Agnes" flood to assess the effect of the dams on the flood hydrographs in the Allegheny River. Simplified assumptions were made for the sensitivity HEC-HMS runs, including an outlet structure consisting only of a broad-crested weir (weir discharge coefficient of 3.0), no tailwater conditions, a linear stage-storage relationship, an average embankment height and spillway width, and spillway crest 8 feet below the top of dam. See Table 11 for the hypothetical dam parameters established for the June 1972 HEC-HMS model. The results of the sensitivity analysis indicate that the dams have a relatively minor effect on the peak flow rates at and downstream of Olean NY, decreasing peak flows by approximately 9,000 cfs (or 10%) at the confluence of the Allegheny River and Olean Creek. This reduction brings the peak flow closer to the observed peak flow of 59,000 cfs.

However, most of the dams constructed before the June 1972 "Agnes" flood did not exist during the July 1942 flood. The only substantial dam constructed prior to the July 1942 flood is the Cuba Lake Dam located in the Olean Creek watershed (NID Identification NY00455 and NY00456), which has the following NID parameters:

- Year Completed = 1872
- Drainage Area = 25.3 mi^2
- Dam Height = 55 feet
- Dam Length = 1,750 feet

- Maximum Storage = 16,498 acre-feet

While not expected to significantly impact the July 1942 hydrographs in the Allegheny River downstream of Olean NY, the Cuba Lake Dam was incorporated into the July 1942 HEC-HMS model.

Figure 29. National Inventory of Dams within the HEC-HMS Model Domain

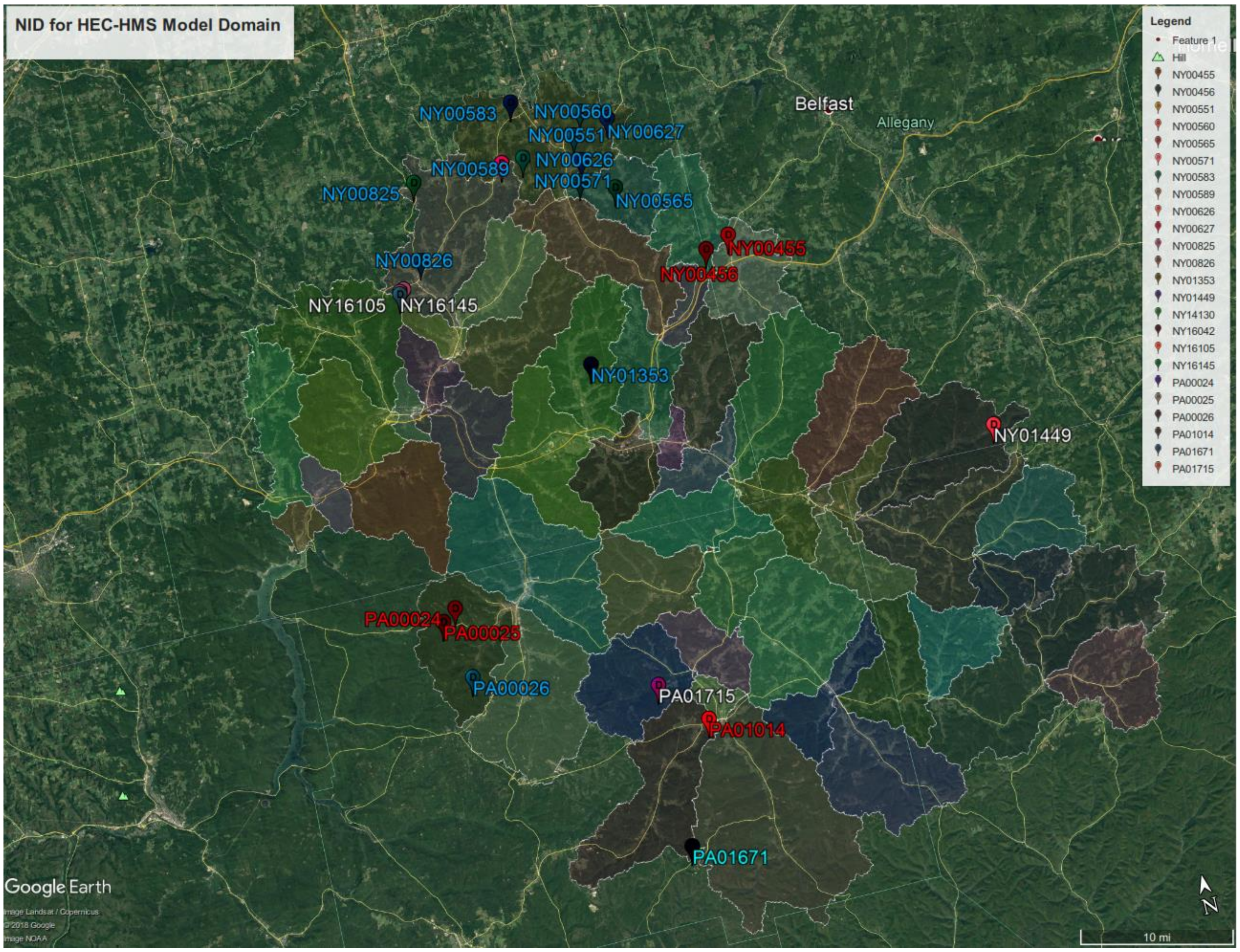


Table 11. Hypothetical Dams used in the "Agnes" HEC-HMS Model

Parameters	NY00565-NY00627	NY00455-NY00456	PA00024-PA00026
Total Drainage Area (mi^2)[1]	43.20	25.30	15.89
Total Storage (acre-feet)	10,442	16,498	4,652
Average Spillway Width (feet)	286	204	80
Average Height (feet)	41	32	53
Assumed Spillway Height (feet)	33	24	46

[1] Total Drainage Areas excludes duplications for dams in series.

2.6 Baseflow Considerations

Review of the 2D modeling results suggested that the watershed is temporarily retaining runoff and gradually releasing volume from the storm in the later portion of the flood hydrograph. This delayed gradual release does not appear to be coming from floodwater retention structures/dams. Runoff being absorbed into a highly permeable upper layer of soil, including in the floodplain areas, and released during the receding side of the runoff hydrograph was considered as a possible explanation. The following features could provide possible explanations for this phenomenon:

- Unconsolidated glacial sediment deposits along the floodplain in the study reach. See Figure 30.
- Formation of boulder and “kame” fields and other features along the glacial edge. See W. D. Seven (W.D. Seven, 1999) for further discussion.
- Fragipans – “dense subsurface soil layers that severely restrict water flow and root penetration” (J.G. Bockheim, 2012). See Figure 31 and E. J. Ciolkosz, et. al. (Edward J. Ciolkosz, 2000) and J. G. Bockheim, et. al. (J.G. Bockheim, 2012) for further discussion.

It was hypothesized that some of the storm volume, represented in the model as a “loss”, enters the riverine system via subsurface flow through highly permeable material overlain (e.g., unconsolidated deposits, “kame” fields, etc.) on a shallow layer of low permeable material (e.g., Fragipan). The hydrologic models do not physically represent this potential surface-subsurface flow interaction. The HEC-HMS model incorporates the “recession baseflow” technique to simulate potential entry of subsurface flow from storm volume. Therefore, the receding side of the HEC-HMS model hydrographs show a more gradual “tail”. Comparatively, the RiverFlow2D model is only representing direct surface runoff and, therefore, shows a more rapidly declining receding side of the hydrographs. The effect of the subsurface flow on the calibration results appears to diminish with larger floods. This is evident by the improved performance of the 2D model for the June 1972 “Agnes” flood.

Figure 30. Glacial Deposits of Pennsylvania (W.D. Seven, 1999)

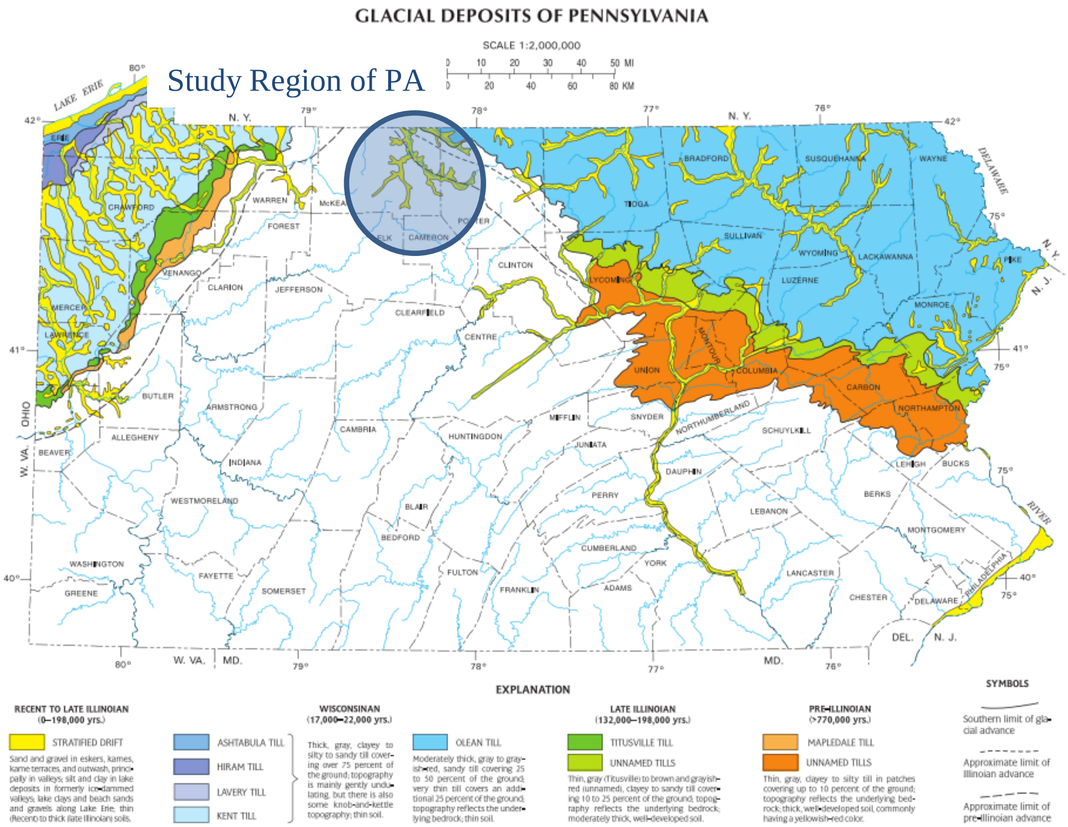
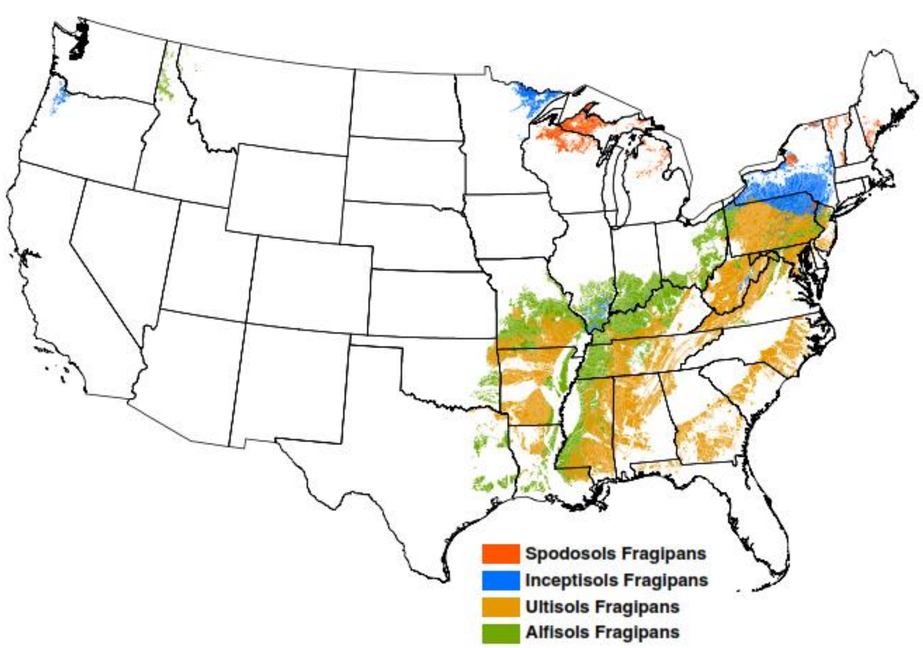


Figure 31. Distribution of Soil Mapping Units with Soils Containing Fragipans in the US (derived from National Survey Laboratory STATSGO Database) (J.G. Bockheim, 2012)



2.7 Post-Calibration Model Adjustments to Account for 1942 Conditions

Recognizing that some conditions between the calibration storms (particularly the June 1972 flood) and the July 1942 flood may vary (e.g. land use, structures, etc.), post-calibration adjustments were made to the models, as described below, prior to applying the July 1942 rainfall. These adjustments, listed below, were made to reduce concerns that flow discrepancies can be attributed to factors other than uncertainties in the rainfall data.

- Reduced the "Ratio to Peak" for the baseflow regression to 0.2 of the values established for the calibration floods due to the significantly higher peak flows in portions of the watershed for the July 1942 flood.
- Manning n-values in the HEC-RAS2D model were originally based on National Land Cover Database (NLCD). These n-values lead to good agreement with the USACE peak water surface profile for the June 1972 "Agnes" flood. However, n-value adjustments were made for the July 1942 HEC-RAS2D model to account for significant land use changes within the floodplain, particularly between Olean, NY and Port Allegany, PA. Changes were primarily from cultivated farmland in 1942 to present-day and 1972 wooded conditions.
- Adjusted the approach embankment elevations and width of the Port Allegany Route 6 Bridge, which collapsed during the 1942 flood, from drawings obtained from PennDOT. See Figure 32.
- Reductions were made to Curve Numbers in the HEC-HMS model (by approximately 20% to 30%), from those calibrated for the "Agnes" flood, to achieve good runoff volume agreement for the July 1942 flood; except for sub-watersheds upstream of Port Allegany, PA (W1030, W1060, W1070, W1080, W1090, W1100, W1230) and the Oswayo Creek upstream of Shinglehouse, PA (W860, W920, W970, and W990). Curve Numbers for these sub-watersheds remained the same for both storms (between approximately 55 and 70). Much of the watershed, except the Upper Allegheny River (upstream of the confluence with Potato Creek) and the upper portion of the Oswayo Creek watershed, had basin-wide average Curve Numbers that were generally consistent with the gridded Curve Numbers in the RiverFlow2D models.
- Due to fast-rising nature of the July 1942 hydrograph at Port Allegany, HEC-RAS2D runs were done using the "Full Momentum" equations to incorporate the "unsteady, advection, and viscous terms" (USACE Hydrologic Engineering Center, 2016) that are disregarded for the "Diffusion Wave" equations. Results from the "Full Momentum" runs show a slower rising limb of the hydrograph, which partially corrects the peak timing discrepancy.

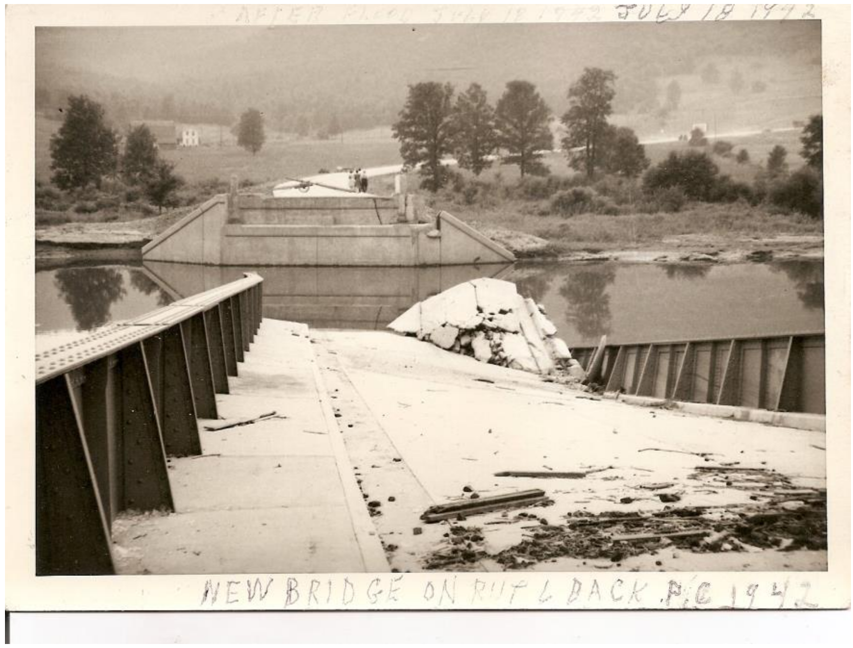


Figure 32. Photo Looking along the destroyed Route 6 Bridge

2.8 Modeling Observations and Limitations

The following summarizes the observations and limitations in the 2D and HEC-HMS models. These observations and limitations were considered when judging refinements to the July 1942 rainfall.

- The RiverFlow2D model appears to perform well for the more intense rainfall events (given the relative comparison between the “Agnes” and “Ivan” floods).
- Subsurface conditions, in the watershed and/or floodplain, appear to be causing attenuation in the flood flows, particularly downstream of Eldred, that are not reflected in the models.
- The RiverFlow2D and HEC-HMS models generally appear to be representing peak flow timing well.
- The Unit Hydrograph in the HEC-HMS model needed adjustment to reconcile the hydrograph from the RiverFlow2D model at Port Allegany and account for a non-linear watershed response in the calibration events. The non-linear response was a key reason for using RiverFlow2D to simulate watershed response in key sub-watersheds and adjusting HEC-HMS parameters to match the RiverFlow2D hydrographs.
- Adjustments to Manning n-values were not constrained by conventional or “textbook” limits in overland flow areas to get the RiverFlow2D model to calibrate.
- Backwater conditions appear to be influencing the observed streamflow hydrograph for the September 2004 (Ivan) flood.
- The effect of hysteresis was considered when comparing HEC-RAS2D hydrographs with observed hydrographs at Eldred and Red House for the July 1942 flood. HEC-RAS2D generates cumulative flow for grid cell faces along the user-defined “profile line” in RAS Mapper to produce a hydrograph, which inherently accounts for the effect of hysteresis. The observed hydrograph, reported on Figure 42 of Water Supply Paper (WSP) 1134-B (Eisenlohr, 1952), was likely developed by an observer or gauge that recorded stage, which was then converted to flow using a pre-defined stage-discharge rating curve. The stage-discharge rating curve likely did not

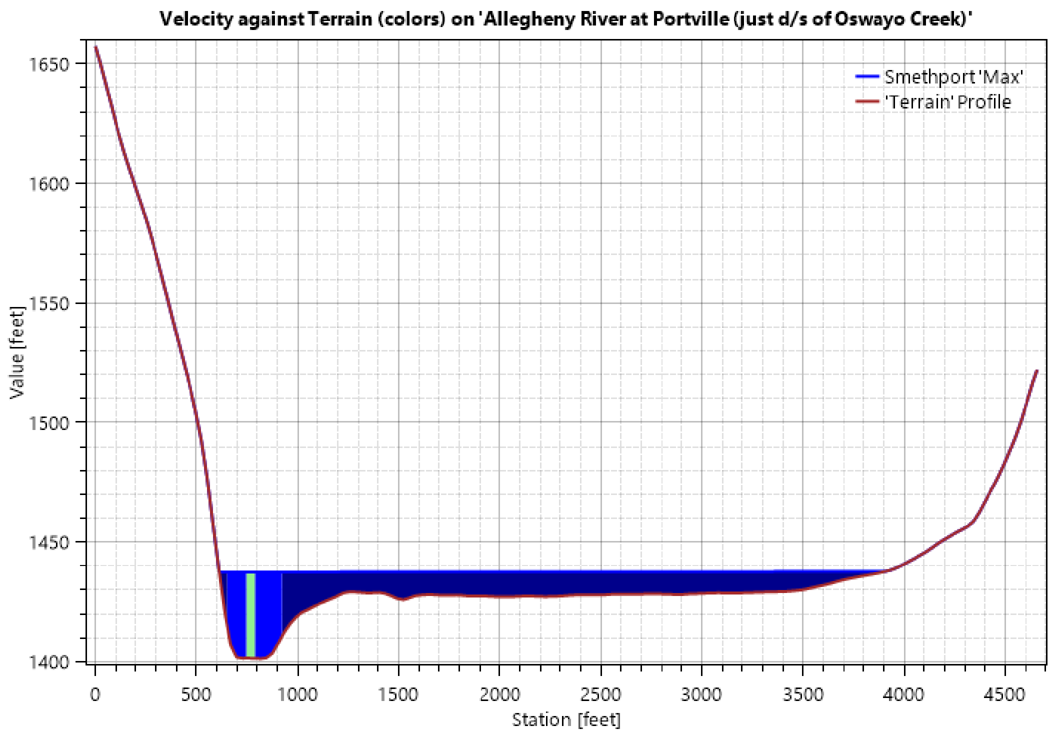
account for hysteresis effect at higher flows. This was considered when judging acceptability of the final hydrographs at Red House, NY and Eldred, PA.

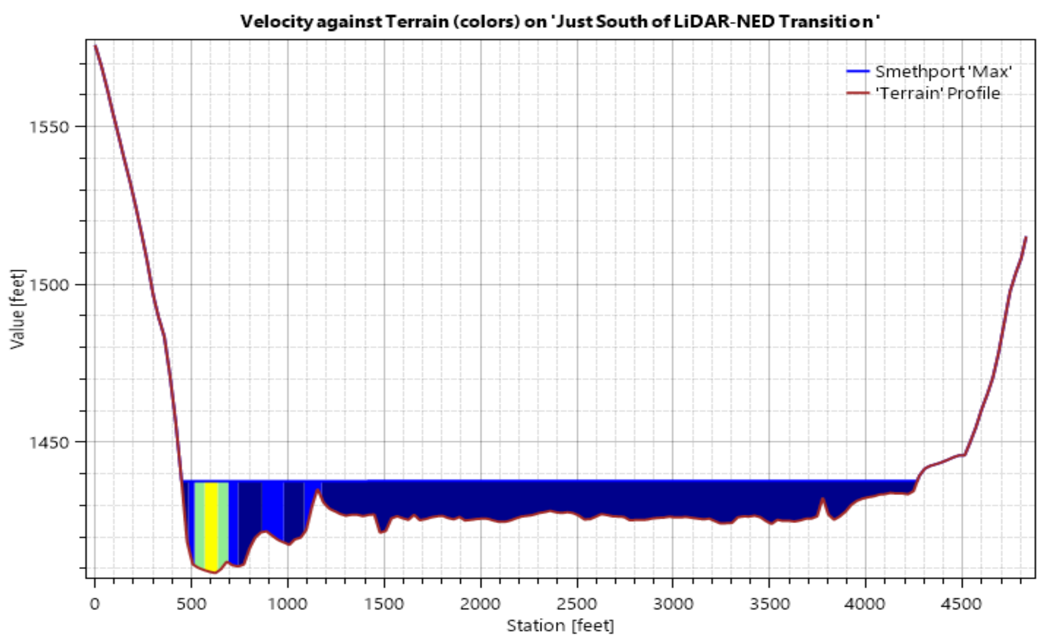
- Early HEC-RAS2D runs were done using the “Diffusion Wave” equations to reduce model time. Due to fast-rising nature of the hydrograph at Port Allegany for the July 1942 flood, HEC-RAS2D runs were revised to use the “Full Momentum” equations to incorporate the “unsteady, advection, and viscous terms” (USACE HEC-RAS, Hydraulic Reference Manual) that are disregarded for the “Diffusion Wave” equations. Results from the “Full Momentum” runs show a slower rising limb of the hydrograph, which partially corrects the peak timing discrepancies at Eldred and Port Allegany, PA.
- There appears to be greater variability than what was expected in the hydrologic response between the storms (September 2004 “Ivan”, June 1972 “Agnes”, and July 1942 “Smethport” floods), as represented by Curve Number and Snyder parameters in the HEC-HMS model. Curve Number and Snyder parameters needed to vary in the HEC-HMS model to achieve good agreement with observed flood data (USGS gauges, newspaper records, etc.) and the calibrated RiverFlow2D models. Sensitivity analyses shows that the potential July 1942 rainfall inaccuracies would not explain the different responses. This was particularly evident in the Potato Creek Watershed (containing the Smethport Borough) where July 1942 Snyder Lag Times were longer (closer to values developed using the SCS regression equation) and Peaking Coefficients lower than the June 1972 calibrated values.
- The model domain contains several levee systems. Table 12 provides information on these systems, obtained from the USACE National Levee Database. Most, except for the Eldred levee, were constructed after the July 1942 flood but before the June 1972 “Agnes” flood. The terrain built for the HEC-RAS2D model includes these levees. However, for the systems in New York (except a portion of the “South of Dodge Creek” levee in Portville, NY), the perception of the levees in the HEC-RAS2D terrain is limited by the resolution of the DEM. Where levees are perceived, the terrain was not manually adjusted to remove the levees for the July 1942 flood, although flooding is permitted to occur behind the levees. While there may be a minor local effect on the HEC-RAS2D model results (particularly for the PA levee systems where LiDAR is available and the levees are well defined in the DEM), a judgement was made that refinements to the DEM to remove the levees would not significantly affect the outcome of the July 1942 flood analysis (and related decisions regarding rainfall) and is not warranted at this time.
- Differences between observed and model water surface elevations in the HEC-RAS2D and portions of the Oswayo Creek RiverFlow2D models may be attributed to the lower resolution NED DEM in New York. As discussed previously, LiDAR is not available in New York so lower resolution NED was used to create the DEM for parts of the model in New York. Initial comparisons at the LiDAR-NED transition in the DEM shows that more floodplain storage and attenuation may be available than currently represented by the NED. See Figure 33 below. The top figure is just on the NED side of the LiDAR-NED transition and the bottom figure is just on the LiDAR side of the LiDAR-NED transition.
- At Bradford, PA, LiDAR shows significantly different channel and floodplain topographic characteristics than in 1942 due primarily to the construction of Route 219 through the city. The DEM was not manually adjusted to account for this difference.
- At some observation points along the Allegheny River, it is not clear if the peak water surface elevations were reported upstream or downstream of bridges. Therefore, some discrepancies may be expected at the bridges simply due to differing data point locations and bridge hydraulics.

Table 12. Summary of Levee Systems in Study Area

Municipality	Description	Year Construction Completed
Coudersport PA	Right Bank Mill Creek	1955
Coudersport PA	Left Bank Allegheny River	1955
Port Allegany PA	Lillibridge Creek – Allegheny River	1950 (approx.)
Eldred PA	Right Bank Allegheny River & Right Bank Barden Brook	1987
Shinglehouse PA	Oswayo Creek	Unknown
Portville NY	North of Dodge Creek & Right Bank Allegheny River	1951
Portville NY	South of Dodge Creek & Right Bank Allegheny River	1951
Olean NY	Left Bank Olean Creek & Right Bank Kings Creek	1952
Olean NY	Right Bank Allegheny River & Olean Creek	1952
Olean NY	Left Bank Kings Creek	1952
Salamanca NY	Left Bank Allegheny River	1971
Salamanca NY	Left Bank Allegheny River	1971
Salamanca NY	Right Bank Allegheny River – West Salamanca	1971

Figure 33. Velocity and Terrain Plot at Cross-Section at LiDAR/NED Transition





3 July 1942 Storm and Flood Analysis

3.1 Collection of Flood Data

Readily available historical information was collected and reviewed to support the July 1942 watershed/flooding analyses. Sources of flood data for the July 1942 flood included USGS streamflow gauge records (at Eldred and Salamanca) and scientific reports from government agencies on the flood that contained peak flows, peak water surface elevations, time-to-peak, and flow hydrographs at key locations along the Allegheny River, its tributaries and small drainages at the storm center. Most of the official government data came from the USGS Water Supply Paper 1134-B (Eisenlohr, 1952), Pennsylvania Department of Forestry and Waters Report (Commonwealth of Pennsylvania, Department of Forestry and Waters, 1943), and newspaper articles from an internet search.

The historical data collection and review included a site visit on August 24 and 25, 2017 to inspect key locations identified during the desktop review, including high water mark locations, areas of greatest impact from the flooding, and other locations determined to be critical to the analysis. The team met with individuals and historic societies with knowledge of or records of the event for additional insight. The site visit focused on populated areas most severely affected by the flood, particularly Port Allegany, Coudersport, Smethport, Eldred, and Portville, NY. Newspaper articles and photos provided visual markers of the flood and depth and time information. Information was geo-referenced to allow for comparison with the July 1942 flood models. See Figure 34.

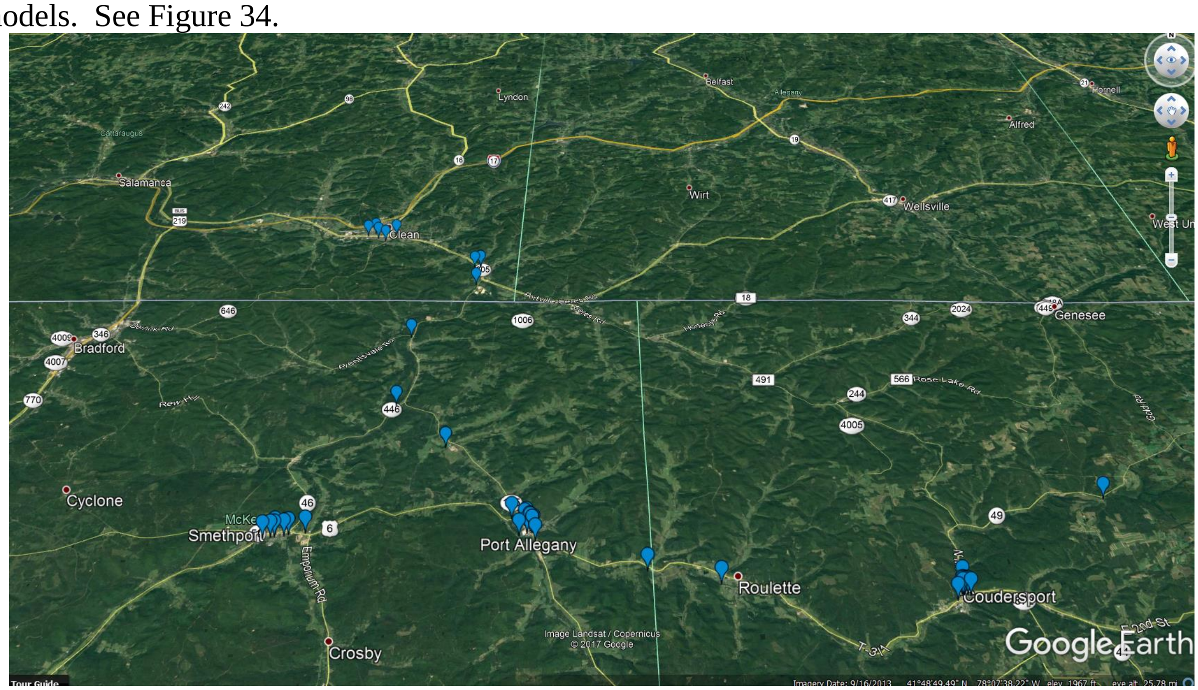


Figure 34. Markers Showing Locations of Field and Desktop Data from the July 1942 Flood

3.2 Initial Findings

The 1-hour gridded (1 km^2) precipitation of the 1942 storm, generated using AWA's SPAS analysis of reported rainfall, was used as input in the flood models. The purpose of this task was to essentially replicate the 1942 flood with the hydrologic and hydraulic models, duplicating the stream and watershed conditions at that time. The results of the model, specifically flow, flood stage, and timing information, were compared with observations from historic records and provided insights on how well flood data corresponds to rainfall data. The objective was to identify watershed regions where reported rainfall agrees with the estimated runoff (flow rates and timing) and observed flooding, or regions where the historic records and model predictions are in disagreement (e.g., rainfall versus peak runoff). Consideration was given to the modeling observations and limitations, discussed in Section 2.8, when making comparisons to inform the rainfall adjustments. Below is a summary of the rainfall observations made in reviewing the initial modeling results:

1. The original rainfall temporal distribution in the sub-watersheds downstream of Couderport and in the Port Allegany region is front loaded (peak intensity occurs early). The initial RiverFlow2D runs show peak flows along local tributaries within the Allegheny River watershed at Port Allegany occurring much earlier than when the peak was reported to have occurred. Since the response or lag time is short and directly correlated to the most intense rainfall period, this suggests that the peak rainfall intensity should be closer to center weighted; approximately 8 hours later than in the original rainfall temporal pattern. See Figure 35 for an illustration at Lillibridge Creek in Port Allegany.

2. The original RiverFlow2D results did not accurately predict the location and magnitudes of the peak flows in Twomile Run and Lillibridge Creek (reported to be 15,000 cfs and 16,000 cfs, respectively). This indicates that adjustments are warranted to the magnitude and spatial and temporal pattern at the Port Allegany storm center. See Figure 36 and Section 3.5 for additional analysis of the storm center rainfall.

The RiverFlow2D model peak time at Seven Bridges matches well with what was observed. However, the peak time in the model is early by approximately 4.5 hours downstream of the confluence between the Allegheny River and Mill Creek at Coudersport. The peak water elevations in Coudersport from the model are also consistently very high, between approximately 6 and 8 feet, from the elevations observed. As shown in

3. Figure 37, the temporal patterns of the Mill Creek sub-watershed inflow (and the associated rainfall) appear to be contributing to the cause. While there is hourly rainfall data available from a gauge located at the boundary of the Allegheny River watershed (Raymond, PA), the temporal distribution within the Mill Creek sub-watershed may vary from the gauge temporal distribution.

4. The RiverFlow2D model shows good peak timing and water surface elevation at Roulette, suggesting that the effect of rainfall issues upstream of Coudersport dampen downstream to Roulette and the rainfall patterns between these locations, including the intense rainfall cell just to the south and west of Coudersport, are stable.

5. The peak flow along the Allegheny River at the Route 6 Bridge, generated by the original RiverFlow2D model, is early (by approximately 8 hours) and underpredicting the peak flow (61,000 cfs versus the observed peak of 77,000 cfs). The underprediction of the peak flow was attributed to the temporal rainfall patterns in the Allegheny Portage watershed (particularly the intense rainfall cell near Liberty PA). As with other parts of the watershed, the Allegheny Portage watershed rainfall is front loaded.

6. Inaccuracies in the broader temporal rainfall patterns over the Oswayo Creek and Tunungwant Creek watersheds appear to be contributing to high and early peak flows along the Allegheny River downstream of Portville, NY (at the Allegheny River's confluence with Oswayo Creek). See Figure 38.

Figure 35. Initial Hyetograph and RiverFlow2D Hydrograph for Lillibridge Creek at Main Street

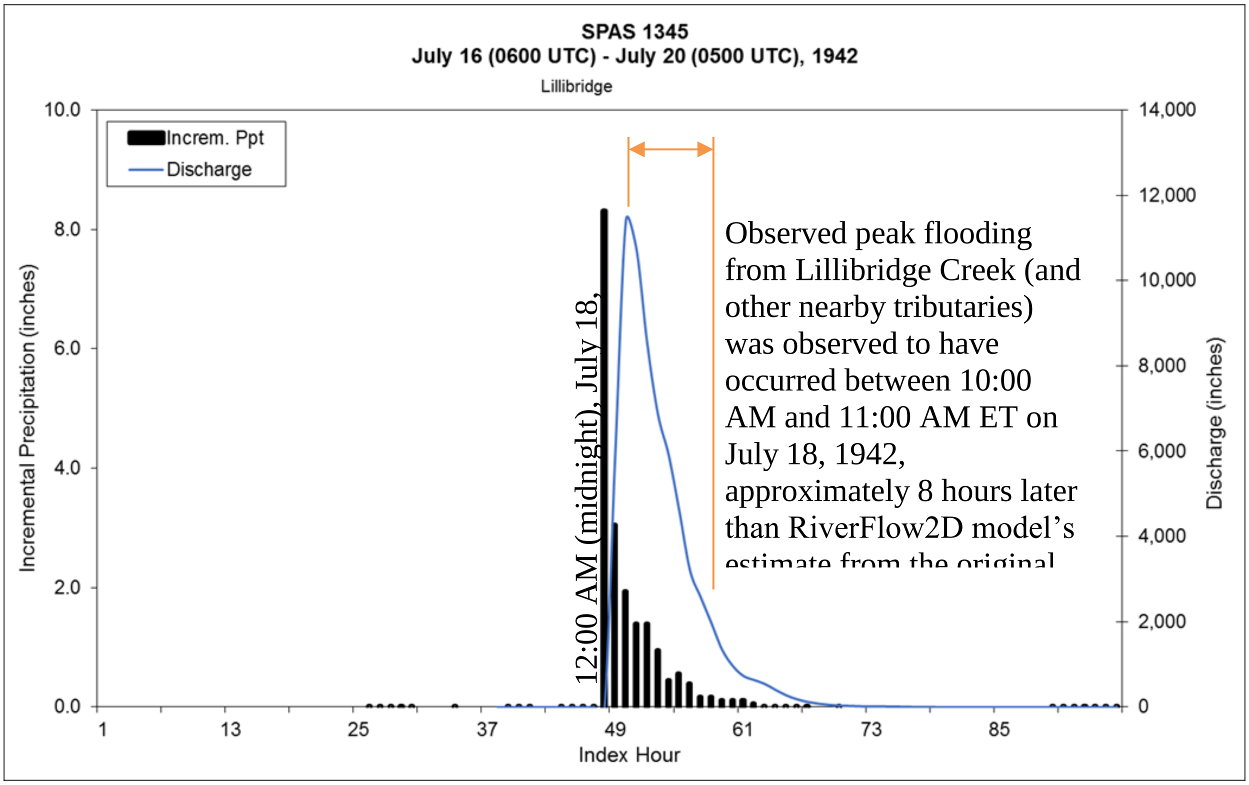


Figure 36. Extreme Rainfall at Port Allegany for Initial Iteration

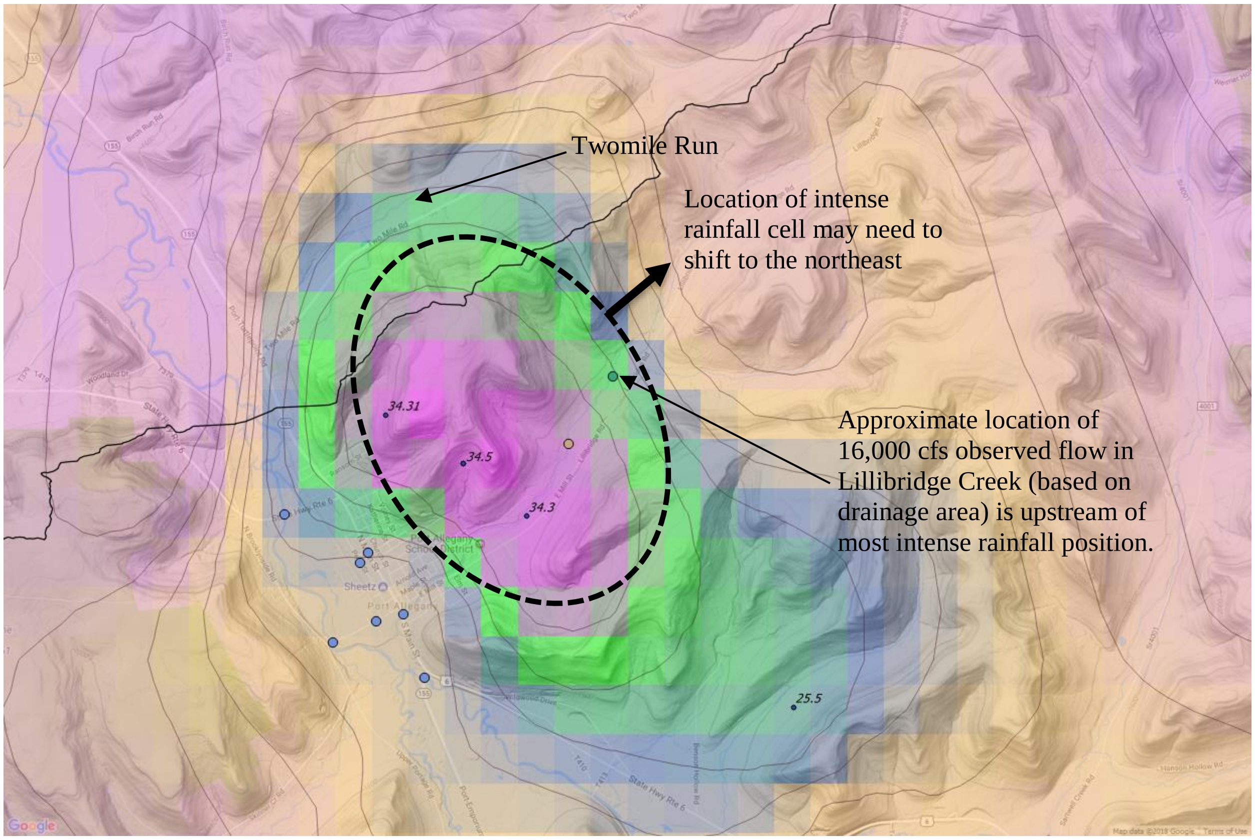


Figure 37. Initial Stage and Flow Hydrographs at Coudersport

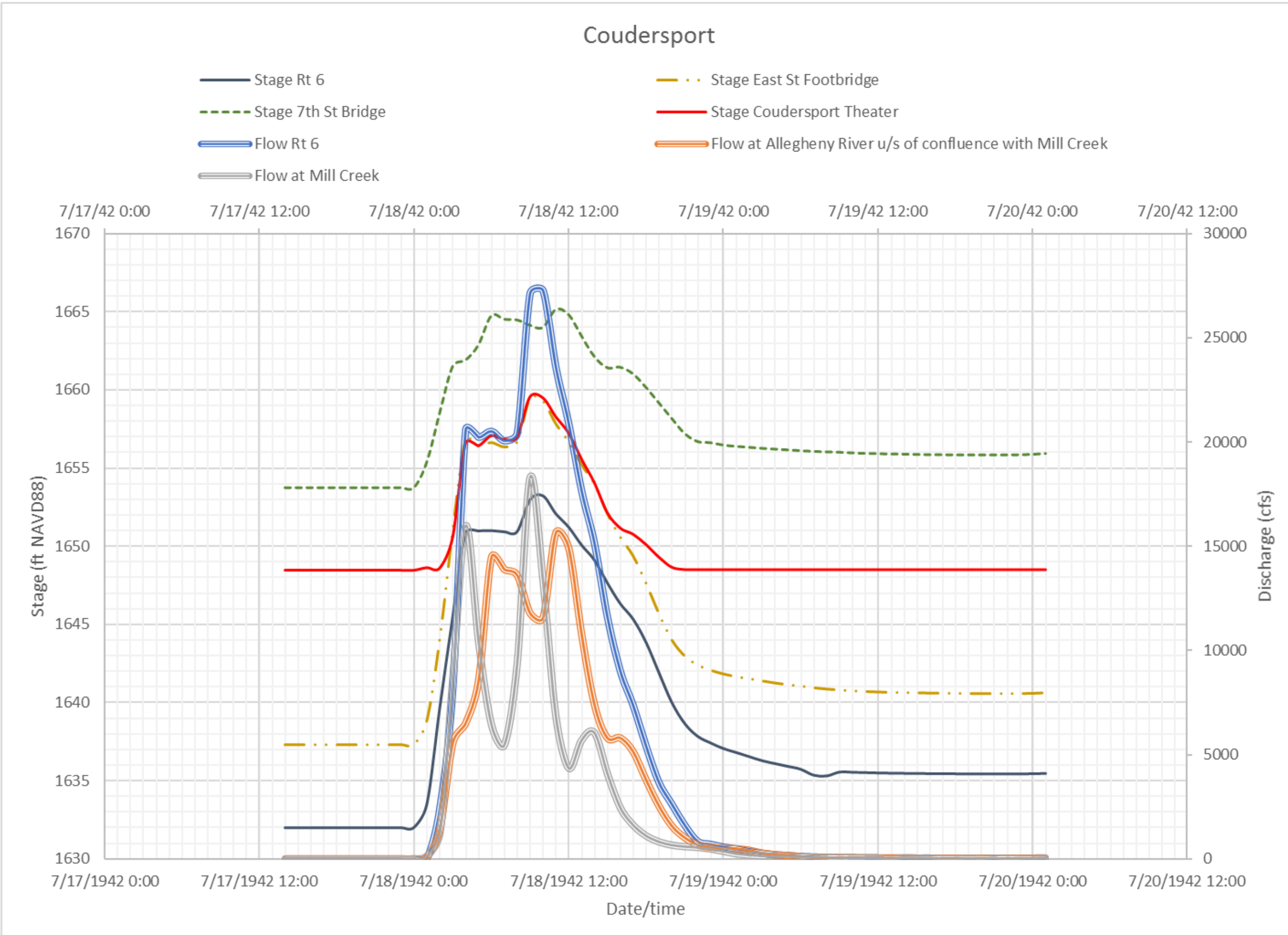
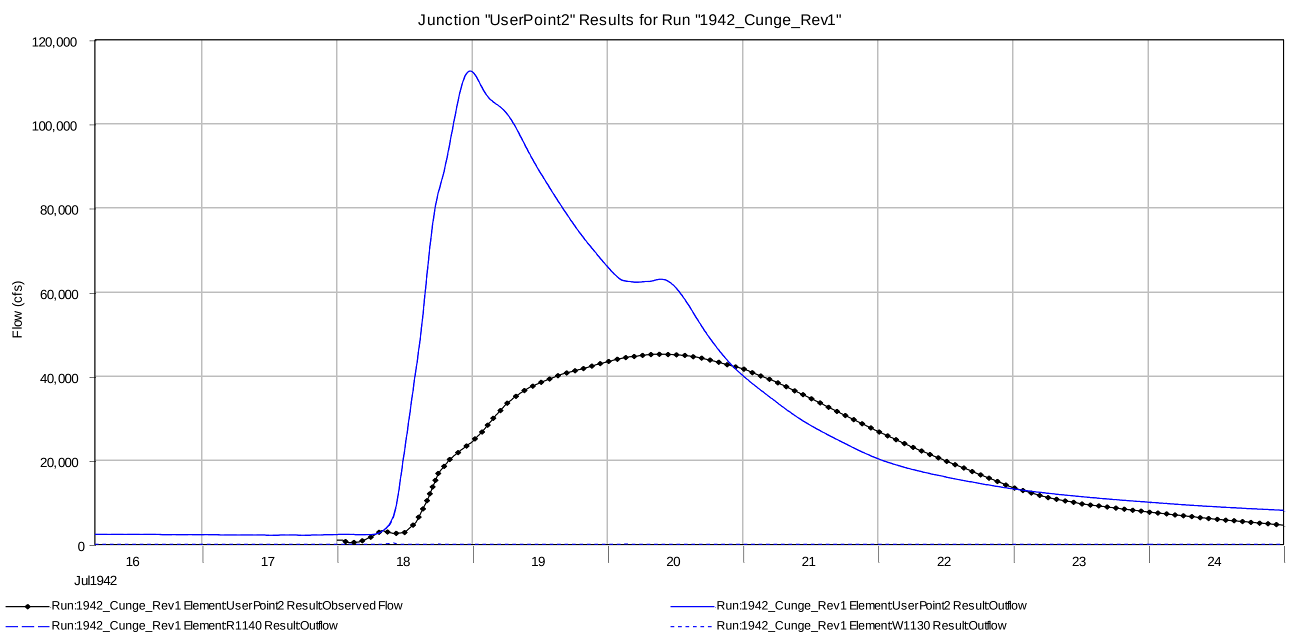


Figure 38. Initial Flow Hydrographs at Red House



3.3 Rainfall Adjustments

The evaluation of model and observed flood data, discussed above, led to iterating adjustments to the SPAS-generated rainfall data for the storm. These included adjustments to the timing, magnitude, and spatial patterns of the rainfall accumulation between observed data points. Each of these adjustments were made to better reconcile rainfall with the hydrology, informed by the calibrated flood models. All changes made to the previous rainfall accumulation patterns and magnitude were explicitly evaluated considering the acceptance of the Smethport rainfall as a world-record rainfall at the 4.5 and 6-hour durations. Most of the flood observations and records were at flood peaks (flows, water surface elevations, and time-to-peak). While peak flood data was helpful in corroborating or adjusting rainfall, a time-distributed representation of the flood (in the form of flow hydrographs) was only available at two USGS gauge locations along the main-stem Allegheny River; Eldred (PA) and Red House (NY). Because the Red House watershed encompassed the entire study domain and key rainfall locations, it represented a key comparison point in judging acceptance. With the rainfall and post-calibration model adjustments, the modeled flow hydrograph at Red House was able to improve as shown in Figure 39. Considering the modeling limitations discussed in Section 2.8, good overall agreement along the Allegheny River for peak water surface profile was also achieved, as indicated in Figure 42. Table 13 shows the peak timing comparison between observed and results from the 2D models. Good peak timing agreement was achieved with the rainfall adjustments; except between Eldred and Olean, where the flood peak is several hours earlier than what was reported. Sensitivity analyses based on broad variations in temporal rainfall patterns led to the conclusion that the peak timing discrepancies along this reach of the Allegheny River were not associated with rainfall inaccuracies. The discrepancy abruptly begins at Eldred, then recovers once the flood wave reaches Salamanca and Red House. The peak timing discrepancy at Eldred remains unresolved since it did not appear to be attributed to rainfall. There is speculation that a natural or man-made feature not represented by the HEC-RAS2D model is providing significant storage and attenuation in the Potato Creek sub-watershed or in the Allegheny River near its confluence with Potato Creek.

A summary of rainfall adjustments is described below. The final adjustments, compared to the original Isohyetal patterns, are depicted in Figure 40 and Figure 41. These figures also show delineations of revised depth-area-duration (DAD) zones for the storm; one for the original and six for the adjusted.

- Revised the rainfall temporal pattern in the sub-watersheds between Coudersport and Port Allegany, deviating from front-loaded storm (timed based on HMR-56) to a pattern more consistent with the surrounding hourly gauges. See discussion in Section 3.4 for a description of additional rainfall refinements at the storm center.
- For the Mill Creek sub-watershed (just upstream of Coudersport PA), factors were applied to further adjust rainfall by reducing the 2 peak hourly depths and redistributing to the other hours to maintain the total rainfall volume. Also, Basin #5 (W1090) bucket surveys were reduced by 20%.
- After reviewing the quality of rainfall data, the spatial extent of the "Bradford 2A" gauge in the Tunungwant Creek Watershed was reduced. This gauge is located in the Bradford, PA area were rainfall collection was sparse. Spatial extend of other high-rainfall gauges seem to show a tighter spatial distribution.

- For the Oswayo Creek Watershed, re-distributed the 2 hours for the second peak over 4 hours in sub-watershed W830 and resolved high "ΔP's" (difference between the SPAS generated rainfall with observed).

Figure 39. Post-Adjustment Allegheny River Hydrographs @ Red House, NY - July 18 to 25, 1942

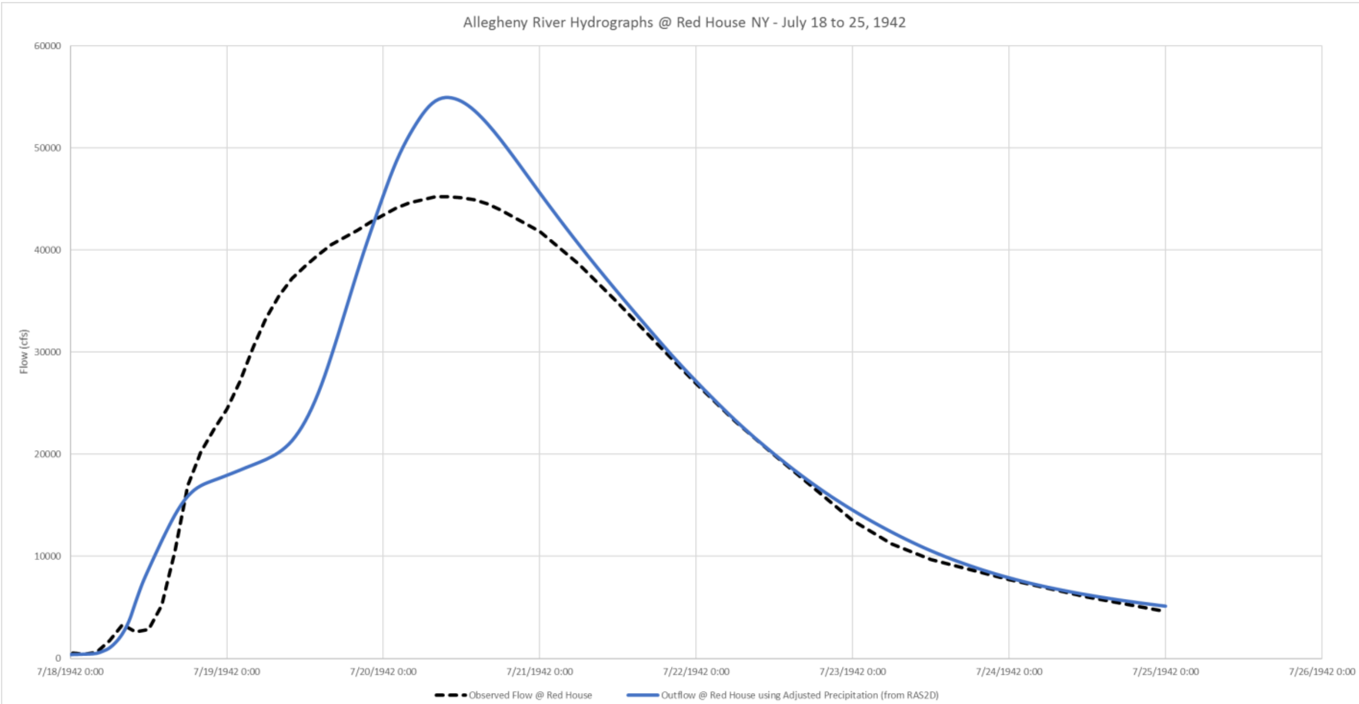


Table 13. Peak Timing Comparison with Rainfall Adjustments

Location	Peak Date/Time (Observed)	Peak Date/Time (2D Models using Ver 10 Rainfall)
Localized/Tributary Flooding:		
Lillibridge Creek - Main St, Port Allegany	7/18/42 10:30 AM	7/18/42 10:00 AM
Two Mile Run	7/18/42 10:30 AM	7/18/42 10:30 AM
Sartwell	7/18/42 10:30 AM	7/18/42 10:00 AM
Allegheny River Flooding:		
Above Roulette (466)	7/18/42 2:00 PM	7/18/42 12:00 PM
Roulette	7/18/42 2:00 PM	7/18/42 1:00 PM
Port Allegany (Route 6 Bridge)	7/18/42 3:30 PM	7/18/42 2:00 PM
Eldred	7/19/42 9:30 AM	7/19/42 12:00 AM
Portville (NY)	7/19/42 3:00 PM	7/19/42 5:00 AM
Olean (NY)	7/19/42 6:30 PM	7/19/42 12:00 PM
Salamanca (NY)	7/20/42 5:00 AM	7/20/42 7:00 AM

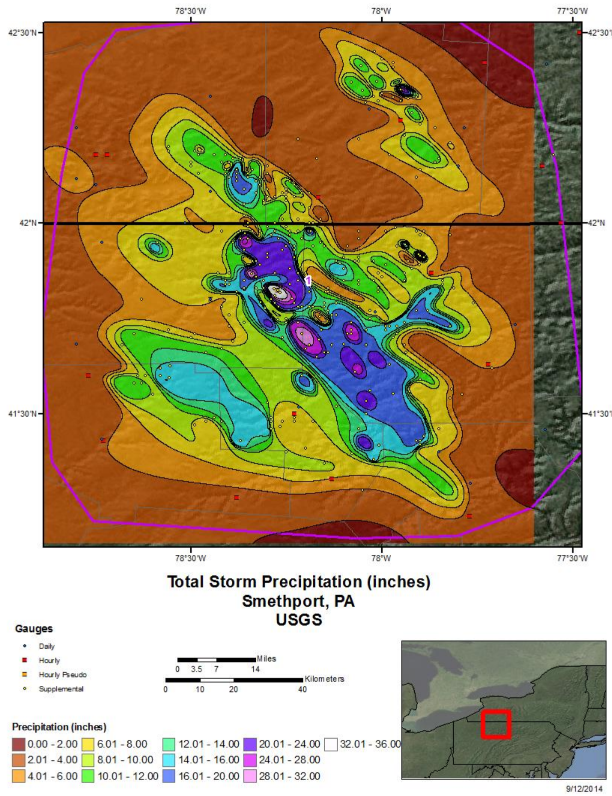


Figure 40. Original Isohyetal Map of the July 1942 Storm

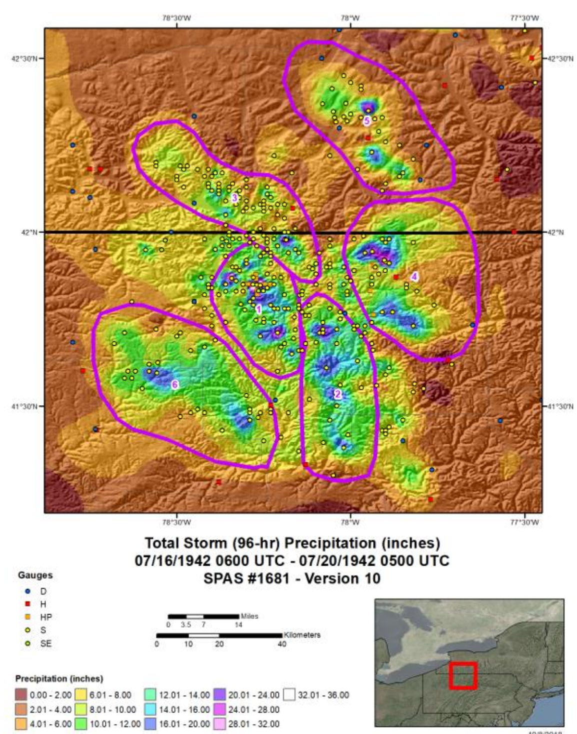
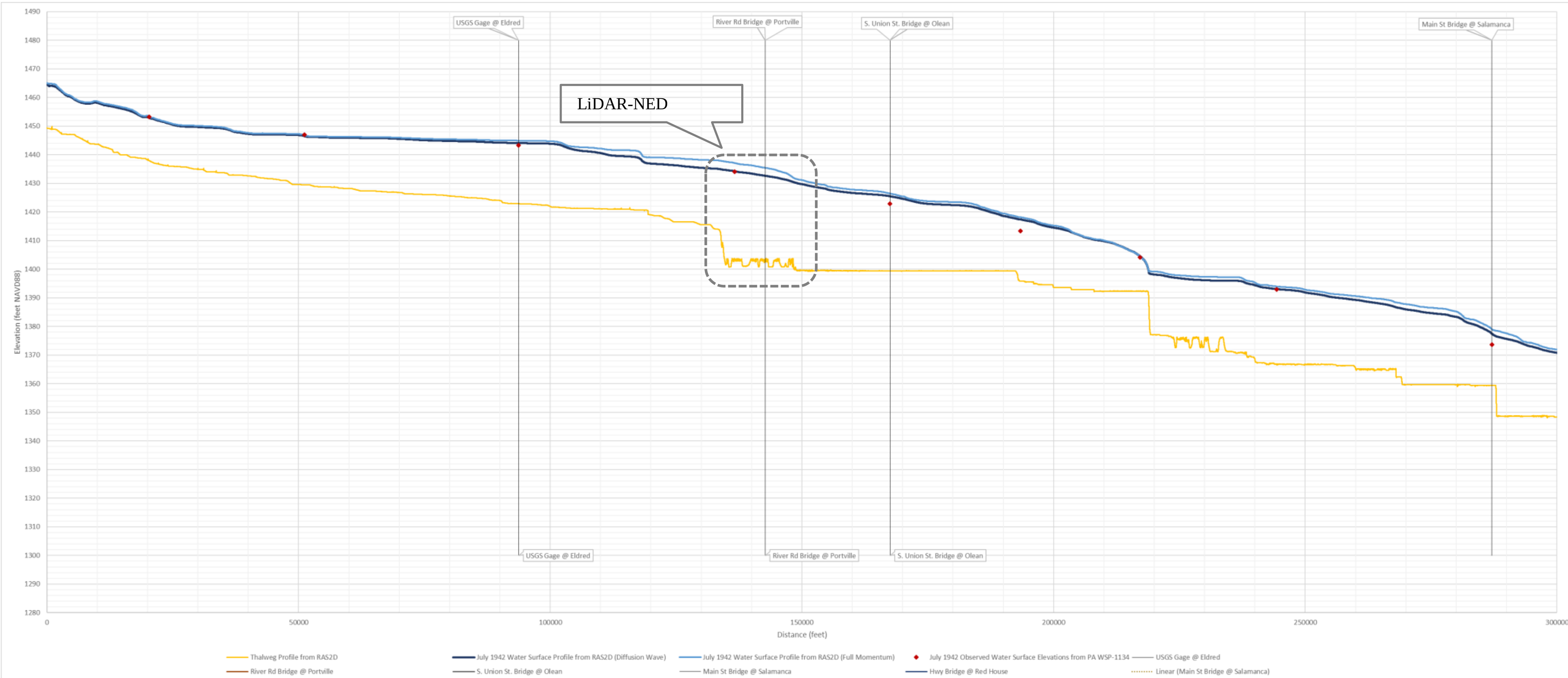


Figure 41. Isohyetal Map of the July 1942 Storm - Post-Adjustments

Figure 42. Post-Adjustment Allegheny River Peak Water Surface Profile for the July 1942 Flood



3.4 Localized Refinements at the Port Allegany Storm Center

Additional analysis of the rainfall and hydrologic record, particularly for the smaller watersheds, was conducted to refine the understanding of the magnitude and temporal patterns of rainfall in and around Port Allegany; the storm center and location of the most significant rainfall observation at Site 275 (Appolt Farm), where the 30.8-inches in approximately 5 hours was estimated. The estimated timing for this observation is shown in Figure 47. The timing applied at the Site 275 location in RiverFlow2D produces reasonable agreement with observed flood data at tributaries near Port Allegany (specifically, Lillibridge Creek and Twomile Creek). However, when this timing is allowed to influence a larger region, significantly higher flows and water surface elevations are produced in the Allegheny River near Port Allegany. From this, it was concluded that Site 275 timing would need to be significantly restricted in its influence and not allowed to influence the broader watersheds in the Port Allegany region.

Additional iterations were conducted to improve agreement in Twomile Creek, Lillibridge Creek, and Allegheny River; while attempting to hydrologically validate the Site 275 rainfall volume and timing. The additional iterations lead to the development of three (3) rainfall timing zones around the storm center (denoted as Storm Center Zones or SCZs); illustrated in Figure 43. Deviating from the original HMR-56 timing (

Figure 44), SCZ 1 rainfall corresponds closest to the "Bolivar" hourly gauge and covers the broader watersheds in the Port Allegany and Coudersport region (Figure 45). With other minor adjustments, the SCZ 1 "Bolivar" timing generally produced reasonable agreement between the model and observed flood data, both in the tributaries and main-stem Allegheny River, with one exception; the Twomile Creek flows was significantly underestimated in RiverFlow2D. Furthermore, as indicated in Figure 45, applying bucket surveyed rainfall to the "Bolivar" timed temporal pattern does not produce cumulative rainfall depths that correspond to the heaviest rainfall observation at Site 275 (Appolt Farm) of 30.8-inches in approximately 5 hours. Therefore, the SCZ 1 ("Bolivar" timed) rainfall was further adjusted locally, creating SCZ 2 and SCZ 3 rainfall timing, while honoring the Site 275 observation and other nearby bucket surveys and achieving reasonable agreement with observed flows in the tributaries and main-stem Allegheny River near Port Allegany. SCZ 3 (at the storm center) is timed to the Site 275 observation (Figure 47), with spatial limits defined in Figure 43. SCZ 2, developed as a transition from SCZ 1 to SCZ 3, is timed as a modified "Bolivar" hourly gauge (

Figure 46) and was based on two key observations:

1. There was no record of high flows occurring in the early (overnight) hours of July 18 along Twomile Creek and Lillibridge Creek. The RiverFlow2D model shows that significant flows would have occurred in these tributaries as a direct result of the first intense rainfall (occurring between 12:00 AM and 1:00 AM on July 18) included in the "Bolivar" timed rainfall.
2. Page 67 of WSP-1134-B (Eisenlohr, 1952) states "the observer who recorded more than 30.8 inches of rain in 4 ¾ hours stated that it seemed to fall at a tremendous rate, but quite uniformly, for the greater part of the time. Also, the drops seemed to be exceptionally large and very close together. From her statement and the record of total rainfall at that point, it may be assumed that the rainfall at no time exceeded a rate of about 10 inches per hour and that there was no "streaming" for that rate and for that size drop."

Consequently, the SCZ 2 rainfall was developed by shifting 5 inches of the "Bolivar" timed rainfall from the first hour (between 12:00 AM and 1:00 AM) to the second heavy 2 hours of rainfall (between 8:00 AM and 10:00 AM) to set the rainfall in this period at 10 inches per hour. As discussed previously, the early burst of rain in the SCZ 1 timing, as indicated by the Bolivar gauge (along with other hourly gauges in the region), appears consistent with the hydrology of the broader watershed. Applying SCZ 2 or SCZ 3 timing (i.e., shifting more rainfall later in the storm) for the broader watershed increases runoff and produces overestimated flows and levels since, given the exponential-shaped loss function associated with the NRCS Direct Runoff Equation, higher runoff occurs later in the storm. The final iterations (Version 10) produced reasonably close matches to flood data while honoring the Site 275 and other bucket surveys in the Port Allegany Region. Modeled peak flows along the tributaries near Port Allegany were converted to unit (cfs per mi^2) flows and plotted (Figure 48) against observed unit flows in the same region (similar to Figure 43 of WSP-1134-B) showing good agreement.

Figure 43. AWA's Total Storm Precipitation (96-hours) at Port Allegany, PA

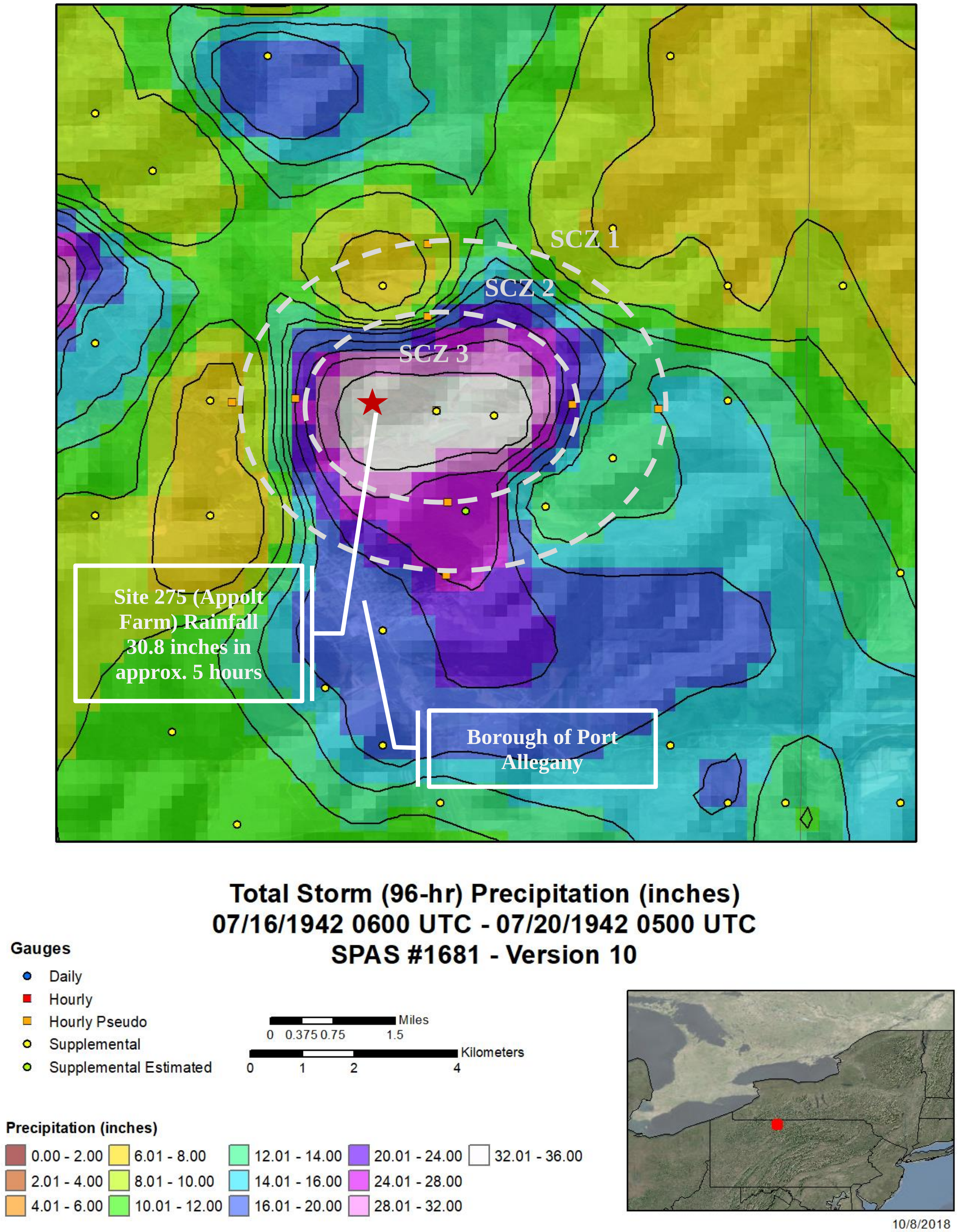


Figure 44. Original Temporal Pattern in Port Allegany, PA, Region (based on HMR-56 Timing)

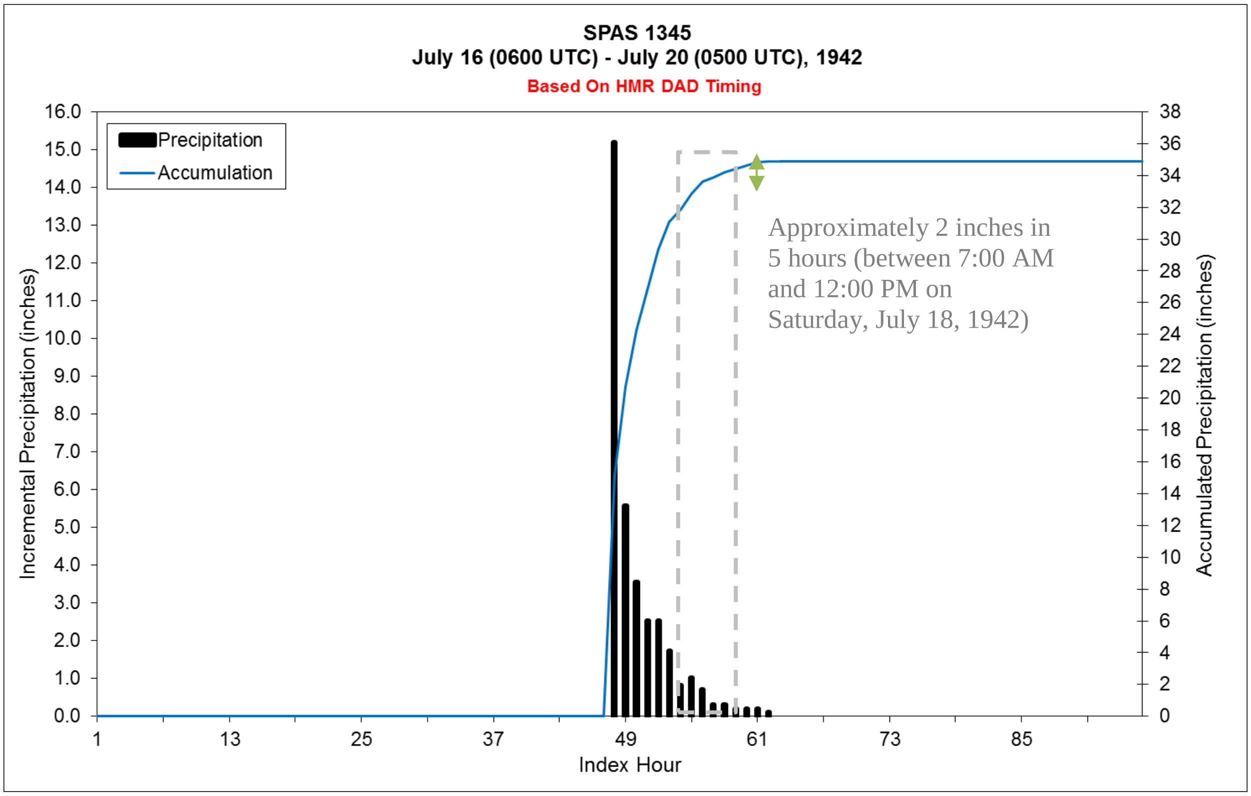


Figure 45. SCZ 1 Temporal Pattern (based on Bolivar Hourly Gauge)

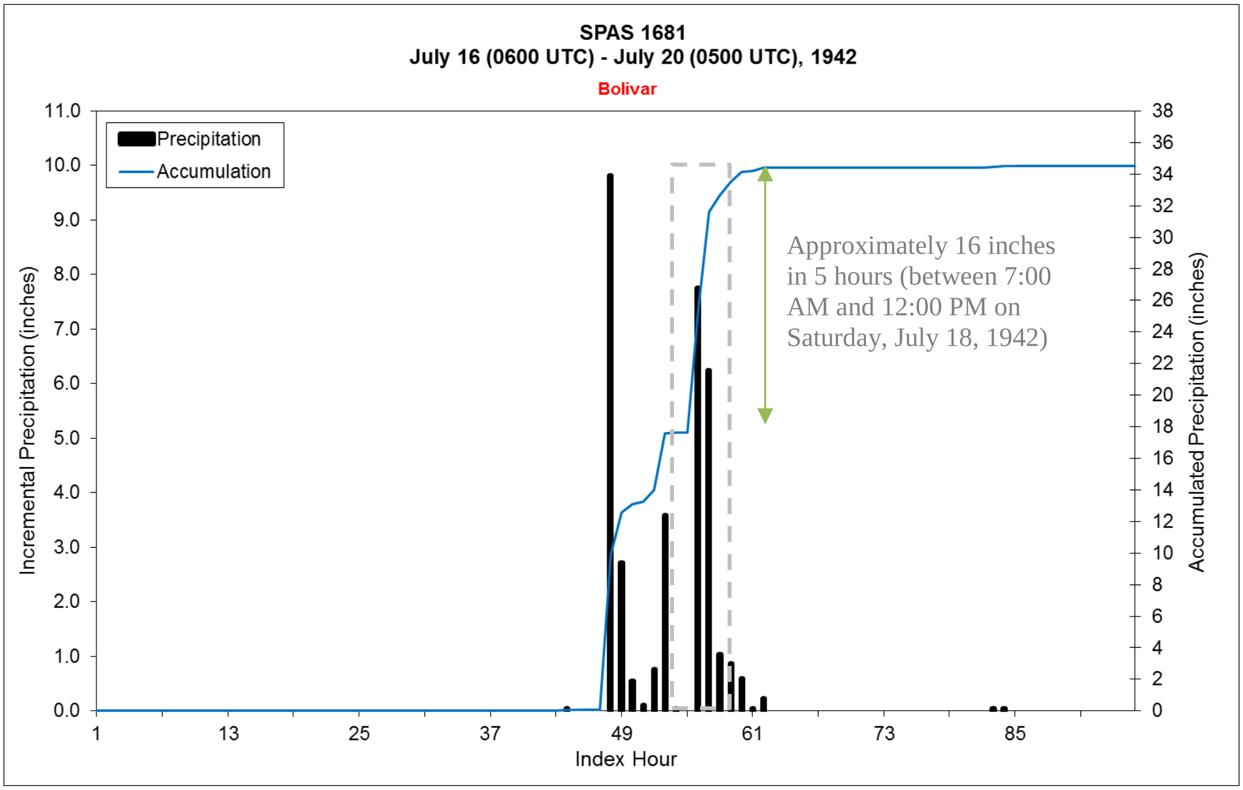


Figure 46. SCZ 2 Temporal Pattern (modified Bolivar Hourly Gauge)

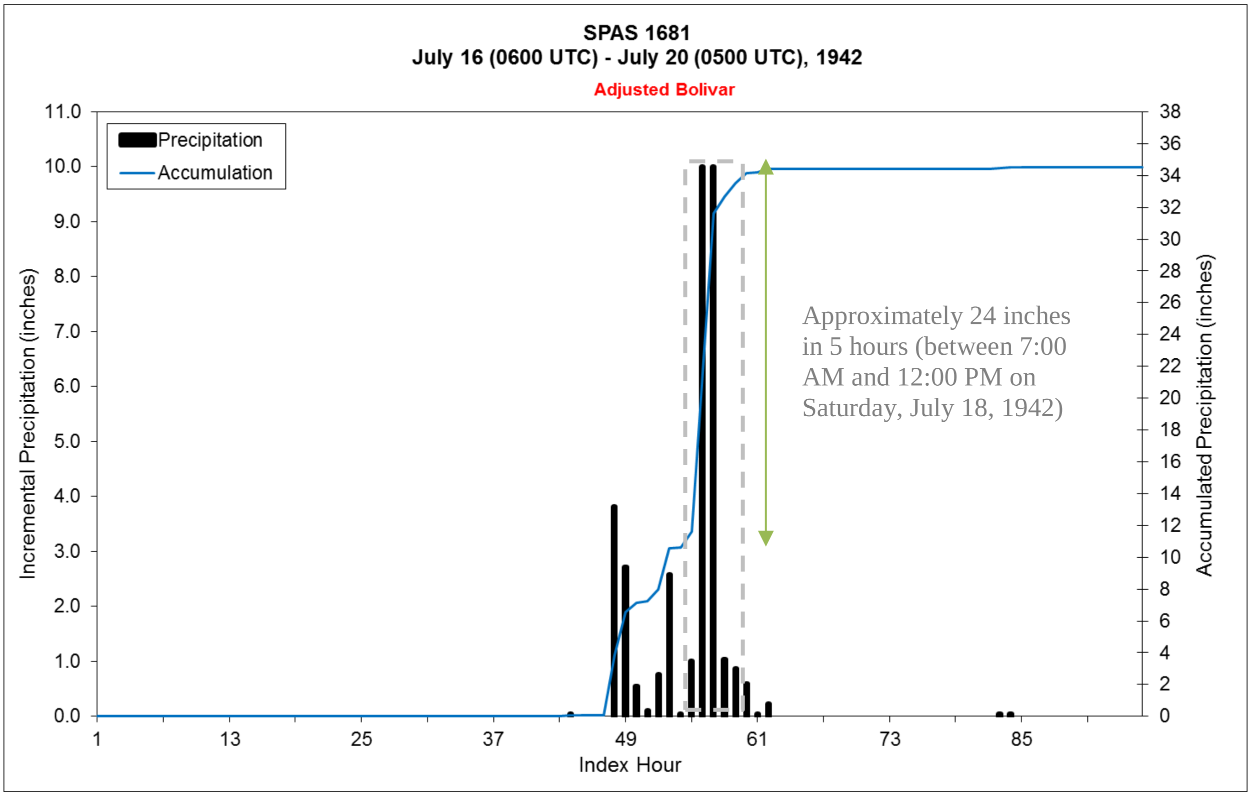


Figure 47. SCZ 3 Temporal Pattern (based on Site 275 (Appolt Farm) Report)

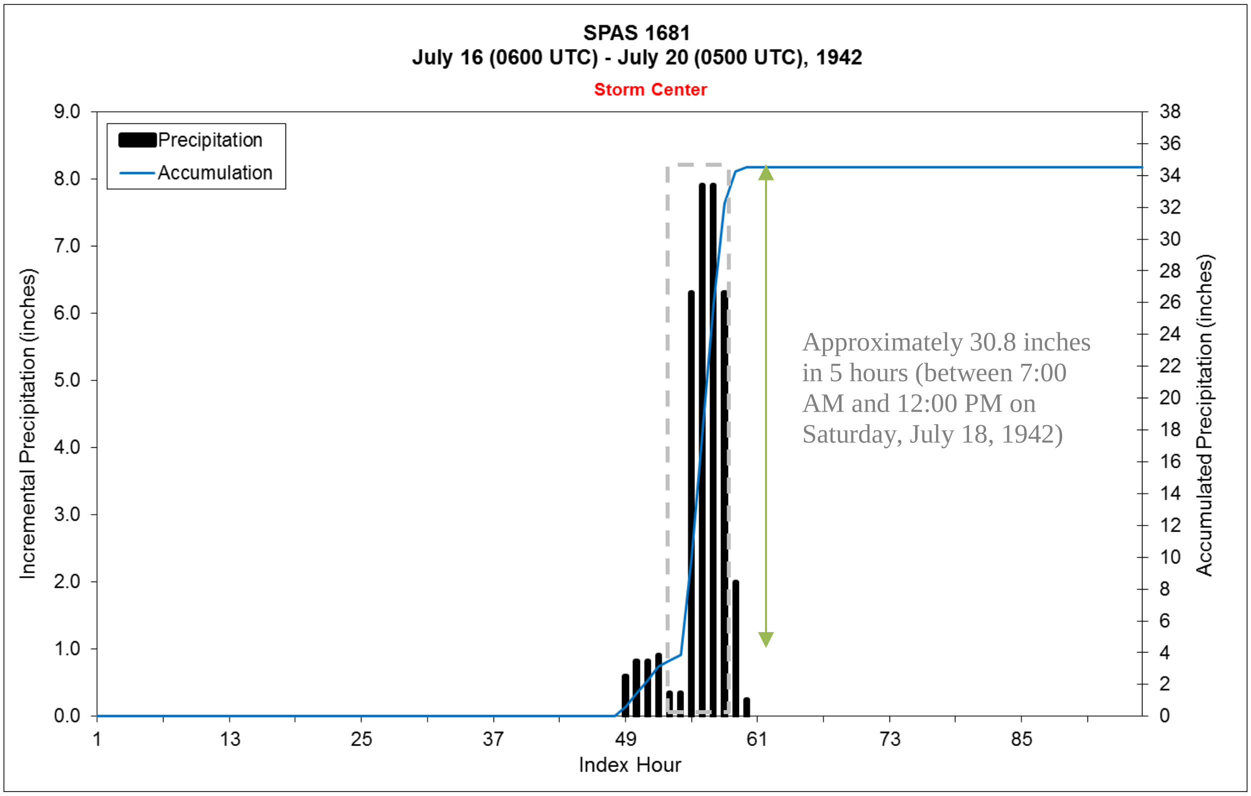
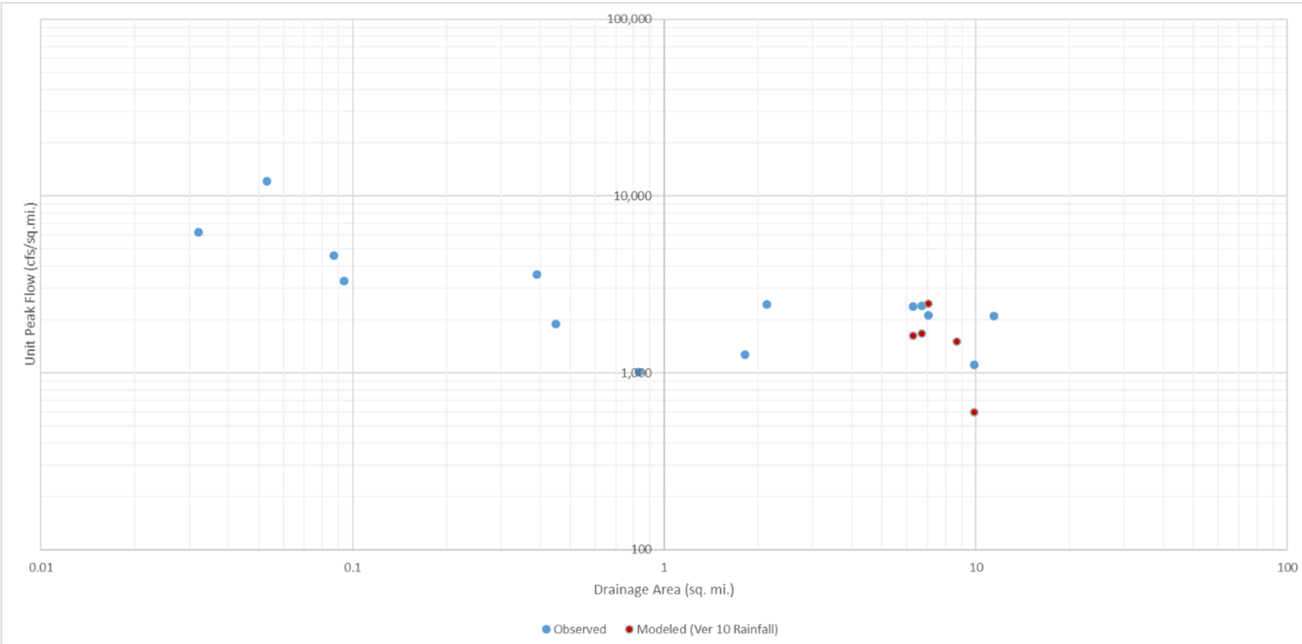


Figure 48. Observed & Modeled Unit Peak Flows vs. Drainage Area for Watersheds near Port Allegany



3.5 Insights into the Most Extreme Rainfall Observation (Site 275)

Even after establishing hydrologically viable rainfall patterns for tributaries and the main-stem Allegheny River near the storm center at Port Allegany, an additional analysis was conducted to further assess the hydrologic viability of the Site 275 observation. As discussed above, the Site 275 timing does produce good agreement with observed flows in Twomile Creek and Lillibridge Creek but significantly overestimates flooding in the main-stem Allegheny River when broadly applied. The additional analysis utilizes observed flows in small drainages and assisted in defining the limits of SCZ 3 in Figure 47. The flow observation locations from small drainages and the Site 275 rainfall observation are shown on Figure 49. Estimated using the NRCS lag time equation, the smallest of these drainage areas have lag times well below 1 hour. As such, observed peak flows are likely governed by sub-hourly rainfall intensities.

Since sub-hourly rainfall patterns are not being defined by the AWA SPAS analysis of the July 1942 storm, an analysis was conducted using the Rational Method (with the Runoff Coefficient (C) calibrated to RiverFlow2D results) to estimate the hourly rainfall intensities needed to produce the observed flows at each location. (See Figure 49 for locations of observed flow locations.) The results, shown in Table 14, indicate that significant rainfall intensities (between 17 and 45 inches per hour) could have occurred at flow locations 016.20, 016.21, and 016.22, located near the Site 275 rainfall observation. Rainfall intensities for other surrounding flow locations, including within the Twomile Creek, Lillibridge Creek, and Sartwell Creek watersheds, were estimated to be between approximately 6 and 16 inches per hour; which is consistent with the "Bolivar" and "modified Bolivar" timing in Figure 45 and

Figure 46, respectively. The significant rainfall intensities needed to produce observed flows at locations 016.20, 016.21, and 016.22 suggest that the Site 275 (Applot) observation is viable but probably included a combination of steady heavy rainfall (consistent with the statement on page 67 of WSP-1134-B, above) and significant short-bursts at intensities between 17 to 45 inches per hour, accumulating to 30.8 inches between 7:00 AM to 12:00 PM on July 18. These extreme bursts may seem to contradict the statement on page 67 of WSP-1134-B but it is likely that the extreme bursts occurred at very localized areas in the headwaters of the small drainages, where no direct observations were made. See Figure 50 for an illustration.

Figure 49. Water Supply Paper 1134-B, Plate 2 (Map of Flood Area showing Locations of Stream-Gaging Stations, Rainfall-Measurement Points, and Isohyetal Lines for July 17-18, 1942)

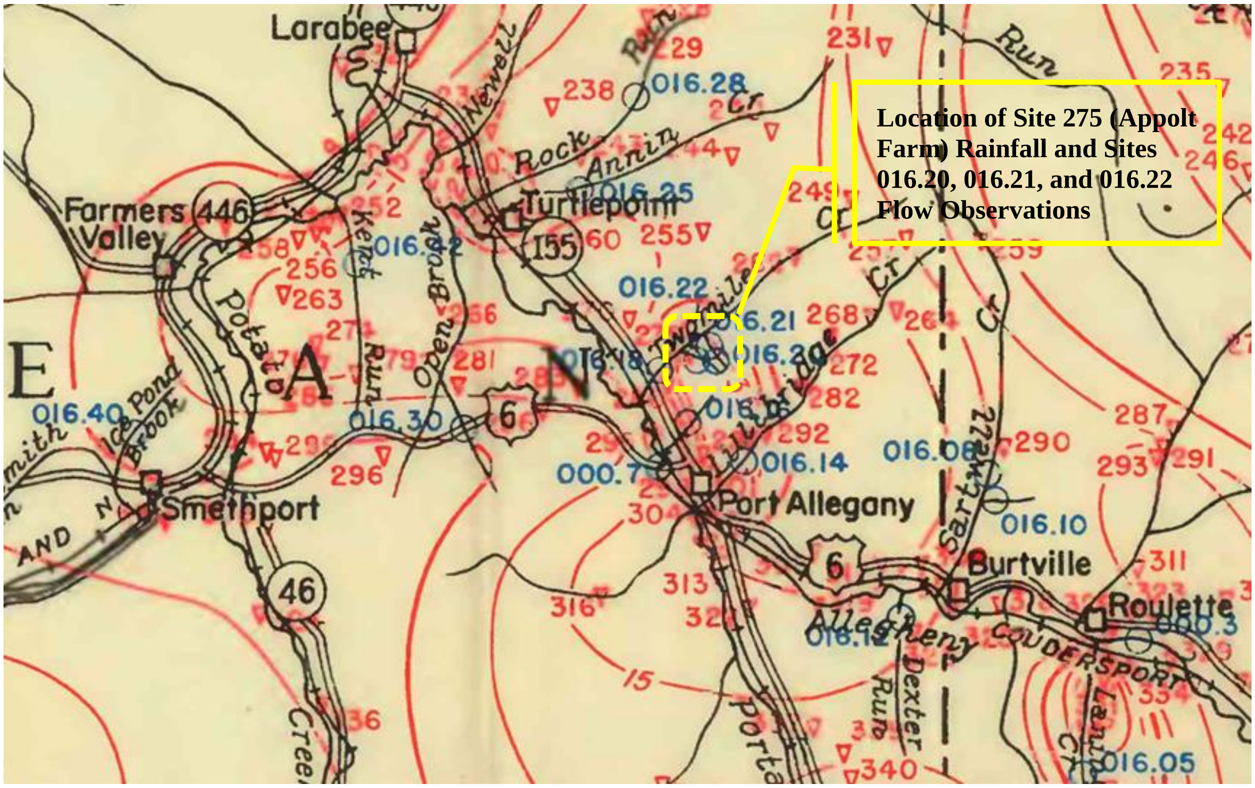


Figure 50. Map of Rainfall and Flow Observations at Storm Center

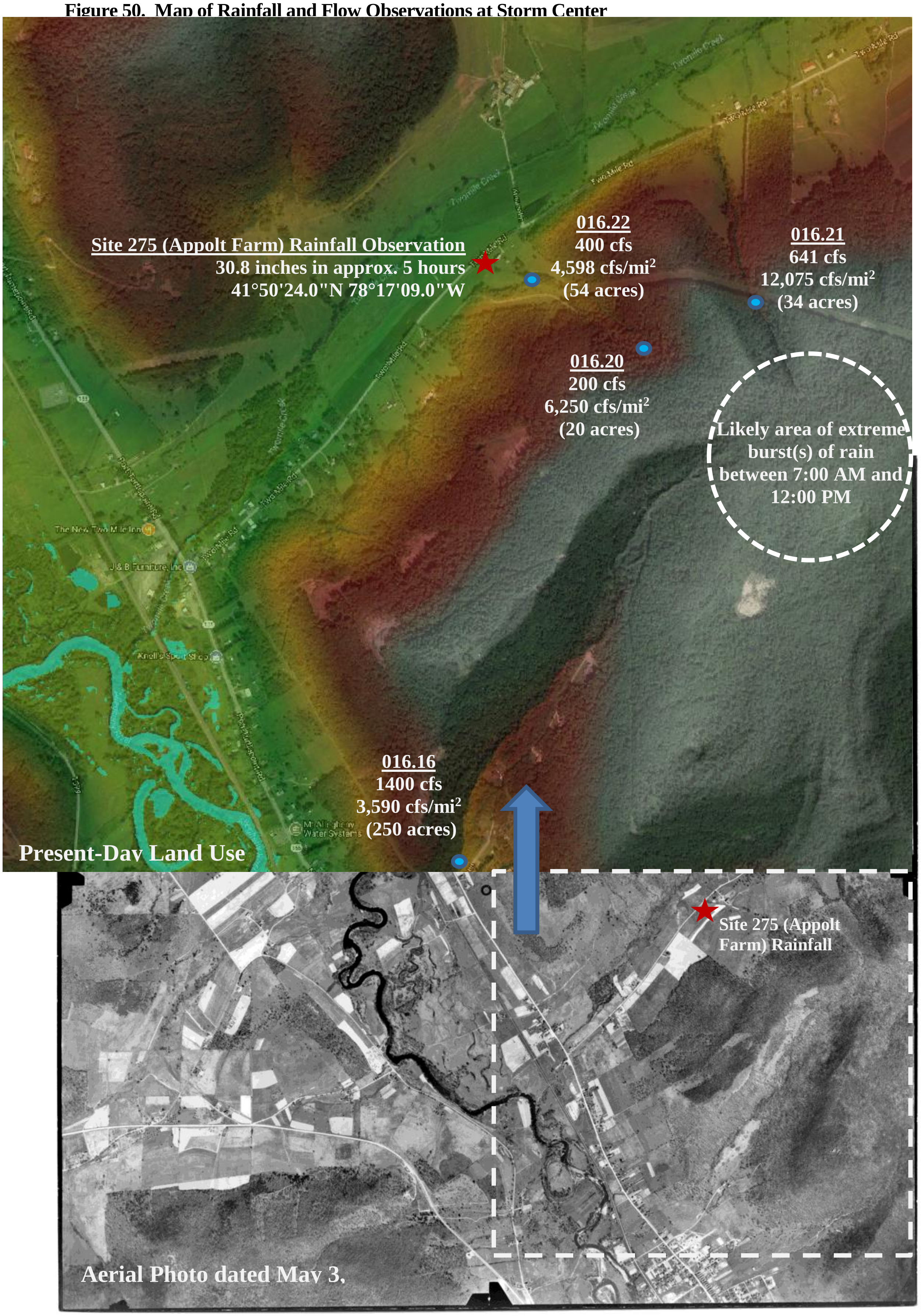


Table 14. Estimate of Rainfall Intensities needed to produce Observed Flows at Small Drainages near Port Allegany (based on Rational Method)

Watershed	Point #	Rational Runoff Coef (C)	Peak Intensity (in/hr)	Drainage Area (acres)	Peak Flow (cfs)	Flow per Sq Mile (cfs/mi^2)
Port Allegany	016.16	0.35	16.1	250	1,406	3,606
Two Mile Run	016.20	0.42	23.2	20	200	6,236
Two Mile Run	016.21	0.42	45.0	34	641	12,096
Two Mile Run	016.22	0.42	17.1	56	400	4,596
Sartwell Creek	016.10	0.32	16.1	60	310	3,297

4 Conclusions

PMP depths across much of the region covered by HMR 51 are greatly influenced by the exceptional July 1942 storm in the Smethport/Port Allegany region of north-central Pennsylvania. The rainfall measurement dataset for this storm includes several “bucket surveys”, which significantly influence the depth-area-duration characteristics of the storm. However, the quality of the “bucket survey” measurements is uncertain. Given the significance of this world-record-setting event in developing PMP values, an analysis of the resulting flood (using advanced modeling techniques and observed flood data) provided key insights into the rainfall observations. In some areas, the flood analysis corroborated the rainfall observations. In other areas, such as the upper Allegheny River (at and upstream of Port Allegany), Tunungwant Creek, and upper Oswayo Creek watersheds, flood data did not fully support the magnitude, spatial, and/or temporally information provided in the HMRs or as reported in hourly and “bucket survey” rainfall data.

Considering uncertainties in the flood models and quality of the flood data in addressing hydrologic differences, adjustments were made to the rainfall data until reasonable agreement was reached between the flood models, flood observations, and rainfall analysis. This combined the best aspects of the meteorological and hydrological analyses to improve the representation of the rainfall accumulation, to a reasonable extent given the data available. Of particular focus was the location of the storm center near Port Allegany, PA, where the world-record-setting “bucket survey” rainfall that exceeded 30 inches in 4.5 hours was observed. From the flood analysis of the tributaries and small drainages at the storm center, it was concluded that the reported rainfall could have occurred, but its influence was very limited and there was a high-degree of spatial variability. The analysis led to refinements to the temporal and spatial patterns of the rainfall at the highly significant storm center. In the end, the flood analysis resulted in a more accurate depth-area-duration representation of this very important storm in Pennsylvania’s PMP development.

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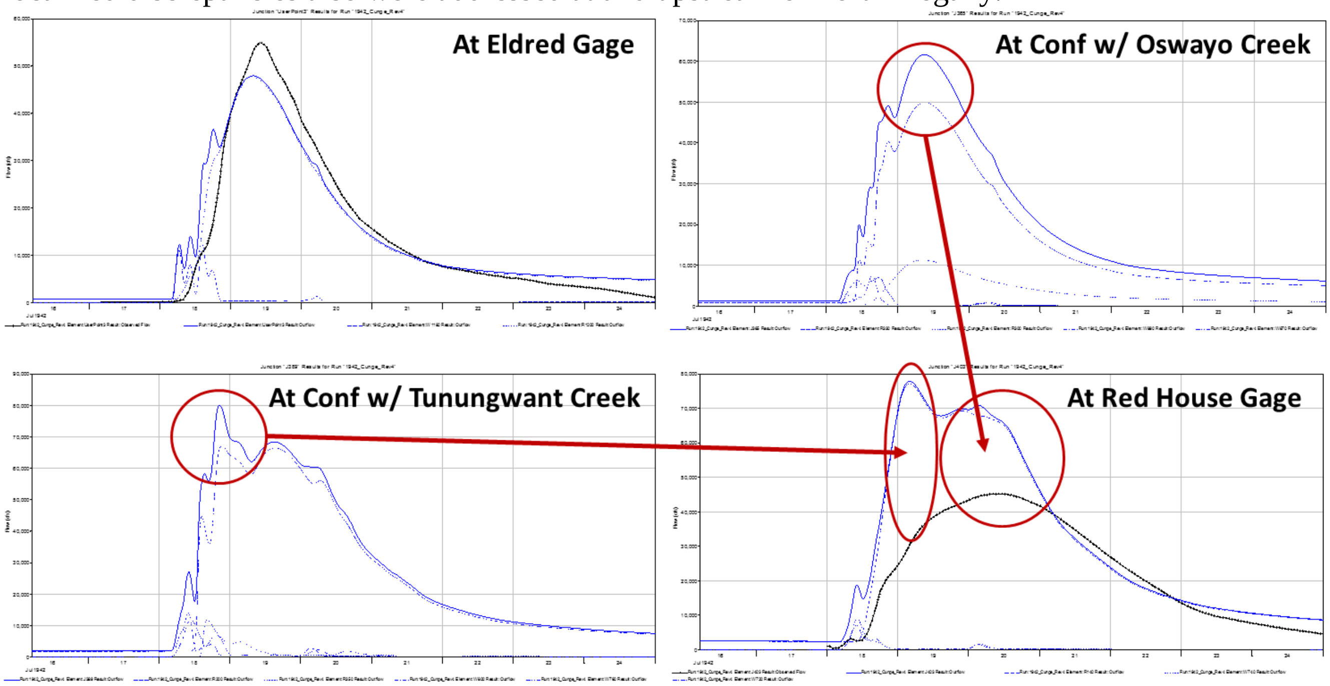
6 National Inventory of Dams Database – Summary Table

Table 15. National Inventory of Dams Database Summary

NID ID	Dam Name	Owner Name	Primary Purpose	Dam Type	River	City	County	State	Dam Length (Ft.)	Dam Height (Ft.)	Hydraulic Height (Ft.)	Volume	Year Completed	Spillway Width	Max Storage	Drainage Area
NY00456	Cuba Lake Outlet Spillway Dam	NYS Office Of General Services; Cuba Lake District	Recreation	Concrete	Cuba Lake Outlet	Maplehurst	Allegany	NY	136	9	0	0	1919	102	16,498	25.30
NY00455	Cuba Lake Dam	NYS Office Of General Services; Cuba Lake District	Recreation	Earth	Oil Creek	Cuba	Allegany	NY	1,750	55	0	0	1872	102	16,498	25.30
NY00571	Ischua Creek Watershed Dam #6a	Cattaraugus County	Flood Control	Earth	Gates Creek	Franklinville	Cattaraugus	NY	1,043	63	0	0	1971	488	3,890	19.00
NY00583	Ischua Creek Watershed Dam #1	Cattaraugus County	Flood Control	Earth	Ischua Creek	Machias	Cattaraugus	NY	490	27	0	0	1964	530	3,677	13.10
PA00026	Bradford City No 5 Dam	Bradford City Water Authority	Water Supply	Earth	West Branch Tunungwant Creek	-	Mckean	PA	1,200	68	68	544,000	1957	0	3,390	6.60
NY00565	Ischua Creek Watershed Dam #5	Cattaraugus County	Flood Control	Earth	Tr-Gates Creek	Franklinville	Cattaraugus	NY	1,693	54	0	0	1961	376	1,643	6.40
NY00626	Ischua Creek Watershed Dam #4	Cattaraugus County	Flood Control	Earth	Saunders Creek	Franklinville	Cattaraugus	NY	900	51	0	0	1961	309	1,011	4.10
NY16042	Bentley Wildlife Marsh Dam	Martyn Z. & Joan M. Bentley	Fish and Wildlife Pond	Earth	Bakerstand Creek	Machias	Cattaraugus	NY	1,100	10	0	0	2001	80	910	5.15
PA00024	Bradford City No 2 Dam	Bradford City Water Authority	Water Supply	Earth	Gilbert Run	-	Mckean	PA	850	44	44	166,222	1886	0	760	4.49
NY00560	Ischua Creek Watershed Dam #2	Cattaraugus County	Flood Control	Earth	Johnson Creek	Franklinville	Cattaraugus	NY	1,400	42	0	0	1961	160	647	2.80
NY00551	Ischua Creek Watershed Dam #3	Cattaraugus County	Flood Control	Earth	Tr-Ischua Creek	Franklinville	Cattaraugus	NY	1,220	38	0	0	1966	330	646	3.70
PA00025	Bradford City No 3 Dam	Bradford City Water Authority	Water Supply	Earth	Marilla Brook	-	McKean	PA	770	47	47	170,897	1898	0	502	4.80
NY00627	Harwood Lake Dam	NYS Dec Region 9	Recreation	Earth	Tr-Ischua Creek	Franklinville	Cattaraugus	NY	1,070	22	0	0	1963	110	350	0.00
NY01449	Beaver Lake Dam	Alma Rod & Gun Club	Recreation	Earth	Honeoye Creek	Alma	Allegany	NY	180	7	0	0	-	6	320	0.00
NY00589	Camp Lakeland Pond Dam	The Woods At Bear Creek, Llc	Recreation	Earth	Tr-Bear Creek	Franklinville	Cattaraugus	NY	850	47	0	0	1964	75	221	0.50
NY16145	Tannenbaum Reservoir Dam	Win-Sum Ski Corporation	Other	Earth	-	Ellicottville	Cattaraugus	NY	3,000	31	0	0	2006	0	220	0.00
PA01014	Hamlin Lake Park Dam	Borough of Smethport	Recreation	Earth	Marvin Creek	-	McKean	PA	653	10	10	8,465	1915	0	144	56.70
NY16105	Holimont Upper Reservoir Dam	Holimont Inc	Other	Earth	None	Ellicottville	Cattaraugus	NY	0	35	0	0	2003	0	129	0.00
NY00825	Edgar Ploetz Recreational Pond Dam	David Ploetz	Recreation	Earth	Beaver Meadow Creek	Ashford	Cattaraugus	NY	380	22	0	0	1969	17	91	0.60
PA01671	Clark Dam	Albert Clark	Recreation	Earth	Warner Brook	-	McKean	PA	600	16	16	17,778	1966	0	55	0.39
NY01353	Vee Pond Dam	Mary C Schlosser	Other	Earth	Morgan Hollow Run	Allegany	Cattaraugus	NY	245	16	0	0	1947	30	50	0.93
NY00826	William O Nannen Pond Dam	John D Northrup	Recreation	Earth	Tr-Great Valley Creek	Ellicottville	Cattaraugus	NY	1,230	15	0	0	1964	3	36	5.60
NY14130	Sunset Saddle Dam	Holimont Inc	Other	Earth	None	Ellicottville	Cattaraugus	NY	750	20	0	0	-	26	34	0.01
PA01715	Elk Lick Scout Reservation Dam	Allegheny Highlands Council	Recreation	Earth	Tr South Branch Cole Creek	-	McKean	PA	415	12.5	12.5	7,925	-	0	18	1.42

7 Log of Rainfall and Modeling Iterations and Sensitivity Analyses

The objective of the modeling and rainfall adjustments is to resolve the following broad hydrograph discrepancies between Eldred and Red House for the July 1942 flood. More localized discrepancies also were addressed at and upstream of Port Allegany.



7.1 Log of Rainfall Iterations and Sensitivity Analyses

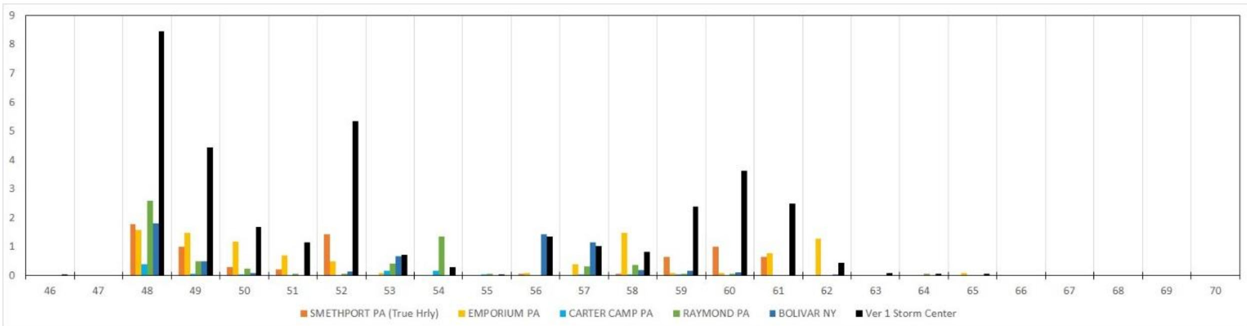
General:

- Sensitivity runs were conducted using HEC-HMS to determine if staggering the timing of the start of rainfall by 2 to 4 hours (earlier in the northern watersheds and later in the southern watersheds, as indicated by the hourly gage data) to determine if a better timing match would result with the flood data along the Allegheny River downstream of Port Allegany. The results did not lead to significant improvements so the start of the rainfall throughout the watershed (midnight 7/18/42 to 7/19/42) was maintained.

Upper Allegheny River Watershed to Port Allegany:

- Revised rainfall temporal pattern in the sub-watersheds between Couderport and Port Allegany from front loaded to be consistent with the pattern developed for Lillibridge Creek (moving away from the HMR-56 pattern and timed to the Bolivar gage); including Allegheny Portage.
- For the Mill Creek sub-watershed (just upstream of Coudersport PA), factors were applied to further adjust rainfall by reducing the 2 peak hourly depths and redistributing to the other hours to maintain the total volume. Also reduced Basin #5 (W1090) buckets by 20%.
- Basin-wide average rainfalls were revised at the Port Allegany sub-basins (1030, 1060, 1070, 1080, 1090, 1100, and 1230) for the HEC-HMS model to remove the HMR-56 generic distribution and interpolate to hourly and pseudo-hourly gage stations. (Sub-basins 1030 and 1090 were the

only Port Allegany sub-basins that were not originally temporally configured to HMR-56.) The worksheet numbers correspond the basin average precipitation identified by basin numbers in the image below. The updates will be run as SPAS 1681 versus the original SPAS 1345. For version 1 update, we let SPAS perform the spatially weighted temporal pattern (black bars image below). The image below shows the surrounding hourly stations incremental precipitation, if the “Raymond” hourly gage were used solely we would get ~14.5" in one hour (close to the 15" in HMRs) and version 1 accumulates ~8.5".



- For watersheds 1030 and 1090, the following factors were applied to further adjust rainfall (based on the most recent basin-wide averages after you re-interpolated to hourly gages) in the HEC-HMS model by reducing the 2 peak hourly depths and redistributing to the other hours to maintain the total volume:

  W1030
  - 7/18/42 05:00 – Reduce rainfall depth by 30% from 4.06 inches to 2.84 inches
  - 7/18/42 11:00 – Reduce rainfall depth by 30% from 2.07 inches to 1.45 inches
  - All other hours – Increase hourly rainfall values by 46.86%
  - These changes should maintain the total basin-wide average rainfall depth of 10.05 inches

  W1090
  - 7/18/42 05:00 – Reduce rainfall depth by 30% from 4.76 inches to 3.33 inches
  - 7/18/42 11:00 – Reduce rainfall depth by 30% from 2.41 inches to 1.69 inches
  - All other hours – Increase hourly rainfall values by 44.68%
  - These changes should maintain the total basin-wide average rainfall depth of 11.98 inches

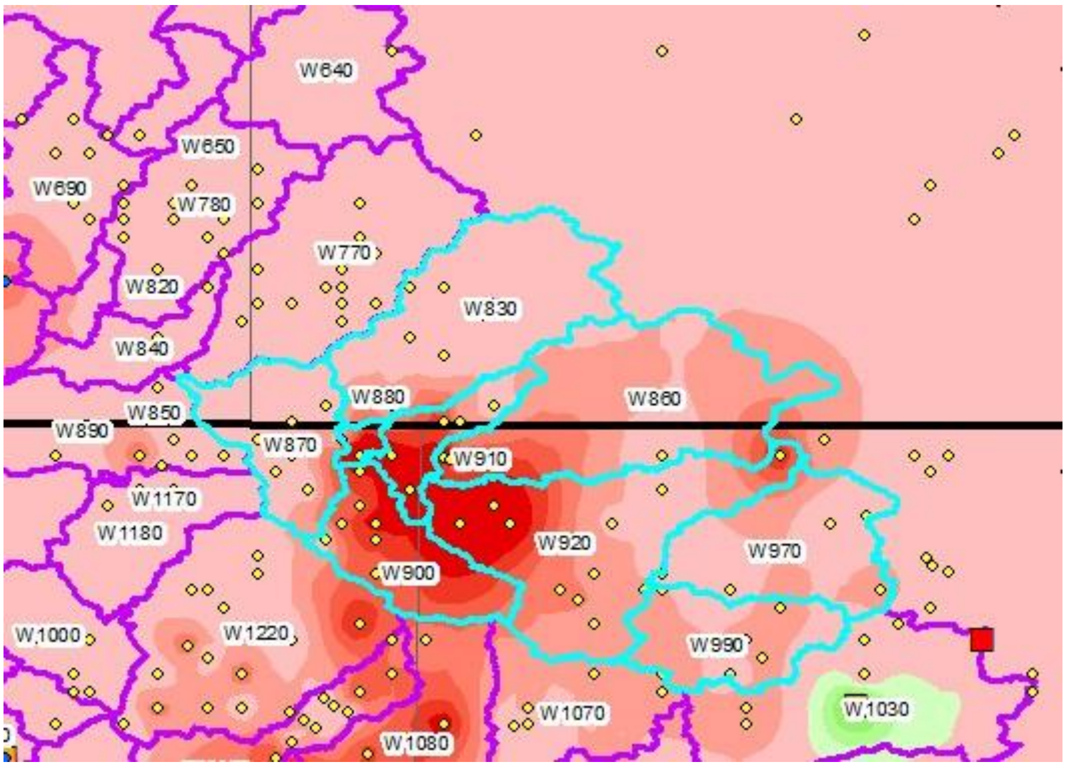
- Basin-wide average adjustments within W1030 and W1090, along with the other gage interpolation adjustments made in the sub-basins at and upstream of Port Allegany, were applied to the gridded rainfall data for the 2D model. In order to create a seamless spatial grid for hydrologic and DAD purposes, two hourly pseudo stations were created; 1 for W1030 and 1 for W1090 based on the basin-wide adjustment above (this should maintain the basin average values in these basins) and then the 34" supplemental stations (storm center) will be shifted slightly to the northeast a couple miles.

Potato Creek Watershed:

- Tried shifting rainfall 3 hours later and evenly distributing the middle 11 hours over the same period (average), as a sensitivity analysis, but this had minimal affect in affecting initial discrepancies along Potato Creek.

Oswayo Creek Watershed:

- Re-distributed the 2 hours for the second peak over 4 hours in sub-watershed W830. This sub-watershed seems to be driving a very high peak flow in Oswayo Creek that did not occur.
- Adjustments were made to sub-basins W770 and W780; globally reducing rainfall depths for each hour by 30%. The hydrologic analysis is suggesting that the overall rainfall in these sub-basins (collected by bucket surveys) may be high. There doesn't seem to be justification for changing the temporal patterns because of a nearby hourly gage.
- There are high ΔP's (difference between the SPAS generated rainfall with observed), as shown in red in the figure below.



ΔP's in the Upper Oswayo Creek and Allegheny River Watersheds

Tunungwant Creek Watershed:

- After reviewing the quality of the data, the spatial extent of the "Bradford 2A" gage was reduced. This gage is located in the Bradford PA area were rainfall collection was sparse. Spatial extend of other high-rainfall gages seem to show a tighter spatial distribution. The basin-wide average rainfalls for sub-basins W950, W960, and W800 were regenerated.

7.2 Log of Modeling Iterations and Sensitivity Analyses

Oswayo Creek Watershed:

- Revised Snyder Peaking Coefficients from 1972 Agnes flood to July 1942 flood: W900, W970, W990: from 0.92 to 0.40.
- Revised the EGL slope for the Muskingum-Cunge Routing for R300 from 0.0001 to 0.00015 to achieve a better match with the HEC-RAS2D hydrograph.
- Updates to HEC-HMS, following final runs in RiverFlow2D:

- Soil data indicates lower permeable soils upstream of Shinglehouse. Therefore, RCNs of approximately 35 were maintained downstream of Shinglehouse and 55 upstream of Shinglehouse to match the RiverFlow2D model.
- An article from Shinglehouse (upper Oswayo Creek Watershed) states the rain began at 11:00 PM Thursday (7/16) evening and continued for 12 hours. The current hyetographs have the heavy rain starting at 0:00 on 7/18. It's possible that there's more variation in the start time of the heavy rain.

Tunungwant Creek Watershed:

- Updates to HEC-HMS, following final runs in RiverFlow2D:
  - RCNs of 45 was established for the Tunungwant Creek watersheds upstream of Bradford PA (W950 and W960) to match the RiverFlow2D model. An RCN of 30 was maintained downstream of Bradford (W800).

Potato Creek Watershed:

- Sensitivity analyses in the Potato Creek Watershed at Smethport PA (HEC-HMS Junction 325). The initial HEC-HMS runs (using Agnes-Calibrated Snyder Lag Times and Peaking Coefficients) contradict a report in the McKean County Miner, Thursday, July 23, 1942, No. 30, Volume 80:

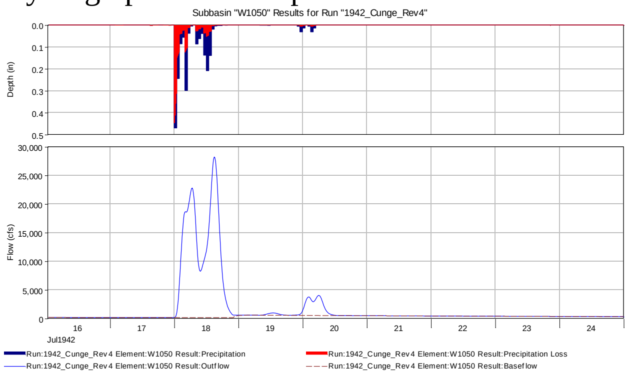
  "Water entered the residence near the East Smethport bridge, occupied by Mr. and Mrs. Axel Safstrom, for the first time since the house was erected, and reached a high-water mark of 40 inches above the first floor."
  *"**At the crest of the flood Saturday night [7/18/42 PM to 7/19/42 AM]**, a roaring torrent flowed over East Street from the Shawmut Railroad crossing to the East Side Garage, adjacent to the Pennsylvania Railroad Tracks in East Smethport – a distance of approximately half a mile."*

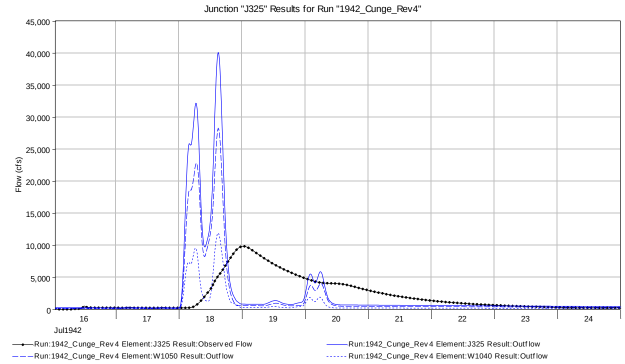
  Conducted sensitivity analyses by adjusting Agnes-calibrated Snyder parameters to try resolving timing discrepancy at Smethport for the July 1942 flood. Also investigated the of a dam providing storage and attenuating the runoff hydrograph but evidence of a dam in the Potato Creek watershed was not found.
  Iterations are described in detail below. The results lead to the conclusion that rainfall adjustments would not resolve the discrepancy and, for an unknown reason, there was a dramatically different watershed response for the July 1942 flood compared to the June 1972 Agnes flood. Therefore, the following changes were made to the Snyder parameters in the HEC-HMS model:

Sub-Watershed ID	June 1972 Agnes Calibrated Parameters		Adjusted Parameters for the July 1942 Flood	
	Lag Time (hours)	Peaking Coefficient	Lag Time (hours)	Peaking Coefficient
W1000	1.31	0.8	8.94	0.4
W1010	1.12	0.8	10.75	0.4
W1020	0.94	0.8	8.13	0.4
W1040	2.16	0.8	14.58	0.4
W1050	2.66	0.8	16.06	0.4

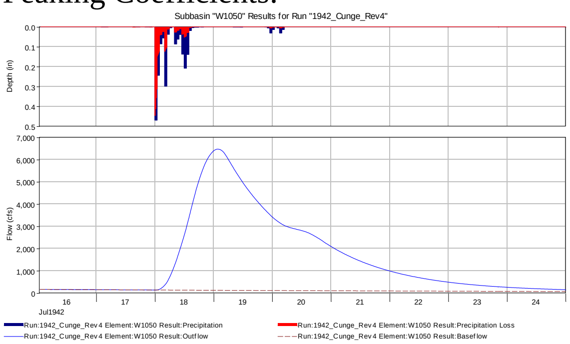
Using Agnes-Calibrated Snyder Parameters

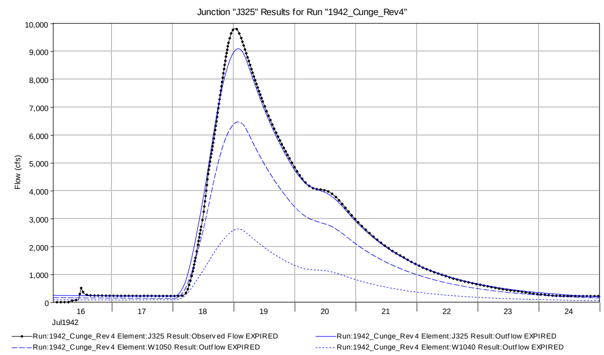
Hydrographs at Smethport:



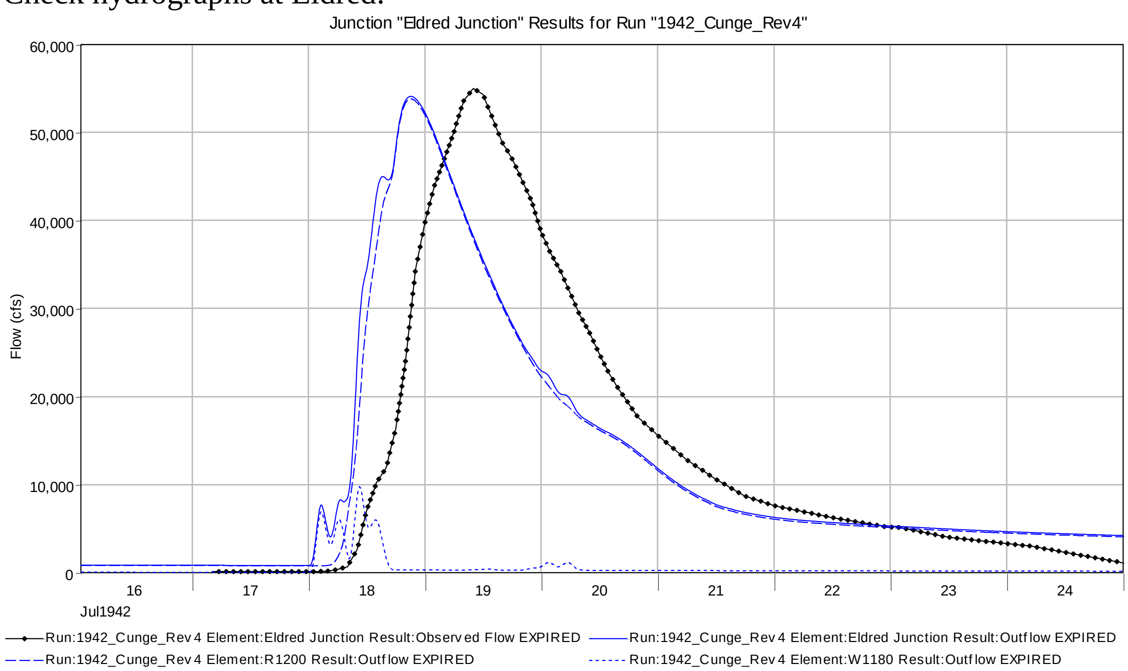


HEC-HMS at Junction 325 based on Rev 4 Rainfall with longer Lag Times and lower Peaking Coefficients:

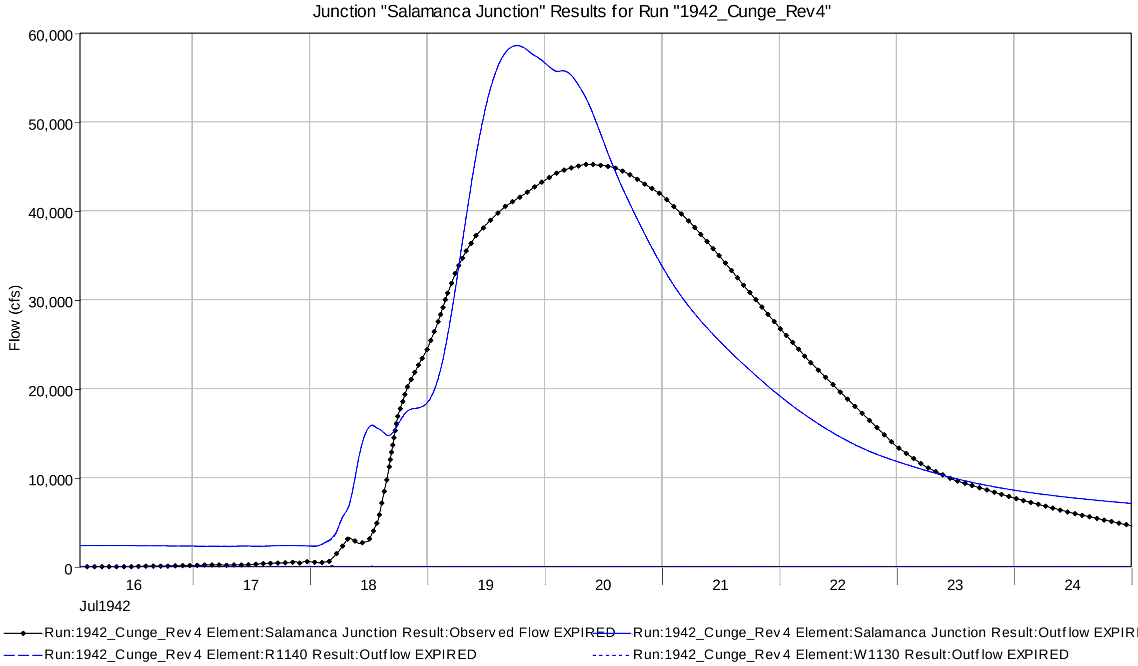




Check hydrographs at Eldred:

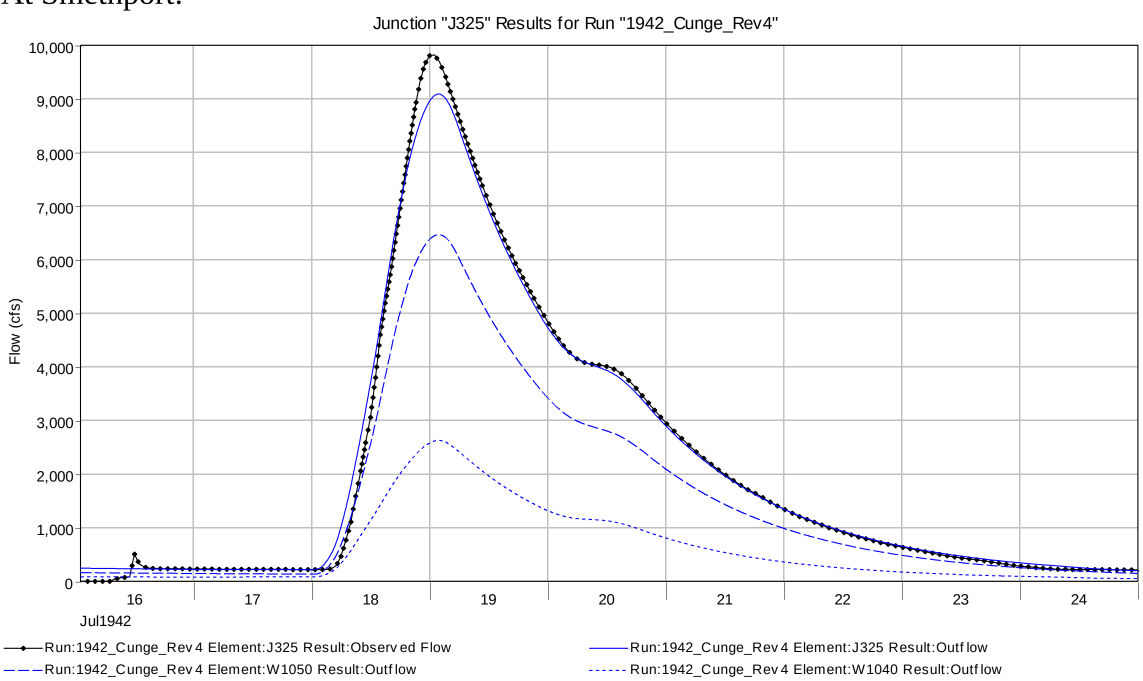


Check hydrographs at Salamanca:

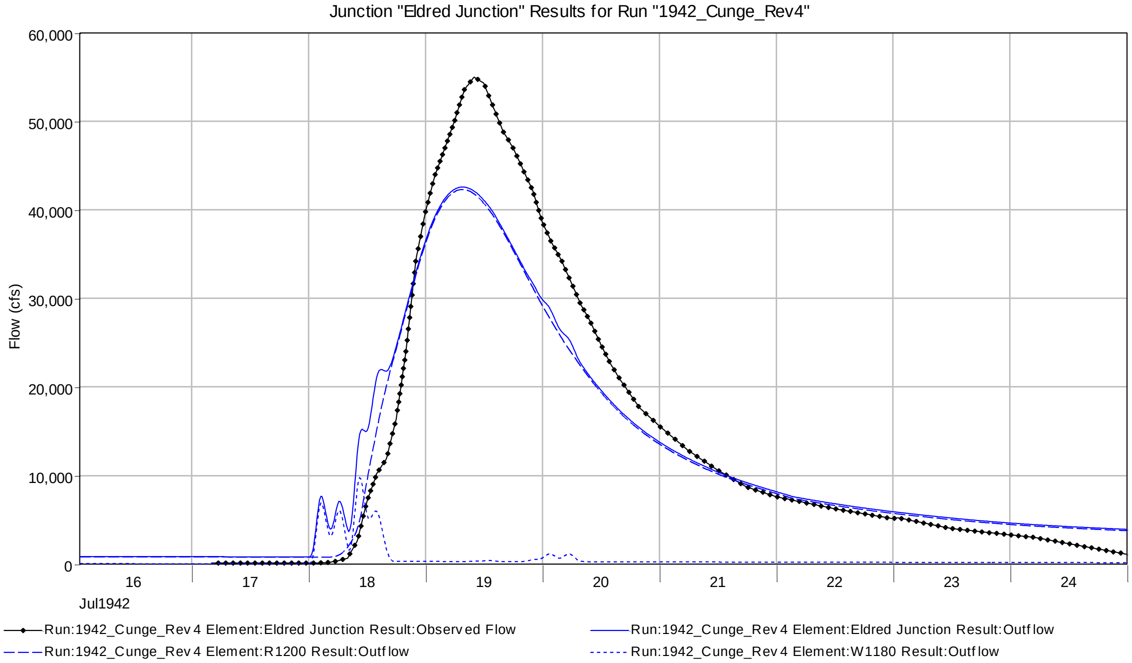


<u>Using SCS Regression Lag Times X 1.5 and reducing the Peaking Coefficients from 0.8 (for Agnes) to 0.4 for Smethport in the Potato Creek Watershed</u>

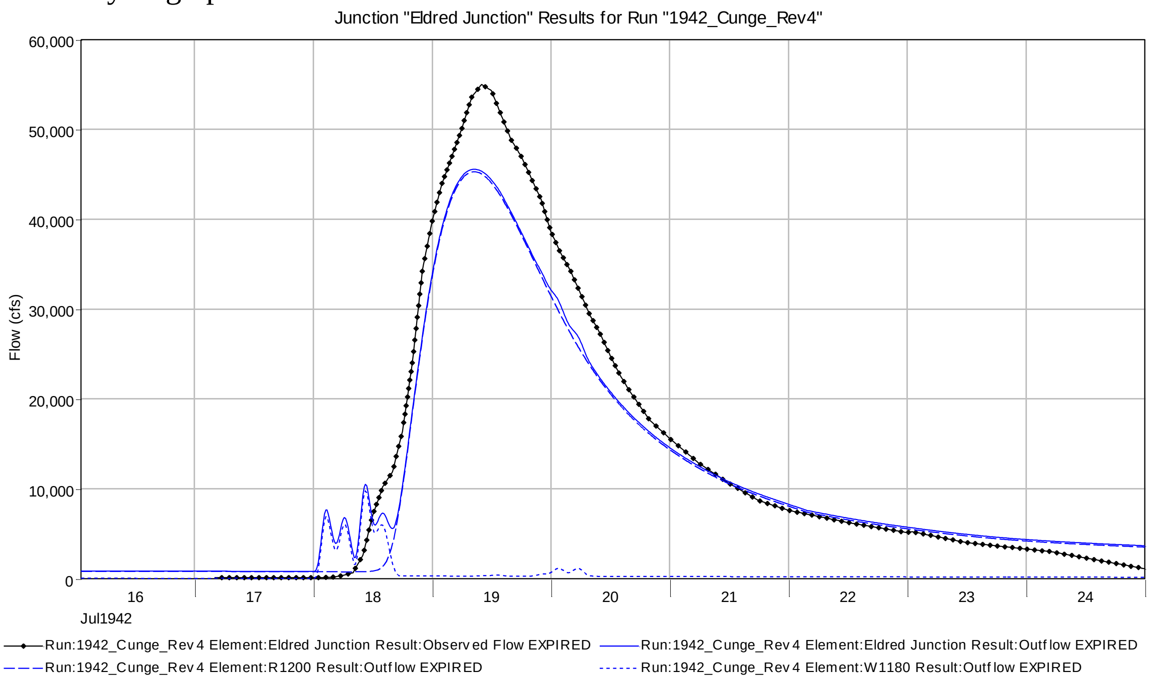
At Smethport:



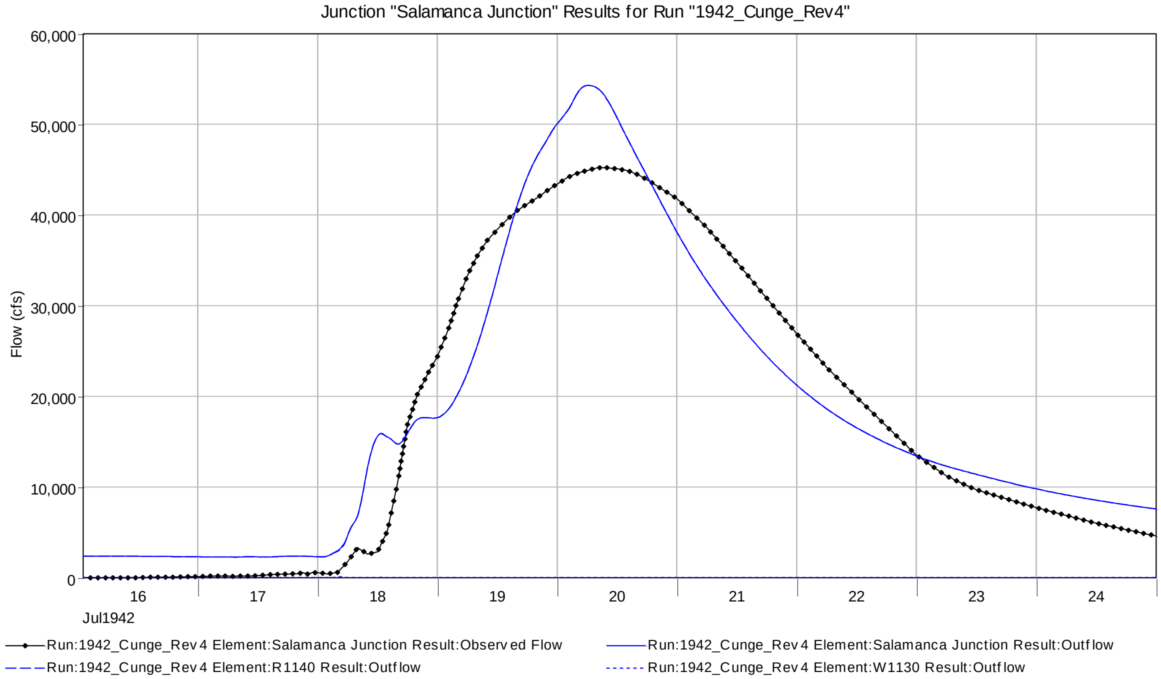
Check hydrographs at Eldred:



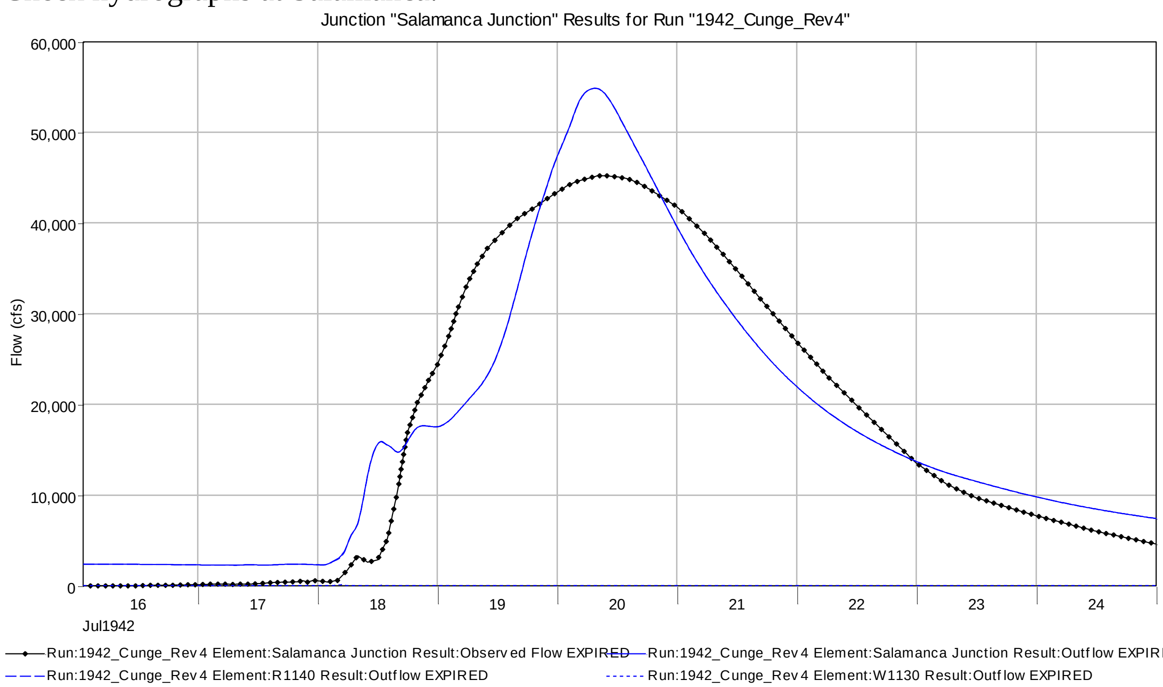
Changing 1220 as well, to SCS lag and 0.3 peaking coefficient,
Check hydrographs at Eldred:



Check hydrographs at Salamanca:

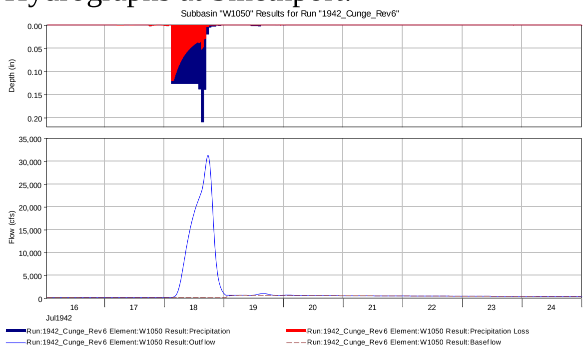


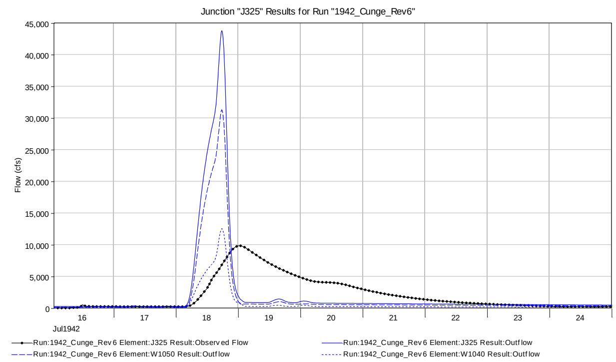
Changing 1220 as well, to SCS lag and 0.3 peaking coefficient,
Check hydrographs at Salamanca:



Rev 6 "Sensitivity" Rainfall with Agnes-Calibrated Snyder Lag Times and Peaking Coefficients to check if rainfall adjustments would resolve discrepancy

Hydrographs at Smethport:





Main-Stem Allegheny River:

- Final Manning n-values for HEC-RAS2D Model (NRCS and Chow)

	Agnes Values	July 1942 Values
Channel	0.035	0.035
Cropland and Pasture	0.07 (Chow)	0.07
Industrial/Commercial	0.15 (NRCS)	0.15
Mixed Forest	0.16 (NRCS)	0.07 (override for areas previously cropland))
Residential/Urban	0.08 (NRCS)	0.08
Water Body	0.04 (NRCS)	0.04
Wetlands (Forested)	0.12 (NRCS)	0.12

- Sensitivity analysis was conducted using higher 1947 Manning n-values for Mixed Forest and Wetlands in the HEC-RAS2D Model to determine if the higher n-values helped to resolve early timing and high peak flow discrepancies for the 1947 model. The theory, in applying the sensitivity n-values, was that the 1947 flood reached the forested canopy, creating a higher effective roughness. The results did not address the timing and peak issue; therefore, the n-values reverted to Agnes values except in Override areas (above).

	Agnes Values	July 1942 Values
Channel	0.035	0.035
Cropland and Pasture	0.07 (Chow)	0.07
Industrial/Commercial	0.15 (NRCS)	0.15
Mixed Forest	0.16 (NRCS)	0.27 (from USGS equation when water reaches canopy)
Residential/Urban	0.08 (NRCS)	0.08
Water Body	0.04 (NRCS)	0.04
Wetlands (Forested)	0.12 (NRCS)	0.27 (Mostly wooded so equate to Mixed Forest)

- Decreased n-values in the Route 6 construction zone to 0.03 (bare soil or short grass).
- Following the collapse of the Route 6 bridge in Port Allegany during the 1942 flood, the bridge design was revisited resulting in the increase of the bridge approach embankments elevation and widening of the bridge span. Based on the historical drawings of the Route 6 bridge, the lowest point of the left abutment was at elevation 1473.95 ft NAVD88 and the lowest point of the right abutment was at elevation 1473.75 ft NAVD88. That is approximately 4 to 5 feet below the existing bridge elevation. The bridge opening during the 1942 flood was approximately 240 ft wide, which is 80 feet narrower than the current bridge opening. Therefore, to ensure that

hydraulics at this critical location are modeled accurately and the bridge approach embankments are not causing an artificial increase in the water surface elevation upstream of the Route 6 bridge, the DEM was revised using the information obtained from historical drawings and the "Feature Stamping" procedure in the Aquaveo SMS software used as the GIS interface for the RiverFlow2D software. The results of the adjustments showed only a slight reduction in peak flood elevation at the bridge. The model shows that the roadway profile is subject to tailwater submergence, thus limiting the reduction in peak flood level due to the roadway embankment adjustment.

- Adjusted slopes in Muskingum-Cunge to get HMS to match RF2D and RAS2D to Portville.
    - R489 from 0.000326 to 0.0006
    - R1240 from 0.000171 to 0.0005
    - R260 from 0.001 to 0.0001
    - R230 from 0.0006 to 0.0001
    - R220 from 0.001 to 0.0001
    - R200 from 0.001 to 0.0002
    - R300 from 0.00015 to 0.0008
    - R330 from 0.0017 to 0.0005
- Sensitivity analysis was conducted to determine the effect of dams within the model domain. A review of the dams and results of the sensitivity analysis resulted in the inclusion of only one substantial dam in the HEC-HMS model (Cuba Lake Dam).
- To address apparent excess runoff in the Oswayo Creek and Tunungwant Creek sub-watersheds (for the Agnes flood), tried decreasing Curve Numbers by 30% in the W770, W780, W830, W860, W870, W880, W900, W910, W920, W970, W990, W800, W950, and W960 sub-watersheds. These Curve Number reductions were further refined by approximately 20% to 30%, from those calibrated for the "Agnes" flood, to achieve good runoff volume agreement for the July 1942 flood; except for sub-watersheds upstream of Port Allegany, PA (W1030, W1060, W1070, W1080, W1090, W1100, W1230) and the Oswayo Creek upstream of Shinglehouse, PA (W860, W920, W970, and W990). Curve Numbers for these sub-watersheds remained the same for both storms (between approximately 55 and 70).
- Reduced the "Ratio to Peak" for the HEC-HMS baseflow regression to 0.2 of the values established for the calibration floods due to the significantly higher peak flows in portions of the watershed for the July 1942 flood.

Appendix H
GIS PMP Tool Documentation

Table of Contents

1. PMP Tool Description and Usage

The PMP Evaluation Tool employed in this study uses a Python-based script designed to run within the ArcGIS environment. ESRI's ArcGIS Desktop Basic software, version 10.4 or later, is required to run the tool, and it is recommended that the user have a basic familiarity with the operation of this software. The tool provides gridded PMP values at a spatial resolution of 90 arc-seconds (equivalent to .025 x .025 decimal degrees) for a user-designated drainage basin or area at user-specified durations, in addition to basin average PMP depths and temporally distributed accumulations.

1.1 File Structure

The tool, source script, and the storm databases are stored within the 'PMP_Evaluation_Tool' project folder. The file and directory structure within the 'PMP_Evaluation_Tool' folder should be maintained as it is provided, as the script will locate various data based on its relative location within the project folder. If the subfolders or geodatabases within are relocated or renamed, then the script must be updated to account for these changes.

The file structure consists of only two subfolders: Input and Script. The 'Input' folder contains all input GIS files (Figure 1.1). There are three ArcGIS file geodatabase containers within the 'Input' folder: DAD_Tables.gdb, Storm_Adj_Factors.gdb, and Non_Storm_Data.gdb. The DAD_Tables.gdb contains the DAD tables (in file geodatabase table format) for each of the SPAS-analyzed storm DAD zones included in the storm database. The Storm_Adj_Factors.gdb contains a feature class for each storm center and stores the adjustment factors for each grid point as a separate feature. These feature classes are organized into feature datasets, according to storm type (General, Local, and Tropical). The storm adjustment factor feature classes share their name with their DAD Table counterpart. The naming convention is SPAS_XXXX_Y, where XXXX is the SPAS storm ID number and Y is the DAD zone number. In the case of a hybrid storm (i.e., a storm that is run as both a general and local storm type), there will be a suffix "_gen" or "_loc" to differentiate the storm type specific to the adjustment factors in the feature class. Finally, the Non_Storm_Data.gdb contains spatial data not directly relating to the input rainfall depth or adjustment factors such as the grid network vector files. The geodatabase also contains the temporal distribution pattern tables and a table and a feature class of the storm center locations.

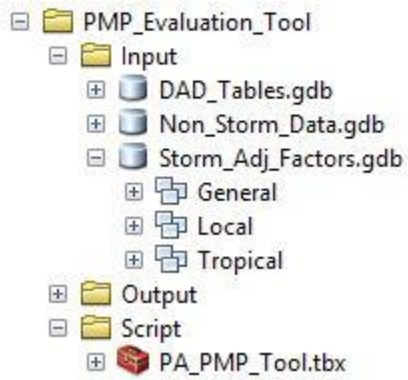


Figure 1.1 - PMP tool file structure.

The 'Script' folder contains an ArcToolbox called PA_PMP_Tool.tbx. The toolbox contains a script tool called 'Gridded PMP Tool' that is used to calculate basin PMP. ArcGIS Desktop should be used for viewing the GIS tool file structure and interacting with the input and output geospatial data. A typical operating system's file browser does not allow access to the geodatabase containers and cannot be used to directly run the tool.

1.2 Usage

The 'Gridded PMP Tool' tool stored within the PA_PMP_Tool.tbx. ArcToolbox opens and runs the script within the ArcGIS environment and can be run from ArcCatalog or an ArcMap map session. In addition to running as a standalone tool, the tool can be incorporated into Model Builder or be called as a sub-function of another script.

To run the tool, the user navigates to the PA_PMP_Tool.tbx toolbox, expands it, and opens the Gridded PMP tool. The dialogue window opens and the user populates input parameters (see Figure 1.2) and clicks the 'OK' button. The tool will run in the foreground and display text output in the Messages window. Processing time can vary greatly depending on AOI size, the number of durations selected, and computer hardware. Most basins generally take a 10 to 20 minutes to analyze all three storm types. The tool produces PMP output described in Section 1.4.

1.3 Input Parameters

The tool requires twelve parameters as input to define the area and durations to be analyzed (Table 1.1).

Table 1.1 - Parameters for the PMP calculation tool.

Parameter # (in script)	Display Name	Data Type	Type	Direction	MultiValue
0	Input basin outline shapefile or feature class	Feature Layer	Required	Input	No
1	Location of "PMP_Evaluation_Tool' Folder	Folder	Required	Input	No
2	Output Folder	Folder	Required	Input	No
3	Local storm durations	String	Optional	Input	Yes
4	General storm durations	String	Optional	Input	Yes
5	Tropical storm durations	String	Optional	Input	Yes
6	Use basin area size for areal average	Boolean	Required	Input	No
7	Area-size to use (sqmi)	Double	Optional	Input	No
8	Apply weighted average to border grid cells	Boolean	Required	Input	No
9	Include sub-basin averages	Boolean	Optional	Input	No
10	Sub-basin field	Field	Optional	Input	No
11	Include depth-duration chart in ouput	Boolean	Optional	Input	No
12	Apply temporal distributions	Boolean	Optional	Input	No

Figure 1.2 shows the tool dialogue window with each of the input parameters. The first parameter required by the tool dialogue is a feature layer, such as a basin shapefile or feature class, designed to outline the area of interest (AOI) for the PMP analysis. If the AOI dataset does not have a surface projection, the tool will apply the Albers Equal Area projection for the purpose of calculating the AOI area size. If the feature layer has multiple features (or polygons), the tool will use the combined area as the analysis region. Only the selected polygons will be used if the tool is run from the ArcMap environment with selected features highlighted. If the AOI shapefile extends beyond the project analysis domain PMP will only be calculated for grid cells inside the project domain. The AOI shapefile or feature class should not have any spaces or symbol characters in the filename.

The second parameter requires the path of the 'PMP_Evaluation_Tool' folder. The default location of the folder is set within the tool parameters, but it can be changed if the user wishes to link the tool to another set of input datasets. The 'PMP_Evaluation_Tool' project folder should be stored locally at a location that can be accessed (both read/write) by ArcGIS desktop. The user will need to set the 'Output Folder' path which provides the tool with the location to create the output PMP files. The user must have read/write privileges for this folder location. The user then selects the durations to be run for each storm type. The next parameter allows the user may override the default to use the input basin feature area size for areal-average PMP calculations and enter a custom area (in square miles). A manually entered area-size will override the basin area-size in the PMP calculations. Next, the user has the option to have the tool perform a weighted analysis on the grid cells underlying the AOI boundary. If this option is checked each boundary grid cell depth will be weighted by the portion of the cell's area inside the basin for the purposed of the basin area PMP table calculations. There is an option to include sub-basin averages. This will calculate an average PMP depth for each feature in the input basin feature class from the overall basin PMP. The average sub-basin depths will be based on the area-size of the overall basin. If the 'weighted' option was selected above it will also be applied to the sub-basin averages. If the AOI has multiple features (or sub-basins) the 'Include sub-basin averages' option can be selected to calculate the basin average PMP over each sub-basin. The user must select a field within the AOI to be used to identify each sub-basin. The field can be of numeric or text data type, but must have a unique ID for each polygon. The user can also choose to include a depth-duration chart .png image in the output folder for each storm type. Finally, the user can select the option to apply the appropriate temporal distribution patterns to the basin average PMP for each storm type. This function needs all durations of PMP to be calculated so if this option is selected the tool will automatically run all durations for all storm types.

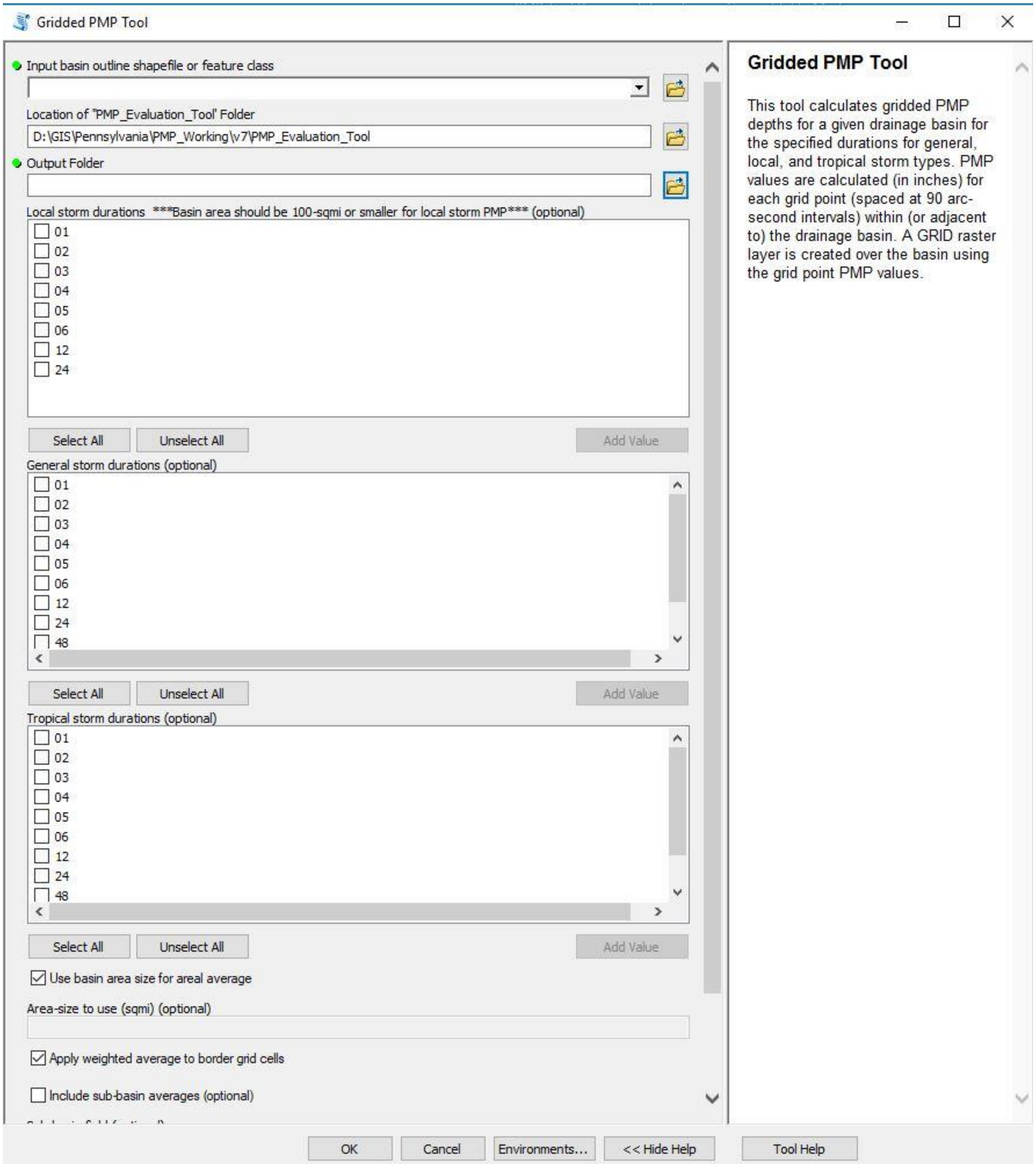


Figure 1.2: The PMP Evaluation Tool input dialogue window

The Validation tab of the tool properties contains some custom scripting to handle the input parameter formatting.

1.4 Tool Output

Once the tool has been run, the output file geodatabases will be populated with the model results. The GIS files can then be brought into an ArcMap, or other compatible GIS environments, for mapping and analysis. The tool is set to have overwrite capabilities; if output data exists, it will be overwritten the next time the tool is run, if the same output folder and same parameters are used.

A separate output folder is created for each storm type and the output is organized within file geodatabases and named according to the input basin feature name and analyzed PMP area. Each output file geodatabase contains a feature class which stores each grid point centroid within the basin as a separate feature. Each feature has a field for the grid ID, latitude, longitude, analysis zone, elevation, PMP (for each duration), and the contributing storm ID. The PMP raster files are also stored within the file geodatabase. The naming convention for the raster files is the storm type and duration (L for local/MCS, G for general, and T for tropical), followed by the input basin feature name, and ending with the basin area (in square miles). If temporal patterns were applied, the output tables will also be in the geodatabase. A folder named CSV is also created and all of the geodatabase tables are exported to csv files. An example of the output file structure is shown in Figure 1.3.

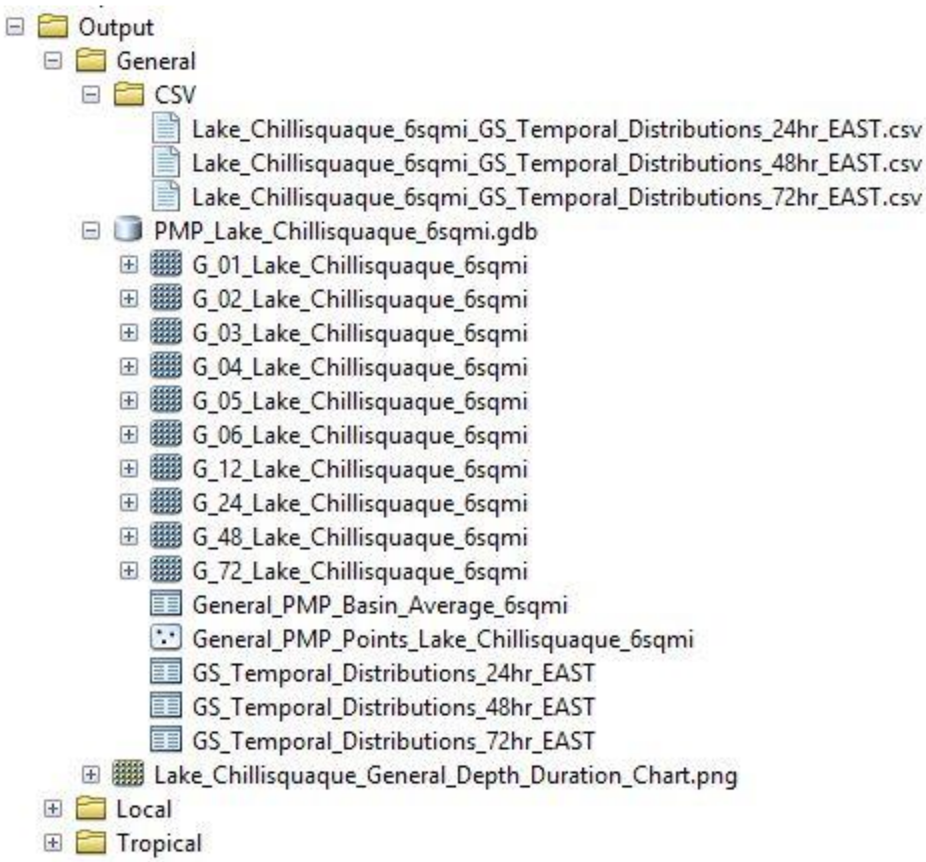


Figure 1.3: Example of the PMP tool output file structure

1.5 Python Script

Due to the large number of storm datasets and grid points within the project domain, a scripted process is well suited for comparing each value efficiently and accurately for a given area of interest and make the necessary calculations. ArcGIS has integrated the Python scripting language to allow for the custom development of geoprocessing operations and toolsets. Python can be used to access the geoprocessing, data management, and looping functionality needed to process the PMP calculations for a basin. The gridded PMP analysis script has been added to an ArcToolbox and can be run as a tool within the ArcGIS environment. The script has been imported and stored internally within the Gridded PMP Tool and all the parameters for the tool have been set. The script can be accessed by exporting it from the tool to a '.py' file. The Python code can be opened and edited within any text editor. A hardcopy version of the code is given in Appendix H.

The python script uses the arcpy, arcpy.analysis, arcpy.management, arcpy.conversion, numpy, pandas, and matplotlib.pyplot modules. Python and these modules are included within the ArcGIS for Desktop package. The script is designed to run as efficiently as possible with a minimal amount of code and complexity. To achieve this, the script is organized into functions that are called as needed. The primary PMP analysis calculations are calculated within the pmpAnalysis() function which is called separately for each PMP storm type analyzed. Within the broader pmpAnalysis() function, several smaller functions are called to perform various tasks:

createPMPfc()	Creates the PMP_Points feature class to store vector (point) results
getAOIarea()	Calculates the area of the input basin
dadLookup()	Gets the DAD value for the current storm based on basin area or AOI defined by the user
updatePMP()	Records the largest adjusted rainfall value (PMP)
outputPMP()	Produces output PMP GIS files and tables
basinAve()	Calculates the basin average PMP
basinZone()	Returns the transposition zone and side of Appalachian Divide of AOI for the temporal distribution application
temporalDistLS()	Local storm temporal distribution application
temporalDist_24hr()	24-hour General and tropical storm distribution application
temporalDist_48hr()	48-hour General and tropical storm distribution application
temporalDist_72hr()	72-hour General and tropical storm distribution application
checkTemporal()	Checks to make sure temporally distributed depths are not exceeding PMP for any durations
temporalCritStacked()	Critically stacked temporal distribution

There is extensive documentation within the code in the form of '# comments'. These comments provide guidance toward its functionality and describe the code.

While the script performs many actions, its primary purpose is to iterate through both the storm list and the grid points within the drainage basin area of interest (AOI), comparing each, and creating output based on the maximum values. To accomplish this, several layers of nested iterative "for" loops are used.
The following high-level algorithm broadly describes the script process:

- Calculate Basin Area (in mi^2)
- For each Storm Type (general, tropical, and local)
  - For each duration
    - For each storm in database

- Lookup storm's depth-area-duration (DAD) value for AOI size
- For each grid point in basin
    - Calculate total adjusted rainfall (TAR) by multiplying DAD value by total adjustment factor for the grid point
    - If TAR > PMP, the TAR becomes the new PMP value for that grid point

- Create PMP point feature class for the storm type
- Create PMP raster GRID files for each duration
- Create basin/sub-basin average tables
- Create a depth-duration chart
- Apply temporal distributions

1.6 Known Issues and Troubleshooting

The GIS PMP tool has undergone a beta testing program during development. One goal of the beta testing program was to identify possible issues with the GIS tool. The following guidelines may prevent issues with running the GIS tool.

- Ensure you version of ArcGIS Desktop is version 10.4 (or later) and maintenance is current.
- Ensure all file and path names do not have spaces or non-alphanumeric symbols (e.g. #, $, %). Underscores are acceptable and a good alternative to using spaces.
- Close any other applications or instances of ArcMap that may interfere with the current session, files, or file paths that will be used by the tool.
- Ensure that the tool folder, output location, and AOI files are all stored locally and not over a network location.

If the points above have been verified and issues persist, the user may try the following actions to address the issue:

- Close out ArcMap session and all open ArcGIS applications and restart session.
- Restart computer. This may be required to completely clear any locks on files or memory.
- Run the Repair Geometry tool on the AOI shapefile or feature class to correct any geometry issues within the file.
- Rename AOI file. Change tool and/or output folder paths.
- If issues persist it may be necessary to contact ESRI support or perform a clean ArcGIS installation or upgrade.

Appendix I
GIS Tool Python Script

```
''' ---------------------------------------------------------------------------
Name: Gridded PMP Tool Python Script

Script Version: 2

Python Version: 2.7

ArcGIS Version: ArcGIS Desktop 10.6.1

Author: Applied Weather Associates

Usage:  The tool is designed to be executed within an the ArcMap environment with an open
MXD session.

Description:
   This tool calculates PMP depths for a given drainage basin for the
specified durations.  PMP point values are calculated (in inches) for each
grid point (spaced at 90 arc-second intervals) over the project domain. The
points are converted to gridded PMP datasets for each duration.


---------------------------------------------------------------------------'''

###############################################################################
## import Python modules

import sys
import arcpy
import os
import traceback
from arcpy import env
import arcpy.analysis as an
import arcpy.management as dm
import arcpy.conversion as con
import numpy as np
import pandas as pd
from pandas import ExcelFile
import matplotlib.pyplot as plt
from heapq import nlargest


env.overwriteOutput = True                                    # Set overwrite option
env.addOutputsToMap = False

###############################################################################
## get input parameters
```

```
basin = arcpy.GetParameter(0)                                    # get AOI Basin Shapefile
home = arcpy.GetParameterAsText(1)                                   # get location of 'PMP'
Project Folder
outLocation = arcpy.GetParameterAsText(2)
if arcpy.GetParameter(12) == False:
   locDurations = arcpy.GetParameter(3)                             # get local storm durations
(string)
   genDurations = arcpy.GetParameter(4)                             # get general storm
durations (string)
   tropDurations = arcpy.GetParameter(5)                            # get tropical storm
durations (string)
else:
   locDurations = ('01','02','03','04','05','06','12','24')
   genDurations = ('01','02','03','04','05','06','12','24','48','72')
   tropDurations = ('01','02','03','04','05','06','12','24','48','72')

weightedAve = arcpy.GetParameter(8)                                          # get option to
apply weighted average (boolean)
#outputTable = arcpy.GetParameter(9)                                         # get file path
for basin average summary table
includeSubbasin = arcpy.GetParameter(9)                               # get option add
subbasin averages (boolean)
subbasinIDfield = arcpy.GetParameterAsText(10)                               # Subbasin ID
field from AOI Basin Shapefile
ddChart = arcpy.GetParameter(11)                                      # get option to create
depth-duration chart(boolean)
runTemporal = arcpy.GetParameter(12)                                         # get option to
run temporal distributions (boolean)

dadGDB = home + "\\Input\\DAD_Tables.gdb"                         # location of DAD tables
adjFactGDB = home + "\\Input\\Storm_Adj_Factors.gdb"                   # location of feature
datasets containing total adjustment factors
arcpy.AddMessage("\nDAD Tables geodatabase path:  " + dadGDB)
arcpy.AddMessage("Storm Adjustment Factor geodatabase path:  " + adjFactGDB)

#mxd = arcpy.mapping.MapDocument("CURRENT")
#df = arcpy.mapping.ListDataFrames(mxd)[0]
basAveTables = []                                  # global list of Basin Average Summary tables

def pmpAnalysis(aoiBasin, stormType, durList):

   ###################################################################################
   ## Create PMP Point Feature Class from points within AOI basin and add fields
   def createPMPfc():
```

```
        arcpy.AddMessage("\nCreating feature class: 'PMP_Points' in Scratch.gdb...")
        dm.MakeFeatureLayer(home + "\\Input\\Non_Storm_Data.gdb\\Vector_Grid", "vgLayer")
# make a feature layer of vector grid cells
        dm.SelectLayerByLocation("vgLayer", "INTERSECT", aoiBasin)                       #
select the vector grid cells that intersect the aoiBasin polygon
        dm.MakeFeatureLayer(home + "\\Input\\Non_Storm_Data.gdb\\Grid_Points", "gpLayer")
# make a feature layer of grid points
        dm.SelectLayerByLocation("gpLayer", "HAVE_THEIR_CENTER_IN", "vgLayer")
# select the grid points within the vector grid selection
        con.FeatureClassToFeatureClass("gpLayer", env.scratchGDB, "PMP_Points")
# save feature layer as "PMP_Points" feature class
        arcpy.AddMessage("(" + str(dm.GetCount("gpLayer")) + " grid points will be analyzed)\n")

        # Add PMP Fields
        for dur in durList:
            arcpy.AddMessage("\t...adding field: PMP_" + str(dur))
            dm.AddField(env.scratchGDB + "\\PMP_Points", "PMP_" + dur, "DOUBLE")

        # Add STORM Fields (this string values identifies the driving storm by SPAS ID number)
        for dur in durList:
            arcpy.AddMessage("\t...adding field: STORM_" + str(dur))
            dm.AddField(env.scratchGDB + "\\PMP_Points", "STORM_" + dur, "TEXT", "", "", 16,
"Storm ID " + dur + "-hour")

        # Add STNAME Fields (this string values identifies the driving storm by SPAS ID number)
#        for dur in durList:
#            arcpy.AddMessage("\t...adding field: STNAME_" + str(dur))
#            dm.AddField(env.scratchGDB + "\\PMP_Points", "STNAME_" + dur, "TEXT", "", "",
50, "Storm Name " + dur + "-hour")

        return

    ###########################################################################
    ##  Define getAOIarea() function:
    ##  getAOIarea() calculates the area of AOI (basin outline) input shapefile/
    ##  featureclass.  The basin outline shapefile must be projected.  The area
    ##  is sqaure miles, converted from the basin layers projected units (feet
    ##  or meters).  The aoiBasin feature class should only have a single feature
    ##  (the basin outline).  If there are multiple features, the area will be stored
    ##  for the final feature only.

    def getAOIarea():
        sr = arcpy.Describe(aoiBasin).SpatialReference          # Determine aoiBasin spatial
reference system
        srname = sr.name
        srtype = sr.type
```

```
    srunitname = sr.linearUnitName                                          # Units
    arcpy.AddMessage("\nAOI basin spatial reference:  " + srname + "\nUnit type: " +
srunitname + "\nSpatial reference type: " + srtype)

    aoiArea = 0.0
    rows = arcpy.SearchCursor(aoiBasin)
    for row in rows:
      feat = row.getValue("Shape")
      aoiArea += feat.area
    if srtype == 'Geographic':                       # Must have a surface projection.  If one
doesn't exist it projects a temporary file and uses that.
      arcpy.AddMessage("\n***The basin shapefile's spatial reference 'Geographic' is not
supported.  Projecting temporary shapefile for AOI.***")
      arcpy.Project_management(aoiBasin,env.scratchGDB + "\\TempBasin",102039)     #
Projects AOI Basin (102039 = USA_Contiguous_Albers_Equal_Area_Conic_USGS_version)
      TempBasin = env.scratchGDB + "\\TempBasin"       # Path to temporary basin created in
scratch geodatabase
      sr = arcpy.Describe(TempBasin).SpatialReference   # Determine Spatial Reference of
temporary basin
      aoiArea = 0.0
      rows = arcpy.SearchCursor(TempBasin)        # Assign area size in square meters
      for row in rows:
        feat = row.getValue("Shape")
        aoiArea += feat.area
      aoiArea = aoiArea * 0.000000386102              # Converts square meters to square miles
    elif srtype == 'Projected':
      if srunitname == "Meter":
        aoiArea = aoiArea * 0.000000386102        # Converts square meters to square miles
      elif srunitname == "Foot" or "Foot_US":
        aoiArea = aoiArea * 0.00000003587      # Converts square feet to square miles
      else:
        arcpy.AddMessage("\nThe basin shapefile's unit type '" + srunitname + "' is not
supported.")
        sys.exit("Invalid linear units")           # Units must be meters or feet

    aoiArea = round(aoiArea, 3)
    arcpy.AddMessage("\nArea of interest: " + str(aoiArea) + " square miles.")

    if arcpy.GetParameter(6) == False:
      aoiArea = arcpy.GetParameter(7)                # Enable a constant area size
    aoiArea = round(aoiArea, 1)
    arcpy.AddMessage("\n***Area used for PMP analysis: " + str(aoiArea) + " sqmi***")
    return aoiArea

  ###########################################################################
  ##  Define dadLookup() function:
```

```
    ##  The dadLookup() function determines the DAD value for the current storm
    ##  and duration according to the basin area size.  The DAD depth is interpolated
    ##  linearly between the two nearest areal values within the DAD table.
    def dadLookup(stormLayer, duration, area):                  # dadLookup() accepts the current
storm layer name (string), the current duration (string), and AOI area size (float)
        #arcpy.AddMessage("\t\tfunction dadLookup() called.")
        durField = "H_" + duration                              # defines the name of the duration field (eg.,
"H_06" for 6-hour)
        dadTable = dadGDB + "\\" + stormLayer
        rows = arcpy.SearchCursor(dadTable)

        try:
            row = rows.next()        # Sets DAD area x1 to the value in the first row of the DAD table.
            x1 = row.AREASQMI
            y1 = row.getValue(durField)
            xFlag = "FALSE"          # xFlag will remain false for basins that are larger than the
largest DAD area.
        except RuntimeError:        # return if duration does not exist in DAD table
            return

        row = rows.next()
        i = 0
        while row:                                              # iterates through the DAD table - assiging the
bounding values directly above and below the basin area size
            i += 1
            if row.AREASQMI < area:
                x1 = row.AREASQMI
                y1 = row.getValue(durField)
            else:
                xFlag = "TRUE"     # xFlag is switched to "TRUE" indicating area is within DAD
range
                x2 = row.AREASQMI
                y2 = row.getValue(durField)
                break

            row = rows.next()
        del row, rows, i

        if xFlag == "FALSE":
            x2 = area                  # If x2 is equal to the basin area, this means that the largest DAD
area is smaller than the basin and the resulting DAD value must be extrapolated.
            arcpy.AddMessage("\t\tThe basin area size: " + str(area) + " sqmi is greater than the
largest DAD area: " + str(x1) + " sqmi.\n\t\tDAD value is estimated by extrapolation.")
            y = x1 / x2 * y1                                    # y (the DAD depth) is estimated by extrapolating
the DAD area to the basin area size.
            return y                                            # The extrapolated DAD depth (in inches) is returned.
```

```
        # arcpy.AddMessage("\nArea = " + str(area) + "\nx1 = " + str(x1) + "\nx2 = " + str(x2) + "\ny1 = " + str(y1) + "\ny2 = " + str(y2))

        x = area                                    # If the basin area size is within the DAD table area range, the DAD depth is interpolated
        deltax = x2 - x1                            # to determine the DAD value (y) at area (x) based on next lower (x1) and next higher (x2) areas.
        deltay = y2 - y1
        diffx = x - x1

        y = y1 + diffx * deltay / deltax

        if x < x1:
            arcpy.AddMessage("\t\tThe basin area size: " + str(area) + " sqmi is less than the smallest DAD table area: " + str(x1) + " sqmi.\n\t\tDAD value is estimated by extrapolation.")

        return y                                    # The interpolated DAD depth (in inches) is returned.

    ###########################################################################
    ##  Define updatePMP() function:
    ##  This function updates the 'PMP_XX_' and 'STORM_XX' fields of the PMP_Points
    ##  feature class with the largest value from all analyzed storms stored in the
    ##  pmpValues list.
    def updatePMP(pmpValues, stormID, duration):          # Accepts four arguments: pmpValues - largest adjusted rainfall for current duration (float list); stormID - driver storm ID for each PMP value (text list); and duration (string)
        pmpfield = "PMP_" + duration
        stormfield = "STORM_" + duration
        stormTextField = "STNAME_" + duration

        gridRows = env.scratchGDB + "\\PMP_Points"            # iterates through PMP_Points rows
        i = 0
        with arcpy.da.UpdateCursor(gridRows, (pmpfield, stormfield)) as cursor:
            for row in cursor:
                row[0] = pmpValues[i]          # Sets the PMP field value equal to the Max Adj. Rainfall value (if larger than existing value).
                row[1] = stormID[i]            # Sets the storm ID field to indicate the driving storm event
                cursor.updateRow(row)
                i += 1
        del row, gridRows, pmpfield, stormfield, i
        arcpy.AddMessage("\n\t" + duration + "-hour PMP values update complete. \n")
        return

    ###########################################################################
```

```
    ##  The outputPMP() function produces raster GRID files for each of the PMP durations.
    ##  Aslo, a space-delimited PMP_Distribition.txt file is created in the 'Text_Output' folder.
    def outputPMP(type, area, outPath):
        desc = arcpy.Describe(basin)
        basinName = desc.baseName
        pmpPoints = env.scratchGDB + "\\PMP_Points"            # Location of 'PMP_Points' feature
class which will provide data for output

        outType = type[:1]
        outArea = str(int(round(area,0))) + "sqmi"
        outGDB = "PMP_"+ basinName + "_" + outArea +".gdb"
        if not arcpy.Exists(outPath + "\\" + outGDB):                      # Check to see if
PMP_XXXXX.gdb already exists
            arcpy.AddMessage("\nCreating output geodatabase '" + outGDB + "'")
            dm.CreateFileGDB(outPath, outGDB)
        arcpy.AddMessage("\nCopying PMP_Points feature class to " + outGDB + "...")
        con.FeatureClassToFeatureClass(pmpPoints, outPath + "\\" + outGDB, type +
"_PMP_Points_" + basinName + "_" + outArea)
        pointFC = outPath + "\\" + outGDB + "\\" + type + "_PMP_Points_" + basinName + "_" +
outArea
        # addLayerMXD(pointFC)  # calls addLayerMDX function to add output to ArcMap
session

        arcpy.AddMessage("\nBeginning PMP Raster Creation...")

        for dur in durList:         # This code creates a raster GRID from the current PMP point layer
            durField = "PMP_" + dur
            outLoc = outPath + outGDB +"\\" + outType + "_" + dur + "_" + basinName + "_" +
outArea
            arcpy.AddMessage("\n\tInput Path: " + pmpPoints)
            arcpy.AddMessage("\tOutput raster path: " + outLoc)
            arcpy.AddMessage("\tField name: " + durField)
            con.FeatureToRaster(pmpPoints, durField, outLoc, "0.025")
            arcpy.AddMessage("\tOutput raster created...")
        del durField, outLoc, dur

        arcpy.AddMessage("\nPMP Raster Creation complete.")

        if includeSubbasin:                                  # Begin subbasin average calculations
            subbasinID = []
            with arcpy.da.SearchCursor(basin, subbasinIDfield) as cursor:   # Create list of subbasin
ID names
                for row in cursor:
                    subbasinID.append(row[0])
```

```
        subIDtype = arcpy.ListFields(basin, subbasinIDfield)[0].type    # Define the datatype of
the subbasin ID field

        if subIDtype != "String":           # Convert subbasin IDs to a string, if they are not already
            subbasinID = [str(i) for i in subbasinID]

        subNameLen = max(map(len, subbasinID))     # Define the length of the longest subbasin
ID

        # arcpy.AddMessage("\nList of subbasins...\n" + "\n".join(subbasinID))

        arcpy.AddMessage("\nCreating Subbasin Summary Table...")
        tableName = type + "_PMP_Subbasin_Average" + "_" + outArea
        tablePath = outPath + "\\" + outGDB + "\\" + tableName
        dm.CreateTable(outPath + "\\" + outGDB, tableName)            # Create blank table

        dm.AddField(tablePath, "STORM_TYPE", "TEXT", "", "", 10, "Storm Type")         #
Create "Storm Type" field
        dm.AddField(tablePath, "SUBBASIN", "TEXT", "", "", subNameLen, "Subbasin")      #
Create "Subbasin" field

        cursor = arcpy.da.InsertCursor(tablePath, "SUBBASIN")          # Create Insert cursor and
add a blank row to the table for each subbasin
        for sub in subbasinID:
            cursor.insertRow([sub])
        del cursor, sub

        dm.CalculateField(tablePath, "STORM_TYPE", "'" + type + "'", "PYTHON_9.3")      #
populate storm type field

        i = 0
        for field in arcpy.ListFields(pmpPoints, "PMP_*"):   # Add fields for each PMP duration
and calculate the subbasin averages
            fieldName = field.name
            arcpy.AddMessage("\n\tCalculating subbasin average for " + fieldName + "
(weighted)...\n")
            dm.AddField(tablePath, fieldName, "DOUBLE", "", 2)      # Add duration field
            subAveList = []
            for subbasin in subbasinID:                              # Loop through each subbasin
                if subIDtype != "String":                          # Define an SQL expression that
specifies the current subbasin
                    sql_exp = """{0} = {1}""".format(arcpy.AddFieldDelimiters(basin,
subbasinIDfield), subbasin)
                else:
                    sql_exp = """{0} = '{1}'""".format(arcpy.AddFieldDelimiters(basin,
subbasinIDfield), subbasin)
```

```
                dm.MakeFeatureLayer(basin, "subbasinLayer", sql_exp)
                outLayer = outPath + "\\" + outGDB + "\\subbasin_" + str(subbasin)
                subBasAve = basinAve("subbasinLayer", fieldName)        # Call the basAve()
function passing the subbasin and duration field
                arcpy.AddMessage("\tSubbasin average for " + str(subbasin) + ":  " +
str(subBasAve) + "")
                subAveList.append(subBasAve)          # Add subbasin average to list
            p = 0
            with arcpy.da.UpdateCursor(tablePath, fieldName) as cursor: # Update the subbasin
average summary table with the subbasin averages
                for row in cursor:
                    row = subAveList[p]
                    cursor.updateRow([row])
                    p += 1

   ##           dm.CalculateField(tablePath, fieldName, fieldAve, "PYTHON_9.3")       # Assigns
the basin average
   ##           dur = durList[i]                        # following lines add alias field names to basin
average table (ArcGIS 10.2.1 or later)
   ##           if dur[0] == "0":
   ##               dur = dur[1:]
   ##           fieldAlias = dur + "-hour PMP"
   ##           dm.AlterField(tablePath, fieldName, "#", fieldAlias)
            i += 1
        arcpy.AddMessage("\nSubbasin summary table complete.")

    arcpy.AddMessage("\nCreating Basin Summary Table...")
    tableName = type + "_PMP_Basin_Average" + "_" + outArea
    tablePath = outPath + "\\" + outGDB + "\\" + tableName
    dm.CreateTable(outPath + "\\" + outGDB, tableName)         # Create blank table
    cursor = arcpy.da.InsertCursor(tablePath, "*")             # Create Insert cursor and add a
blank row to the table
    cursor.insertRow([0])
    del cursor

    dm.AddField(tablePath, "STORM_TYPE", "TEXT", "", "", 30, "Storm Type")         #
Create "Storm Type" field
    dm.CalculateField(tablePath, "STORM_TYPE", "'" + type + "'", "PYTHON_9.3")      #
populate storm type field

    i = 0
    for field in arcpy.ListFields(pmpPoints, "PMP_*"):         # Add fields for each PMP
duration and calculate the basin average
        fieldName = field.name
        fieldAve = basinAve(basin, fieldName)      # Calls the basinAve() function - returns the
average (weighted or not)
```

```
        dm.AddField(tablePath, fieldName, "DOUBLE", "", 2)      # Add duration field
        dm.CalculateField(tablePath, fieldName, fieldAve, "PYTHON_9.3")       # Assigns the
basin average
##          dur = durList[i]                              # following lines add alias field names to basin
average table (ArcGIS 10.2.1 or later)
##          if dur[0] == "0":
##             dur = dur[1:]
##          fieldAlias = dur + "-hour PMP"
##          dm.AlterField(tablePath, fieldName, "#", fieldAlias)
        i += 1
      arcpy.AddMessage("\nSummary table complete.")
      basAveTables.append(tablePath)

##                The following lines export a .png image depth duration chart and PMP summary
excel file to the output folder
      if ddChart:
        xValues = durList                                  #Get list of durations for chart
        xValues = [int(i) for i in xValues]               #Convert duration list to integers
        ax1 = plt.subplot2grid((1,1), (0,0))    #Create variable for subplot in chart
        yValues = []
        pmpFields = [field.name for field in arcpy.ListFields(tablePath, "PMP_*")] # Selects
PMP fields for yValues
        with arcpy.da.SearchCursor(tablePath, pmpFields) as cursor:              # Adds PMP
depths to yValues
           yValues = next(cursor)
        del cursor, pmpFields

        stormFields = [field.name for field in arcpy.ListFields(pmpPoints, "Storm_*")] # Selects
Controlling Storm fields
        contStorms = []                         # List of controlling storms for a single duration
        listOfContStorms = []                   # List of controlling storms for all durations (list of
lists)
        i = 0                                   # iterator (for "Storm_*" fields)
        while i < len(stormFields):                      # iterates through controlling storm fields
           with arcpy.da.SearchCursor(pmpPoints, stormFields) as cursor:    # Search cursor
returns list of unique controlling storms
              contStorms = sorted({row[i] for row in cursor})
           listOfContStorms.append(contStorms)                         # Add unique storms for current
duration to list of controlling stomrs
           i += 1
        del cursor

        plt.plot(xValues,yValues)                #Creates chart
        plt.xlabel('Storm Duration in Hours')
        plt.ylabel('Rainfall Depth in Inches')
```

```
        plt.title(basinName + " (" + outArea + ") " + type + ' Storm Basin Average PMP\nDepth
Duration Chart')
        ax1.grid(True)                          #Creates grid lines in chart
        yTop = max(yValues) + 1
        ax1.set_ylim(top = yTop)                #Sets y axis values to match depths +1 1
        ax1.set_xticks(xValues)                 #Sets x axis values to match durations
##          i = 0
##          xy = zip(xValues, yValues)
##          while i < len(stormFields):                  # iterates through controlling storm fields
##              pointXY = xy[i]
##              yLabel = '{0:.1f}'.format(yValues[i])       # round PMP depth to 1 decimal and
convert to string
##              stormLabel = str(listOfContStorms[i])       # convert controlling storm ID(s) to string
##              stormLabel = stormLabel.replace("u", "")    # remove unicode "u"
##              stormLabel = stormLabel.replace("'", "")    # remove unicode ","
##              stormLabel = stormLabel.replace("[", "")    # remove unicode "["
##              stormLabel = stormLabel.replace("]", "")    # remove unicode "]"
##              #ax1.annotate(yLabel + '"\n' + stormLabel, xy=xy[i], textcoords='offset points',
size=8, annotation_clip=True)
##              ax1.annotate(yLabel + '"\n' + stormLabel, xy=xy[i], textcoords='data', size=8,
annotation_clip=True)
##              i += 1
##          del xy

        plt.savefig(outPath + "\\" + basinName + "_" + type + "_Depth_Duration_Chart.png")
        #Save image
        plt.close()                        #Close chart to remove from memory
        arcpy.AddMessage("\nDepth Duration Chart exported to output folder.")
        del xValues, yValues, #df, dfLimited
        return
    return

  ###########################################################################
  ##  The basin() returns the basin average PMP value for a given duration field.
  ##  If the option for a weighted average is checked in the tool parameter the script
  ##  will weight the grid point values based on proportion of area inside the basin.
  def basinAve(aoiBasin, pmpField):
    pmpPoints = env.scratchGDB + "\\PMP_Points"         # Path of 'PMP_Points' scratch
feature class
    if weightedAve:
        #arcpy.AddMessage("\tCalculating sub-basin average for " + pmpField + "(weighted)...")
        vectorGridClip = env.scratchGDB + "\\VectorGridClip"       # Path of 'VectorGridClip'
scratch feature class

        dm.MakeFeatureLayer(home + "\\Input\\Non_Storm_Data.gdb\\Vector_Grid",
"vgLayer")              # make a feature layer of vector grid cells
```

```
        dm.SelectLayerByLocation("vgLayer", "INTERSECT", aoiBasin)
# select the vector grid cells that intersect the aoiBasin polygon

        an.Clip("vgLayer", aoiBasin, vectorGridClip)    # clips aoi vector grid to basin
        dm.AddField(pmpPoints, "WEIGHT", "DOUBLE")          # adds 'WEIGHT' field to
PMP_Points scratch feature class
        dm.MakeFeatureLayer(vectorGridClip, "vgClipLayer")       # make a feature layer of
basin clipped vector grid cells
        dm.MakeFeatureLayer(pmpPoints, "pmpPointsLayer")    # make a feature layer of
PMP_Points feature class

        dm.AddJoin("pmpPointsLayer", "ID", "vgClipLayer", "ID")
# joins PMP_Points and vectorGridBasin tables
        dm.CalculateField("pmpPointsLayer", "WEIGHT", "!vectorGridClip.Shape_Area!",
"PYTHON_9.3")            # Calculates basin area proportion to use as weight for each grid cell.
        dm.RemoveJoin("pmpPointsLayer", "vectorGridClip")

        dm.SelectLayerByLocation("pmpPointsLayer", "INTERSECT", "vgLayer")

        na = arcpy.da.TableToNumPyArray("pmpPointsLayer",(pmpField, 'WEIGHT'))
# Assign pmpPoints values and weights to Numpy array (na)
        wgtAve = np.average(na[pmpField], weights=na['WEIGHT'])    # Calculate weighted
average with Numpy average
        del na
        return round(wgtAve, 2)

    else:
        if includeSubbasin:
            #arcpy.AddMessage("\tCalculating sub-basin average for " + pmpField + "(non-
weighted)...")
            vectorGridClip = env.scratchGDB + "\\VectorGridClip"       # Path of 'VectorGridClip'
scratch feature class

            dm.MakeFeatureLayer(home + "\\Input\\Non_Storm_Data.gdb\\Vector_Grid",
"vgLayer")              # make a feature layer of vector grid cells
            dm.SelectLayerByLocation("vgLayer", "INTERSECT", aoiBasin)
# select the vector grid cells that intersect the aoiBasin polygon

            dm.MakeFeatureLayer(pmpPoints, "pmpPointsLayer")       # make a feature layer of
PMP_Points feature class

            dm.SelectLayerByLocation("pmpPointsLayer", "INTERSECT", "vgLayer")

            na = arcpy.da.TableToNumPyArray("pmpPointsLayer", pmpField)
# Assign pmpPoints values and weights to Numpy array (na)
            fieldAve = np.average(na[pmpField])         # Calculates aritmetic mean
```

```
            del na
            return round(fieldAve, 2)

        else:
            arcpy.AddMessage("\tCalculating basin average for " + pmpField + "(not
weighted)...")
            na = arcpy.da.TableToNumPyArray(pmpPoints, pmpField)
# Assign pmpPoints values to Numpy array (na)
            fieldAve = np.average(na[pmpField])                 # Calculates aritmetic mean
            del na
            return round(fieldAve, 2)

    ##########################################################################
    ##  This basinZone() function returns a list containing transposition zone ID
    ##  (as an integer) and side of continental divide of the the basin centroid
    ##  (as text "East" or "West")


    def   basinZone(bas):           ## This function returns the transposition zone and side of
continental divide of the the basin centroid
        tempBasin = env.scratchGDB + "\\tempBasin"
        tempCentroid = env.scratchGDB + "\\tempCentroid"
        joinFeat = home + "\\Input\\Non_Storm_Data.gdb\\Vector_Grid"
        joinOutput = env.scratchGDB + "\\joinOut"
        dm.Dissolve(bas, tempBasin)
        desc = arcpy.Describe(tempBasin)
        sr = desc.spatialReference
        #dm.FeatureToPoint(tempBasin, tempCentroid, "INSIDE")

        dm.CreateFeatureclass(env.scratchGDB,"tempCentroid","POINT",spatial_reference = sr)
        with arcpy.da.InsertCursor(tempCentroid, "SHAPE@XY") as iCur:
            with arcpy.da.SearchCursor(tempBasin,"SHAPE@") as sCur:
                for sRow in sCur:
                    cent = sRow[0].centroid         # get the centroid
                    iCur.insertRow([(cent.X,cent.Y)])# write it to the new feature class

        an.SpatialJoin(tempCentroid, joinFeat, joinOutput)
        centZone = arcpy.da.SearchCursor(joinOutput, ("TRANS_ZONE",)).next()[0]
        centDivide = arcpy.da.SearchCursor(joinOutput, ("DIVIDE",)).next()[0]
        del tempBasin, tempCentroid, joinFeat, joinOutput, desc, sr
        return (centZone, centDivide)

    ##########################################################################
    ##  The temporalDist() functions applies the temporal distributions scenarios
    ##  to PMP.
```

```
   def temporalDistEM1(stormType, outPath, location, areaSize):            # Local Storm 1-hr EM
Temporal Distribution Function
      basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + areaSize
# Location of basin average PMP table

      if stormType == "Local":
         arcpy.AddMessage("\n***Local Storm - 1-hour EM PMP Temporal Distribution***")

         temporalDistTable_1hr = home +
"\\Input\\Non_Storm_Data.gdb\\LS_TEMPORAL_DISTRIBUTIONS_01HR_EM"  # 1-hour
EM Temporal distribution factors table
         outTable = outPath + "\\LS_Temporal_Distributions_01hr_EM"
         arcpy.AddMessage("\n\tCreating temporal distribution table:...")
         dm.Copy(temporalDistTable_1hr, outTable)            # Copy 1-hour temporal dist. factors
table to output location
         distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_1hr,
"LS*")]     # Create a list of 1-hour distribution field names
         arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))
         oneHour = arcpy.da.SearchCursor(basinPMP, ("PMP_01",)).next()[0]       # Gets 1-hour
PMP depth
         for distribution in distributionList:                  # Loops thourgh each 1-hour temporal
distribution
            arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
            with arcpy.da.UpdateCursor(outTable, distribution) as cursor:        # Cursor to apply
temporal factor to 1-hour PMP
               for row in cursor:
                  row[0] = row[0] * oneHour
                  cursor.updateRow(row)
               del row, cursor
         checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)
      return


   def temporalDistEM2(stormType, outPath, location, areaSize):      # Local Storm 2-hr EM
Temporal Distribution Function
      basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + areaSize
# Location of basin average PMP table

      if stormType == "Local":
         arcpy.AddMessage("\n***Local Storm - 2-hour EM PMP Temporal Distribution***")

         temporalDistTable_2hr = home +
"\\Input\\Non_Storm_Data.gdb\\LS_TEMPORAL_DISTRIBUTIONS_02HR_EM"  # 2-hour
Temporal distribution factors table
         outTable = outPath + "\\LS_Temporal_Distributions_02hr_EM"
```

```
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
        dm.Copy(temporalDistTable_2hr, outTable)                # Copy 2-hour temporal dist.
factors table to output location
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_2hr,
"LS*")]     # Create a list of 2-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))
        twoHour = arcpy.da.SearchCursor(basinPMP, ("PMP_02",)).next()[0]        # Gets 2-hour
PMP depth
        for distribution in distributionList:       # Loops through each 2-hour temporal distribution
          arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
          with arcpy.da.UpdateCursor(outTable, distribution) as cursor:         # Cursor to apply
temporal factor to 2-hour PMP
            for row in cursor:
              row[0] = row[0] * twoHour
              cursor.updateRow(row)
            del row, cursor
        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)
      return


  def temporalDistLS2(stormType, outPath, location, areaSize):      # Local Storm 2-hr
Temporal Distribution Function
      basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + areaSize
# Location of basin average PMP table

      if stormType == "Local":
        arcpy.AddMessage("\n***Local Storm - 2-hour PMP Temporal Distribution***")

        temporalDistTable_2hr = home +
"\\Input\\Non_Storm_Data.gdb\\LS_TEMPORAL_DISTRIBUTIONS_02HR"  # 2-hour
Temporal distribution factors table
        outTable = outPath + "\\LS_Temporal_Distributions_02hr"
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
        dm.Copy(temporalDistTable_2hr, outTable)        # Copy 2-hour temporal dist. factors
table to output location
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_2hr,
"LS*")]     # Create a list of 2-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))

        oneHour = arcpy.da.SearchCursor(basinPMP, ("PMP_01",)).next()[0]    # Gets 1-hour
PMP depth
        twoHour = arcpy.da.SearchCursor(basinPMP, ("PMP_02",)).next()[0]     # Gets 2-hour
PMP depth
```

```
        for distribution in distributionList:       # Loops through each 2-hour temporal
distribution
            arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
            accumPMP = 0
            with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:
# Cursor to apply temporal factor to 2-hour PMP
                for row in cursor:
                    if row[1] <= 6:         # Leave loop once a specified row is reached
                        accumPMP +=  (twoHour - oneHour) / 12
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 6 and row[1] <= 18:      # Constrain update to rows 7-18
                        accumPMP += oneHour * row[0]
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 18 and row[1] <= 24:       # Constrain update to rows 19-24
                        accumPMP +=  (twoHour - oneHour) / 12
                        row[0] = accumPMP
                        cursor.updateRow(row)
                del row, cursor
        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)  # Calls
checkTemporal function
    return


def temporalDistEM3(stormType, outPath, location, areaSize):   # Local Storm 3-hr EM
Temporal Distribution Function
    basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + areaSize
# Location of basin average PMP table

    if stormType == "Local":
        arcpy.AddMessage("\n***Local Storm - 3-hour EM PMP Temporal Distribution***")

        temporalDistTable_3hr = home +
"\\Input\\Non_Storm_Data.gdb\\LS_TEMPORAL_DISTRIBUTIONS_03HR_EM"  # 3-hour
Temporal distribution factors table
        outTable = outPath + "\\LS_Temporal_Distributions_03hr_EM"
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
        dm.Copy(temporalDistTable_3hr, outTable)        # Copy 3-hour temporal dist. factors
table to output location
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_3hr,
"LS*")]     # Create a list of 3-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))
        threeHour = arcpy.da.SearchCursor(basinPMP, ("PMP_03",)).next()[0]   # Gets 3-hour
PMP depth
```

```
            for distribution in distributionList:                    # Loops thourgh each 3-hour temporal
distribution
                arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
                with arcpy.da.UpdateCursor(outTable, distribution) as cursor:      # Cursor to apply
temporal factor to 3-hour PMP
                    for row in cursor:
                        row[0] = row[0] * threeHour
                        cursor.updateRow(row)
                    del row, cursor
            checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)
        return


    def temporalDistLS(stormType, outPath, location, areaSize):      # Local Storm 6-hr Temporal
Distributions Function
        basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + areaSize
# Location of basin average PMP table

        if stormType == "Local":
            arcpy.AddMessage("\n***Local Storm - 6-hour PMP Temporal Distributions***")

            temporalDistTable_6hr = home +
"\\Input\\Non_Storm_Data.gdb\\LS_TEMPORAL_DISTRIBUTIONS_06HR_" + location[1]  #
6-hour Temporal distribution factors table (based on side of Appalachian Divide)
            outTable = outPath + "\\LS_Temporal_Distributions_6hr_" + location[1]
            arcpy.AddMessage("\n\tCreating temporal distribution table:...")
            dm.Copy(temporalDistTable_6hr, outTable)        # Copy 6-hour temporal dist. factors
table to output location
            distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_6hr,
"LS*")]     # Create a list of 6-hour distribution field names
            arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))
            sixHour = arcpy.da.SearchCursor(basinPMP, ("PMP_06",)).next()[0]    # Gets 6-hour
PMP depth
            for distribution in distributionList:          # Loops thourgh each 6-hour temporal
distribution
                arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
                with arcpy.da.UpdateCursor(outTable, distribution) as cursor:     # Cursor to apply
temporal factor to 6-hour PMP
                    for row in cursor:
                        row[0] = row[0] * sixHour
                        cursor.updateRow(row)
                    del row, cursor
            checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)
        return
```

```
    def temporalDistEM12(stormType, outPath, location, areaSize):   # Local Storm 12-hr EM
Temporal Distribution Function
        basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + areaSize
# Location of basin average PMP table

        if stormType == "Local":
            arcpy.AddMessage("\n***Local Storm - 12-hour PMP Temporal Distributions***")

            temporalDistTable_12hr = home +
"\\Input\\Non_Storm_Data.gdb\\LS_TEMPORAL_DISTRIBUTIONS_12HR_EM"  # 12-hour
EM Temporal distribution factors table
            outTable = outPath + "\\LS_Temporal_Distributions_12hr_EM"
            arcpy.AddMessage("\n\tCreating temporal distribution table:...")
            dm.Copy(temporalDistTable_12hr, outTable)       # Copy 12-hour temporal dist. factors
table to output location
            distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_12hr,
"LS*")]     # Create a list of 12-hour distribution field names
            arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))
            twelveHour = arcpy.da.SearchCursor(basinPMP, ("PMP_12",)).next()[0]      # Gets 12-
hour PMP depth

            for distribution in distributionList:         # Loops thourgh each 12-hour temporal
distribution
                arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
                with arcpy.da.UpdateCursor(outTable, distribution) as cursor:      # Cursor to apply
temporal factor to 12-hour PMP
                    for row in cursor:
                        row[0] = row[0] * twelveHour
                        cursor.updateRow(row)
                    del row, cursor
            checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)
        return


    def temporalDist_EM24(stormType, outPath, location, areaSize):      # 24-hr EM Temporal
Distributions Function - Applies to Local, General, and Tropical storms
        basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + areaSize
# Location of basin average PMP table

        if stormType == "Local":
            arcpy.AddMessage("\n***Local Storm - 24-hour PMP EM Temporal Distribution***")

            temporalDistTable_24hr = home +
"\\Input\\Non_Storm_Data.gdb\\LS_TEMPORAL_DISTRIBUTIONS_24HR_EM"  # Local
storm 24-hour Temporal distribution factors table
            outTable = outPath + "\\LS_Temporal_Distributions_24hr_EM"
```

```
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
        dm.Copy(temporalDistTable_24hr, outTable)                    # Copy 24-hour
temporal dist. factors table to output location
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_24hr,
"LS*")]    # Create a list of 24-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))


        sixHour = arcpy.da.SearchCursor(basinPMP, ("PMP_06",)).next()[0]              # Gets
06-hour PMP depth
        twelveHour = arcpy.da.SearchCursor(basinPMP, ("PMP_12",)).next()[0]           # Gets
12-hour PMP depth
        twentyfourHour = arcpy.da.SearchCursor(basinPMP, ("PMP_24",)).next()[0]
# Gets 24-hour PMP depth

        for distribution in distributionList:    # Loops thourgh each 24-hour temporal distribution
            arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
            accumPMP = 0
            with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:
# Cursor to apply temporal factor to 24-hour PMP
                for row in cursor:
                    if row[1] <= 72:
                        accumPMP +=  (twentyfourHour - twelveHour) / 144
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 72 and row[1] <= 108:
                        accumPMP +=  (twelveHour - sixHour) / 72
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 108 and row[1] <= 180:
                        accumPMP += sixHour * row[0]
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 180 and row[1] <= 216:
                        accumPMP +=  (twelveHour - sixHour) / 72
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 216 and row[1] <= 288:
                        accumPMP +=  (twentyfourHour - twelveHour) / 144
                        row[0] = accumPMP
                        cursor.updateRow(row)
                del row, cursor
        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)

    if stormType == "General":
```

```
        arcpy.AddMessage("\n***General Storm - 24-hour PMP EM Temporal
Distribution***")

        temporalDistTable_24hr = home +
"\\Input\\Non_Storm_Data.gdb\\GS_TEMPORAL_DISTRIBUTIONS_24HR_EM"  # General
storm 24-hour EM Temporal distribution factors table
        outTable = outPath + "\\GS_Temporal_Distributions_24hr_EM"
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
        dm.Copy(temporalDistTable_24hr, outTable)      # Copy 24-hour temporal dist. factors
table to output location
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_24hr,
"GS*")]     # Create a list of 24-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))


        sixHour = arcpy.da.SearchCursor(basinPMP, ("PMP_06",)).next()[0]    # Gets 06-hour
PMP depth
        twelveHour = arcpy.da.SearchCursor(basinPMP, ("PMP_12",)).next()[0]      # Gets 12-
hour PMP depth
        twentyfourHour = arcpy.da.SearchCursor(basinPMP, ("PMP_24",)).next()[0]
# Gets 24-hour PMP depth

        for distribution in distributionList:       # Loops thourgh each 24-hour temporal
distribution
            arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
            accumPMP = 0
            with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:
# Cursor to apply temporal factor to 24-hour PMP
                for row in cursor:
                    if row[1] <= 72:
                        accumPMP +=  (twentyfourHour - twelveHour) / 144
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 72 and row[1] <= 108:
                        accumPMP +=  (twelveHour - sixHour) / 72
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 108 and row[1] <= 180:
                        accumPMP += sixHour * row[0]
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 180 and row[1] <= 216:
                        accumPMP +=  (twelveHour - sixHour) / 72
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 216 and row[1] <= 288:
```

```
                    accumPMP +=  (twentyfourHour - twelveHour) / 144
                    row[0] = accumPMP
                    cursor.updateRow(row)
                del row, cursor
            checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)


        if stormType == "Tropical":
            arcpy.AddMessage("\n***Tropical Storm - 24-hour PMP EM Temporal 
Distribution***")

            temporalDistTable_24hr = home + 
"\\Input\\Non_Storm_Data.gdb\\TS_TEMPORAL_DISTRIBUTIONS_24HR_EM"  # 24-hour 
Tropical storm Temporal distribution factors table
            outTable = outPath + "\\TS_Temporal_Distributions_24hr_EM"
            arcpy.AddMessage("\n\tCreating temporal distribution table:...")
            dm.Copy(temporalDistTable_24hr, outTable)                    # Copy 24-hour 
temporal dist. factors table to output location
            distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_24hr, 
"TS*")]     # Create a list of 24-hour distribution field names
            arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))


            sixHour = arcpy.da.SearchCursor(basinPMP, ("PMP_06",)).next()[0]              # Gets 
06-hour PMP depth
            twelveHour = arcpy.da.SearchCursor(basinPMP, ("PMP_12",)).next()[0]           # Gets 
12-hour PMP depth
            twentyfourHour = arcpy.da.SearchCursor(basinPMP, ("PMP_24",)).next()[0]       
# Gets 24-hour PMP depth

            for distribution in distributionList:   # Loops thourgh each 24-hour temporal distribution
                arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
                accumPMP = 0
                with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:  
# Cursor to apply temporal factor to 24-hour PMP
                    for row in cursor:
                        if row[1] <= 72:
                            accumPMP +=  (twentyfourHour - twelveHour) / 144
                            row[0] = accumPMP
                            cursor.updateRow(row)
                        if row[1] > 72 and row[1] <= 108:
                            accumPMP +=  (twelveHour - sixHour) / 72
                            row[0] = accumPMP
                            cursor.updateRow(row)
                        if row[1] > 108 and row[1] <= 180:
                            accumPMP += sixHour * row[0]
```

```
                    row[0] = accumPMP
                    cursor.updateRow(row)
                if row[1] > 180 and row[1] <= 216:
                    accumPMP +=  (twelveHour - sixHour) / 72
                    row[0] = accumPMP
                    cursor.updateRow(row)
                if row[1] > 216 and row[1] <= 288:
                    accumPMP +=  (twentyfourHour - twelveHour) / 144
                    row[0] = accumPMP
                    cursor.updateRow(row)
            del row, cursor
        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)

    return


def temporalDist_24hr(stormType, outPath, location, areaSize):              # General/Tropical
Storm 24-hr Temporal Distributions Function
    basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + areaSize
# Location of basin average PMP table

    if stormType == "General":
        arcpy.AddMessage("\n***" + stormType + " Storm - 24hr PMP Temporal
Distributions***")

        temporalDistTable_24hr = home +
"\\Input\\Non_Storm_Data.gdb\\GS_TEMPORAL_DISTRIBUTIONS_24HR_" + location[1]    #
General Storm Temporal distribution factors table
        outTable = outPath + "\\GS_Temporal_Distributions_24hr_" + location[1]
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
        dm.Copy(temporalDistTable_24hr, outTable)                          # Copy temporal dist.
factors table to output location
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_24hr,
"GS*")]        # Create a list of 24-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))
        twentyfourHour = arcpy.da.SearchCursor(basinPMP, ("PMP_24",)).next()[0]        # Gets
24-hour PMP depth
        for distribution in distributionList:                              # Loops thourgh each 24-hour
temporal distribution
            arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
            with arcpy.da.UpdateCursor(outTable, distribution) as cursor:     # Cursor to apply
temporal factor to 24-hour PMP
                for row in cursor:
                    row[0] = row[0] * twentyfourHour
                    cursor.updateRow(row)
                del row, cursor
```

```
        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)

    if stormType == "Tropical":
        arcpy.AddMessage("\n***" + stormType + " Storm - 24hr PMP Temporal
Distributions***")

        temporalDistTable_24hr = home +
"\\Input\\Non_Storm_Data.gdb\\TS_TEMPORAL_DISTRIBUTIONS_24HR_" + location[1]    #
Tropical Storm Temporal distribution factors table
        outTable = outPath + "\\TS_Temporal_Distributions_24hr_" + location[1]
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
        dm.Copy(temporalDistTable_24hr, outTable)                       # Copy temporal dist.
factors table to output location
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_24hr,
"TS*")]        # Create a list of 24-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))
        twentyfourHour = arcpy.da.SearchCursor(basinPMP, ("PMP_24",)).next()[0]     # Gets
24-hour PMP depth
        for distribution in distributionList:                           # Loops thourgh each 24-hour
temporal distribution
            arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
            with arcpy.da.UpdateCursor(outTable, distribution) as cursor:              # Cursor to
apply temporal factor to 24-hour PMP
                for row in cursor:
                    row[0] = row[0] * twentyfourHour
                    cursor.updateRow(row)
                del row, cursor
        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)
    return


def temporalDist_EM48(stormType, outPath, location, areaSize):   # General/Tropical storm
48-hr EM Temporal Distributions Function
    basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + areaSize
# Location of basin average PMP table

    if stormType == "General":
        arcpy.AddMessage("\n***General Storm - 48-hour PMP EM Temporal
Distribution***")

        temporalDistTable_48hr = home +
"\\Input\\Non_Storm_Data.gdb\\GS_TEMPORAL_DISTRIBUTIONS_48HR_EM"  # 48-hour
general storm EM Temporal distribution factors table
        outTable = outPath + "\\GS_Temporal_Distributions_48hr_EM"
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
```

```
        dm.Copy(temporalDistTable_48hr, outTable)      # Copy 48-hour temporal dist. factors
table to output location
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_48hr,
"GS*")]     # Create a list of 48-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))


        sixHour = arcpy.da.SearchCursor(basinPMP, ("PMP_06",)).next()[0]   # Gets 06-hour
PMP depth
        twelveHour = arcpy.da.SearchCursor(basinPMP, ("PMP_12",)).next()[0]    # Gets 12-
hour PMP depth
        twentyfourHour = arcpy.da.SearchCursor(basinPMP, ("PMP_24",)).next()[0]
# Gets 24-hour PMP depth
        second24 = (arcpy.da.SearchCursor(basinPMP, ("PMP_48",)).next()[0] -
twentyfourHour)/2      # Gets second 24-hr period PMP depth


        for distribution in distributionList:          # Loops thourgh each 24-hour temporal
distribution
            arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
            accumPMP = 0
            with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:
# Cursor to apply temporal factor to 24-hour PMP
                for row in cursor:
                    if row[1] <= 144:
                        accumPMP +=  second24 / 144
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 144 and row[1] <= 216:
                        accumPMP +=  (twentyfourHour - twelveHour) / 144
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 216 and row[1] <= 252:
                        accumPMP +=  (twelveHour - sixHour) / 72
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 252 and row[1] <= 324:
                        accumPMP += sixHour * row[0]
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 324 and row[1] <= 360:
                        accumPMP +=  (twelveHour - sixHour) / 72
                        row[0] = accumPMP
                        cursor.updateRow(row)
                    if row[1] > 360 and row[1] <= 432:
                        accumPMP +=  (twentyfourHour - twelveHour) / 144
```

```
                    row[0] = accumPMP
                    cursor.updateRow(row)
                if row[1] > 432 and row[1] <= 576:
                    accumPMP +=  second24 / 144
                    row[0] = accumPMP
                    cursor.updateRow(row)
            del row, cursor
        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)


    if stormType == "Tropical":
        arcpy.AddMessage("\n***Tropical Storm - 48-hour PMP EM Temporal 
Distribution***")

        temporalDistTable_48hr = home + 
"\\Input\\Non_Storm_Data.gdb\\TS_TEMPORAL_DISTRIBUTIONS_48HR_EM"  # 48-hour 
Tropical storm EM Temporal distribution factors table
        outTable = outPath + "\\TS_Temporal_Distributions_48hr_EM"
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
        dm.Copy(temporalDistTable_48hr, outTable)                       # Copy 48-hour 
temporal dist. factors table to output location
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_48hr, 
"TS*")]     # Create a list of 24-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))


        sixHour = arcpy.da.SearchCursor(basinPMP, ("PMP_06",)).next()[0]       # Gets 06-hour 
PMP depth
        twelveHour = arcpy.da.SearchCursor(basinPMP, ("PMP_12",)).next()[0]       # Gets 12-
hour PMP depth
        twentyfourHour = arcpy.da.SearchCursor(basinPMP, ("PMP_24",)).next()[0]       
# Gets 24-hour PMP depth
        second24 = (arcpy.da.SearchCursor(basinPMP, ("PMP_48",)).next()[0] - 
twentyfourHour)/2     # Gets second 24-hr period PMP depth


        for distribution in distributionList:            # Loops thourgh each 24-hour temporal 
distribution
            arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
            accumPMP = 0
            with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:    
# Cursor to apply temporal factor to 24-hour PMP
                for row in cursor:
                    if row[1] <= 144:
                        accumPMP +=  second24 / 144
                        row[0] = accumPMP
```

```
                    cursor.updateRow(row)
                if row[1] > 144 and row[1] <= 216:
                    accumPMP +=  (twentyfourHour - twelveHour) / 144
                    row[0] = accumPMP
                    cursor.updateRow(row)
                if row[1] > 216 and row[1] <= 252:
                    accumPMP +=  (twelveHour - sixHour) / 72
                    row[0] = accumPMP
                    cursor.updateRow(row)
                if row[1] > 252 and row[1] <= 324:
                    accumPMP += sixHour * row[0]
                    row[0] = accumPMP
                    cursor.updateRow(row)
                if row[1] > 324 and row[1] <= 360:
                    accumPMP +=  (twelveHour - sixHour) / 72
                    row[0] = accumPMP
                    cursor.updateRow(row)
                if row[1] > 360 and row[1] <= 432:
                    accumPMP +=  (twentyfourHour - twelveHour) / 144
                    row[0] = accumPMP
                    cursor.updateRow(row)
                if row[1] > 432 and row[1] <= 576:
                    accumPMP +=  second24 / 144
                    row[0] = accumPMP
                    cursor.updateRow(row)
            del row, cursor
        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)
    return


  def temporalDist_48hr(stormType, outPath, location, areaSize):     # General/Tropical Storm
48-hr Temporal Distributions Function
    basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + areaSize
# Location of basin average PMP table

    if stormType == "General":
        arcpy.AddMessage("\n***" + stormType + " Storm - 48hr PMP Temporal
Distributions***")

        temporalDistTable_48hr = home +
"\\Input\\Non_Storm_Data.gdb\\GS_TEMPORAL_DISTRIBUTIONS_48HR_" + location[1]    #
General Storm Temporal distribution factors table
        outTable = outPath + "\\GS_Temporal_Distributions_48hr_" + location[1]
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
        dm.Copy(temporalDistTable_48hr, outTable)         # Copy temporal dist. factors table to
output location
```

```
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_48hr, 
"GS*")]      # Create a list of 48-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))

        largest24 = arcpy.da.SearchCursor(basinPMP, ("PMP_24",)).next()[0]       # Calculate 
largest 24-hour period PMP
        second24 = (arcpy.da.SearchCursor(basinPMP, ("PMP_48",)).next()[0] - largest24)/2     
# Calculate the next largest 24-hr period PMP and divide by 2

        arcpy.AddMessage("\n\tLargest 24-hour Period: " + str(largest24))
        arcpy.AddMessage("\tFirst 12-hour: " + str(second24))
        arcpy.AddMessage("\tLast 12-hour: " + str(second24))


        for distribution in distributionList:    # Loops thourgh each 24-hour temporal distribution
          arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
          arcpy.AddMessage("\t\tFirst 12-hour Period...")
          accumPMP = 0
          with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:        
# Cursor to evenly distribute half of 2nd largest 24-hr into first 12 hours
            for row in cursor:
              if row[1] <= 48:                                    # Leave loop once a row containing a 
temporal dist. factor (ie, first 12h period) is reached
                accumPMP +=  second24 / 48
                row[0] = accumPMP
                cursor.updateRow(row)
            del row, cursor

          arcpy.AddMessage("\t\tLargest 24-hour Period...")
          with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:        
# Cursor to apply temporal factors to largest 24-hour PMP
            for row in cursor:
              if row[1] > 48 and row[1] <= 144:     # Constrain update to rows 49-144 (second 
24hr period)
                accumPMP = (largest24 * row[0]) + second24
                row[0] = accumPMP
                cursor.updateRow(row)
            del row, cursor

          arcpy.AddMessage("\t\tLast 12-hour Period...")
          whereClause = distribution + " IS NULL"
          with arcpy.da.UpdateCursor(outTable, distribution, whereClause) as cursor:    # Cursor 
to evenly distribute half of 2nd largest 24-hr into last 12 hours
            for row in cursor:
              accumPMP +=  second24 / 48
              row[0] = accumPMP
```

```
                cursor.updateRow(row)
            del row, cursor, accumPMP, whereClause
        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)

    if stormType == "Tropical":
        arcpy.AddMessage("\n***" + stormType + " Storm - 48hr PMP Temporal
Distributions***")

        temporalDistTable_48hr = home +
"\\Input\\Non_Storm_Data.gdb\\TS_TEMPORAL_DISTRIBUTIONS_48HR_" + location[1]    #
Tropical Storm Temporal distribution factors table
        outTable = outPath + "\\TS_Temporal_Distributions_48hr_" + location[1]
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
        dm.Copy(temporalDistTable_48hr, outTable)     # Copy temporal dist. factors table to
output location
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_48hr,
"TS*")]       # Create a list of 48-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))

        largest24 = arcpy.da.SearchCursor(basinPMP, ("PMP_24",)).next()[0]      # Calculate
largest 24-hour period PMP
        second24 = (arcpy.da.SearchCursor(basinPMP, ("PMP_48",)).next()[0] - largest24)/2
# Calculate the third largest 12-hr period PMP and divide by 2


        arcpy.AddMessage("\n\tLargest 24-hour Period: " + str(largest24))
        arcpy.AddMessage("\tFirst 12-hour: " + str(second24))
        arcpy.AddMessage("\tLast 12-hour: " + str(second24))


        for distribution in distributionList:     # Loops thourgh each 24-hour temporal distribution
            arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
            arcpy.AddMessage("\t\tFirst 12-hour Period...")
            accumPMP = 0
            with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:
# Cursor to evenly distribute half of 2nd largest 24-hour PMP to first 12 hours
                for row in cursor:
                    if row[1] <= 48:            # Leave loop once a row containing a temporal dist.
factor (ie, first 12h period) is reached
                        accumPMP +=  second24 / 48
                        row[0] = accumPMP
                        cursor.updateRow(row)
                del row, cursor

            arcpy.AddMessage("\t\tLargest 24-hour Period...")
```

```
            with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:
# Cursor to apply temporal factors to largest 24-hour PMP
                for row in cursor:
                    if row[1] > 48 and row[1] <= 144:       # Constrain update to rows 49-144 (second
24hr period)
                        accumPMP = (largest24 * row[0]) + second24
                        row[0] = accumPMP
                        cursor.updateRow(row)
                del row, cursor

            arcpy.AddMessage("\t\tLast 12-hour Period...")
            whereClause = distribution + " IS NULL"
            with arcpy.da.UpdateCursor(outTable, distribution, whereClause) as cursor:    # Cursor
to evenly distribute half of 2nd largest 24-hr into last 12 hours
                for row in cursor:
                    accumPMP +=  second24 / 48
                    row[0] = accumPMP
                    cursor.updateRow(row)
                del row, cursor, accumPMP, whereClause

        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)
    return


  def temporalDist_72hr(stormType, outPath, location, areaSize):       # General/Tropical Storm
72-hr Temporal Distributions Function
    basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + areaSize
# Location of basin average PMP table

    if stormType == "General":
        arcpy.AddMessage("\n***" + stormType + " Storm - 72hr PMP Temporal
Distributions***")
        temporalDistTable_72hr = home +
"\\Input\\Non_Storm_Data.gdb\\GS_TEMPORAL_DISTRIBUTIONS_72HR_" + location[1]    #
General Storm Temporal distribution factors table
        outTable = outPath + "\\GS_Temporal_Distributions_72hr_" + location[1]
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
        dm.Copy(temporalDistTable_72hr, outTable)                         # Copy temporal dist.
factors table to output location
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_72hr,
"GS*")]       # Create a list of 72-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))

        largest24 = arcpy.da.SearchCursor(basinPMP, ("PMP_24",)).next()[0]
# Calculate largest 24-hour period PMP
```

```
        second24 = arcpy.da.SearchCursor(basinPMP, ("PMP_48",)).next()[0] - largest24
# Calculate 2nd-largest 24-hour period PMP
        third24 = arcpy.da.SearchCursor(basinPMP, ("PMP_72",)).next()[0] -
arcpy.da.SearchCursor(basinPMP, ("PMP_48",)).next()[0]   # Calculate 3rd-largest 24-hour
period PMP

        arcpy.AddMessage("\n\tLargest 24-hour: " + str(largest24))
        arcpy.AddMessage("\tSecond largest 24-hour: " + str(second24))
        arcpy.AddMessage("\tThird largest 24-hour: " + str(third24))

        for distribution in distributionList:    # Loops thourgh each 72-hour temporal distribution
            arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
            arcpy.AddMessage("\t\tFirst 24-hour Period...")
            accumPMP = 0
            with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:
# Cursor to evenly distribute 2nd largest 24-hour
                for row in cursor:
                    if row[1] <= 96:        # Leave loop once a row containing a temporal dist. factor
(ie, second 24h period) is reached
                        accumPMP +=  second24 / 96
                        row[0] = accumPMP
                        cursor.updateRow(row)
                del row, cursor

            arcpy.AddMessage("\t\tSecond 24-hour Period...")
            with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:
# Cursor to apply temporal factors to largest 24-hour PMP
                for row in cursor:
                    if row[1] > 96 and row[1] <= 192:    # Constrain update to rows 97-192 (second
24hr period)
                        accumPMP = (largest24 * row[0]) + second24
                        row[0] = accumPMP
                        cursor.updateRow(row)
                del row, cursor

            arcpy.AddMessage("\t\tThird 24-hour Period...")
            whereClause = distribution + " IS NULL"
            with arcpy.da.UpdateCursor(outTable, distribution, whereClause) as cursor:    # Cursor
to evenly distribute 3nd largest hour over remaining empty rows
                for row in cursor:
                    accumPMP +=  third24 / 96
                    row[0] = accumPMP
                    cursor.updateRow(row)
                del row, cursor, accumPMP, whereClause
        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)
```

```
    if stormType == "Tropical":
        arcpy.AddMessage("\n***" + stormType + " Storm - 72hr PMP Temporal
Distributions***")
        temporalDistTable_72hr = home +
"\\Input\\Non_Storm_Data.gdb\\TS_TEMPORAL_DISTRIBUTIONS_72HR_" + location[1]    #
Tropical Storm Temporal distribution factors table
        outTable = outPath + "\\TS_Temporal_Distributions_72hr_" + location[1]
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
        dm.Copy(temporalDistTable_72hr, outTable)                         # Copy temporal dist.
factors table to output location
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_72hr,
"TS*")]        # Create a list of 72-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))

        largest24 = arcpy.da.SearchCursor(basinPMP, ("PMP_24",)).next()[0]
# Calculate largest 24-hour period PMP
        second24 = arcpy.da.SearchCursor(basinPMP, ("PMP_48",)).next()[0] - largest24
# Calculate 2nd-largest 24-hour period PMP
        third24 = arcpy.da.SearchCursor(basinPMP, ("PMP_72",)).next()[0] -
arcpy.da.SearchCursor(basinPMP, ("PMP_48",)).next()[0]   # Calculate 3rd-largest 24-hour
period PMP

        arcpy.AddMessage("\n\tLargest 24-hour: " + str(largest24))
        arcpy.AddMessage("\tSecond largest 24-hour: " + str(second24))
        arcpy.AddMessage("\tThird largest 24-hour: " + str(third24))

        for distribution in distributionList:   # Loops thourgh each 24-hour temporal distribution
            arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
            arcpy.AddMessage("\t\tFirst 24-hour Period...")
            accumPMP = 0
            with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:
# Cursor to evenly distribute 2nd largest hour
                for row in cursor:
                    if row[1] <= 96:       # Leave loop once a row containing a temporal dist. factor
(ie, second 24h period) is reached
                        accumPMP +=  second24 / 96
                        row[0] = accumPMP
                        cursor.updateRow(row)
                del row, cursor

            arcpy.AddMessage("\t\tSecond 24-hour Period...")
            with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:
# Cursor to apply temporal factors to largest 24-hour PMP
                for row in cursor:
                    if row[1] > 96 and row[1] <= 192:    # Constrain update to rows 97-192 (second
24hr period)
```

```
                    accumPMP = (largest24 * row[0]) + second24
                    row[0] = accumPMP
                    cursor.updateRow(row)
                del row, cursor

            arcpy.AddMessage("\t\tThird 24-hour Period...")
            whereClause = distribution + " IS NULL"
            with arcpy.da.UpdateCursor(outTable, distribution, whereClause) as cursor:  # Cursor
to evenly distribute 3nd largest hour over remaining empty rows
                for row in cursor:
                    accumPMP +=  third24 / 96
                    row[0] = accumPMP
                    cursor.updateRow(row)
                del row, cursor, accumPMP, whereClause

        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)
        return


    def temporalDist_EM72(stormType, outPath, location, areaSize):  # General/Tropical 72-hr
EM Temporal Distributions Function
        basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + areaSize
# Location of basin average PMP table

        if stormType == "General":
            arcpy.AddMessage("\n***General Storm - 72-hour PMP EM Temporal
Distribution***")

            temporalDistTable_72hr = home +
"\\Input\\Non_Storm_Data.gdb\\GS_TEMPORAL_DISTRIBUTIONS_72HR_EM"  # 72-hour
Temporal distribution factors table
            outTable = outPath + "\\GS_Temporal_Distributions_72hr_EM"
            arcpy.AddMessage("\n\tCreating temporal distribution table:...")
            dm.Copy(temporalDistTable_72hr, outTable)                    # Copy 72-hour
temporal dist. factors table to output location
            distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_72hr,
"GS*")]     # Create a list of 72-hour distribution field names
            arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))


            sixHour = arcpy.da.SearchCursor(basinPMP, ("PMP_06",)).next()[0]    # Gets 06-hour
PMP depth
            twelveHour = arcpy.da.SearchCursor(basinPMP, ("PMP_12",)).next()[0]    # Gets 12-
hour PMP depth
            twentyfourHour = arcpy.da.SearchCursor(basinPMP, ("PMP_24",)).next()[0]
# Gets 24-hour PMP depth
```

```
        second24 = (arcpy.da.SearchCursor(basinPMP, ("PMP_48",)).next()[0] -
twentyfourHour)     # Calculate 2nd-largest 24-hour period PMP
        third24 = arcpy.da.SearchCursor(basinPMP, ("PMP_72",)).next()[0] -
arcpy.da.SearchCursor(basinPMP, ("PMP_48",)).next()[0]   # Calculate 3rd-largest 24-hour
period PMP

        for distribution in distributionList:  # Loops thourgh each 72-hour temporal distribution
          arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
          accumPMP = 0
          with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:
# Cursor to apply temporal factor to 72-hour PMP
            for row in cursor:
              if row[1] <= 288:
                accumPMP +=  second24 / 288
                row[0] = accumPMP
                cursor.updateRow(row)
              if row[1] > 288 and row[1] <= 360:
                accumPMP +=  (twentyfourHour - twelveHour) / 144
                row[0] = accumPMP
                cursor.updateRow(row)
              if row[1] > 360 and row[1] <= 396:
                accumPMP +=  (twelveHour - sixHour) / 72
                row[0] = accumPMP
                cursor.updateRow(row)
              if row[1] > 396 and row[1] <= 468:
                accumPMP += sixHour * row[0]
                row[0] = accumPMP
                cursor.updateRow(row)
              if row[1] > 468 and row[1] <= 504:
                accumPMP +=  (twelveHour - sixHour) / 72
                row[0] = accumPMP
                cursor.updateRow(row)
              if row[1] > 504 and row[1] <= 576:
                accumPMP +=  (twentyfourHour - twelveHour) / 144
                row[0] = accumPMP
                cursor.updateRow(row)
              if row[1] > 576 and row[1] <= 864:
                accumPMP +=  third24 / 288
                row[0] = accumPMP
                cursor.updateRow(row)
            del row, cursor
        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)


    if stormType == "Tropical":
```

```
        arcpy.AddMessage("\n***Tropical Storm - 72-hour PMP EM Temporal
Distribution***")

        temporalDistTable_72hr = home +
"\\Input\\Non_Storm_Data.gdb\\TS_TEMPORAL_DISTRIBUTIONS_72HR_EM"  # 72-hour
Temporal distribution factors table
        outTable = outPath + "\\TS_Temporal_Distributions_72hr_EM"
        arcpy.AddMessage("\n\tCreating temporal distribution table:...")
        dm.Copy(temporalDistTable_72hr, outTable)                    # Copy 72-hour
temporal dist. factors table to output location
        distributionList = [field.name for field in arcpy.ListFields(temporalDistTable_72hr,
"TS*")]     # Create a list of 72-hour distribution field names
        arcpy.AddMessage("\n\tDistribution Field Names: " + str(distributionList))


        sixHour = arcpy.da.SearchCursor(basinPMP, ("PMP_06",)).next()[0]            # Gets
06-hour PMP depth
        twelveHour = arcpy.da.SearchCursor(basinPMP, ("PMP_12",)).next()[0]        # Gets 12-
hour PMP depth
        twentyfourHour = arcpy.da.SearchCursor(basinPMP, ("PMP_24",)).next()[0]
# Gets 24-hour PMP depth
        second24 = (arcpy.da.SearchCursor(basinPMP, ("PMP_48",)).next()[0] -
twentyfourHour)       # Calculate 2nd-largest 24-hour period PMP
        third24 = arcpy.da.SearchCursor(basinPMP, ("PMP_72",)).next()[0] -
arcpy.da.SearchCursor(basinPMP, ("PMP_48",)).next()[0]   # Calculate 3rd-largest 24-hour
period PMP

        for distribution in distributionList:    # Loops thourgh each 72-hour temporal distribution
          arcpy.AddMessage("\n\tApplying temporal distribution for: " + distribution)
          accumPMP = 0
          with arcpy.da.UpdateCursor(outTable, [distribution, "TIMESTEP"]) as cursor:
# Cursor to apply temporal factor to 72-hour PMP
            for row in cursor:
              if row[1] <= 288:
                accumPMP +=  second24 / 288
                row[0] = accumPMP
                cursor.updateRow(row)
              if row[1] > 288 and row[1] <= 360:
                accumPMP +=  (twentyfourHour - twelveHour) / 144
                row[0] = accumPMP
                cursor.updateRow(row)
              if row[1] > 360 and row[1] <= 396:
                accumPMP +=  (twelveHour - sixHour) / 72
                row[0] = accumPMP
                cursor.updateRow(row)
              if row[1] > 396 and row[1] <= 468:
```

```
                    accumPMP += sixHour * row[0]
                    row[0] = accumPMP
                    cursor.updateRow(row)
                if row[1] > 468 and row[1] <= 504:
                    accumPMP +=  (twelveHour - sixHour) / 72
                    row[0] = accumPMP
                    cursor.updateRow(row)
                if row[1] > 504 and row[1] <= 576:
                    accumPMP +=  (twentyfourHour - twelveHour) / 144
                    row[0] = accumPMP
                    cursor.updateRow(row)
                if row[1] > 576 and row[1] <= 864:
                    accumPMP +=  third24 / 288
                    row[0] = accumPMP
                    cursor.updateRow(row)
            del row, cursor
        checkTemporal(stormType, outPath, outTable, distributionList, dur, areaSize)
    return


  ##  This portion of the code checks to make sure none of the temporal distributions
  ##  are exceeding the PMP values for any durations.  It adds a table to the output
  ##  folder called CheckTemporal.
##~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
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  def checkTemporal(stormType, outPath, TemporalTable, distributionFields, dur, areaSize):
    basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + areaSize
# Location of basin average PMP table
    pmpFields = [field.name for field in arcpy.ListFields(basinPMP, "PMP_*")]
# PMP duration run
    table = arcpy.Describe(TemporalTable)
    tableName = table.name


    pmp = []             #Creates empty list and updates with PMP values for each duration run
    i = 0
    while i < len(pmpFields):
        with arcpy.da.SearchCursor(basinPMP,pmpFields) as cursor:
            for row in cursor:
                pmp.append(row[i])
                i += 1
    del i, cursor
```

```
    checkTable = arcpy.CreateTable_management(outPath, "Check_" + tableName)
#Creates table in output folder, adds field, and populates field with distributions
    dm.AddField(checkTable, "PATTERN", "TEXT", "", "", 50)
    with arcpy.da.InsertCursor(checkTable, "PATTERN") as cursor:
        for val in distributionFields:
            cursor.insertRow([val])

    maxFields = []                      #Create Max fields for each duration
    for maxField in pmpFields:
        newField = maxField.replace("PMP","MAX")
        maxFields.append(newField)
    del newField

    checkFields = []                    #Create Check fields for each duration
    for checkField in pmpFields:
        newField = checkField.replace("PMP","CHECK")
        checkFields.append(newField)
    del newField

    i = 0                               #Populate fields
    for pmpField in pmpFields:
        dm.AddField(checkTable, pmpField, "DOUBLE", "", "", 50)
        dm.AddField(checkTable, maxFields[i], "DOUBLE", "", "", 50)
        dm.AddField(checkTable, checkFields[i], "TEXT", "", "", 50)
        with arcpy.da.UpdateCursor(checkTable, pmpField) as cursor:
            for row in cursor:
                row = pmp[i]
                cursor.updateRow([row])
            i += 1
    del i, cursor


    step = arcpy.da.SearchCursor(TemporalTable,("MINUTE",)).next()[0]

    if step == 15:
        dic = {"01": 4, "02": 8, "03": 12, "04": 16, "05": 20, "06": 24, "12": 48, "24": 96, "48":
192, "72": 288}  # Dictionary to convert durations into 15-minute timesteps
    elif step == 5:
        dic = {"01": 12, "02": 24, "03": 36, "04": 48, "05": 60, "06": 72, "12": 144, "24": 288,
"48": 576, "72": 864}

    arcpy.AddMessage(str(step) + " Minute distribution Pattern.....")

    i = 0               # Calculates incemental PMP depths from temporal distribution and gets
maximum rainfall for each duration run
    for dur in durList:
```

```
            k = dic[dur]
            maxpmpList = []
            p = 0
            for distribution in distributionFields:
                incPMP = []
                previousRow = 0
                with arcpy.da.SearchCursor(TemporalTable, distributionFields) as cursor:
                    for row in cursor:
                        increment = row[p] - previousRow
                        previousRow = row[p]
                        incPMP.append(increment)
                na = np.array(incPMP)
                sumList = np.convolve(na,np.ones(k))
                maxPMP = max(sumList)
                maxpmpList.append(maxPMP)
                p +=1
            x = 0
            with arcpy.da.UpdateCursor(checkTable, maxFields[i]) as cursor:
# Updates table with max values
                for row in cursor:
                    row = maxpmpList[x]
                    x += 1
                    cursor.updateRow([row])
            i += 1
        del i, k, cursor, x

        with arcpy.da.UpdateCursor(checkTable, '*') as cursor:       # Compares PMP values to max
values for each duration.  If PMP values are larger update check field with PASS if not FAIL
            for row in cursor:
                rec = dict(zip(cursor.fields, row))
                arcpy.AddMessage("\n\tChecking values for distribution....." + rec['PATTERN'])
                for k, v in rec.iteritems():
                    if not k.startswith('PMP_'):
                        continue
                    _, n = k.split('_')
                    mx = rec['MAX_{}'.format(n)]
                    rec['CHECK_{}'.format(n)] = 'FAIL' if v < mx else 'PASS'
                    if rec['CHECK_{}'.format(n)] == 'PASS':
                        arcpy.AddMessage(str(k) + " \n\tPMP value is... " + str(v) + "  \n\tmax rainfall
value is..." + str(mx) + "\n\tThis distribution.... " + rec['CHECK_{}'.format(n)])
                    else:
                        arcpy.AddMessage(str(k) + " \n\tPMP value is... " + str(v) + "  \n\tmax rainfall
value is..." + str(mx) + "\n\tThis distribution.... " + rec['CHECK_{}'.format(n)]+ "\n\t Do not use
this distribution.  Max values for duration are exceeding PMP values.  Use critically stacked
distribution.... ")
                cursor.updateRow([rec[k] for k in cursor.fields])
```

```
        del cursor, k, v, rec
        return


    ###########################################################################
    ##  The temporalCritStacked() function applies the critically stacked
    ##  temporal distributions scenarios.  The function accepts the storm type,
    ##  output .gdb path, AOI area size, PMP duration string (hours), and
    ##  integer timestep duration (minutes). The function outputs a gdb table.


    def temporalCritStacked(stormType, outPath, area, duration, timestep):
# Function applied Critically Stacked temporal distribution
        basinPMP = outPath + "\\" + stormType + "_PMP_Basin_Average_" + area
# Location of basin average PMP table
        if stormType == "Local" and duration == "06":
# These conditional statements define the field name based on storm type, PMP duration, and
timestep duration
            csField = "LS_" + duration + "_HOUR_" + str(timestep) + "MIN_CRIT_STACKED"
        elif stormType == "General":
            csField = "GS_" + duration + "_HOUR_" + str(timestep) + "MIN_CRIT_STACKED"
        elif stormType == "Tropical":
            csField = "TS_" + duration + "_HOUR_" + str(timestep) + "MIN_CRIT_STACKED"
        else:
            arcpy.AddMessage("\n***Invalid storm type: " + stormType)
            return
        arcpy.AddMessage("\n***" + duration + "-hour " + str(timestep) + "-min Critically Stacked
Temporal Distribution***")
        tableName = "Temporal_Distribution_" + duration + "hr_" + str(timestep) +
"min_Crit_Stacked"                    # Output table name
        tablePath = outPath + "\\" + tableName
# Output table full path
        pmpFields = [field.name for field in arcpy.ListFields(basinPMP, "PMP*")]
# Gets the "PMP_XX" field names from the basin avereage PMP table

        if duration == "06":        # These conditional statements define the key durations needed to
build the critically stacked patterns for the following durations...
            keyDurations = [1, 2, 3, 4, 5, 6]
        elif duration == "12":
            keyDurations = [1, 2, 3, 4, 5, 6, 12]
        elif duration == "24":
            keyDurations = [1, 2, 3, 4, 5, 6, 12, 24]
        elif duration == "48":
            keyDurations = [1, 2, 3, 4, 5, 6, 12, 24, 48]
        elif duration == "72":
            keyDurations = [1, 2, 3, 4, 5, 6, 12, 24, 48, 72]
```

```
        elif duration == "96":
            keyDurations = [1, 2, 3, 4, 5, 6, 12, 24, 48, 72, 96]
        elif duration == "120":
            keyDurations = [1, 2, 3, 4, 5, 6, 12, 24, 48, 72, 96, 120]
        else:
            arcpy.AddMessage("\n\t...Critically stacked temporal distribution not available for " +
duration + "-hour duration.")
            return
        timestepLen = int(duration) * 60 / timestep
# number of rows in output table
        xValues = [0]
        for i in keyDurations:        # defines the known x-values (xp) to be used in the interpolation
            xVal = i * timestepLen / int(duration)
            xValues.append(xVal)
        del i, xVal
        yValues = [0]
        d = 0
        for i in keyDurations:        # defines the known y-values (fp) to be used in the interpolation
            pmpDepth = arcpy.da.SearchCursor(basinPMP, pmpFields).next()[d]
            yValues.append(pmpDepth)
            d += 1
        del d, i, pmpDepth

        x = np.arange(0, timestepLen + 1, 1)
# defines the x points at which to interpolate values
        xp = np.asarray(xValues)                    # np.asarray converts lists into numpy arrays
        fp = np.asarray(yValues)
        y = np.interp(x, xp, fp)
        inc = []
        prevDepth = 0
        i = 0
        for depth in np.nditer(y):          # populates incremental depths list 'inc' with y array
            inc.append(depth - prevDepth)
            prevDepth = depth
            i += 1
        del i, prevDepth
        periods = int(duration)               # defines number of periods (known hours) as the duration
        periodLen = 60 / timestep                 # defines number of timesteps (minutes) in each period
        ranks = []
        stackRank = 1
        i = 0
        while i < periods:           # populates list 'ranks' with a rank integer, one entry per period
            ranks.append(stackRank)
            stackRank += periodLen
            i += 1
        del i
```

```
        orderRanks = []
        orderRanks.insert(0, ranks.pop(0))
        for i in range (timestepLen / periodLen):
## orders the ranks according to critically stacked pattern.  Pulls
            if ranks:           ## (pop()) the first rank from the ranks list and places it in the orderRanks
                orderRanks.insert(0, ranks.pop(0))
## list. Places next two ranks at the beginning of the list
            if ranks:          ## and the following at the end of the list.  Repeats until ranks is empty.
                orderRanks.insert(0, ranks.pop(0))
            if ranks:
                orderRanks.append(ranks.pop(0))
        del i
        orderRanks += [orderRanks.pop(0)]
        if orderRanks[0] == max(orderRanks):
## Moves last rank to the end of of orderRanks list.
            arcpy.AddMessage("\n*** moving first rank to last")
            orderRanks.append(orderRanks.pop(max))
        orderInc = []
        n = 0
        for i in range(periods):         # gets the nth largest increment where n is the ordered Rank.
            for q in range(periodLen):
                nthLargest = nlargest(orderRanks[n], inc)[-1]
                orderInc.append(nthLargest)
            n += 1
        del n, i, q
        cumulative = []
        prevInc = 0
        for i in orderInc:          # Converts the incremental depths to cumulatove depths and places
in cumulative list
            value = round(i + prevInc, 2)
            cumulative.append(value)
            prevInc = i + prevInc
            i += 1
        del i, prevInc
        timesteps = x.tolist()    # Converts the timesteps array (x) to a list then removes the first zero
entry
        timesteps.pop(0)
        minutes = []
        minutesInc = timestep
        for i in range(timestepLen):        # Constructs the minutes list to be used in output column
based on timestep interval
            minutes.append(minutesInc)
            minutesInc += timestep
        del i
```

```
        dm.CreateTable(outPath, tableName)
# Create the output geodatabase table
        dm.AddField(tablePath, "TIMESTEP", "DOUBLE")
# Create "TIMESTEP" field
        dm.AddField(tablePath, "MINUTES", "DOUBLE")
# Create "MINUTES" field
        dm.AddField(tablePath, csField, "DOUBLE")
# Create cumulated rainfall field
        zipped = zip(timesteps, minutes, cumulative)
# Zip up lists of output items.
        fields = ('TIMESTEP', 'MINUTES', csField)
# Output table field names
        arcpy.AddMessage("\n\tApplying temporal distribution for: " + csField)
        with arcpy.da.InsertCursor(tablePath, fields) as cursor:
# Cursor to populate output Critically Stacked table
            for i in zipped:
                cursor.insertRow(i)
        del cursor, i
        return


    ###############################################################################
    ##  This portion of the code iterates through each storm feature class in the
    ##  'Storm_Adj_Factors' geodatabase (evaluating the feature class only within
    ##  the Local, Tropical, or general feature dataset).  For each duration,
    ##  at each grid point within the aoi basin, the transpositionality is
    ##  confirmed.  Then the DAD precip depth is retrieved and applied to the
    ##  total adjustement factor to yield the total adjusted rainfall.  This
    ##  value is then sent to the updatePMP() function to update the 'PMP_Points'
    ##  feature class.
##~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~##


    desc = arcpy.Describe(basin)       # Check to ensure AOI input shape is a Polygon. If not - exit.
    basinShape = desc.shapeType
    if desc.shapeType == "Polygon":
        arcpy.AddMessage("\nBasin shape type: " + desc.shapeType)
    else:
        arcpy.AddMessage("\nBasin shape type: " + desc.shapeType)
        arcpy.AddMessage("\nError: Input shapefile must be a polygon!\n")
        sys.exit()

    createPMPfc()       # Call the createPMPfc() function to create the PMP_Points feature class.
```

```
   env.workspace = adjFactGDB          # the workspace environment is set to the
'Storm_Adj_Factors' file geodatabase

   aoiSQMI = round(getAOIarea(),2)      # Calls the getAOIarea() function to assign area of AOI
shapefile to 'aoiSQMI'
   if aoiSQMI > 100 and stormType is "Local":
      arcpy.AddMessage("\n***Warning - Local storm PMP depths only valid for basins 100
square miles or smaller***")

   stormList = arcpy.ListFeatureClasses("", "Point", stormType)    # List all the total adjustment
factor feature classes within the storm type feature dataset.
   for dur in durList:

arcpy.AddMessage("\n***********************************************************
**\nEvaluating " + dur + "-hour duration...")

      pmpList = []
      driverList = []
      gridRows = arcpy.SearchCursor(env.scratchGDB + "\\PMP_Points")
      try:
         for row in gridRows:
            pmpList.append(0.0)                                # creates pmpList of empty
float values for each grid point to store final PMP values
            driverList.append("STORM")               # creates driverList of empty text values for
each grid point to store final Driver Storm IDs
         del row, gridRows
      except UnboundLocalError:
         arcpy.AddMessage("\n***Error: No data present within basin/AOI area.***\n")
         sys.exit()

      for storm in stormList[:]:
         arcpy.AddMessage("\n\tEvaluating storm: " + storm + "...")
         dm.MakeFeatureLayer(storm, "stormLayer")         # creates a feature layer for the
current storm
         dm.SelectLayerByLocation("stormLayer", "HAVE_THEIR_CENTER_IN", "vgLayer")
# examines only the grid points that lie within the AOI
         gridRows = arcpy.SearchCursor("stormLayer")
         pmpField = "PMP_" + dur
         i = 0
         try:
            dadPrecip = round(dadLookup(storm, dur, aoiSQMI),3)
            arcpy.AddMessage("\t\t" + dur + "-hour DAD value:  " + str(dadPrecip) + chr(34))
         except TypeError:                                    # In no duration exists in the DAD
table - move to the next storm
            arcpy.AddMessage("\t***Duration '" + str(dur) + "-hour' is not present for " +
str(storm) + ".***\n")
```

```
            continue
        arcpy.AddMessage("\t\tComparing " + storm + " adjusted rainfall values against current
driver values...")
        transCounter = 0            # Counter for number of grid points transposed to
        for row in gridRows:
            if row.TRANS == 1:        # Only continue if grid point is transpositionable ('1' is
transpostionable, '0' is not).
                try:                                        # get total adj. factor if duration exists
                    transCounter += 1
                    adjRain = round(dadPrecip * row.TAF,1)
                    if adjRain > pmpList[i]:
                        pmpList[i] = adjRain
                        driverList[i] = storm
                except RuntimeError:
                    arcpy.AddMessage("\t\t   *Warning*  Total Adjusted Raifnall value falied to set
for row " + str(row.CNT))
                    break
                del adjRain
            i += 1
        if transCounter == 0:
            arcpy.AddMessage("\t\tStorm not transposable to basin. Removing " + storm + " from
list...\n")
            stormList.remove(storm)
        else:
            arcpy.AddMessage("\t\tTransposed to " + str(transCounter) + "/" + str(i) + " grid
points...\n")
        del row, transCounter
    del storm, gridRows, dadPrecip
    updatePMP(pmpList, driverList, dur)             # calls function to update "PMP Points"
feature class
  del pmpList, stormList

  arcpy.AddMessage("\n'PMP_Points' Feature Class 'PMP_XX' fields update complete for all '"
+ stormType + "' storms.")

  outputPMP(stormType, aoiSQMI, outputPath)              # calls outputPMP() function
  outArea = str(int(round(aoiSQMI,0))) + "sqmi"
  outGDB = outLocation + "\\" + stormType + "\\PMP_" + desc.baseName + "_" + outArea +
".gdb"

  if runTemporal:                                    #Calls temporal distribution functions
    centroidLocation = basinZone(basin)
    arcpy.AddMessage("\nBasin Centroid Transposition Zone: " + str(centroidLocation[0]) +
"\nBasin Centroid side of Appalachian Divide: " + str(centroidLocation[1]))

    for dur in durList:
```

```
        if dur == "01":
            temporalDistEM1(stormType, outGDB, centroidLocation, outArea)
        if dur == "02":
            temporalDistEM2(stormType, outGDB, centroidLocation, outArea)
            temporalDistLS2(stormType, outGDB, centroidLocation, outArea)
        if dur == "03":
            temporalDistEM3(stormType, outGDB, centroidLocation, outArea)
        if dur == "06":
            temporalDistLS(stormType, outGDB, centroidLocation, outArea)
        if dur == "12":
            temporalDistEM12(stormType, outGDB, centroidLocation, outArea)
        if dur == "24":
            temporalDist_24hr(stormType, outGDB, centroidLocation, outArea)
            temporalDist_EM24(stormType, outGDB, centroidLocation, outArea)
            temporalCritStacked(stormType, outGDB, outArea, dur, 15)
        if dur == "48":
            temporalDist_48hr(stormType, outGDB, centroidLocation, outArea)
            temporalDist_EM48(stormType, outGDB, centroidLocation, outArea)
        if dur == "72":
            temporalDist_72hr(stormType, outGDB, centroidLocation, outArea)
            temporalDist_EM72(stormType, outGDB, centroidLocation, outArea)


    i = 0                                                    #Creates CSV files of all output tables
    csvPath = outLocation + "\\" + stormType + "\\CSV_" + desc.baseName + "_" + outArea +
"\\"
    if not arcpy.Exists(outLocation + "\\" + stormType + "\\CSV_" + desc.baseName + "_" +
outArea):
        arcpy.CreateFolder_management(outLocation + "\\" + stormType + "\\", "CSV_" +
desc.baseName + "_" + outArea)
    arcpy.AddMessage("\n\t...Creating output tables as CSV files.. ")
    env.workspace = outGDB
    outTables = arcpy.ListTables()
    for t in outTables:
        arcpy.TableToTable_conversion(t, csvPath, outTables[i] + ".csv")
        i += 1
    xmlFiles = os.listdir(csvPath)
    for file in xmlFiles:
        if file.endswith(".xml"):
            os.remove(os.path.join(csvPath,file))
    return
##~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~~~~##
```

```
def outputBasAveTable():
    arcpy.AddMessage("\nCreating basin average summary table.\n")
    tableList = basAveTables
    for table in tableList:
        arcpy.AddMessage("\t\tMerging tables... " + table)

    dm.Merge(basAveTables, outputTable)
    ##  addLayerMXD(outputTable)  adds output table to ArcMap session

    return
##~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~##


def addLayerMXD(addFC):
    desc = arcpy.Describe(addFC)
    layerName = desc.name
    arcpy.AddMessage("\nAdding " + layerName + " table to current MXD...")
    if desc.dataType == "FeatureClass":
        dm.MakeFeatureLayer(addFC, layerName)
        layer = arcpy.mapping.Layer(layerName)
        arcpy.mapping.AddLayer(df, layer)
        arcpy.AddMessage("\n" + layerName + " added to current map session.\n")
    elif desc.dataType == "Table":
        layer = arcpy.mapping.TableView(desc.catalogPath)
        arcpy.mapping.AddTableView(df, layer)
        arcpy.AddMessage("\n" + layerName + " added to current map session.\n")
    elif desc.dataType == "ArcInfoTable":
        layer = arcpy.mapping.TableView(desc.catalogPath + ".dbf")
        arcpy.mapping.AddTableView(df, layer)
        arcpy.AddMessage("\n" + layerName + " added to current map session.\n")

    del desc, layerName, layer
    return


##~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~##


if locDurations:
    type = "Local"
    durations = locDurations
    dm.CreateFolder(outLocation, type)
```

```
    outputPath = outLocation + "\\Local\\"
    arcpy.AddMessage("\nRunning PMP analysis for storm type: " + type)
    pmpAnalysis(basin, type, durations)          # Calls the pmpAnalysis() function to calculate the
local storm PMP
    arcpy.AddMessage("\nLocal storm analysis
complete...\n*****************************************************************
*************************************")

if genDurations:
    type = "General"
    durations = genDurations
    dm.CreateFolder(outLocation, type)
    outputPath = outLocation + "\\General\\"
    arcpy.AddMessage("\nRunning PMP analysis for storm type: " + type)
    pmpAnalysis(basin, type, durations)          # Calls the pmpAnalysis() function to calculate the
general storm PMP
    arcpy.AddMessage("\nGeneral storm analysis
complete...\n*****************************************************************
*************************************")

if tropDurations:
    type = "Tropical"
    durations = tropDurations
    dm.CreateFolder(outLocation, type)
    outputPath = outLocation + "\\Tropical\\"
    arcpy.AddMessage("\nRunning PMP analysis for storm type: " + type)
    pmpAnalysis(basin, type, durations)          # Calls the pmpAnalysis() function to calculate the
tropical storm PMP
    arcpy.AddMessage("\nTropical storm analysis
complete...\n*****************************************************************
*************************************")

#if arcpy.Describe(outputTable).name:
#    outputBasAveTable()

#arcpy.RefreshTOC()
#arcpy.RefreshActiveView()
#del mxd, df
```

Appendix J
PMP Version Log: Changes to Storm Database and Adjustment Factors

Pennsylvania PMP version Log

- Storms were not transpositioned across the Appalachian crest
- Previous transposition limits from the adjacent Virginia, TVA, and Ohio statewide and several site-specific studies in the region (e.g. Catawba, Conowingo, Ashokan) were utilized as a starting point when storms were common to these other studies

Version 1.0:

- Gathered storm long list
- Initial GTF calculations for sensitivities. All storms were moved to all grids at this stage to allow for an explicit evaluation of GTF factors for each storm. This allowed investigating to be performed regarding the resulting GTF values and variations spatially. This provides explicit data from which to make decisions on transposition limits and/or support decisions made
- No transposition limits set
- No PMP runs

Version 2.0:

- Created 7 transposition zones
- Initial run; included GTF upper limit of 1.50 and lower limit 0.50
- Added transposition constraints to all storms
- Used working version of SPAS 1681 DAD table for Smethport.
- Used working version of updated TVA dewpoint dataset

<u>General Storms</u>

- SPAS 1041_1 (Norwalk, CT) – Moved to zones 1,2,3,4
- SPAS 1047_1 (Tamaqua, PA) – Moved to zones 1,2,3,4
- SPAS 1194_1 (Pinkham Notch, NH) – Moved to zone 5
- SPAS 1195_1 (Pinkham Notch, NH) - Moved to zone 5
- SPAS 1195_2 (Paddy Mountain, WV) - Moved to zone 5
- SPAS 1199_1 (Pinkham Notch, NH) - Moved to zone 5
- SPAS 1201_1 (Halifax, VT) – Moved to zones 2,3,4,5
- SPAS 1202_1 (West Seboeis, ME) - Moved to zones 2,3,4,5
- SPAS 1206_1 (Big Rapids, MI) - Moved to zone 7
- SPAS 1208_1 (Warner Park, TN) - Moved to zone 7
- SPAS 1244_1 (Louisville, KY) - Moved to zone 7
- SPAS 1255_1 (Pittsfield, MA) - Moved to zones 2,3,4,5
- SPAS 1257_2 (East Jewett, NY) - Moved to zones 1,2,3,4
- SPAS 1258_1 (Big Moose, NY) – Removed from short list
- SPAS 1259_1 (Slide Mountain, NY) - Moved to zones 2,3,4,5
- SPAS 1260_1 (Lewiston, ME) - Moved to zones 1,2,3,4
- SPAS 1261_1 (Rumford, ME) – Removed from short list

- SPAS 1263_1 (Kingfield, ME) – Removed from short list
- SPAS 1277_1 (Gilbertsville, KY) - Moved to zone 7
- SPAS 1278_1 (Madisonville, KY) - Moved to zone 7
- SPAS 1286_1 (Aurora College, IL) - Moved to zone 7
- SPAS 1291_1 (Slide Mountain, NY) - Moved to zones 2,3,4,5
- SPAS 1311_1 (McKenzie, TN) - Moved to zone 7
- SPAS 1312A_1 (Rollins Branch, WV) - Moved to zones 5,6
- SPAS 1312A_2 (Rosman, NC) - Moved to zones 5,6
- SPAS 1339_1 (Wellsboro, NC) - Moved to zones 2,3,4,5
- SPAS 1346_1 (Blue Ridge Divide, NC) - Moved to zones 5,6
- SPAS 1350_1 (New Bern, NC) - Moved to zones 1,2
- SPAS 1357_1 (Burnsville, TN) - Moved to zone 7
- SPAS 1362_2 (Robbinsville, VA) - Moved to zone 6
- SPAS 1403_1 (Pinkham Notch, NH) - Moved to zone 5
- SPAS 1433_1 (Collinsville, IL) - Moved to zone 7
- SPAS 1514_1 (Vade Mecum, NC) - Moved to zones 1,2
- SPAS 1533_1 (Montebello, VA) - Moved to zones 2,3,4,5
- SPAS 1565_1 (Paterson, NJ) - Moved to zones 1,2
- SPAS 1566_1 (Paterson, NJ) - Moved to zones 1,2

Hybrid Storms

- SPAS 1340_1 (Big Meadows, VA) - Moved to zones 2,3,4,5
- SPAS 1629_1 (Hector, NY) - Moved to zones 2,3,4,5

Local Storms

- SPAS 1017_1 (Sparta, NJ) - Moved to zones 2,3,4
- SPAS 1040_1 (Tabernacle, NJ) - Moved to zones 1,2
- SPAS 1049_1 (Delaware County, NY) - Moved to zones 2,3,4,5
- SPAS 1209_1 (Wooster, OH) - Moved to zone 7
- SPAS 1226_1 (College Hill, OH) - Moved to zone 7
- SPAS 1343_1 (Johnson City, TN) - Moved to zone 6
- SPAS 1345_1 (Smethport, PA) - Moved to zone 6
- SPAS 1362_1 (Coeburn, VA) - Moved to zones 6,7
- SPAS 1402_1 (Little Barren, TN) - Moved to zones 6,7
- SPAS 1402_2 (Rosedale, TN) - Moved to zones 6,7
- SPAS 1406_1 (Rapidan, VA) - Moved to zones 3,4,5
- SPAS 1415_1 (Islip, NY) - Moved to zones 1,2
- SPAS 1426_1 (Cooper, MI) - Moved to zone 7
- SPAS 1489_1 (Jewell, MD) - Moved to zones 1,2
- SPAS 1534_1 (Ewan, NJ) - Moved to zones 1,2
- SPAS 1536_1 (Glenville, WV) - Moved to zones 6,7
- SPAS 1546_1 (Little River, VA) - Moved to zones 6,7

- SPAS 1547_1 (Catskill, NY) - Moved to zones 1,2,3,4
- SPAS 1548_1 (Redbank, PA) - Moved to zones 6,7
- SPAS 1550_1 (Johnstown, PA) - Moved to zone 6

<u>Tropical Storms</u>

- SPAS 1198_1 (Pinkham Notch, NH) - Moved to zone 5
- SPAS 1198_2 (Mt Mansfield, VT) - Moved to zones 5,6
- SPAS 1224_1 (Maplecrest, NY) - Moved to zones 3,4,5
- SPAS 1243_1 (Westfield, MA) - Moved to zones 1,2,3,4
- SPAS 1275_1 (Montgomery Dam, PA) - Moved to zones 7
- SPAS 1275_2 (Montgomery Dam, PA) - Moved to zones 1,2,3,4,5
- SPAS 1276_1 (Wellsville, NY) - Moved to zones 6,7
- SPAS 1276_2 (Zerbe, PA) - Moved to zones 1,2,3,4,5
- SPAS 1298_1 (Harrisburg, PA) - Moved to zones 2,3,4
- SPAS 1299_1 (Alta Pass, NC) - Moved to zones 3,4,5
- SPAS 1312B_2 (Rosman, NC) - Moved to zones 5,6
- SPAS 1341_1 (Buck, CT) - Moved to zones 1,2
- SPAS 1342_1 (Mt Mitchell, NC) - Moved to zones 5,6
- SPAS 1490_1 (Easton, MD) - Moved to zones Moved to zones 1,2
- SPAS 1491_1 (Tyro, VA) - Moved to zones 3,4,5
- SPAS 1517_2 (Moncure, NC) - Moved to zones 1,2
- SPAS 1517_3 (Settle, NC) - Moved to zones 1,2
- SPAS 1526_1 (Raleigh, NC) - Moved to zones 1,2
- SPAS 1535_1 (Edenton, NC) - Moved to zones 1,2
- SPAS 1535_2 (Upper Sherando, VA) - Moved to zones 3,4,5
- SPAS 1551_1 (Richmond, VA) - Moved to zones 1,2
- SPAS 1552_1 (Southport 5N, NC) - Moved to zones 1,2
- SPAS 1552_2 (Yorktown, VA) - Moved to zones 1,2
- SPAS 1552_3 (Pomton Lake, NJ) - Moved to zones 1,2
- SPAS 1552_4 (Cairo, NY) - Moved to zones 1,2,3,4,5
- SPAS 1567_1 (Tuckerton, NJ) - Moved to zones 1,2
- SPAS 1628_1 (Jefferson, OH) - Moved to zone 6
- SPAS 1679_1 (Slide Mountain, NY) - Moved to zones 3,4,5

Version 3.0:

- Used SPAS 1345 DAD for Smethport

Version 4.0:

- SPAS 1219_1 – Removed from short list
- SPAS 1298_1 – Updated transposition to include zones 1,5 (1,2,3,4,5)
- SPAS 1275_1 - Updated transposition to include zone 6 (6,7)
- SPAS 1243_1 - Updated transposition to include zone 5 (1,2,3,4,5)

- SPAS 1340_1 - Updated transposition to remove zone 2 (3,4,5)
- SPAS 1047_1 - Updated transposition to include zone 5 (1,2,3,4,5)
- SPAS 1259_1 - Updated transposition to remove zone 2 (3,4,5)
- SPAS 1291_1 - Updated transposition to remove zone 2 (3,4,5)
- SPAS 1339_1 - Updated transposition to remove zone 2 (3,4,5)
- SPAS 1491_1 - Updated transposition to remove zone 5 (3,4)
- SPAS 1547_1 - Updated transposition to include zone 5 (1,2,3,4,5)
- SPAS 1286_1 - Updated transposition to include zone 6 (6,7)
- SPAS 1206_1 - Updated transposition to include zone 6 (6,7)
- Merged NOAA Atlas 14 Volume 2 and Volume 10 precipitation frequency datasets.

Version 5.0:

- SPAS 1258_1 – Removed from short list
- SPAS 1261_1 - Removed from short list
- SPAS 1263_1 - Removed from short list
- Removed Medford, WI storm from short list
- Removed Paris Waterworks, IN storm from short list
- Removed Newcomerstown, OH storm from short list
- SPAS 1628_1 - Updated transposition to include zone 7 (6,7)
- SPAS 1286_1 – Updated DAD table to include hours 1-6
- Added SPAS 1630_1 (Bolton, ONT) as Tropical storm. Moved to zones 6,7.
- Added SPAS 1669_1 (Evergreen, NC) as Tropical storm. Moved to zones 1,2
- Added SPAS 1673_1 (Harrow, ONT) as Local storm. Moved to zone 7. Estimated PF based on nearest NOAA 14 values.
- Changed SPAS 1286_1 (Aurora College, IL) from General storm to a Hybrid (G/L) storm. Used 6-hr precipitation frequency for both.
- SPAS 1345_1 (Smethport, PA) – Held MTF to 1 – used SPAS 1681 version 10 DAD
- Incorporated sensitivity from 5.2
- Added hurricane Florence to short list. Not included in this PMP run.

Version 5.1:

General Storms

- SPAS 1339_1 (Wellsboro, PA) – Added zone 2 to match what was done in Virginia (2,3,4,5)

Tropical Storms

- SPAS 1491_1 (Tyro, VA) – Limited to south of 40° N (3,4)
- SPAS 1299_1 (Alta Pass, NC) Limited to south of 40° N (3,4,5)

Version 5.2:

General Storms

- SPAS 1339_1 (Wellsboro, PA) – Added zone 1 & 2 (1,2,3,4,5)

- SPAS 1629_1 (Hector, NY) – Added zone 1 (1,2,3,4,5)

<u>Tropical Storms</u>

- SPAS 1491_1 (Tyro, VA) – Added zone 5 (3,4,5) – No limit on Lat (zone 5 is above 40°N)
- SPAS 1299_1 (Alta Pass, NC) same as 5.1 limited to south of 40° N (3,4,5)

Version 6.0:

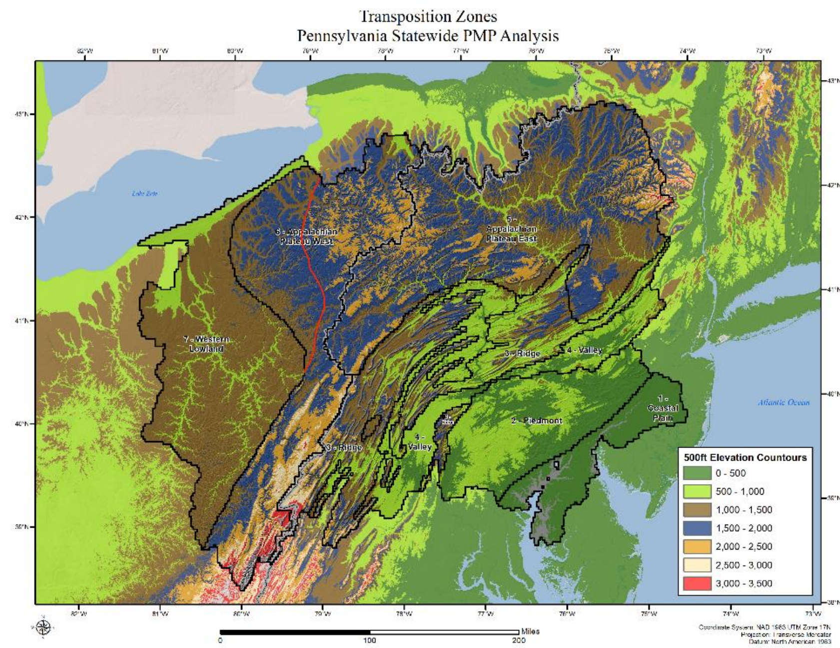
- Smethport (SPAS 1681) was broken into 6 dad zones.

Version 6.1:

- Removed Smethport (SPAS 1681) and Catskill (SPAS 1547) from Local storm list to see how much larger they are than next largest storm.

Version 6.2:

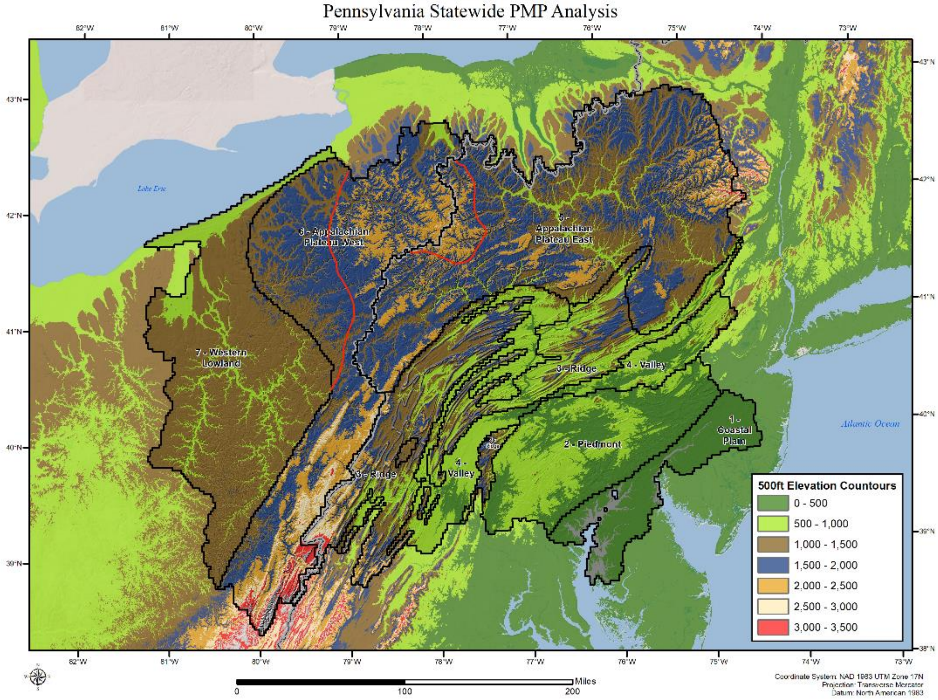
- Updated transposition limits for Smethport (SPAS 1681) to the following custom limits on attached image.



Version 6.3:

- Updated transposition limits for Smethport (SPAS 1681) to the following custom limits on attached image.

Transposition Zones
Pennsylvania Statewide PMP Analysis



Version 6.4:

- Lowered the upper GTF cap from 1.5 to 1.2 for Catskill, NY (SPAS 1547).

Version 7.0:

- Updated SPAS 1299_1 (Alta Pass, NC) to limited to south of 41° N (3,4,5)
- Added SPAS 1697_1 (Ironwood, MI) as General storm. Moved to zone 7
- Added SPAS 1698_1 (Bellefontaine, OH) as General storm. Moved to zone 7
- Added SPAS 1699_1 (Hayward, WI) as Hybrid storm. Moved to zone 7
- Added SPAS 1700_1 (Elliot City, MD) as Local storm. Moved to zones 1 & 2
- Added SPAS 1006_1 (West Shokan, NY) as Tropical storm. Moved to zones 3,4, and 5
- Lowered the upper GTF cap from 1.5 to 1.2 for Catskill, NY (SPAS 1547) and capped MTF at 1. Used a storm rep dew point value of 73°.
- Added 10 1-mile buffers around Smethport transposition from v6.2. Allowed storm to go to transposition zones 3,5,6, and 7 but each mile outside of v6.2 zone reduced TAF by 2.5%.

Version 7.1:

- Used 6 inches for storm center 6-hr precipitation frequency value for SPAS 1547_1 (Catskill)

Version 7.2:

- Used 6.5 inches for storm center 6-hr precipitation frequency value for SPAS 1547_1 (Catskill)

Version 7.3:

- Used a storm rep value of 73 degrees for SPAS 1547_1 (Catskill) – GTF capped at 1.2, MTF = 1

Version 7.4:

- Used a storm rep value of 75 degrees for SPAS 1547_1 (Catskill) – GTF capped at 1.2, MTF = 1

Version 7.5:

- Used version 7 but removed Catskill from Storm List

Version 8:

- Based off of version 7.5 but Set MTF to 1 for all storms to remove it from adjustments.

Version 9:

- Based off version 8.   Added Catskill, Set IPMF to 1.13 and capped GTF at 1.2.
- Added SPAS 1720_1 Swansboro, NC as Tropical storm. Moved to zones 1 & 2
-

Version 9.1:

- Used an average of the next 9 and 25 adjacent grid cells precipitation at the storm center instead of using a point value.

Version 9.2:

- Allowed SPAS 1299 to go to all of zones 3, 4, and 5.

Version 9.4:

- Used v9.2. Smoothing of precipitation frequency depth in two locations that were producing unreasonably high PMP values. See report for details. This is the final version.

Appendix K
Project Review Board Memos

PO Box 175
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http://www.appliedweatherassociates.com

December 12, 2018

Memo for Record

To: Pennsylvania Statewide PMP Project Review Board

Subject: Catskill, NY 1819 PMP Analysis Background and Recommendations

Introduction

This memo addresses the Review Board request to summarize the AWA investigations and storm analysis process used to derive the rainfall analysis and PMP development associated with the Catskill, NY July 1819 storm (SPAS 1547).

Background

This storm is of particular importance for this study because it currently controls PMP depths for durations from 1 to 3-hours and for area sizes less than 10-square miles. This directly effects numerous dams in Pennsylvania. Although the storm occurred prior to official observations, settlements along the Husdon River Valley provided several written and oral accounts of the rainfall. These accounts are captured in the American Journal of Science, and Arts, volume IV, 1822, Article XII, "An account of a remarkable storm which occurred at Catskill, July 26, 1819" (Appendix 1). The fact that the storm was significant enough to be captured in the literature demonstrates that it was an unusual event. Further discussions and analysis of this storm are provided in Hydrometeorological Report 1 (HMR 1), Page 66 (Weather Bureau, 1940) (Figure 1).

Given the above information, there is no doubt a significant rainfall event occurred. Unfortunately, the rainfall occurred without the aid of standard observations, both the exact amount of rainfall and the incremental accumulation are highly subjective. Therefore, when a storm with a large amount of uncertainty controls PMP depths, further investigation and justification is required to include or exclude from derivation of PMP.

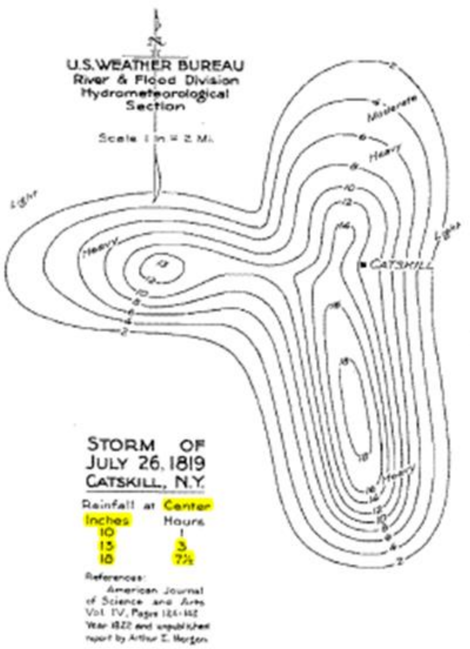

Figure 25

is determined by the Catskill, New York, storm of July 26, 1819, which is reported to have lasted 7-1/2 hours and produced 18 inches of rain at the center. Fortunately a description of this storm is available which gives estimates of rain at several points and outlines the limits of heavy rainfall. From these data it was possible to prepare an isohyetal map which is reproduced in Figure 25. An area-depth curve was derived as shown in Figure 26 which gives a lower value for 80 square miles than the September 1932 storm for a similar period.

On the basis of the analysis of the July 1819 storm it was decided that a high-intensity, short-duration storm of this type would not be the most critical over the Ompompanoosuc Basin. Also plotted in Figure 24 are maximum rainfall values from Miami Conservancy data from 7,561 station-years of record in the New England States, and the

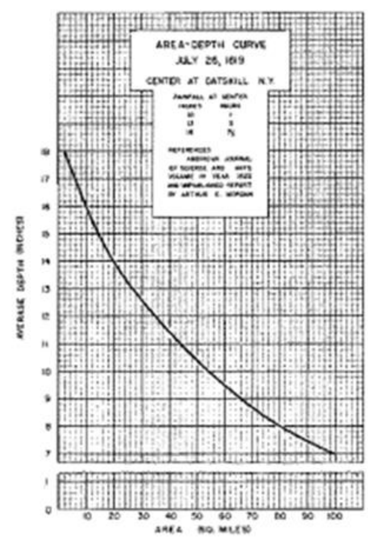

Figure 26

-- 66 --

Figure 1: Storm discussion and information from HMR 1

Storm Discussion

The Catskill, NY 1819 storm is similar to other storms in the region where low-level moisture advects in the region from the south and east originating from the warm water associated with the Gulf Stream in the Atlantic. The storm location is located just east of the first major topographical feature in the area, the Catskill Mountains, on the west side of the Hudson River Valley. The combination of access to low-level moisture and topographical lift proved an ideal environment for storm initiation and heavy rainfall production. In addition, most of the rainfall with this storm occurred within a 6-hour period. Therefore, this storm type is considered a local storm and could reasonably occur within regions east of the Appalachian Crest, i.e. Pennsylvania transposition zones 1, 2, 3, 4, and 5.

Reasons for inclusion

- Evidence of extreme local rainfall event
- Occurred in a season and location similar to other extreme local storms in the region that are used for PMP development
- Controlling of PMP depths, therefore provides a conservative application for high hazard structures
- Used in HMR 1

Reasons for elimination

- Lack of accurate storm accumulation and spatial information
- Uncertainty regarding storm maximization
- Resulting depths significantly greater than other well observed storm and previous design values
- Unadjusted storm adjustments result in values far exceeding world record rainfall depths

Summary/Recommendation

AWA recommends this storm continued to be used in the PMP development. However, AWA recommends that adjustments to the storm adjustment factors be applied to better account for the uncertainty of the factors and to allow the storm to more accurately conform to other PMP-type local storms in the region. AWA recommends applying the following adjustments:

- Limit the Geographical Transposition Factor (GTF) to 1.20
- Limit the Moisture Transposition Factor (MTF) to 1.00

Limiting the GTF has precedent in several recent PMP studies, including Wyoming (Kappel et al., 2014), Virginia (Kappel et al., 2015), Tennessee Valley Authority (Kappel et al., 2015), and Texas (Kappel et al., 2016). This has been applied for the same reasons discussed regarding the Catskill storm, to correct for uncertainty in a controlling storm and to provide a more reasonable fit with other more accurately analyzed storms.

Similarly, adjustments to the MTF has precedent in several PMP studies, Colorado-New Mexico (2018) and Eel River (on going). Again, this application of the MTF has been utilized to produce more reasonable adjustments factors for storms that control PMP and contain a significant amount of uncertainty and result in depths that are anomalously high compared to more accurately analyzed storm events.

References

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Weather Bureau, 1940: Maximum Possible Precipitation Over The Ompompasoosuc Basin Above Union Village, Vermont, A Study of Meteorological Causes of Record Storms and Quantitative Estimates of Critical Precipitation Rates, Hydrometeorological Report 1, pp205.

Appendix 1-Catskill Storm Discussion

THE

AMERICAN

JOURNAL OF SCIENCE,

AND ARTS.

CONDUCTED BY

BENJAMIN SILLIMAN,

PROFESSOR OF CHEMISTRY, MINERALOGY, ETC. IN YALE COLLEGE; CORRESPONDING MEMBER OF THE SOCIETY OF ARTS, MANUFACTURES AND COMMERCE OF LONDON, MEMBER OF THE ROYAL MINERALOGICAL SOCIETY OF DRESDEN, AND OF VARIOUS LITERARY AND SCIENTIFIC SOCIETIES IN AMERICA.

VOL. IV.....1822.

NEW-HAVEN:

PRINTED AND PUBLISHED BY S. CONVERSE, FOR THE EDITOR.

Art. XII.—*An account of a remarkable storm which occurred at Catskill, July 26, 1819.*

[Read before the Catskill Lycæum.]

To Prof. Silliman,

Dear Sir—Agreeably to your request, I now transmit to you an account of the great storm, which occurred here on Monday afternoon the 26th July, 1819. At that time I was absent on a journey, in the state of Pennsylvania. Of course I am indebted to others for that class of facts which relate to the immediate phenomena of the storm. I reached home on the following Monday; and during that week spent much of the time in collecting facts relative to it; and have since from time to time, visited various places, where uncommon ravages were occasioned, and have spared no pains in obtaining all the information of an interesting nature which could be collected. Every fact communicated by others, or observed by myself, was immediately committed to writing. The manuscript has lain by me about fifteen months. I have more than once, visited several of the places, where peculiar ravages exist, and believe the account to be in no degree exaggerated.

I am respectfully, yours, &c.

BENJAMIN W. DWIGHT.

Catskill, February 5, 1821.

ACCOUNT OF A STORM, &c.

In several places in the mountainous country of New-England, it has been supposed by many of the inhabitants, that *clouds have in various instances burst*, or suddenly discharged great quantities of water. As the phenomena indicated by this phraseology have, in almost all instances, in which they have occurred, in that section of the country, existed in thinly settled regions, or in the night, in consequence of which the accounts given of them are imperfect; I suppose that it may be gratifying to some of your readers, to see a detailed account of the storm, which occurred here.

This storm exhibited phenomena analagous to those, which have occurred from what is called the bursting of a cloud, and in some respects more remarkable than any, of which I have heard.

To render the description more intelligible, a few explanatory observations may be useful.

The *township* of Catskill is situated on the West side of the Hudson, and is bounded on the East by that river; on the North by the township of Athens; on the West by Cairo; and on the South by Saugerties. The *town* is estimated to be about one hundred and twenty miles north from the city of New-York. Three rivers, or creeks, as they are here customarily called, have their courses in part, through this township; the Kistatom, the Kaaterskill, and the Catskill. The Kiskatom rises, if I am correctly informed, between the Catskill mountains and the Round Top,* a mountain in Cairo; and runs about five miles in the township of Catskill, and empties into the Kaaterskill. The Kaaterskill is a fine mill stream, which rises in the Catskill mountains, and empties into the Catskill, about two miles from the mouth of the latter stream.

The Catskill, which I shall usually denominate the *Creek*, rises in Middleburgh, in Scoharie County, and empties after a course of about forty miles, into the Hudson. The Catskill mountains lie westward from the town, and are distant from it in their nearest part, about seven or eight miles. *The town* is situated along the creek, and commences at

* The highest peak of the Catskill mountains is also called Round Top.

the point of land, formed by the junction of that stream and the Hudson. The principal buildings are situated along Main-Street, which commences about a quarter of a mile from the Hudson, and lies on the east side of the creek, to which it is in a good degree parallel, throughout its whole course. Several dwelling houses, stores, and other buildings, are situated on Water-Street, nearer to the creek; and several on the hill, east of Main-Street; and others elsewhere. There are a number of streets, and lanes, which intersect these streets at right angles, and pass to the creek. The hill rises abruptly to the height of about one hundred and fifty feet. Main-Street is estimated to be about thirty or forty feet above low water mark.

From the point of land formed by the junction of the Hudson and Catskill, a wharf has been extended, about one fourth of a mile, to a small island, in the Hudson, formed by the opposing currents of the two streams. To the south end of this island there have been considerable additions of *made land.* The whole of this ground is now called the *Point.* On it several dwelling houses, stores, and other buildings, have been erected.

At the north end of Main-Street the Catskill and Susquehannah turnpike commences, and runs in a W. N. W course about eighty-eight miles, to the Susquehannah river. From two to two and a half miles from the Point, is situated along this road, the small village of Jefferson. About two miles further, on the same road, is the village of Madison; and two miles beyond Woolcott's mills.

The village of Jefferson is built on an elevated plain, lying on the north side of the creek, and is about three fourths of a mile in length, and nearly half a mile in breadth. The land rises abruptly from the interval, which borders the creek, to the height of about one hundred and fifty feet. The margin of this plain, or hill, which faces the Southeast, was probably in antient times, the border of a lake, which at some remote period burst its barriers, and emptied its waters into the Hudson. At Madison there was a large lake, the banks of which are distinctly visible, at a considerable distance, and strikingly so from the south end of Schuneman's mountain. The dam existed at the mill seat of the late Ira Day, Esq.

The state of the weather previously to the commencement of the storm was as follows :—

The sky was cloudy, *the air thick*, (to adopt common language) and very sultry ; the clouds were low and heavy, the wind blew from the S. W. Debility and languor were generally complained of. No thermometrical, or barometrical observations were made, within my knowledge.

About half past 3 o'clock P. M. three distinct clouds, dense and black, arose in the southeast, in quick succession. A brisk shower followed. A fresh wind blew for a little period ; but before 4 o'clock a calm ensued, which lasted nearly an hour. A short suspension of the rain took place soon after 5 o'clock. The whole quantity which had descended between this time, and the commencement of the storm, was considerable. About half past five, another dense and black cloud accompanied by a fresh wind, arose from the S. W. Shortly before the cloud reached the zenith, three vivid streaks of lightning issued from it, appearing like branches of the same flash. These were followed by three very sharp peals of thunder, instantaneously succeeding each other.

About the same time, or immediately after, a very thick and dark cloud rose *up* rapidly from the N. E. They met immediately over the town. At this instant a powerful rain commenced. The air soon after became so obscure, that trees, and buildings, and other large objects, could not be discerned at the distance of a few yards. The obscurity did not appear to arise from a fog, of the usual kind ; but from the abundance of the rain, and the low descent of the clouds, which appeared to rest upon the ground, or to hang a little above it. After the clouds met, the wind became very variable, and blew for short periods from almost every point of the compass. At times it came with so much force as to drive the rain in a very unusual manner, through the crevices in doors and windows, and the roofs of dwelling houses. Many houses which had never before been known to leak, at this time admitted great quantities of water. In several instances the wind suddenly abated, and a calm of a few minutes ensued. The lightning and thunder were unusually severe. The thunder frequently resembled a violent crash, and was as sudden, and of as short continuance, as the sound occasioned by the firing of a cannon, or by the snapping of a whip. The rain decended at times in very large drops; and at times in streams, and sheets.

During the storm four or five intermissions each of about eight or ten minutes occurred, also in the rain. In each instance it excited a hope that the storm was approaching its termination; but this hope was soon dissipated, by the appearance of fresh torrents. The extreme violence of the rain terminated before half past six o'clock, though it continued to descend with considerable briskness until about nine; and moderately until about ten; and it did not entirely cease until about eleven. The quantity which fell from the commencement to the termination of the storm, it is difficult to ascertain with exactness. It seems probable from the facts herein after mentioned, that it exceeded fifteen inches on a level. Some remarkable phenomena occurred in various places.

At the Point, just before the clouds met, two sloops were observed sailing before the wind, under a full press of sail, one sailing rapidly up stream, the other more rapidly down. They met near the north end of the island, when the N. E. wind prevailed. About the same time the sloop Admiral started from the lower wharf for New-York. At the moment of starting two persons on board, received slight electrical shocks, from one of the three streaks of lightning before mentioned. Several panes of glass were also broken in a store, situated a few feet distant. One of these persons, immediately after the shock noticed strong luminous flashes, or sparks, on one of his arms, and felt a jar throughout his frame, and a sensation similar to that which is experienced, when the hand or foot is asleep; the other felt a jar similar to that occasioned by a smart blow, upon the breast. No other injury was done to the store, nor any whatever to the vessel. When the sloop had proceeded on her course about three fourths of a mile, the air had become so obsure, that those on board were unable at the distance of a few yards, to discern any objects. At this time, another flash of lightning was discharged about the vessel, and one of the persons before mentioned, received a much more powerful shock, which occasioned his falling down instantaneously upon the deck. He was at this time drenched in water, and from this cause probably, soon revived, so far as to get up, and find his way into the cabin. In a little time he felt no other inconvenience from the shock, than a sensation of numbness, which affected his arms for an indefinite period. While he lay upon the deck, a young gentleman standing near him, observed numerous flashes, or sparks, of light, about his body, strongly resembling those issuing from a firebrand, when whirled swiftly round. They were accompanied by a crackling, or snapping noise. Another person on board, experienced a lighter shock, which occasioned so much numbnes in one of his arms, that for a few minutes, he was unable to use it. There was an iron spindle at the top of the mast, for suspending the colours; but no lightning rod. No injury however was done to the vessel. Was that part of the cloud, from which the lightning issued, lower than the top of the mast? Several of those who where on the deck observed that, at this time the rain descended in streams, and sheets. The young gentleman above mentioned states that, at one period the water on the quarter deck accumulated so rapidly from the rain only, as to be higher than the tops of his shoes.

A gentleman, who was in the south store, at the Point, feeling much anxiety for his friends on board the sloop, observed the phenomena of the storm, with more exactness, than any other person, with whom I have conversed. His account is as follows. When the two clouds met, they appeared to fall down upon the river, between the store and Livingston's wharf, upon the east bank. The cloud rested upon the water in such a manner, that he could discover no space between them. As it came over it appeared extremely dark at the bottom, and as white as a snow bank at the top. The air suddenly became so obscure, that he was unable to see any part of a large perriauger, which lay at his wharf thirty feet distant, except that he could barely discern the poles. He particularly noticed that, he could not see any appearance of drops of rain; but the water appeared to descend in large streams, and sheets. The descent of rain was most copious between a quarter before 6 o'clock, and a quarter after 6. In this half hour he estimates the descent of water to have exceeded twelve inches upon a level. At an inn, thirty rods northward, the family were unable to see a large sloop, lying in the creek, at the distance of twenty rods. At another inn, in the near neighbourhood, a man, who stood for a considerable period at the front door, was unable to see any part of a large barn, only four rods distant. Some time after the clouds met, two different persons residing in this house, distinctly observed a water spout, rising up from the river, and nearly opposite, with a broad bottom, and ascending with a whirling motion to the clouds, in form of a pretty regular cone. The innkeeper some time in the afternoon, noticed two other water spouts, from three fourths of a mile to a mile up stream. These rose up in like manner, with broad bottoms, and terminated in points, as they reached the clouds. At what period these phenomena occurred, they could not distinctly recollect. The whole quantity of water which fell at the Point, is estimated to have exceeded fifteen inches upon a level. I am persuaded that this estimate is not too large.

The rain extended with equal, or greater, violence about eight miles west, from the Point, about three miles north, and about seven miles south. On the east side of the Hudson, at a little distance, it did not descend with peculiar violence, or in a very unusual quantity. At Athens, four miles north, it was far less severe, than in Catskill; and at Cairo, ten miles west, it was light. Should we then estimate the whole tract, on which the rain descended with peculiar violence, and in quantities never before known, in this section of the country, since its first settlement at eighty square miles, we probably should not be very wide from the truth; and on this whole tract, I am persuaded that, the water fell full fifteen inches upon a level. On a considerable part of the tract, there is reason to believe that, the quantity exceeded eighteen inches.

In proof of the correctness of this estimate, I alledge the following facts.

Main-street was flooded to such a degree that, notwithstanding the descent to the creek is rapid, a sloop's boat might have sailed, in many parts of it, without difficulty, and for a considerable time.

A large tub, measuring twenty-six inches across at the top, in the inside, and very nearly as large at the bottom, and fifteen and a half inches deep, was standing in an open yard, about thirty rods west of the south end of Main-street, and north of the dwelling house of Mr. J. D. It was empty when the rain commenced, and before sunset it was filled, and had run over. Several persons, who had examined it from time to time, were of opinion, that no water could have fallen into it, except that which descended directly from the clouds. In front of the house, on the south side, is a large court yard. From the gate to the front door is a gravelled walk, several rods in length. This walk is raised higher than the adjoining grounds on each side. The owner returning home a little before sunset, found the water on this walk, from six inches to a foot deep. The water at this height must have been constantly and rapidly passing off into the creek. It is not known that water has been accumulated here from any other rain, to the depth of half an inch.

About forty or fifty rods N. W. from this place, a small wash-tub, standing in open ground, being twelve inches in depth, and having two inches of water in it when the rain commenced, was observed about sunset to be full and running over. How long it had been filled is not known.

Two empty potash kettles, each of the capacity of ninety gallons, standing on the west sides of a high and spacious building, about the middle of Main-street, the one about twelve, the other about sixteen feet from the building, so situated that they probably caught no water, except that which descended perpendicularly from the clouds, were nearly or quite filled. Much of the rain descended in a very slanting direction.

A common sized pail, in a yard fifty rods north, and a wash-tub, in another yard, were both filled, and ran over, before sunset.

A large bathing-tub, situated on the west side of a high building, and so posited that it could not probably have caught more than two thirds as much as it would have done in open ground, had thirteen inches of water in it.

At Mr. John Ashley's farm, five miles west from the court house, a common sized wash-tub, standing in open ground, was filled, and ran over, before sunset.

I have been credibly informed that, at Madison, in a field, lying north of the turnpike, a large tub, estimated to be sixteen inches in depth, and an iron kettle, of the capacity of twelve to fifteen gallons, both empty when the rain commenced, and both standing many yards distant from any building, were filled, and ran over.

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March 4, 2019

Memo for Record

To: Pennsylvania Statewide PMP Project Review Board

Subject: Pennsylvania PMP over the Conowingo Basin Discussion

Introduction

This memo addresses the Review Board request to summarize the AWA investigations regarding the difference between the updated statewide PMP depths and the site-specific PMP over the Conowingo Dam basin and specifically comparison against the controlling storm, Agnes June 1972 (SPAS 1276_2). There was concern that the storm adjustment process and specifically the Geographic Transposition Factor (GTF) was reducing the storm more than the observed storm amounts over the Conowingo Basin. This was noted first because the recent site-specific PMP completed by AWA for the Conowingo Basin in 2015 produced PMP depths which were approximately 20% greater than the statewide PMP results. In addition, the Agnes June 1972 (SPAS 1276_2) storm was the main controlling storm in both studies. AWA was therefore asked to compare the SPAS analyzed rainfall over the basin with PMP to ensure the storm was appropriately enveloped

Background

Below is a summary of the Conowingo Dam investigation findings:

The Pennsylvania PMP depths range from 27% to over 100% greater than the Agnes June 1972 (SPAS 1276_2) SPAS depths over the Conowingo Basin. Therefore, there are no locations where the Pennsylvania PMP depths do not far exceed the Agnes June 1972 (SPAS 1276_2) rainfall accumulation depths. This is shown in Figure 1. Figures 2 and 3 provide the Agnes June 1972 (SPAS 1276_2) rainfall depths over the basin and the Pennsylvania PMP depths over the basin for reference.

The site-specific PMP utilized the standard HMR 52 approach of centering the storm over the basin and assuming an elliptical spatial pattern with PMP depths decreasing from the center of the storm. This is very different than the observed storm pattern over the basin (Figure 2) and very different than the precipitation frequency patterns over the basin as represented by the GTF variation (Figure 4). The average GTF values over the 27,000-sqmi basin is 0.82. Of course, at the storm center location, the GTF value is 1.00. The value generally decreases inland and increases towards the east and south. This is a direct reflection of the spatial variations in the precipitation frequency accumulation patterns. This also fits very well with the observed spatial pattern of the storm itself. Therefore, this confirms the process is behaving exactly as expected.

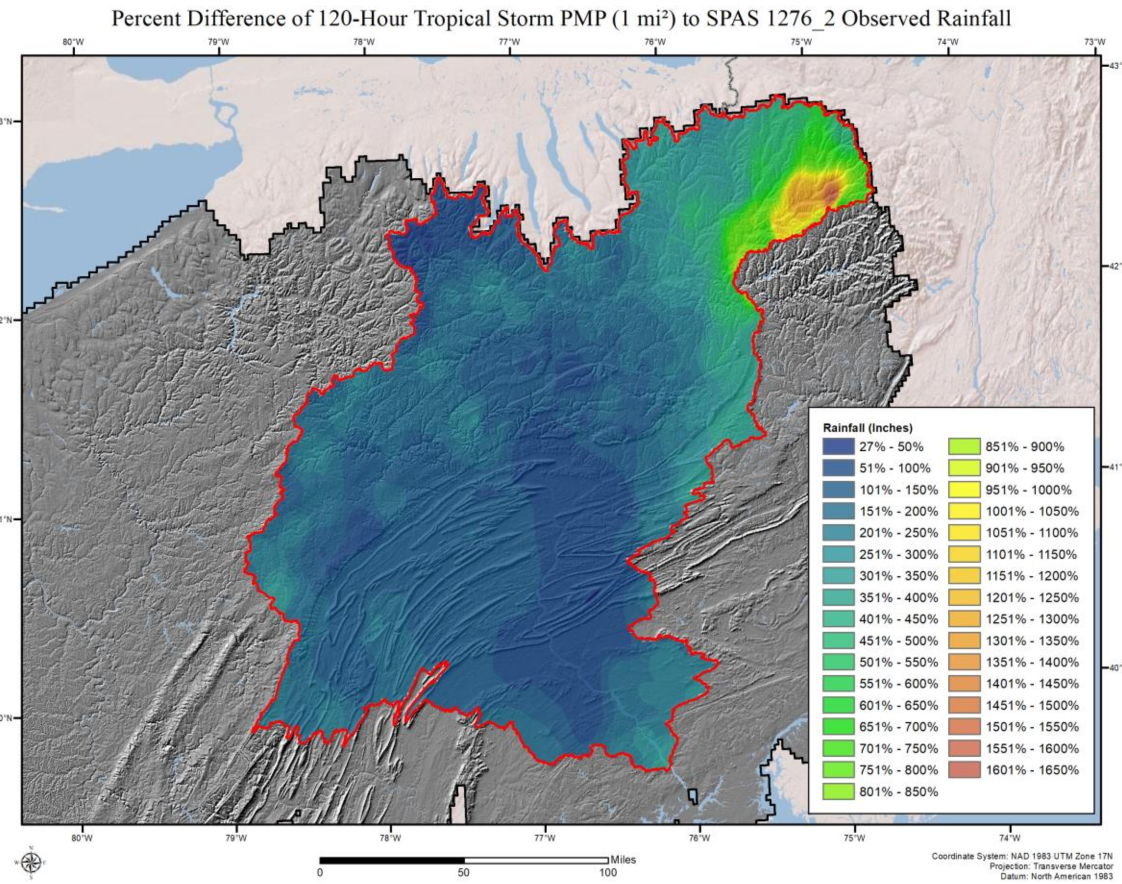

Figure 1: Percent difference between Pennsylvania PMP and Agnes rainfall over the Conowingo Basin

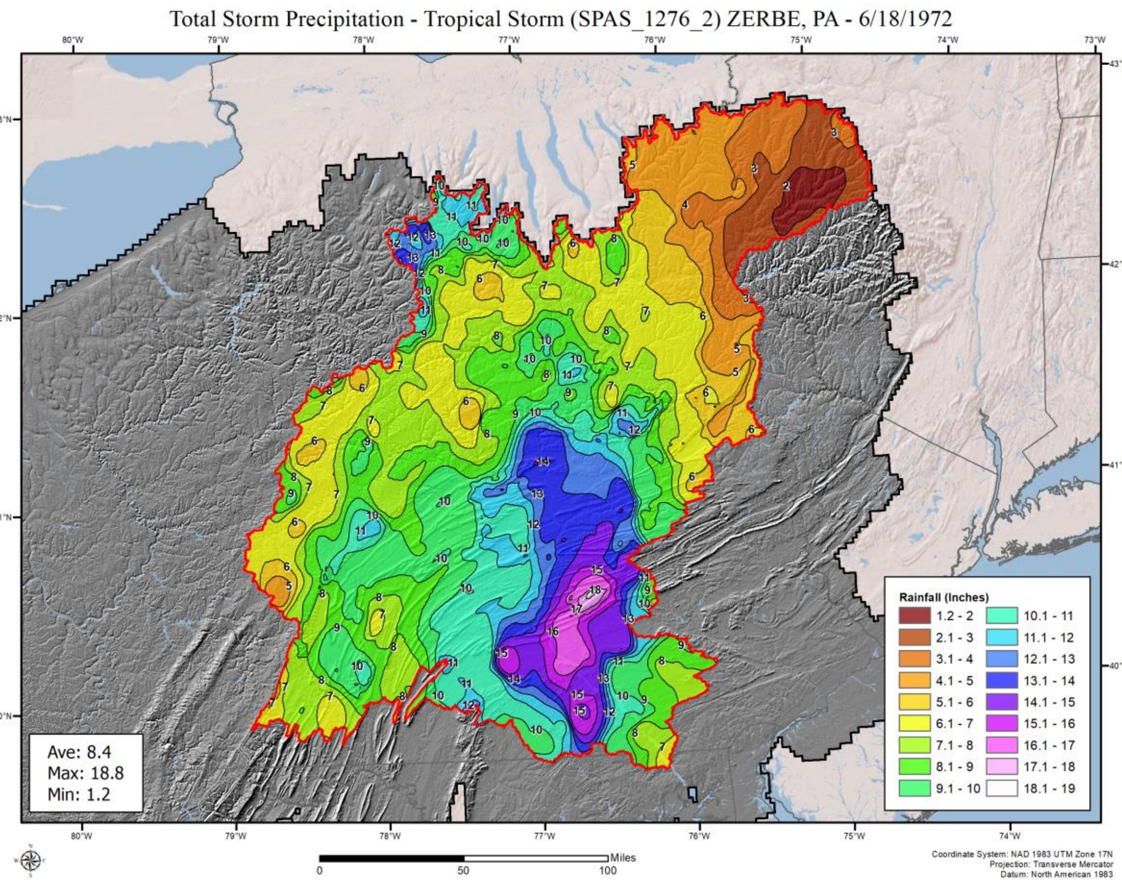

Figure 2: Agnes total storm rainfall over the Conowingo Basin

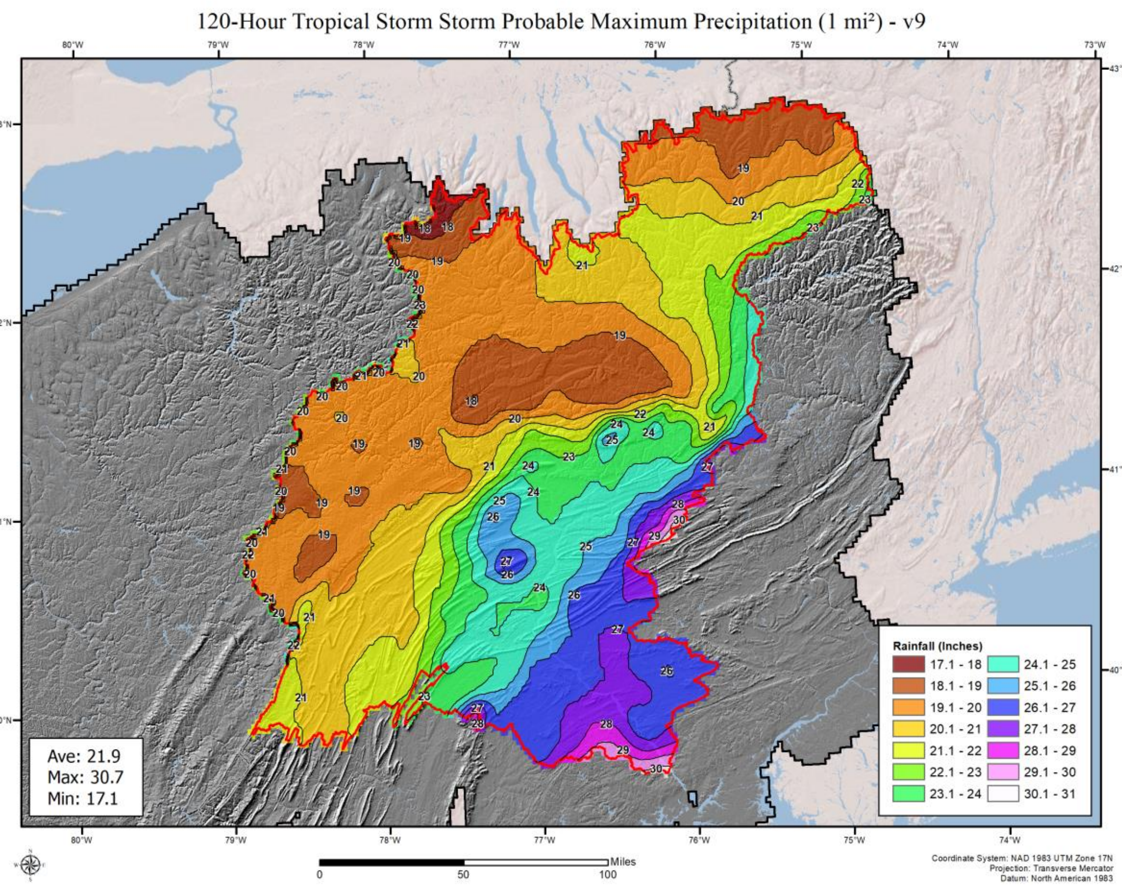

Figure 3: Pennsylvania PMP depths over the Conowingo Basin

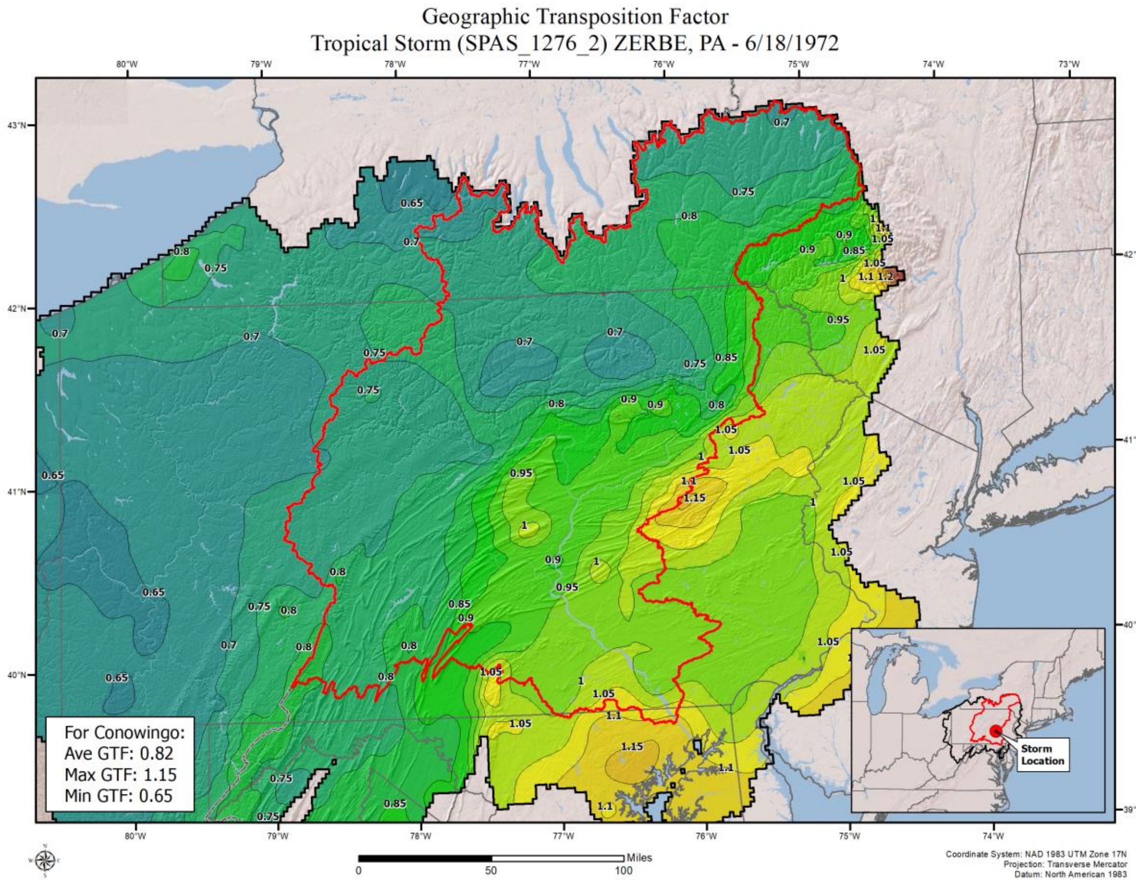

Figure 4: Geographic Transposition Factor over the Conowingo Basin for the Agnes June 1972 storm

Summary/Recommendation

No errors or issues were found in this investigation and the Pennsylvania PMP process is producing PMP depths that are reasonable and as expected. The Pennsylvania PMP depths are all significantly greater than the Agnes June 1972 (SPAS 1276_2) rainfall accumulation over the Conowingo Basin. This demonstrated that the HMR 51/52 process of assuming a storm center over the centroid of a basin where there is a large amount of spatial variability because of basin area size and/or topography results in a potentially overly conservative PMP depths. This is because the HMR 51/52 process does not account for the meteorological and topographic interactions and spatial patterns that actually occur. Of course, this is one of the reasons the authors of HMR 51 delineated the “stippled” regions.

Appendix L
Project Review Board Letter

April 5, 2019

Mr. Roger Adams, PE
Division of Dam Safety
Pennsylvania Department of Environmental Protection
400 Market Street
Harrisburg, PA 17101

Subject: Board of Consultants Final Report on PA PMP Study Report

Dear Mr. Adams:

Attached is the Board of Consultant's (BOC) Final Report on the PA PMP Study Report. The BOC appreciates this opportunity to be involved in this important study supporting the Pennsylvania Department of Environmental Protection (DEP) Bureau of Waterways Engineering and Wetlands (BWEW).

Background

In 2017, the Pennsylvania DEP BWEW engaged the services of Applied Weather Associates, LLC (AWA) and subconsultant Aterra Solutions to perform a probable maximum precipitation (PMP) study for the purpose of updating PMP values for the entire state of Pennsylvania. AWA was tasked with the following:

- Perform a hydrometeorological analysis of significant storms that influence PMP values in Pennsylvania. In addition to major storms included in the HMR 51 analysis, consider all additional major storm events which have occurred in subsequent years. Updated tools and methodologies should be applied for estimating extreme precipitation depth, area, and duration relationships for the entire area of the Commonwealth of Pennsylvania.

- Reevaluate the 1942 Smethport Storm and associated rainfall reports. Because of the storm's significant influence on PMP depths in Pennsylvania, a thorough reevaluation of this event (depths, areas, and durations) using current methods and all available historic data is necessary.

- Provide a final report to include PMP maps for the specified areas and durations in GIS format. Also, a GIS-based program will be provided to allow the user to extract the exact PMP values for any location in Pennsylvania.

- Coordinate an independent review of the study by a Board of Consultants (BOC) having expertise in hydrology, dams, and meteorology.

The BWEW, through AWA, engaged the services of four committee members to perform the independent review: Barry Keim, Ph.D., Louisiana State Climatologist/Professor at LSU; Arthur Miller, Ph.D, PE, D.WRE, of AECOM, and Professor Emeritus, Pennsylvania State University; and Kyle Imhoff, Ph.D., Pennsylvania State Climatologist/Professor, Penn State University; and John Harrison, P.E., D.WRE, Principal, Schnabel Engineering. In addition, representatives of the Federal Energy Regulatory Commission, United States Army Corps of Engineers, Natural Resources Conservation Service, Pennsylvania Department of Conservation and Natural Resources, Pennsylvania Fish and Boat Commission, Pennsylvania American Water Company, and Gannett Fleming, to varying degrees, attended meetings and provided input on the study results.

Five formal meetings and several conference calls were held to hear progress updates by AWA and Aterra, and to participate in discussions regarding process and methodology for the study. Four meetings were held in Harrisburg, and one meeting (June 2018) was held in Lancaster following the ASDSO Regional Conference. Formal Meetings were held on the following dates:

- August 8-9, 2017
- January 17-18, 2018
- June 6-7, 2018
- October 25-26, 2018
- February 27-28, 2019

Conclusions Regarding Study Analyses

The BOC was charged with reviewing and assessing each phase of AWA's statewide PMP study and for providing oversight, as necessary, to confirm the study methodology was consistent with accepted PMP theories and procedures. Among other things, the BOC assessed the hydrology and meteorology of the project and reviewed each phase of the analysis.

The current study provides warm season PMP values, which are valid from May through October. PMP estimates are provided for Local (intense, short duration), Tropical, and General Storm distributions. Results appear to reflect the most current practices used for defining PMP, including comprehensive storm analysis procedures, Storm Precipitation Analysis System (SPAS), use of geographical information systems (GIS), quantification of orographic effects, updated maximum dew point climatologies for storm maximization and transposition, and an updated understanding of the weather and climate throughout the state. The BOC understands that the study used the same general procedures as the National Weather Service's HMR reports and World Meteorological Organization's PMP Manual for in-place maximizations and overall approach. The BOC understands that the PMP development procedures also utilize newer techniques and datasets, such as incorporation of updated precipitation frequency analysis data available from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14, to calculate the Geographic Transposition Factors (GTFs) for each storm. The BOC further understands that the application of these procedures has been accepted in other AWA studies throughout the United States. Although this study produced deterministic values, the BOC realizes that there is some subjectivity associated with the PMP development procedures, such as selection of storms used for PMP, determination of storm adjustment factors, and storm transposition limits. The BOC provided guidance on appropriate storm transposition limits, considering both the meteorological and geographic limitations associated with each respective storm. The BOC believes the PMP estimates of this study provide much improved and geographically specific results over those presently being utilized from HMR 51.

Use of the moisture transposition factor (MTF) has been controversial in past PMP studies due to potential double counting of moisture in conjunction with the geographic transposition factor (GTF). The current study set the MTF = 1.0, which nullifies its use in this study. The BOC concurs with this decision.

The 1942 Smethport Storm was analyzed in detail by Aterra using a variety of models. The entire study domain was analyzed using USACE's HEC-HMS Version 4.2 software, using the runoff curve number (RCN) approach for loss/retention estimation and the Snyder Unit Hydrograph for runoff transformation. Upstream of Port Allegany in the basin having the most intense rainfall, RiverFlow2D, a fully distributed 2D modeling approach, was utilized. Downstream of Port Allegany, HEC-RAS2D was utilized along the main-stem Allegheny River. The data available for the 1942 Smethport Storm presented numerous challenges, including:

- Lack of recording rainfall gages in the region of most intense precipitation.
- Lack of data with high temporal resolution (hourly and/or sub-hourly data).
- Highly variable temporal distributions throughout the study region (shorter duration, high intensity precipitation in the Port Allegany region based on reported accounts; longer duration, 2-peaked rainfall distributions recorded by the surrounding recording gages).
- Highly variable bucket surveys.
- Varying rainfall distributions assigned by evaluating agencies.
- Changing land uses between the 1942 storm and the calibration storms.
- Post-1942 levee construction.
- Discrepancies between NRCS soil classifications across the New York – Pennsylvania border.
- Difference of USGS and USACE flows at Eldred for 1972 calibration storm.
- Challenges in inferring results from relatively low intensity calibration storms to high intensity runoff Smethport Storm.

We understand that model calibration involved adjustments to lag times, runoff curve numbers, Manning's n values, and baseflow recession constants. Once a reasonable agreement was attained for the calibration storms, the calibrated model was used to assess the 1942 storm depths and temporal and spatial distributions. Aterra and AWA worked together making iterative adjustments to the hydrologic model and SPAS-generated rainfall distributions until reasonable agreement was attained with downstream discharge hydrographs and recorded peak stages and timing along the Allegheny River. The BOC believes the hydrologic study provides a reasonable representation of the temporal and spatial rainfall distribution of the 1942 Smethport Storm given the challenges presented by the available data.

The BOC accepts AWA's estimates for probable maximum precipitation (PMP) for the Commonwealth of Pennsylvania, informed in part by Aterra's hydrologic evaluation of the 1942 Smethport Storm. The BOC used our best professional judgment in evaluating the work of AWA and Aterra. We note that the final PMP estimates are based on the historical record of the past century and more, with the underlying assumption that this record across the eastern United States region yields insight into the PMP across the Commonwealth of Pennsylvania.

The study also involved evaluations and discussions of appropriate temporal distributions for the PMP, particularly the Local PMP distribution. The team agreed that the temporal distribution issue would not be resolved within the PMP Report and would be addressed in a supplementary meeting devoted to this issue.

The BOC performed the duties described above, but it should be noted that the BOC acted in an advisory capacity only. Specifically, no calculations were performed by the BOC, nor were detailed reviews of calculations performed by the BOC. It has been the BOC's expectation that AWA and Aterra utilized adequate quality assurance and control procedures to provide assurance that the calculations were performed accurately and without error. As such, the BOC does not make any warranty, express or implied, regarding use of any information or method shown in the Probable Maximum Precipitation Study for the Commonwealth of Pennsylvania report, or assume any future liability regarding use of any information or method contained therein. These results are applicable to Pennsylvania only and should not be used in other states.

Respectfully submitted,

John Harrison

Barry Keim

Kyle Imhoff

Art Miller