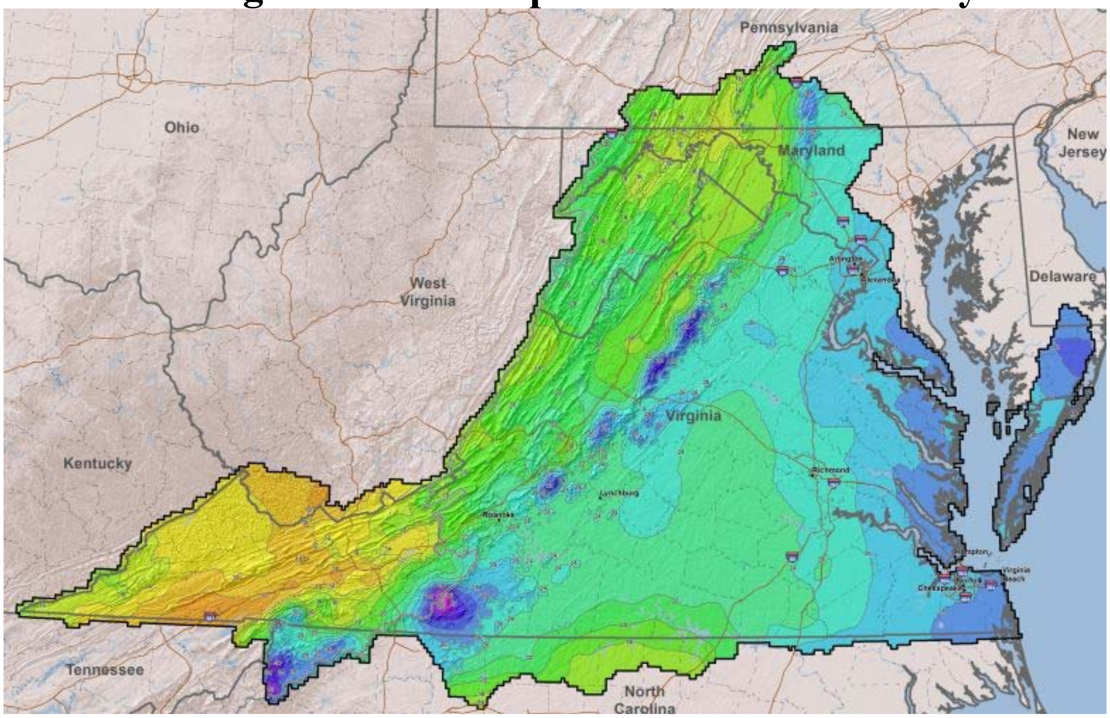
2018 Virginia PMP Temporal Distribution Analysis



Prepared for

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Table of Contents

List of Figures

List of Tables

1.0 Introduction

The information provided is a companion to the Virginia Probable Maximum Precipitation (PMP) study completed by Applied Weather Associates (AWA) in December 2015 (Kappel et al., 2015). This study addresses the discussion from Section 8.8 of that report. In terms of temporal patterns for dam and spillway designs, Virginia previously deferred to the Natural Resource Conservation Service (NRCS) and its guidelines. The NRCS design manual, TR-60, Earth Dams and Reservoirs, provides a Dimensionless Design Storm temporal distribution curve (Figure 2-4, page 2-12) that has been used in Virginia in the past (NRCS, 2005). In addition to the TR-60 Dimensionless Design Storm temporal distribution curve, Virginia has also allowed the use of the NRCS 5-point 24-hour dimensionless rainfall distribution for 24-hour events only (NRCS, Version 2.2 2010).

This study provides background regarding the information analyzed, the methods used to quantify and evaluate each storm's temporal accumulation pattern, the recommended temporal patterns that resulted from this evaluation, and how to apply the data.

AWA analyzed all storms utilized in the Virginia PMP study to develop temporal accumulation patterns associated with each storm type and general region. Rainfall accumulation of each storm and the time over which the main rainfall accumulated were completed during these investigations. Storms were grouped by geographic location (east versus west of the Appalachian Crest) and by storm type: local, general, and tropical. Figure 1 provide an image of the study region with the Appalachian crest, which divides the drainage between the Atlantic Ocean and Gulf of Mexico. This boundary separates the geographic grouping used in this analysis. During these analyses, consideration was given to the synoptic meteorological patterns that created each storm type, access to moisture sources, and the general topographical setting. Discussions with the Virginia Department of Conservation and Recreation dam safety personnel aided significantly in the development of the recommended temporal patterns.

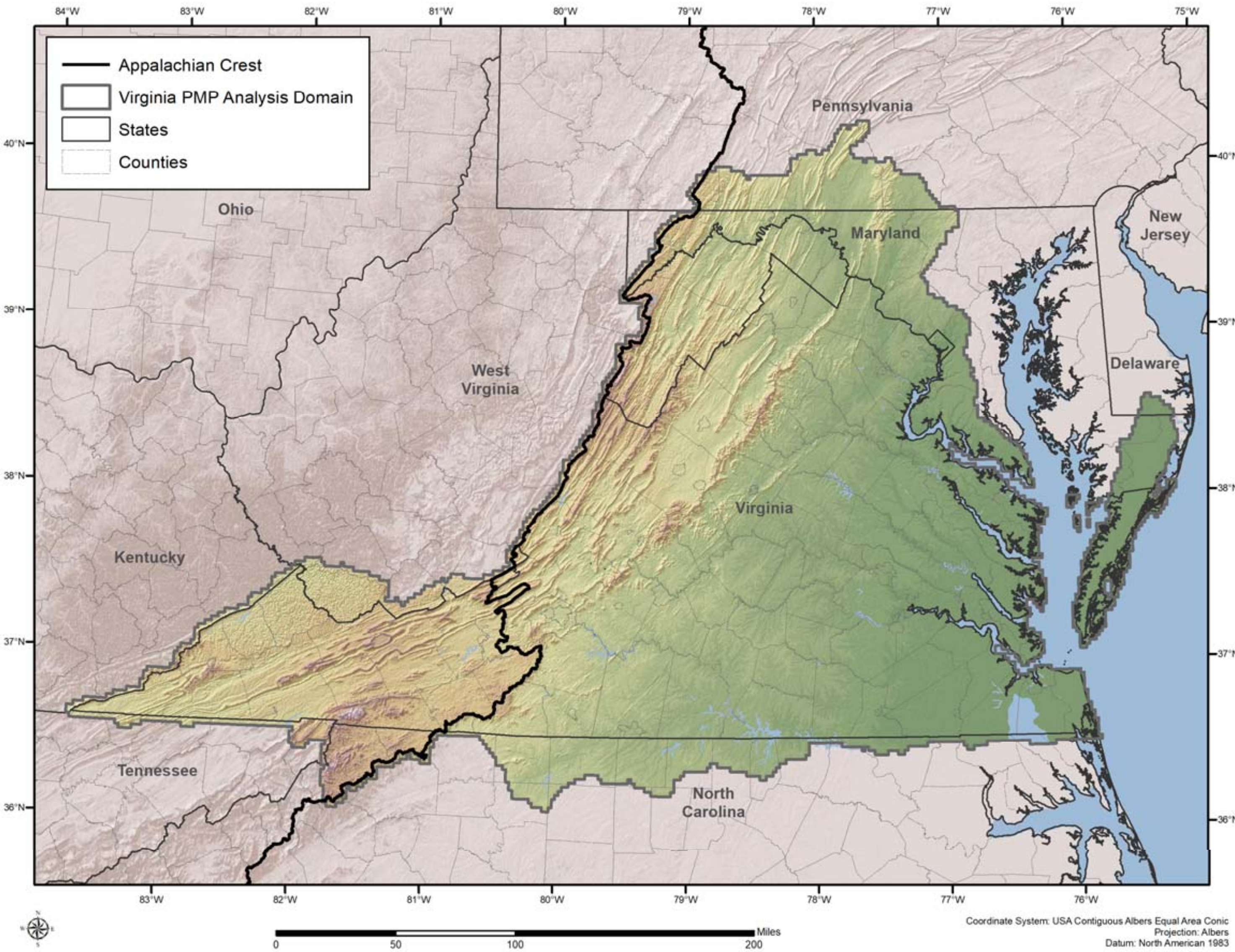

Figure 1. Virginia PMP analysis domain with Appalachian crest drainage divide shown

2.0 Development of the Temporal Patterns

2.1 Standardized Timing Distributions by Storm Type

All storms used to determine the PMP values for Virginia were used to derive the preceding temporal accumulation patterns. Each storm was analyzed using the SPAS program, which provides hourly gridded rainfall data as part of the standard output. This allowed explicit evaluations of the rainfall accumulation to be analyzed in detail. The storms analyzed are provided in Table 1. The location of the storm center associated with each SPAS Depth-Area-Duration zone was used for the temporal distribution calculations.

In terms of storm types, local storms are characterized by short duration (6-hours or less) and small area size high intensity rainfall accumulations. They can be associated with large-scale weather patterns and/or influenced by local moisture sources. General storms produce precipitation over longer durations (greater than 6-hours) and cover larger areas with comparatively lower intensity rainfall accumulations. General storms are produced by large-scale synoptic patterns generally associated with areas of low pressure and fronts. Tropical storms produce precipitation over longer durations (greater than 6-hours) and cover larger areas similar to general storms. However, tropical storms often include embedded convection that can produce intense rainfall accumulations. Tropical storms are associated with direct landfalling tropical systems and/or remnant tropical moisture originating most often from the Atlantic Ocean and occasionally the Gulf of Mexico.

The Significant Precipitation Period (SPP) for each storm was selected by excluding relatively small rainfall accumulations at the beginning and end of the rainfall duration for each storm. Accumulated rainfall (R) amounts during the SPP were used in the analysis for the hourly storm rainfall. The total rainfall during the SPP was used to normalize the hourly rainfall amounts. The time scale (T_S) was computed to describe the time duration when half of the rainfall accumulated (R). The procedures used to calculate these parameters are listed below.

2.1.1 Parameters used in the temporal analysis process

SPP - Significant Precipitation Period when the majority of the rainfall occurred
R - Accumulated rainfall at the storm center during the SPP
R_n - Normalized R
T - Time when R occurred
T_{50} - Time when $R_n = 0.5$
T_s - Shifted time around when 50% of the rainfall occurred
max24hr - Maximum 24-hour point rainfall at storm center location
max12hr - Maximum 12-hour point rainfall at storm center location
max6hr - Maximum 6-hour point rainfall at storm center location

Table 1. SPAS storm events used in Virginia temporal distribution development

Storm Name	State	Lat	Lon	Year	Month	Day	Total Rainfall in Inches	Precipitation Source	East or West App Crest	TYPE
WELLSBORO	PA	41.7042	-77.2292	1889	5	30	10.11	SPAS 1339	E	G
JEWELL	MD	38.7300	-76.5700	1897	7	26	15.88	SPAS 1489	E	L
VADE MECUM	NC	36.3100	-80.2800	1908	8	23	18.00	SPAS 1514	E	G
ST GEORGE	GA	30.521	-82.020	1911	8	28	19.10	SPAS 1515	E	T
COOPER	MI	42.371	-85.588	1914	8	31	13.39	SPAS 1426	W	L
ALTA PASS	NC	35.8792	-81.8708	1916	7	13	24.90	SPAS 1299 Zone 1	E	T
KINGSTREE	NC	33.6625	-79.8292	1916	7	13	16.79	SPAS 1299 Zone 2	E	T
JOHNSON CITY	TN	36.3042	-82.0625	1924	6	13	16.14	SPAS 1343	W	L
BOYDEN	IA	43.196	-95.996	1926	9	17	24.22	SPAS 1427	W	L
MONCURE	NC	35.600	-79.070	1929	9	29	11.55	SPAS 1517 zone 2	E	T
SETTLE	NC	35.9500	-80.7000	1929	9	29	9.97	SPAS 1517 zone 3	E	T
ELBA	AL	31.363	-86.121	1929	3	12	29.73	SPAS 1305	W	G
GLENVILLE	GA	34.8600	-84.2900	1929	9	23	21.20	SPAS 1516	W	T
GLENVILLE	GA	34.8833	-84.2833	1929	9	23	20.88	SPAS 1516 Zone 2	W	T
FAIRFIELD	TX	31.680	-96.130	1932	9	2	19.58	SPAS 1428	W	G
EASTON	MD	38.8600	-76.0700	1935	9	4	17.00	SPAS 1490	E	T
PINKHAM NOTCH	NH	44.246	-71.221	1936	3	9	9.70	SPAS 1194	E	G
PINKHAM NOTCH	NH	44.246	-71.221	1936	3	16	12.37	SPAS 1195 Zone 1	E	G
PADDY MOUNTAIN	WV	39.0200	-78.5600	1936	3	16	8.32	SPAS 1195 Zone 2	E	G
MCKENZIE	TN	36.4400	-87.9100	1937	1	17	19.86	SPAS 1311	W	G
SIMPSON	KY	38.104	-83.296	1939	7	4	20.82	SPAS 1344	W	L
EWAN	NJ	39.688	-75.181	1940	9	1	24.30	SPAS 1534	E	L
BLUE RIDGE DIVIDE	NC	35.0375	-83.0792	1940	8	28	14.09	SPAS 1346	W	G
HEMPSTEAD	TX	30.130	-96.054	1940	11	22	21.29	SPAS 1430	W	G
HALLETT	OK	36.246	-96.613	1940	9	2	24.00	SPAS 1429 Zone 2	W	L
MT MITCHELL	NC	36.3000	-81.4500	1940	8	10	20.27	SPAS 1342	W	T
BIG MEADOWS	VA	38.5458	-78.4042	1942	10	12	19.77	SPAS 1340	E	G
BIG MEADOWS	VA	38.5458	-78.4042	1942	10	12	19.77	SPAS 1340	E	L
SMETHPORT	PA	41.8722	-78.2771	1942	7	17	34.91	SPAS 1345	W	L
WARNER	OK	35.479	-95.329	1943	5	6	25.24	SPAS 1431	W	G
MOUNDS	OK	35.846	-96.071	1943	5	15	19.27	SPAS 1432	W	L
GLENVILLE	WV	38.8950	-80.7708	1943	8	4	15.04	SPAS 1536	W	L
COLLINSVILLE	IL	38.671	-90.004	1946	8	12	19.07	SPAS 1433	W	G
HOLT	MO	39.454	-94.329	1947	6	18	17.62	SPAS 1434	W	L
LITTLE RIVER	VA	38.8625	-79.1875	1949	6	17	15.13	SPAS 1546	E	L
HARRISONBURG DAM	LA	31.788	-91.813	1953	5	11	25.34	SPAS 1435	W	G
SLIDE MOUNTAIN	NY	42.017	-74.417	1955	8	11	14.70	SPAS 1003	E	T
WEST SHOKAN	NY	41.950	-74.320	1955	10	14	18.50	SPAS 1006	E	T
WESTFIELD	MA	42.120	-72.700	1955	8	17	20.09	SPAS 1243	E	T

Table 1. SPAS storm events used in Virginia temporal distribution development (continued)

Storm Name	State	Lat	Lon	Year	Month	Day	Total Rainfall in Inches	Precipitation Source	East or West App Crest	TYPE
ROSMAN	NC	37.7375	-81.5958	1964	9	26	9.22	SPAS 1312A ZONE 1	W	G
ROSMAN	NC	35.1458	-82.8042	1964	9	26	17.86	SPAS 1312A Zone 2	W	G
ROSMAN	NC	35.1375	-82.8375	1964	10	3	17.53	SPAS 1312B Zone 2	W	T
EDGERTON	MO	40.413	-95.513	1965	7	18	20.76	SPAS 1183	W	G
ROSEDALE	TN	36.1792	-84.2292	1965	7	24	13.32	SPAS 1402 Zone 2	W	L
BURTON DAM	GA	34.796	-83.696	1967	8	21	18.42	SPAS 1380	W	G
TYRO	VA	37.8125	-79.0042	1969	8	19	27.23	SPAS 1491	E	T
ZERBE	PA	40.5375	-76.6208	1972	6	18	18.79	SPAS 1276	E	T
BURNSVILLE	TN	34.8375	-88.3958	1973	3	14	12.15	SPAS 1357	W	G
COEBURN	VA	37.2792	-81.8042	1977	4	2	15.66	SPAS 1362	W	L
JOHNSTOWN	PA	40.3958	-78.9542	1977	7	18	12.64	SPAS 1550	W	L
DANDRIDGE	TN	37.2625	-84.9708	1984	5	7	9.62	SPAS 1376	W	L
MONTEBELLO	VA	37.813	-79.163	1985	11	1	22.56	SPAS 1533	E	G
AMERICUS	GA	32.096	-84.229	1994	7	4	28.09	SPAS 1317	W	T
RAPIDAN	VA	38.4150	-78.3350	1995	6	27	28.39	SPAS 1406	E	L
ANTREVILLE	SC	34.855	-82.225	1995	8	26	19.99	SPAS 1373	E	T
REDBANK	PA	41.2600	-79.1600	1996	7	19	9.42	SPAS 1548	W	L
PINKHAM NOTCH	NH	44.260	-71.340	1999	9	15	10.55	SPAS 1198 Zone 1	E	T
SOUTHPORT 5 N	NC	34.0050	-77.9950	1999	9	14	24.30	SPAS 1552 ZONE 1	E	T
YORKTOWN	VA	37.2750	-76.5550	1999	9	14	19.22	SPAS 1552 ZONE 2	E	T
POMTON LAKE	NJ	40.995	-74.285	1999	9	15	14.62	SPAS 1552 ZONE 3	E	T
CAIRO	NY	42.295	-74.005	1999	9	15	11.71	SPAS 1552 ZONE 4	E	T
MT MANSFIELD	VT	44.5300	-72.8100	1999	9	15	11.35	SPAS 1198 Zone 2	W	T
SPARTA	NJ	41.030	-74.640	2000	8	11	16.70	SPAS 1017	E	L
EDENTON	NC	35.8625	-76.5042	2003	9	17	7.96	SPAS 1535 Zone 1	E	T
UPPER SHERANDO	VA	37.913	-79.029	2003	9	17	20.22	SPAS 1535 Zone 2	E	T
TABERNACLE	NJ	39.881	-74.690	2004	7	13	15.63	SPAS 1040	E	L
MONTEGOMERY DAM	PA	40.605	-76.465	2004	9	18	8.80	SPAS 1275 Zone 2	E	T
RICHMOND	VA	37.7050	-77.3750	2004	8	30	14.38	SPAS 1551	E	T
MONTGOMERY DAM	PA	40.6450	-80.3850	2004	9	18	8.79	SPAS 1275	W	T
HALIFAX	VT	42.7700	-72.7500	2005	10	7	15.40	SPAS 1201	E	G
TAMAQUA	PA	41.6750	-75.3750	2006	6	26	12.26	SPAS 1047	E	G
RALEIGH	NC	34.340	-81.010	2006	6	13	9.32	SPAS 1526	E	T
DELAWARE COUNTY	NY	42.010	-74.900	2007	6	19	11.69	SPAS 1049	E	L
DOUGLASVILLE	GA	33.870	-84.769	2009	9	19	25.37	SPAS 1218	W	G
NEW BERN	NC	35.1750	-77.2150	2010	9	27	23.44	SPAS 1350	E	G
WARNER PARK	TN	36.0611	-86.9056	2010	4	30	19.71	SPAS 1208	W	G
MAPLECREST	NY	42.300	-74.160	2011	8	27	22.91	SPAS 1224	E	T
HARRISBURG	PA	39.9850	-76.4950	2011	9	4	18.32	SPAS 1298	E	T
ISLIP	NY	40.805	-73.065	2014	8	13	14.23	SPAS 1415	E	L

2.1.2 Procedure used to calculate parameters

1. Determine the SPP. Inspect each storm's rainfall data for "inconsequential" rainfall at either the beginning and/or the end of the records. Remove these "tails" from calculations. Generally, used criteria < 0.1 inch/hour intensity. No internal rainfall data are deleted.
2. Recalculate the accumulated rainfall records for R.
3. Plot the SPAS rainfall and R mass curves and inspect for reasonableness.
4. Normalize the R record by dividing all values by the total R to produce R_n for each hour, R_n ranges from 0.0 to 1.0.
5. Determine T_{50} using the time when $R_n = 0.5$.
6. Calculate T_s by subtracting T_{50} from each value of T. Negative time values precede the time to 50% rainfall, and positive values follow.
7. Determine max24hr and max6hr precipitation, convert accumulations into a ratio of the cumulative rainfall to the total accumulated rainfall for that duration.
8. Prepare graphs of a) T vs R, b) T vs R_n, c) T_s vs R_n, and d) maximum point precipitation for General (24-hour), Tropical (24-hour), and Local (6-hour) storm events.

2.2 Results of the Analysis

To further categorize the storms for final analysis, the storms were separated by storm type (local, general, tropical) and whether they occurred east or west of the Appalachian Crest. This delineation was applied because of the difference in the low-level moisture source region, with the Gulf of Mexico and local sources providing moisture west of the Appalachian Crest and the Atlantic Ocean providing moisture east of the Appalachian Crest. In addition, topographical interactions are different between the regions. These differences result in different rainfall accumulation patterns. The effects of topographic differences within each of these regions (such as the Blue Ridge or interior valleys) are captured in the PMP magnitudes but do not affect the temporal pattern of accumulation derived by storm type in each region.

Following the procedures and description from the previous section, results are presented below for the each storm type. Figures 1-8 show graphs for general and Figures 17-24 show graphs for tropical SPAS storm events comparing (a) T vs R, (b) T vs R_n, (c) T_s vs R_n, and (d) maximum point precipitation for storm events east and west of the Appalachian Crest. Figures 9-16 show similar graphs except for the local SPAS storm events.

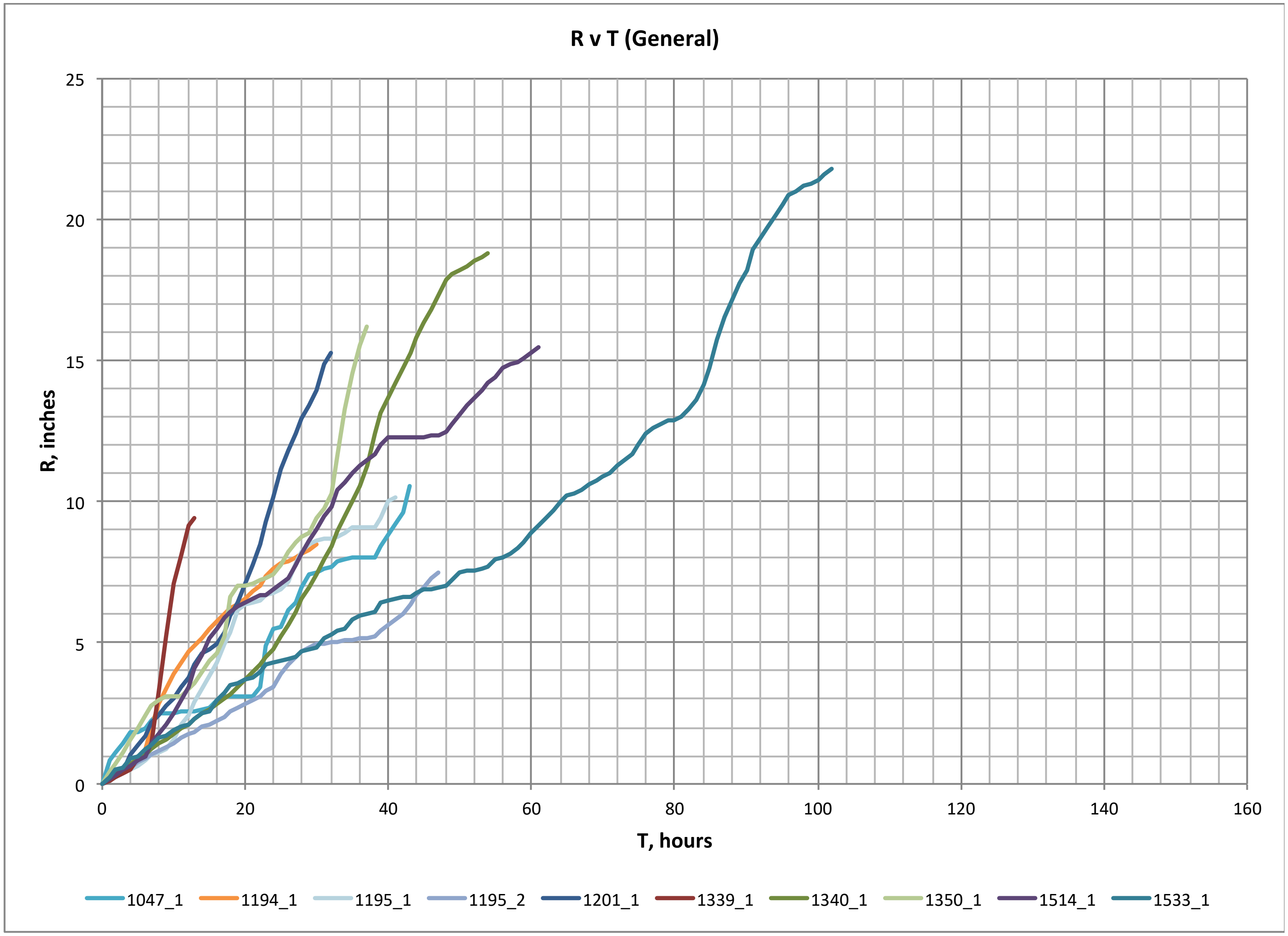

Figure 2. SPAS Rainfall (R) versus time for general storms east of the Appalachian Crest

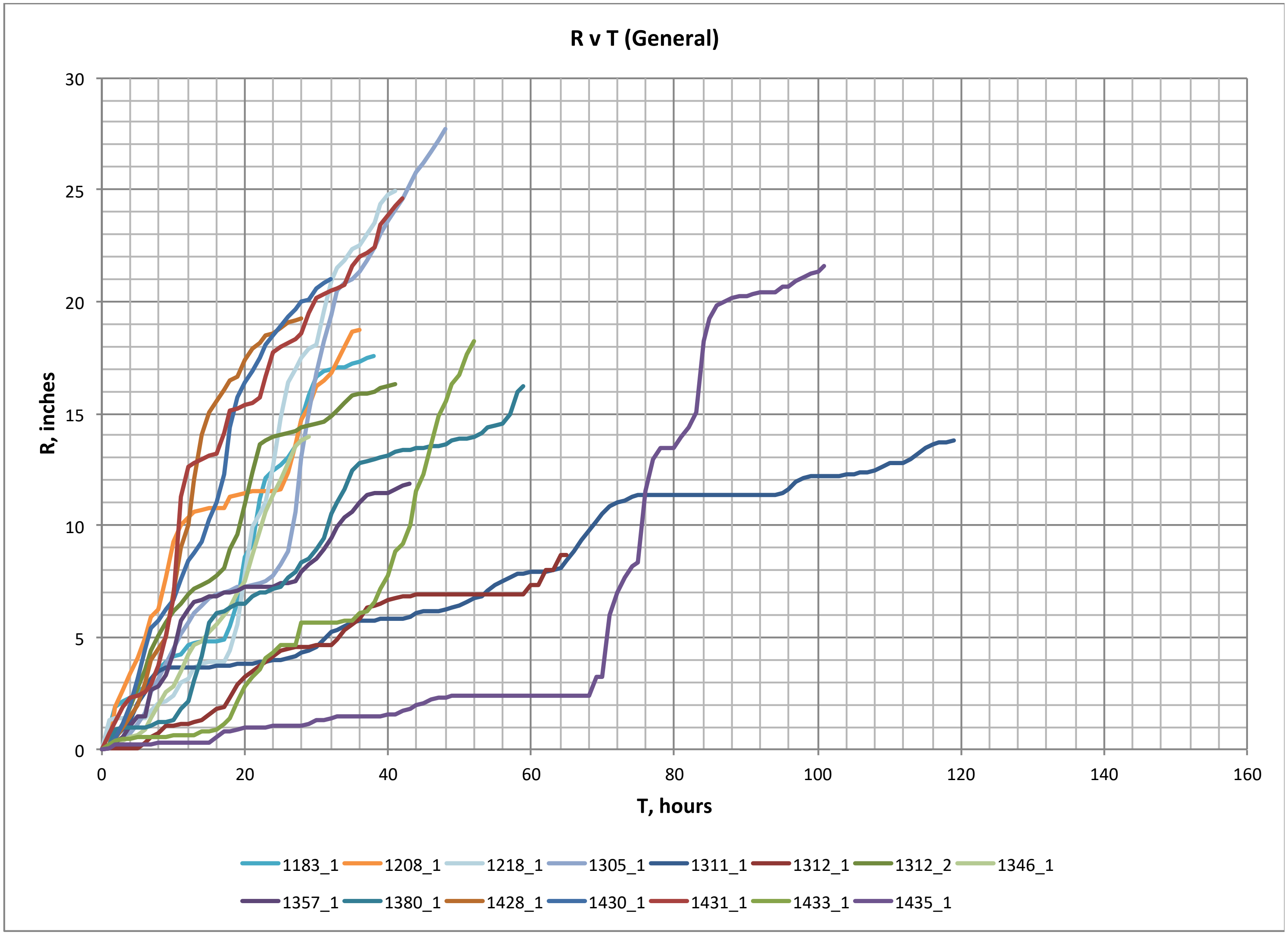

Figure 3. SPAS rainfall (R) versus time for general storms west of the Appalachian Crest

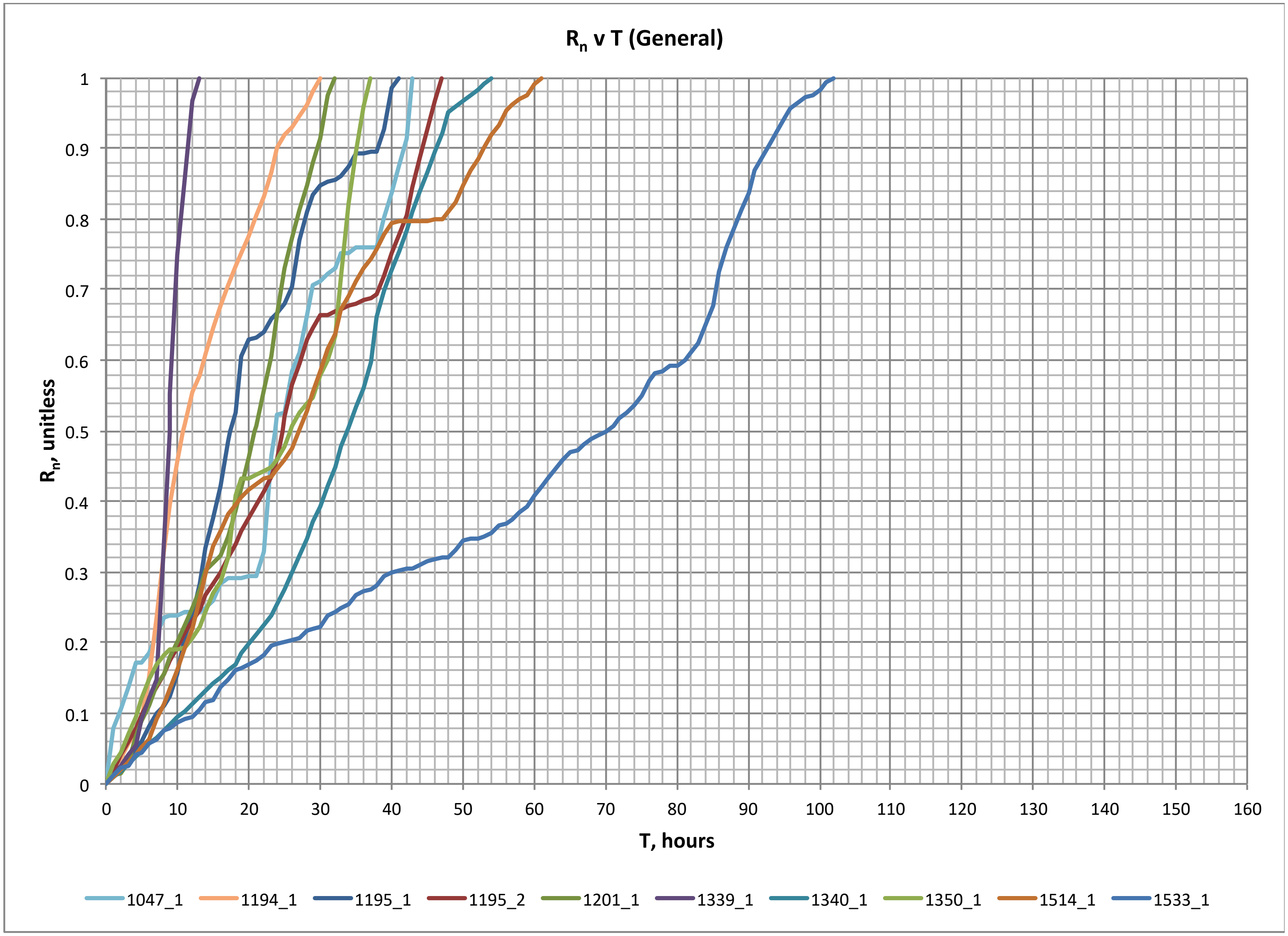

Figure 4. Normalized rainfall (Rn) versus time for general storms east of the Appalachian Crest

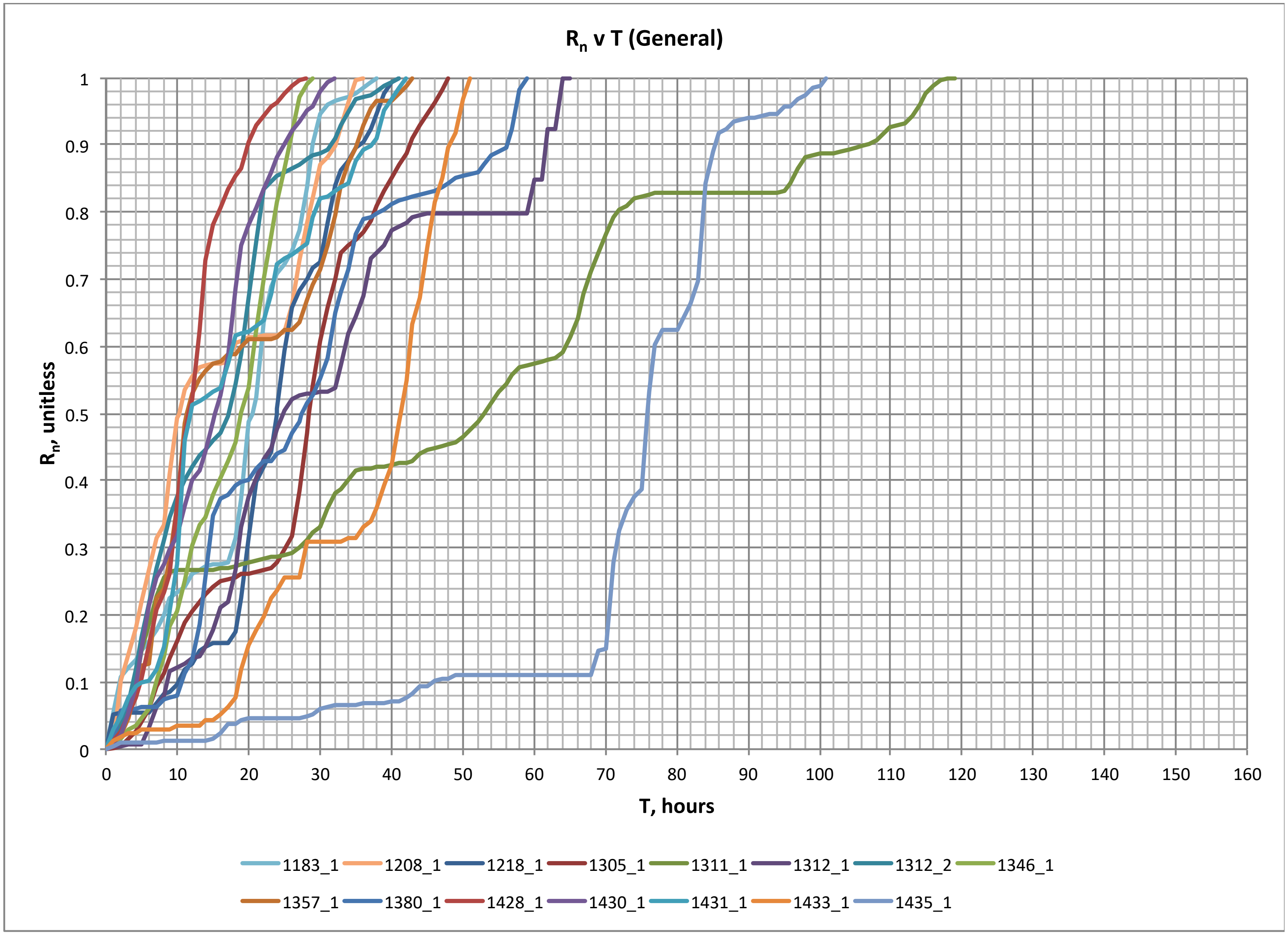

Figure 5. Normalized rainfall (Rn) versus time for general storms west of the Appalachian Crest

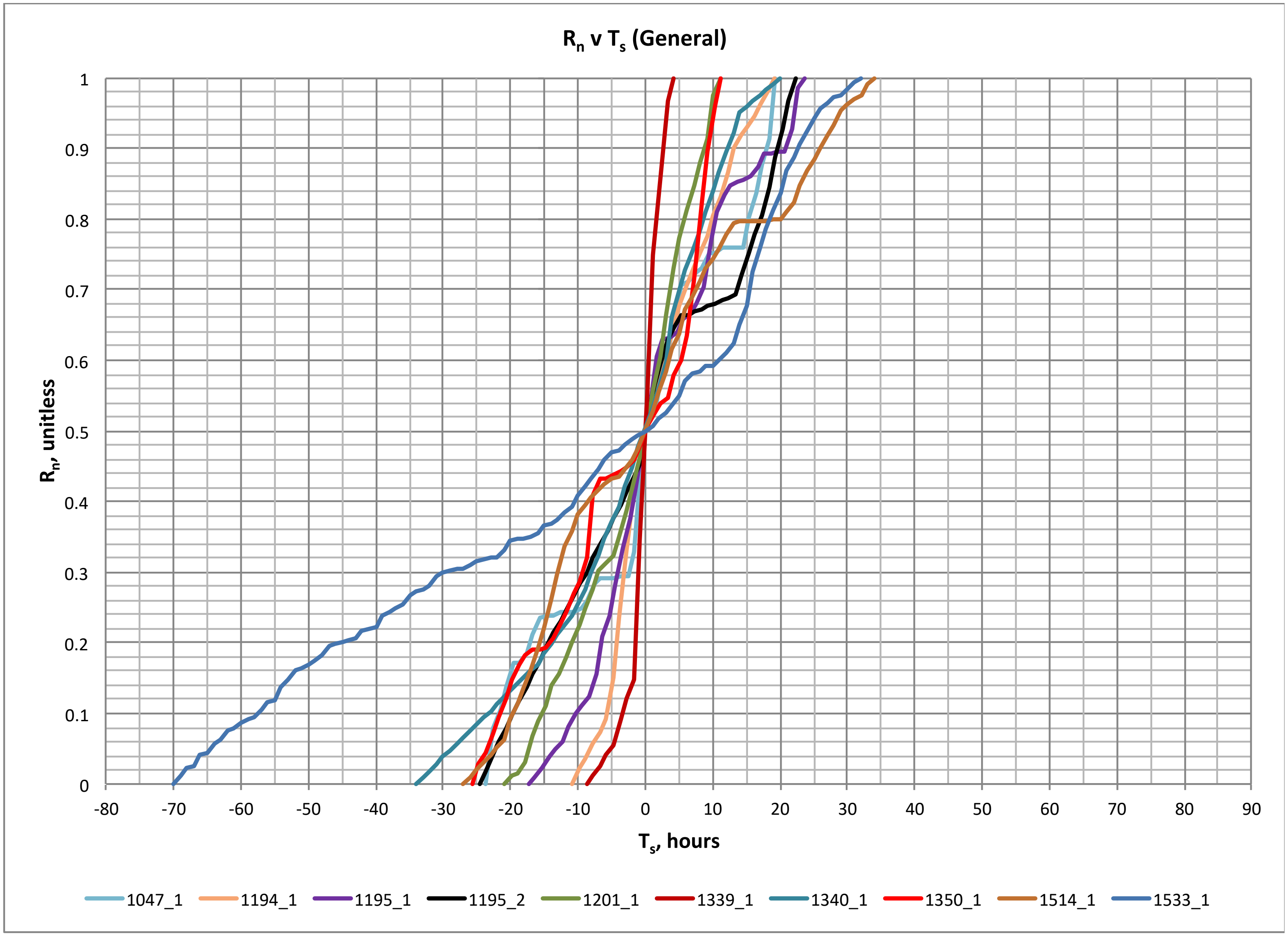

Figure 6. Normalized rainfall (Rn) versus shifted time (Ts) for general storms east of the Appalachian Crest

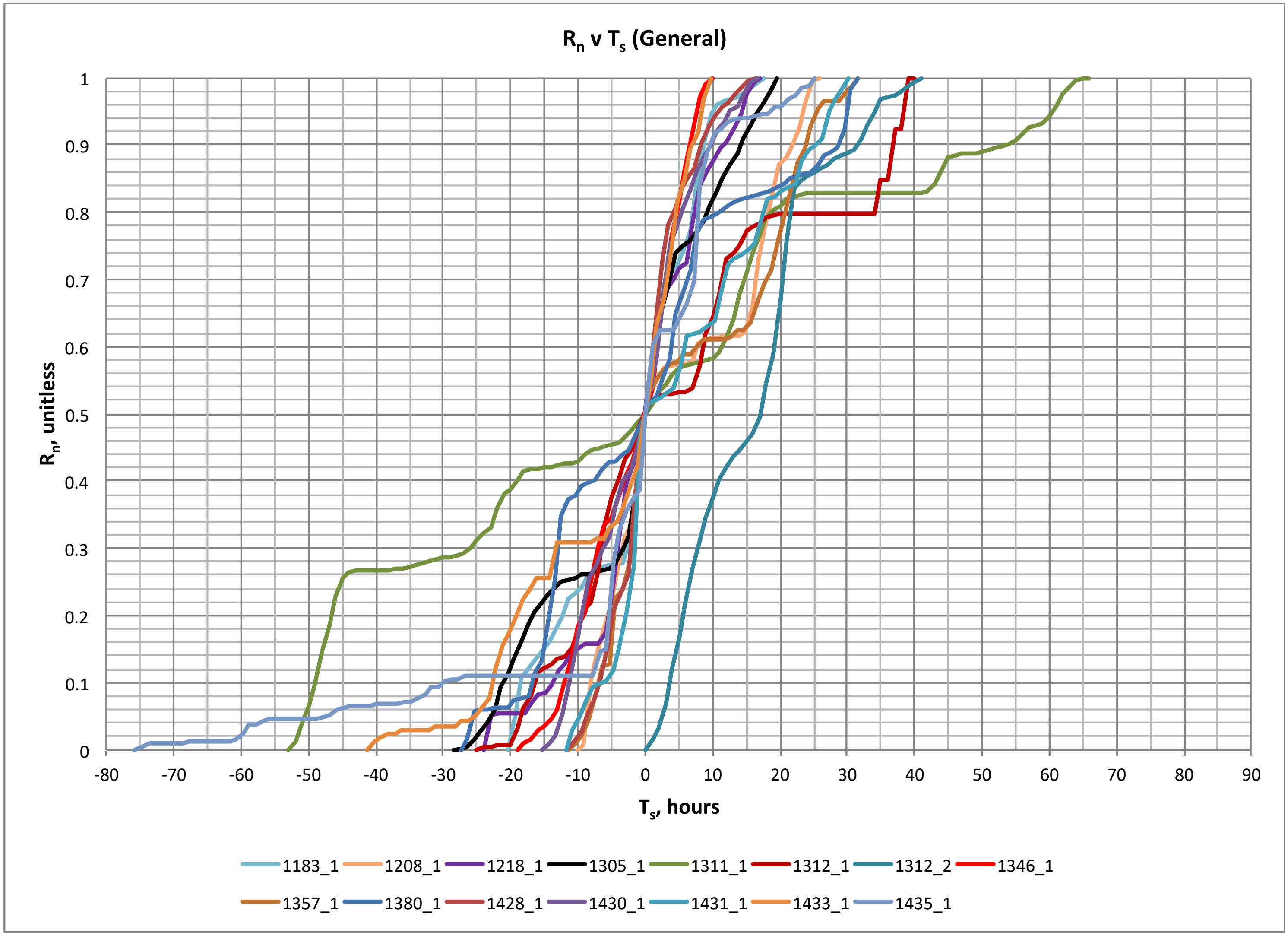

Figure 7. Normalized rainfall (Rn) versus shifted time (Ts) for general storms west of the Appalachian Crest

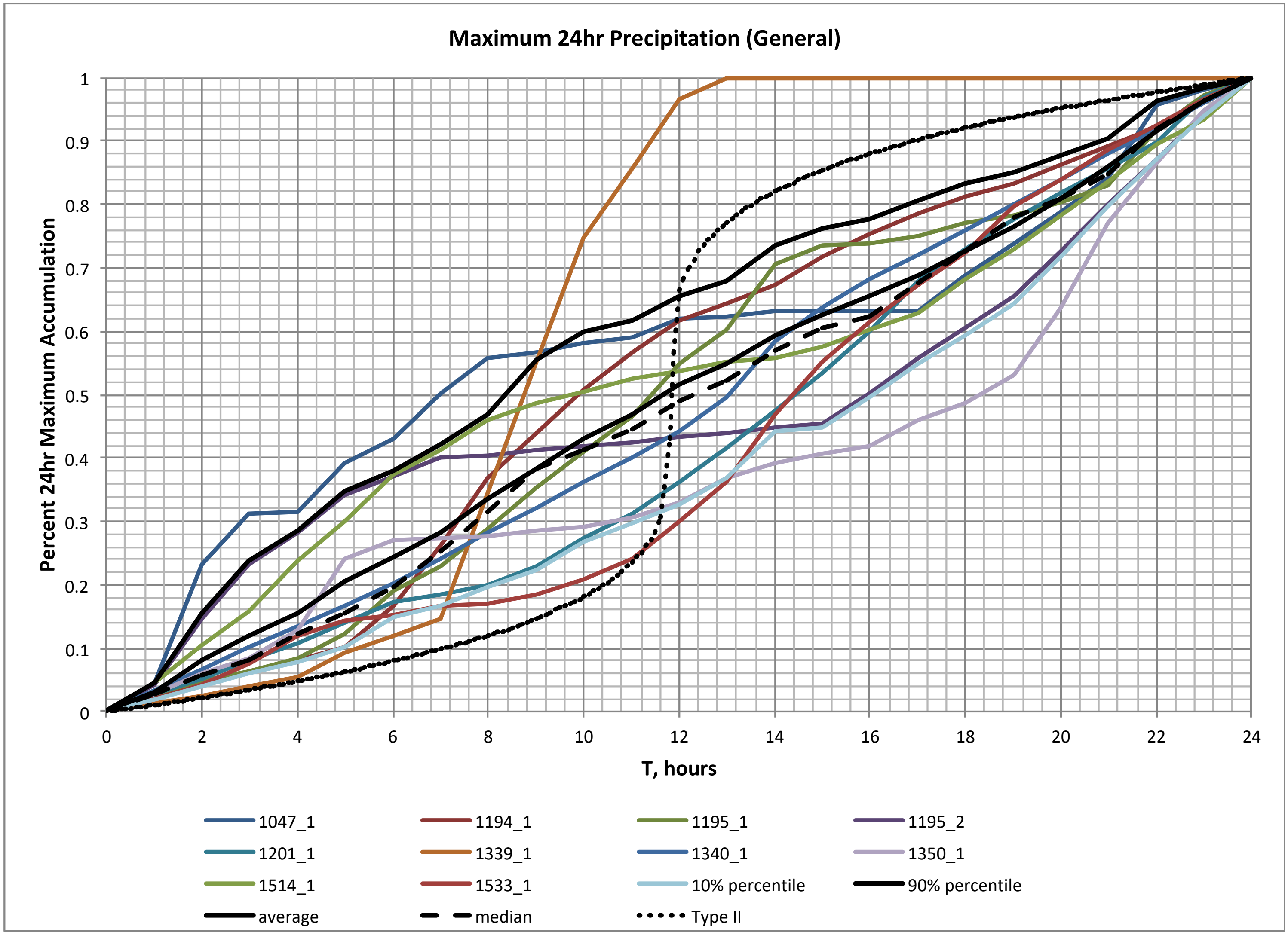

Figure 8. Maximum 24-hour point rainfall versus time for general storms east of the Appalachian Crest (NRCS Type II curve included for comparison)

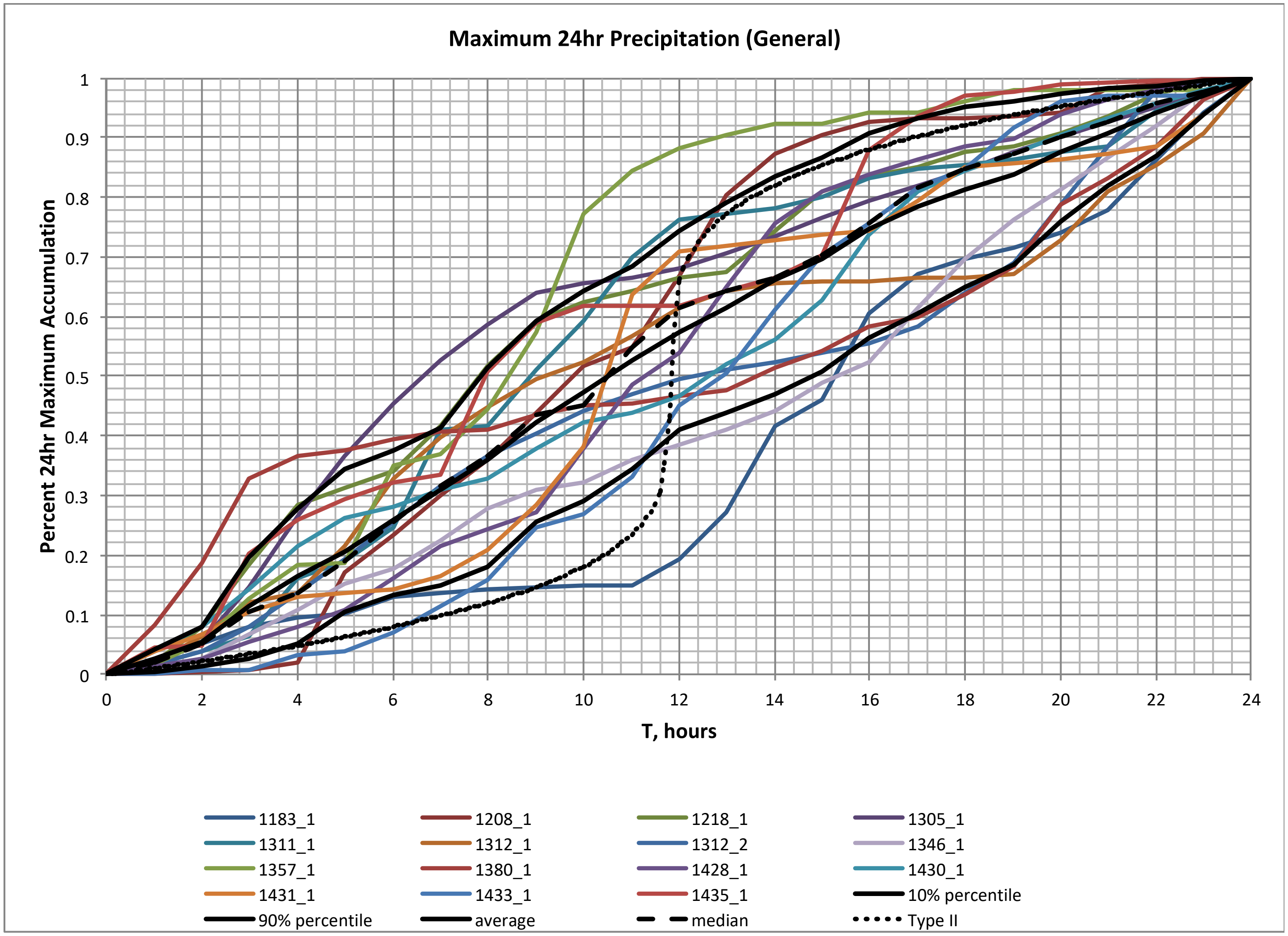

Figure 9. Maximum 24-hour point rainfall versus time for general storms west of the Appalachian Crest (NRCS Type II curve included for comparison)

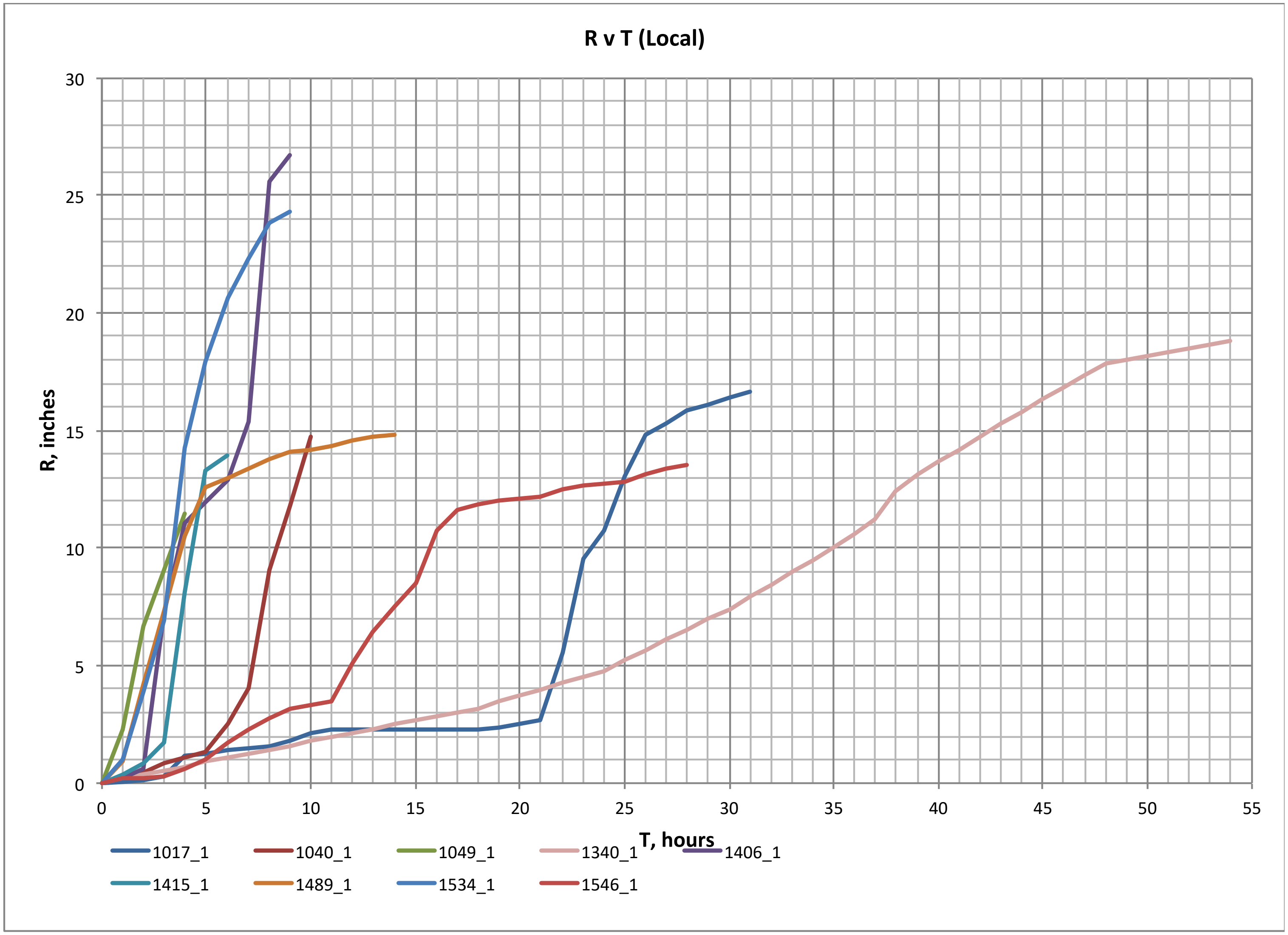

Figure 10. SPAS rainfall (R) versus time for local storms east of the Appalachian Crest

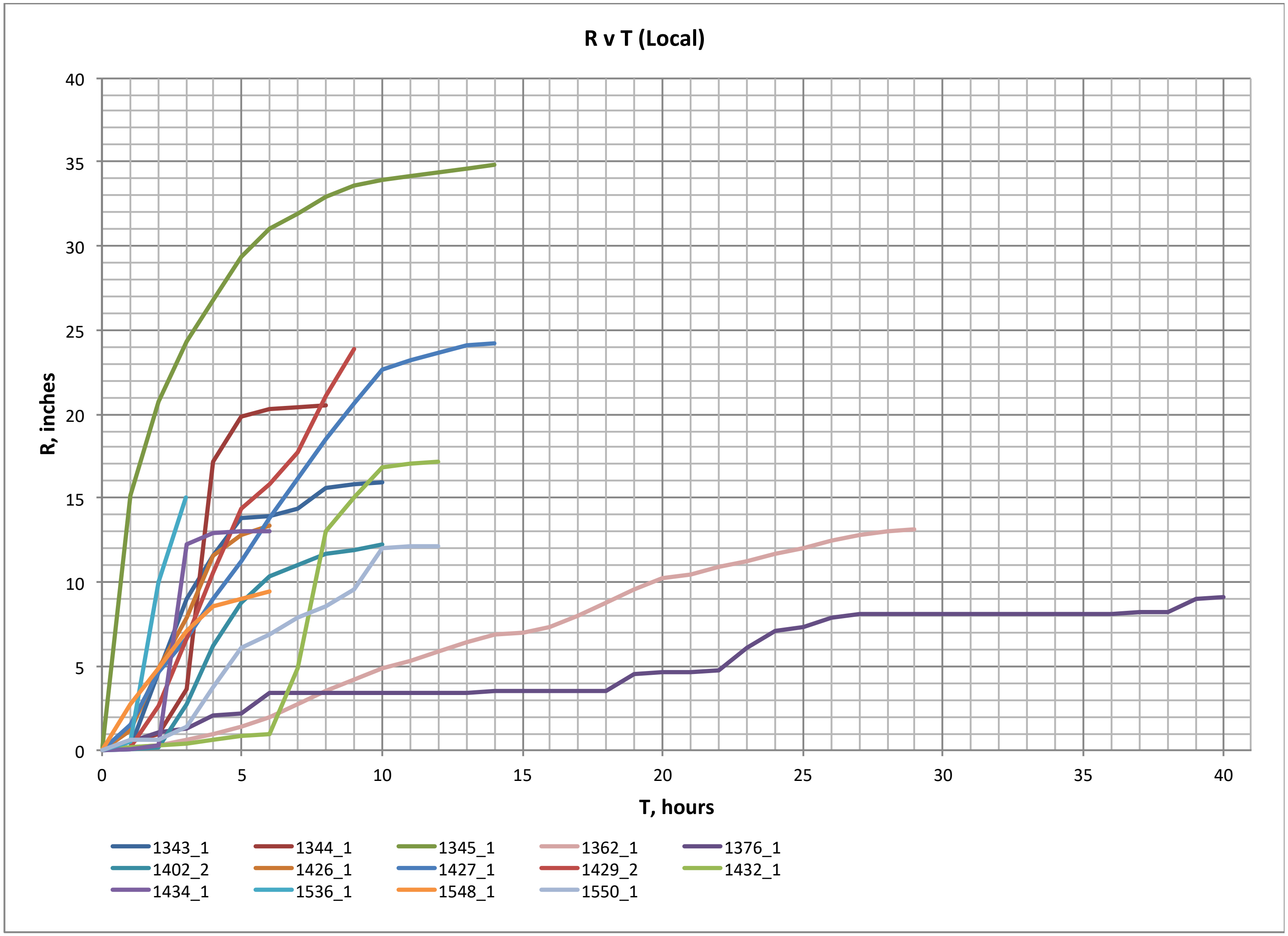

Figure 11. SPAS rainfall (R) versus time for local storms west of the Continental Divide

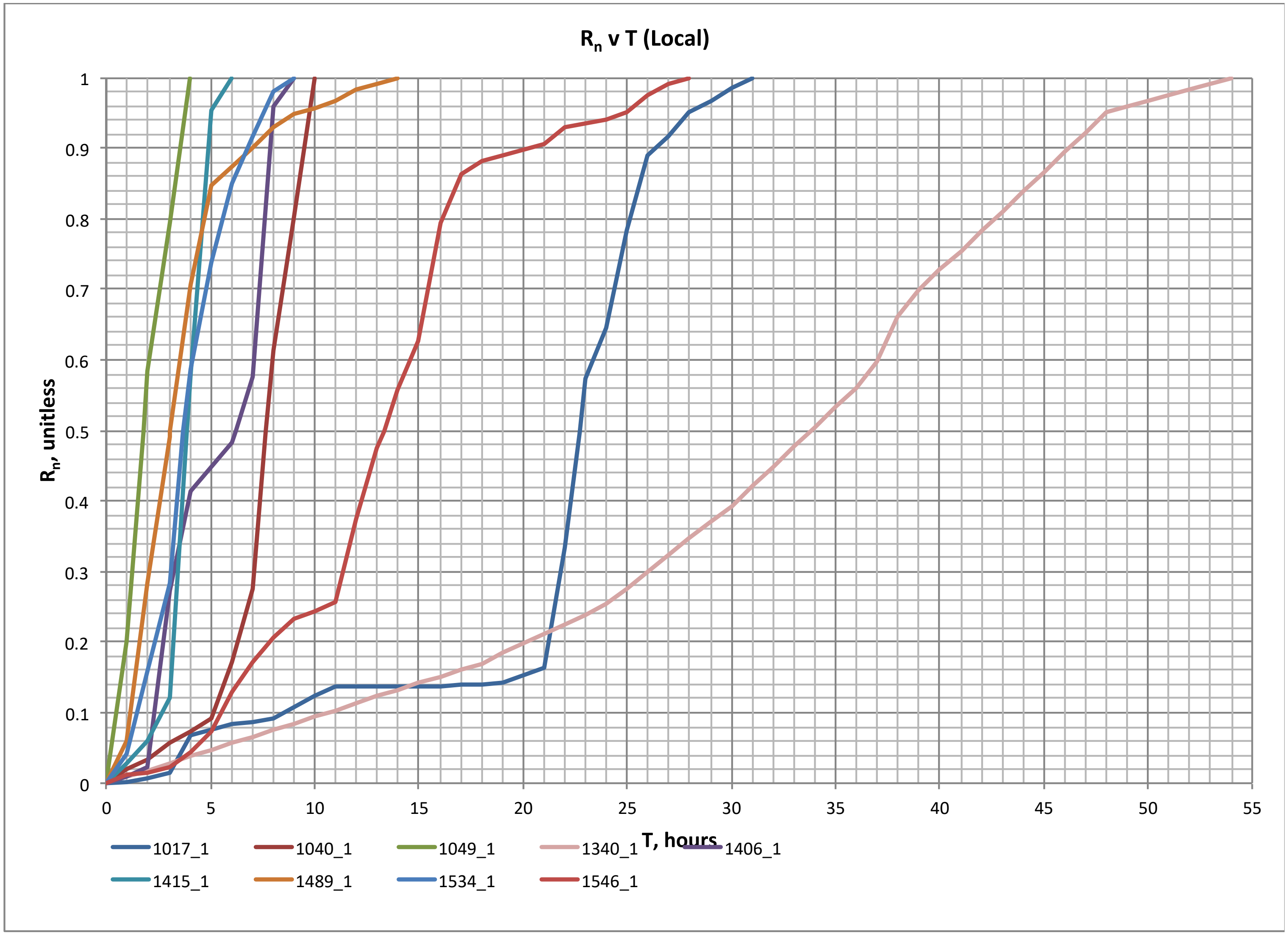

Figure 12. Normalized rainfall (Rn) versus time for local storms east of the Appalachian Crest

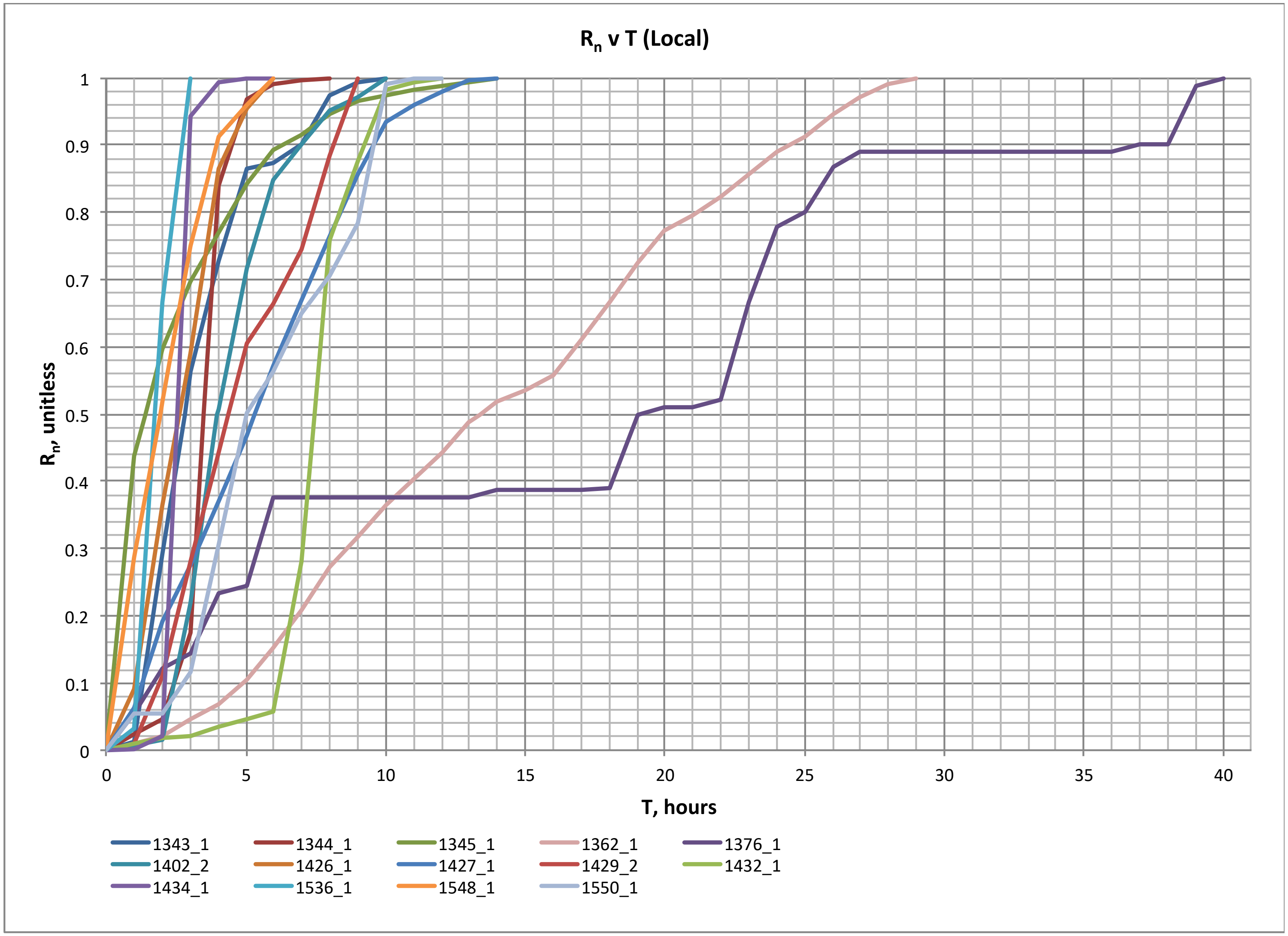

Figure 13. Normalized rainfall (Rn) versus time for local storms west of the Appalachian Crest

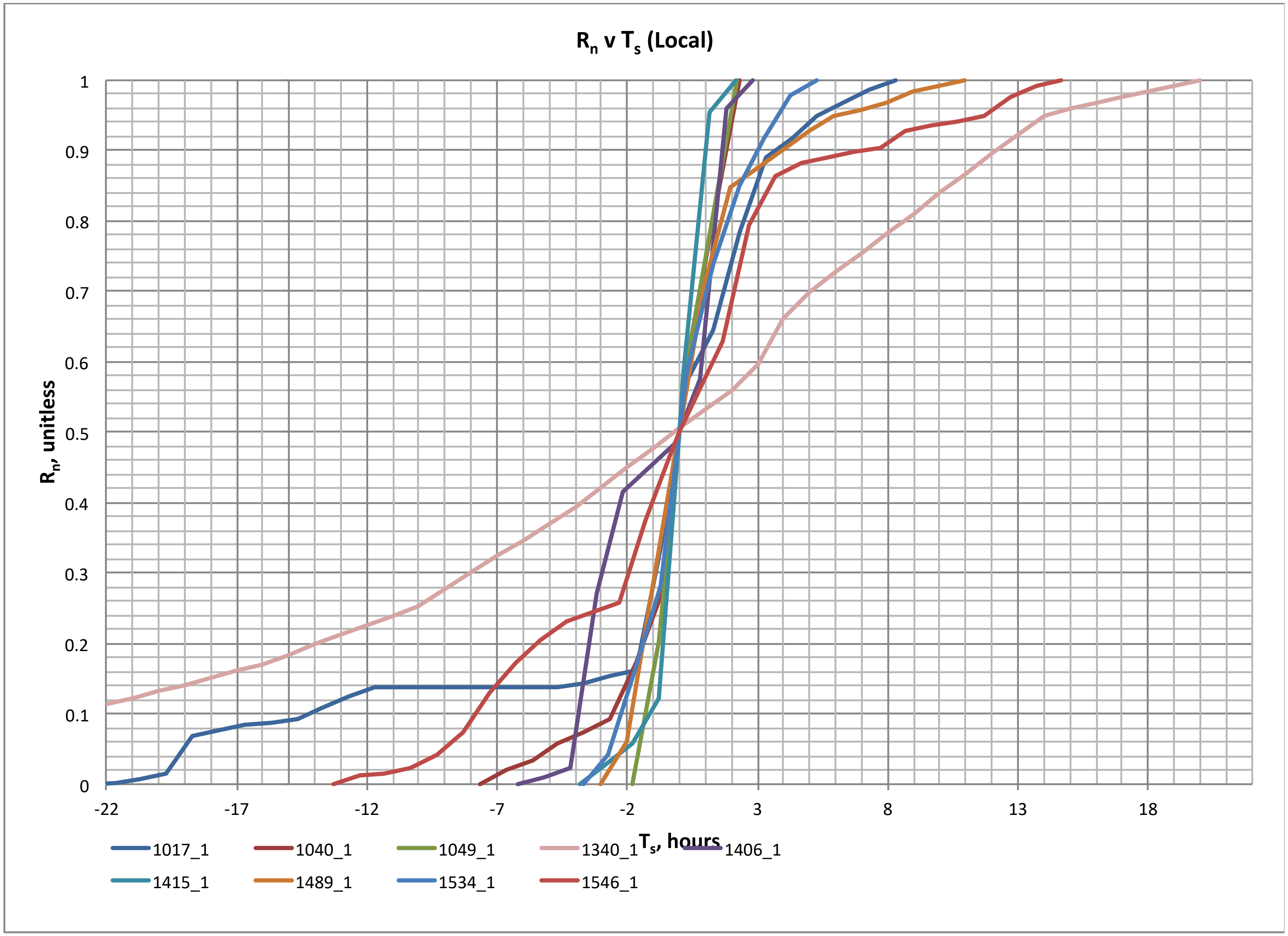

Figure 14. Normalized rainfall (Rn) versus shifted time (Ts) for local storms east of the Appalachian Crest

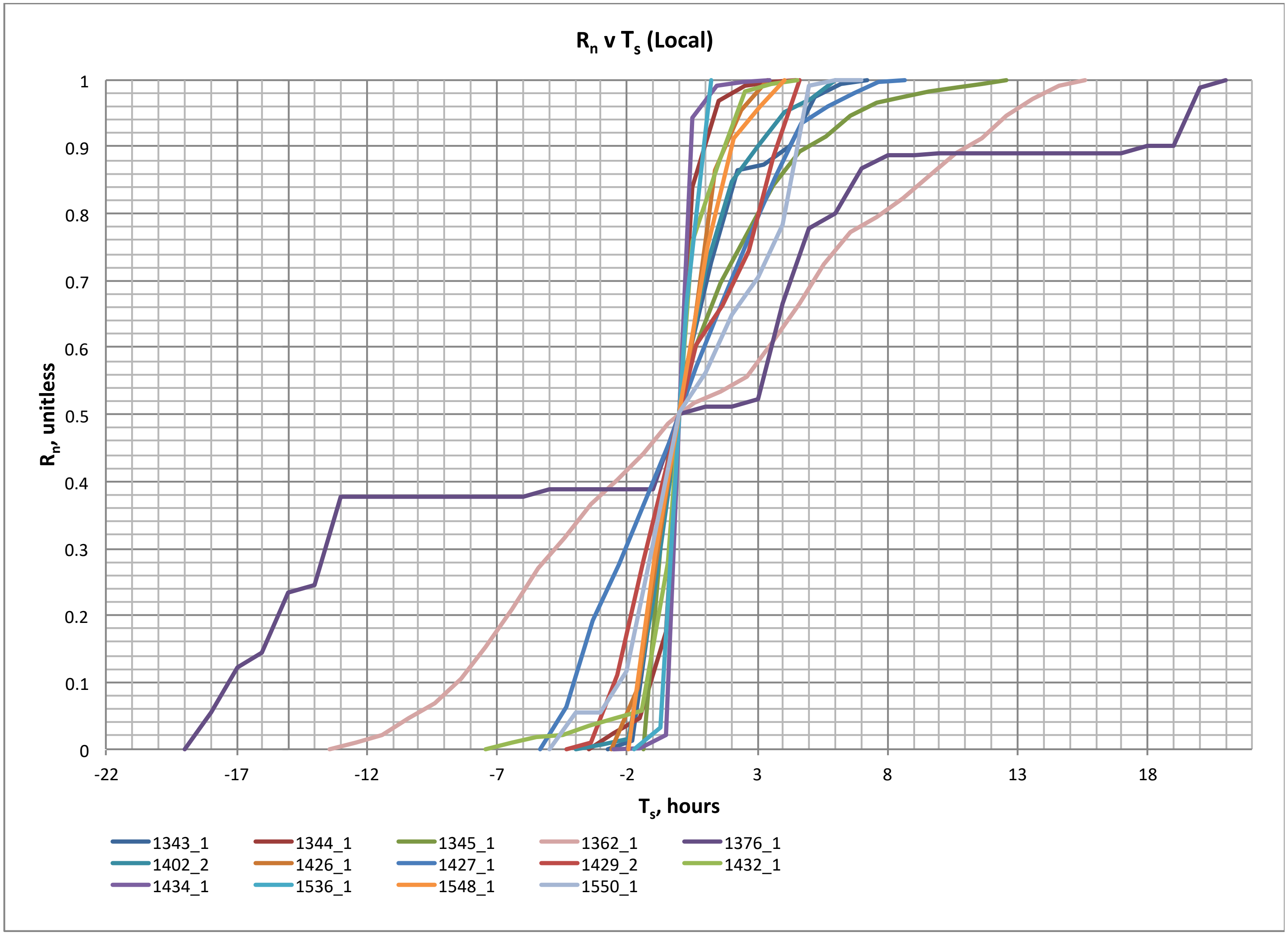

Figure 15. Normalized rainfall (Rn) versus shifted time (Ts) for local storms west of the Appalachian Crest

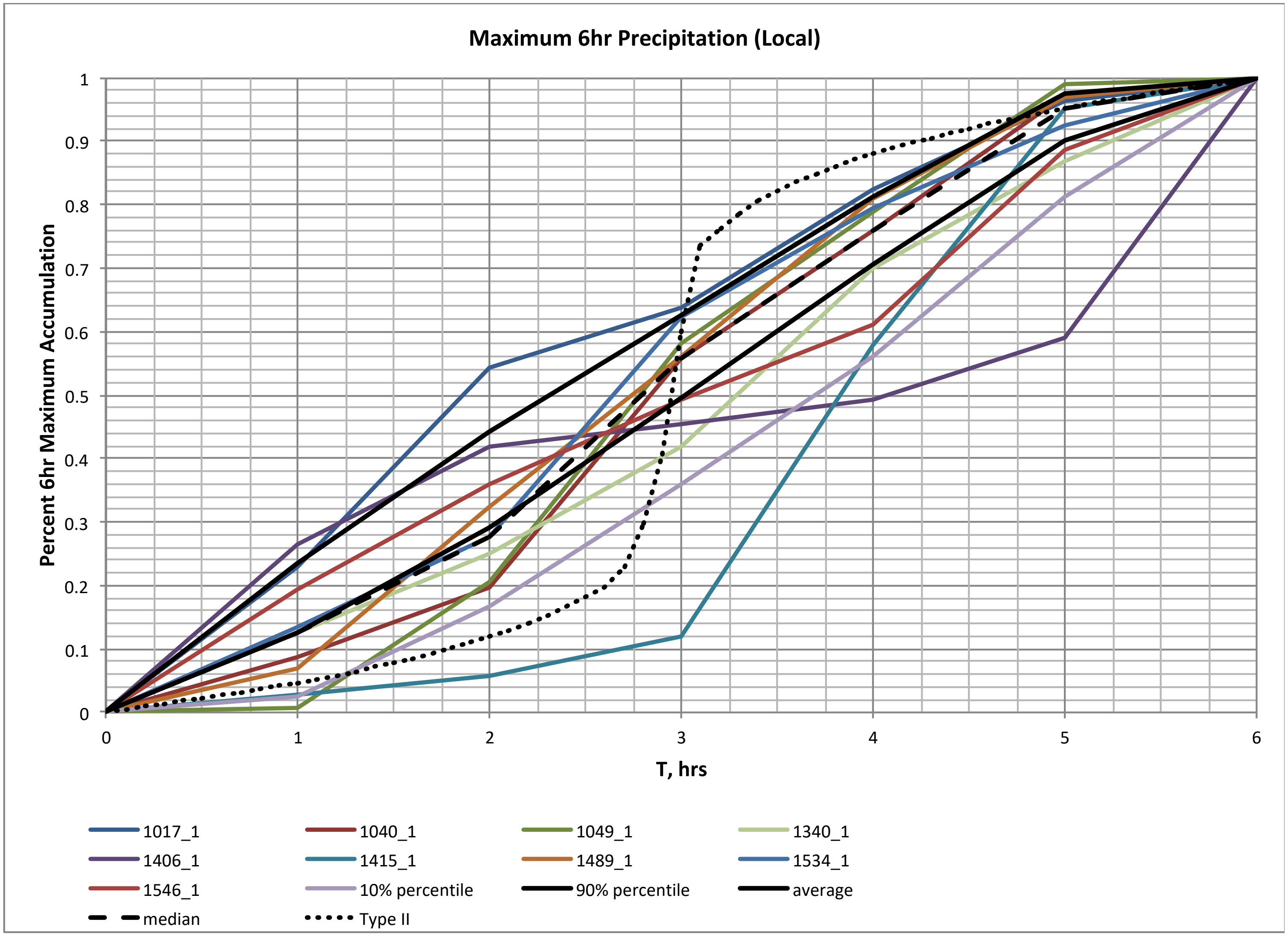

Figure 16. Maximum 6-hour point rainfall versus time for local storms east of the Appalachian Crest

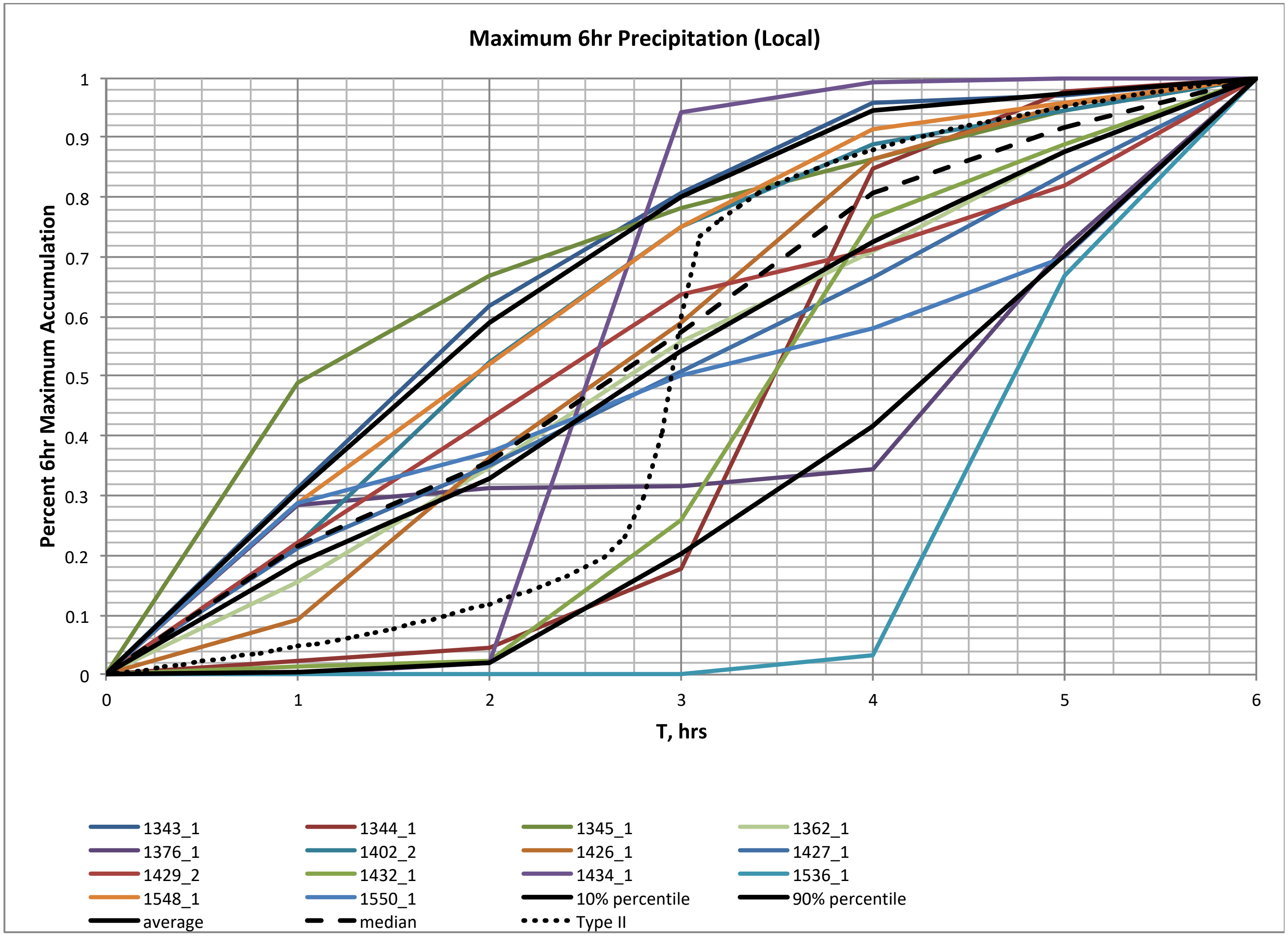

Figure 17. Maximum 6-hour point rainfall versus time for local storms west of the Appalachian Crest

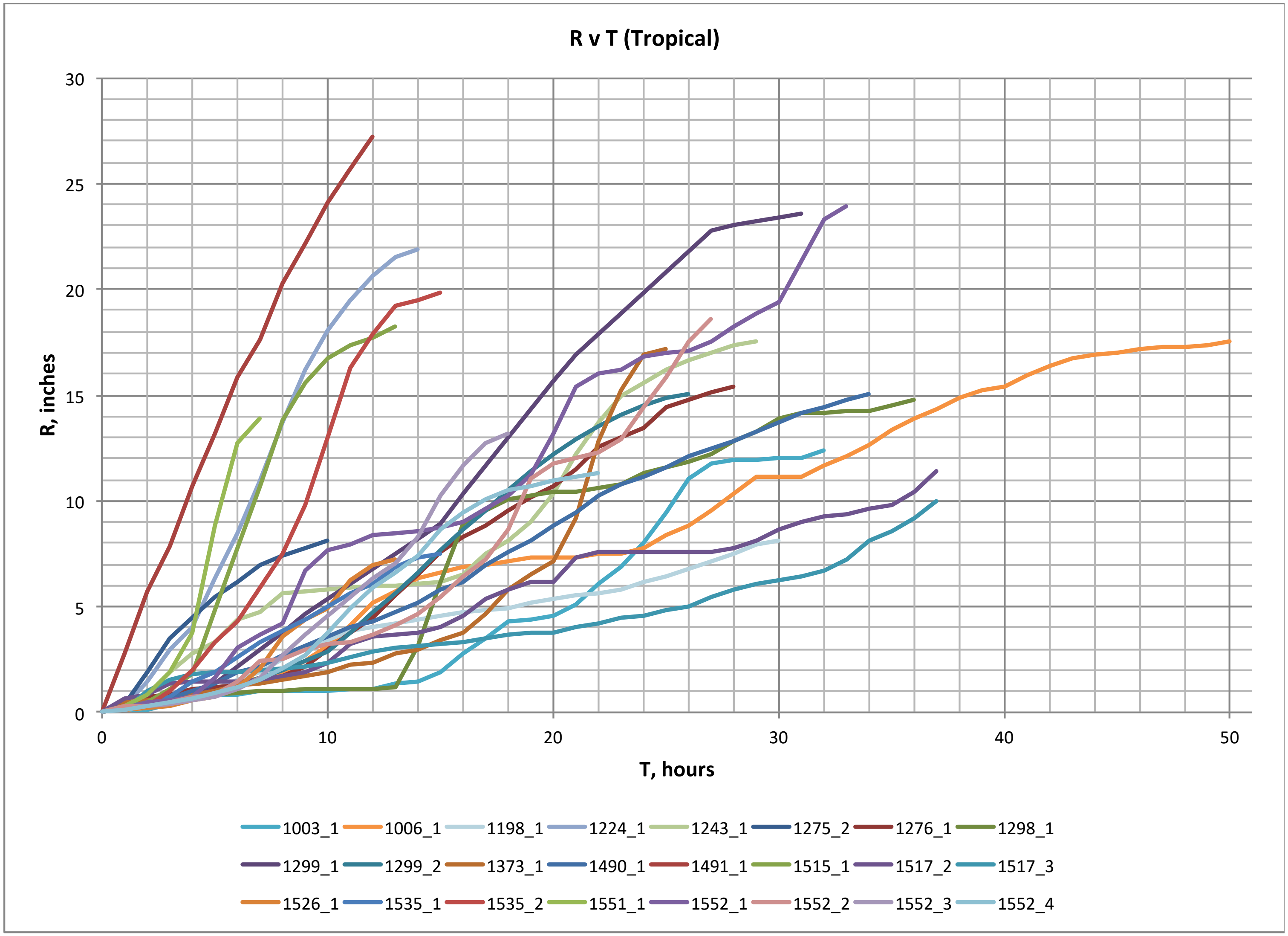

Figure 18. SPAS rainfall (R) versus time for tropical storms east of the Appalachian Crest

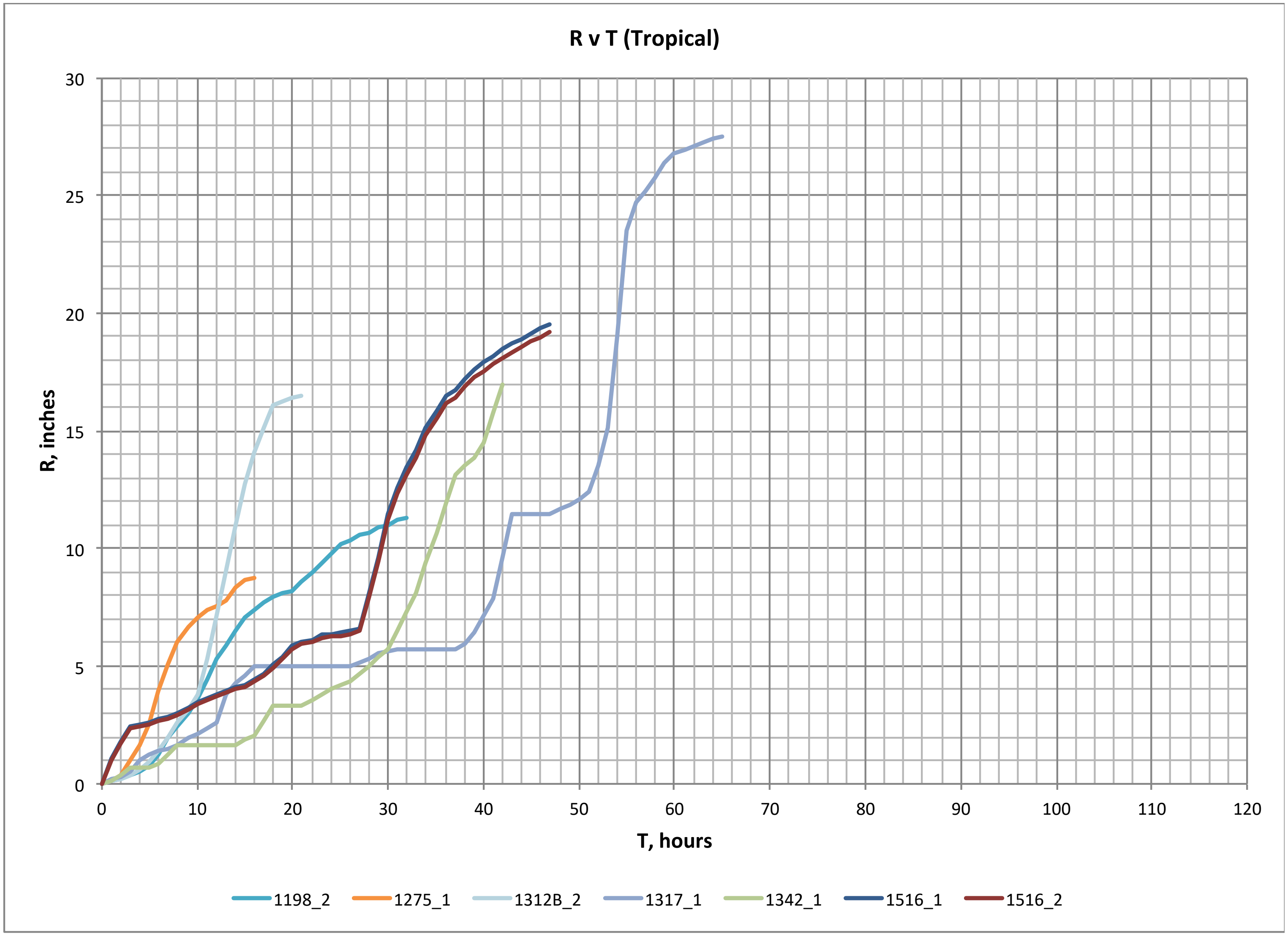

Figure 19. SPAS rainfall (R) versus time for tropical storms west of the Continental Divide

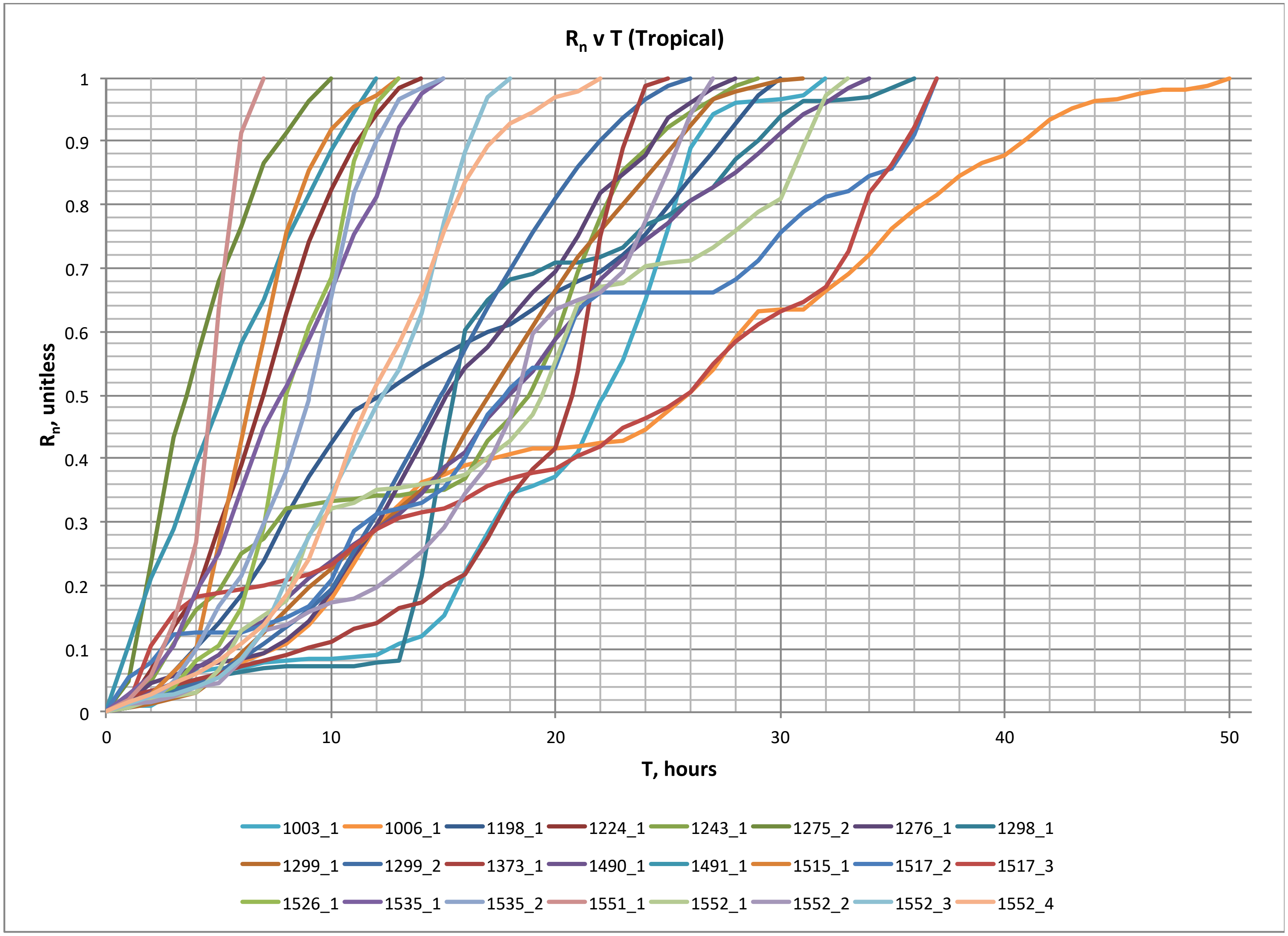

Figure 20. Normalized rainfall (Rn) versus time for tropical storms east of the Appalachian Crest

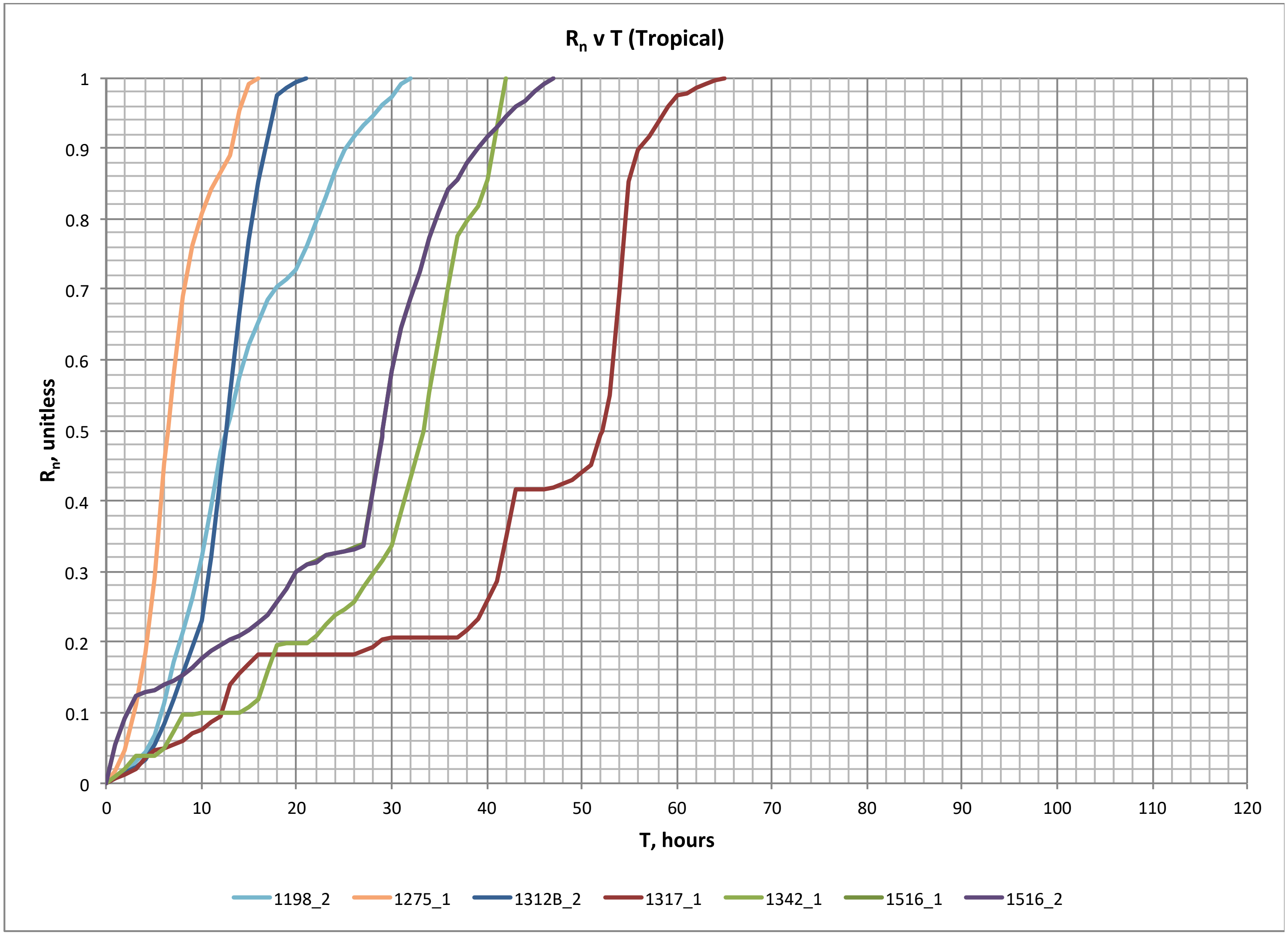

Figure 21. Normalized rainfall (Rn) versus time for tropical storms west of the Appalachian Crest

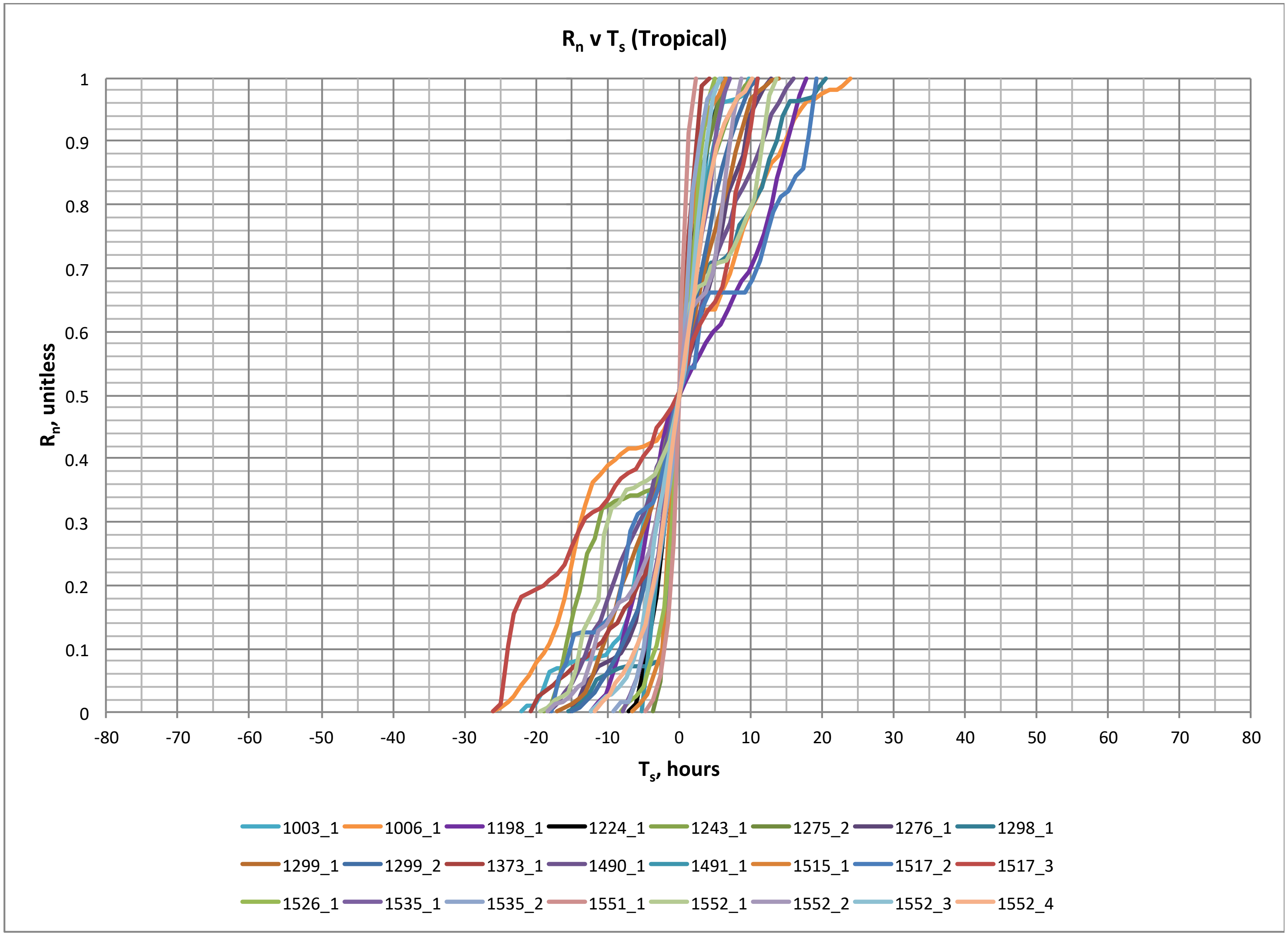

Figure 22. Normalized rainfall (Rn) versus shifted time (Ts) for tropical storms east of the Appalachian Crest

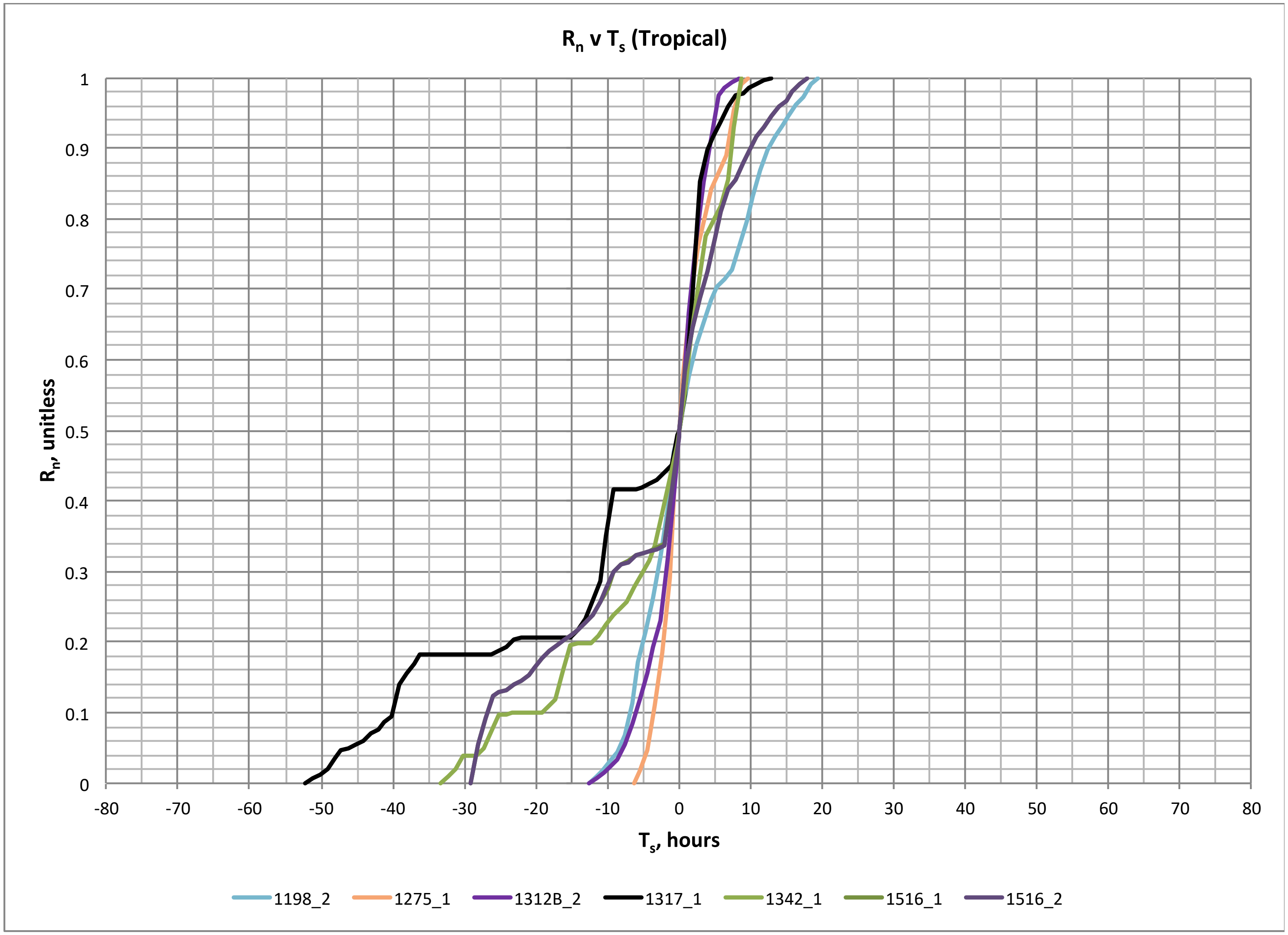

Figure 23. Normalized rainfall (Rn) versus shifted time (Ts) for tropical storms west of the Appalachian Crest

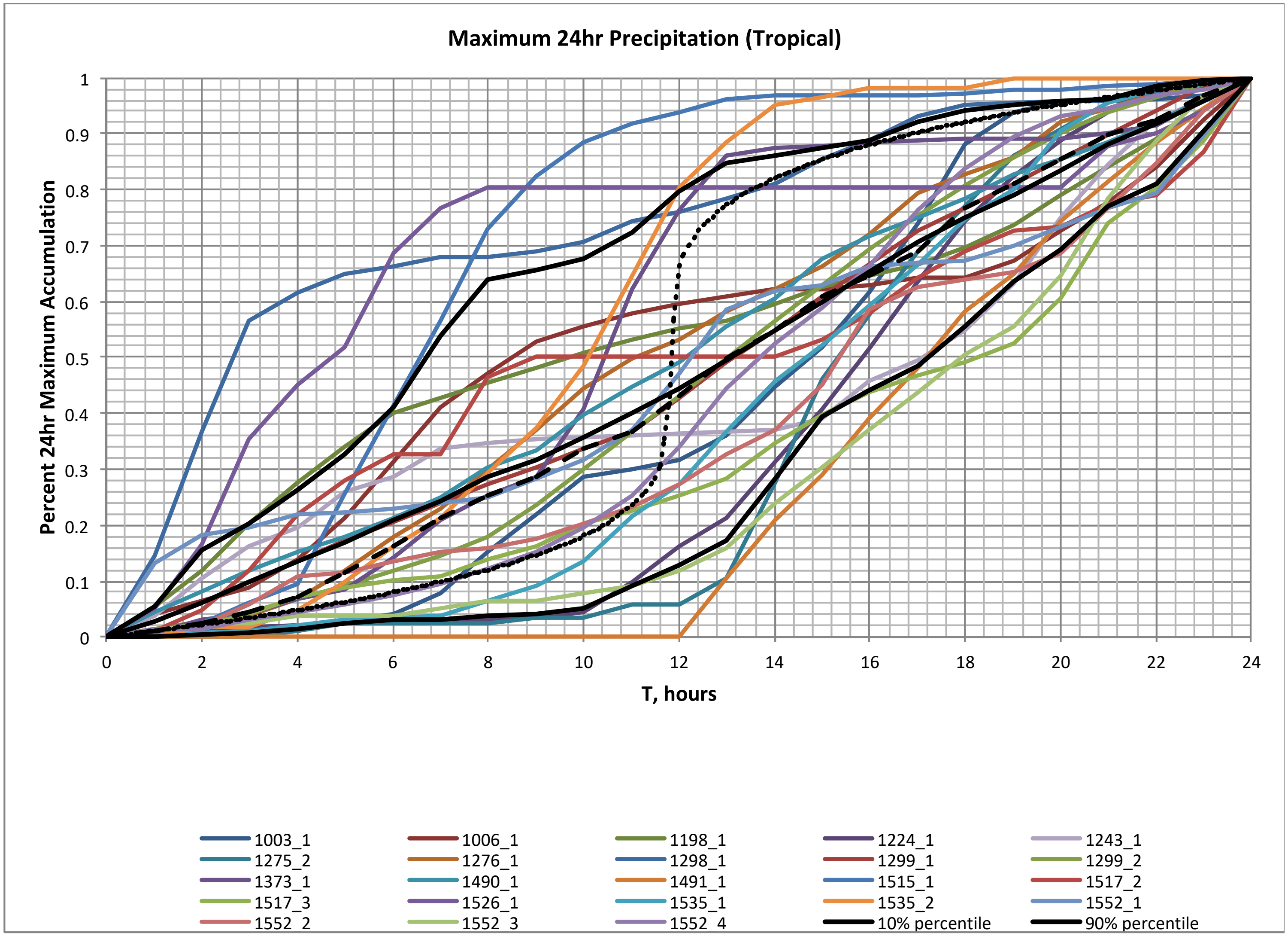

Figure 24. Maximum 6-hour point rainfall versus time for tropical storms east of the Appalachian Crest

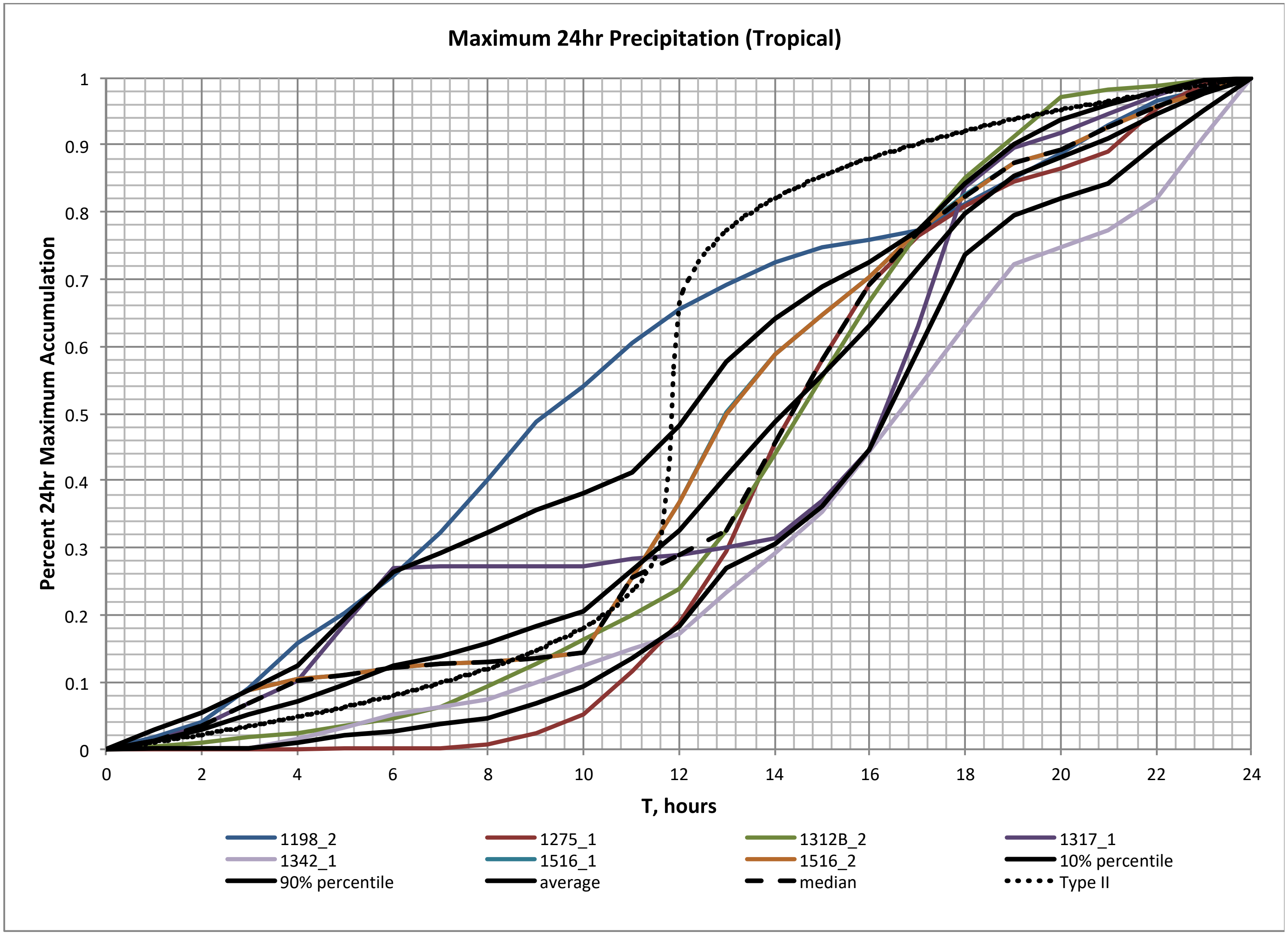

Figure 25. Maximum 6-hour point rainfall versus time for tropical storms west of the Appalachian Crest

2.3 Huff Curve Methodology

Huff curves provide a method of characterizing storm mass curves. They are a probabilistic representation of accumulated storm depths for corresponding accumulated storm durations expressed in dimensionless form. The development of Huff curves are described in detail in Huff (1967) and Bonta (2003), a summary of the steps are listed below.

For each SPAS storm center mass curve, the SPP amounts (R, noted in above section) were identified, the SPP were non-dimensionalized and convert into percentages of the total precipitation amount at one-hour time step. The non-dimensionalized duration values were interpolated and extracted at 0.02 increments from 0 to 1. Storms were grouped by geographic location (east versus west of the Appalachian Crest) and by storm type: local, general, and tropical. The uniform incremental storm data (by duration and location) were combined and probabilities of occurrence were estimated at each 0.02 increment. Probabilities were estimated as 0.1 increments. Recommended curves (50th) were smoothed using a non-linear regression.

The curves can be generically described as:

- 90th curve - the 90th curve indicates that 10% of the corresponding storms had distributions that fell above and to the left of the curve (front-loaded)
- 50th curve - the 50th curve indicates that 50% of the corresponding storms had distributions that fell above and below the curve (mid-loaded)
- 10th curve - the 10th curve indicates that 10% of the corresponding storms had distributions that fell below and to the right of the curve (back-loaded)

The raw data results are presented below (Figures 25-30); the final curves selected for use were smoothed and provided at 6-minute time steps. Based on several discussions with AWA and VA DCR about which Huff Curve represented a critical temporal pattern that was meteorologically appropriate to apply for Virginia basins it was decided that the 50th percentile curve would be utilized for all storm types and locations. The raw 50th percentile data (Figures 25-30) were smoothed using a best-fit non-linear regression, time-steps were provided at 6-minute intervals (Figures 31-36) For 24-hour storm duration, two temporal patterns were provided: i) 24a pattern represents a continuous rainfall for the entire period (based on Huff curve) and ii) 24b pattern maintains the 12-hour temporal pattern with a uniform distribution for the last 12-hours (represents a storm were most precipitation occurs in a 12-hour period). The final four temporal patterns by storm type and location are shown in Figures 31-36. The final curves were placed into a spreadsheet that performs all calculations for all temporal scenarios for use in hydrologic modeling. The Excel spreadsheet "VA_Temporal_50th_Final" was provided as a digital appendix.

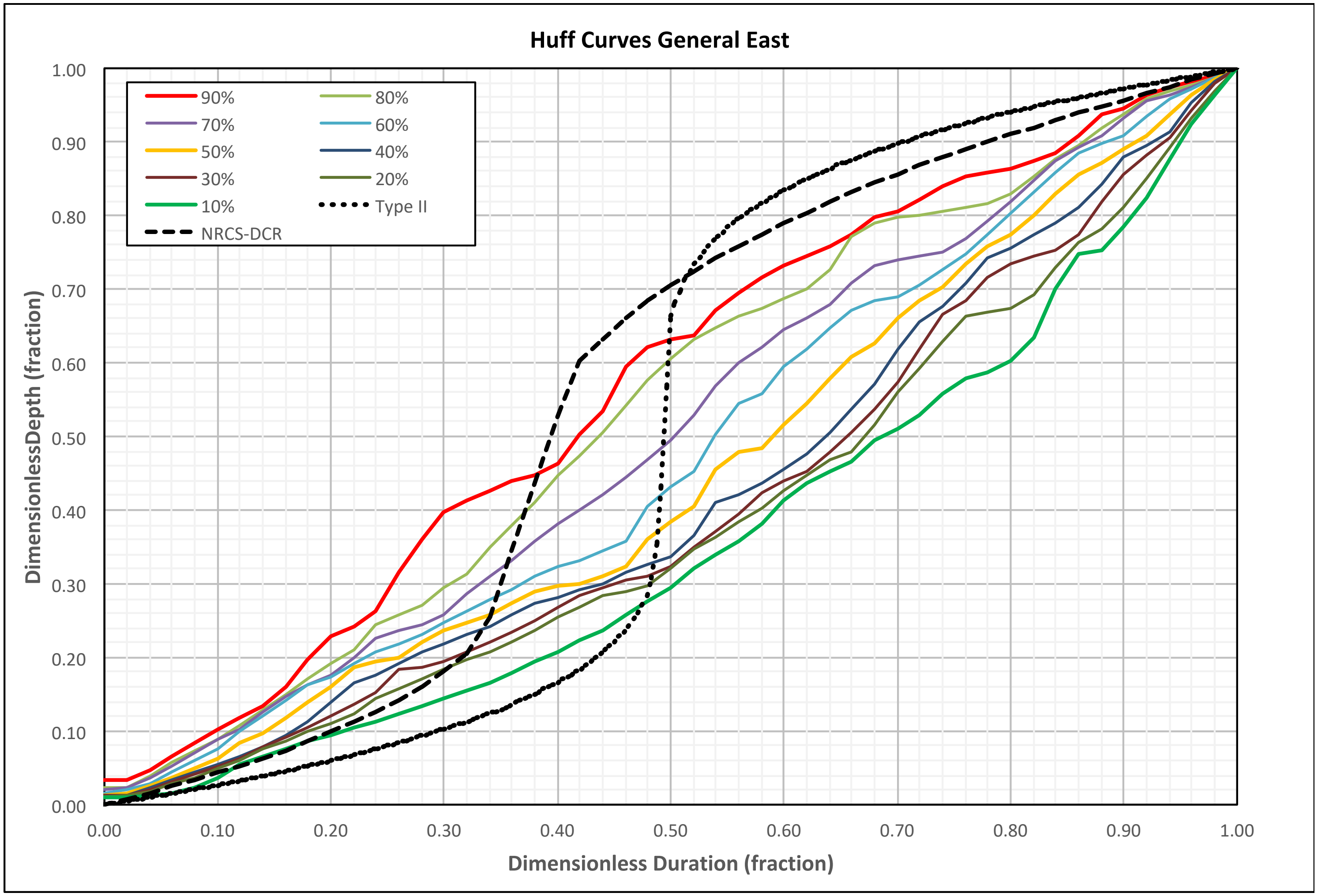

Figure 26. Raw Huff temporal curves for general storms east of the Appalachian Crest

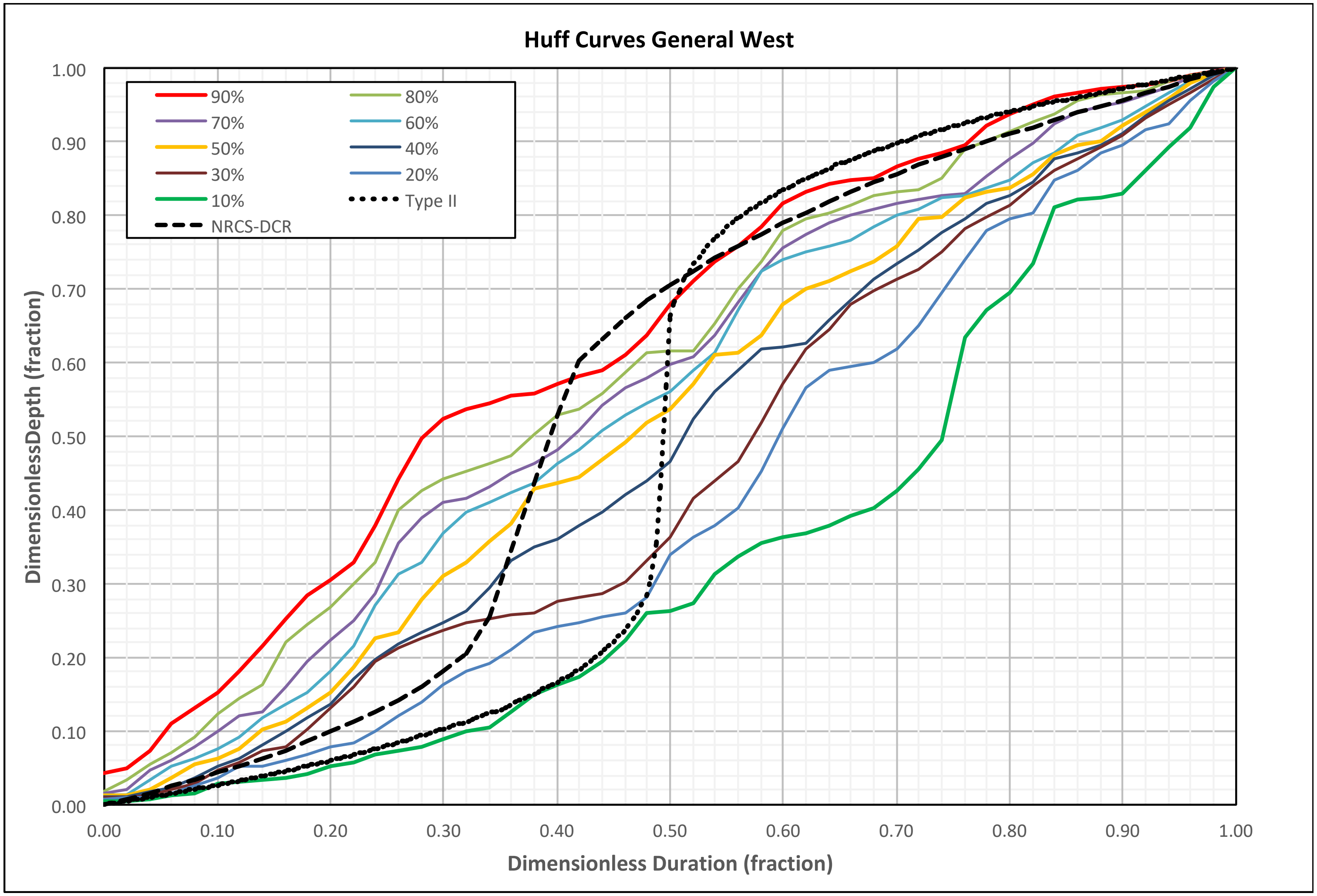

Figure 27. Raw Huff temporal curves for general storms west of the Appalachian Crest

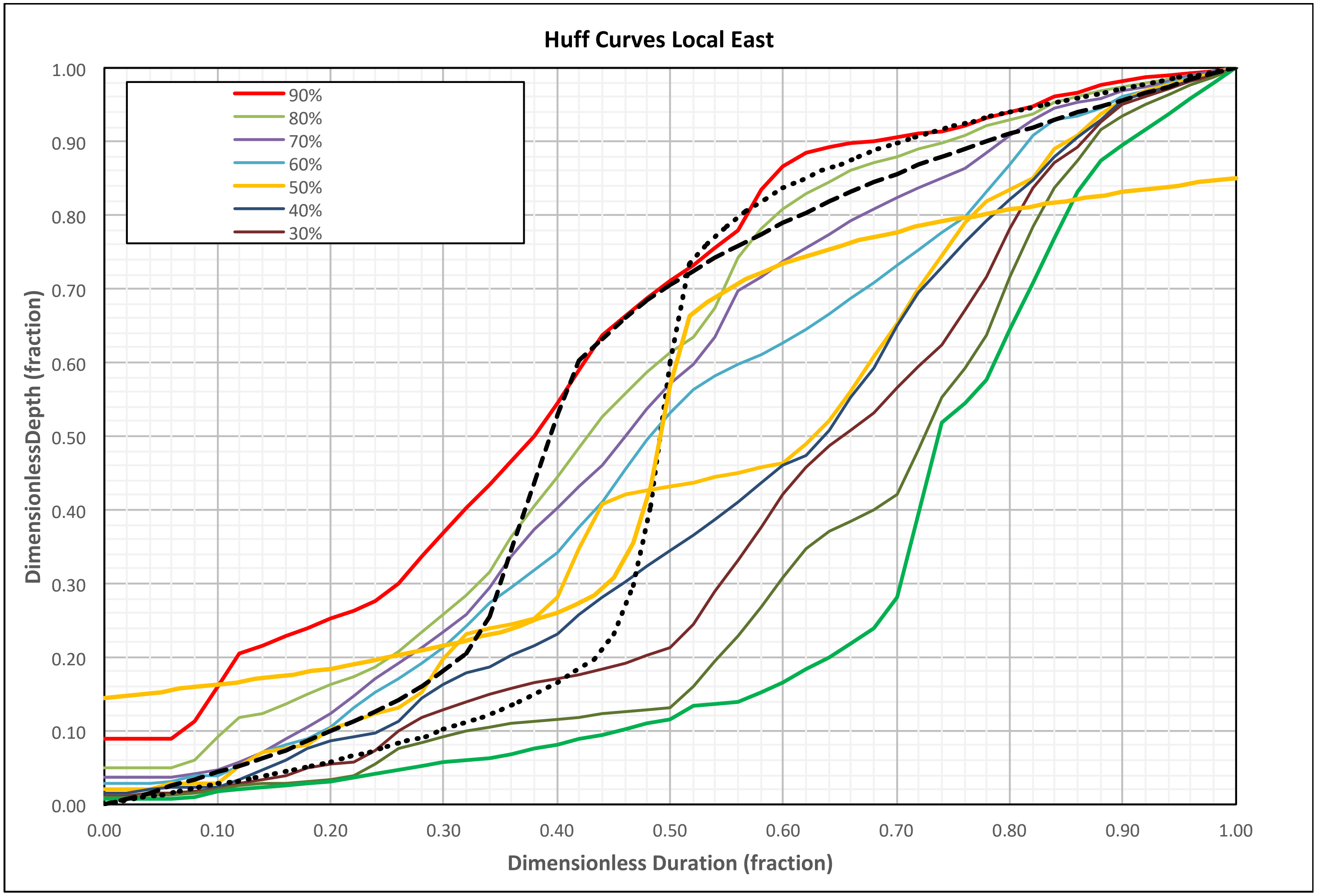

Figure 28. Raw Huff temporal curves for local storms east of the Appalachian Crest

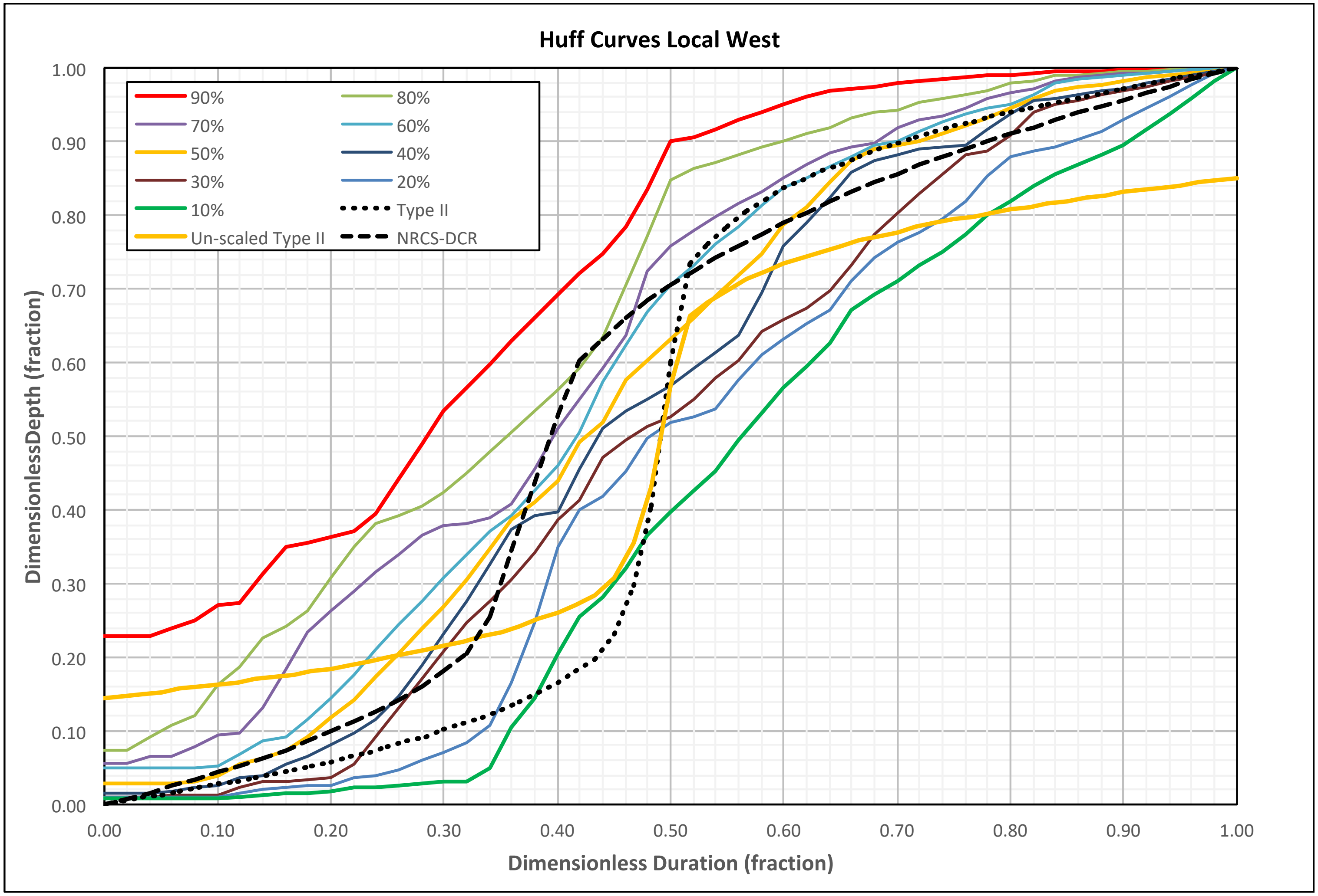

Figure 29. Raw Huff temporal curves for local storms west of the Appalachian Crest

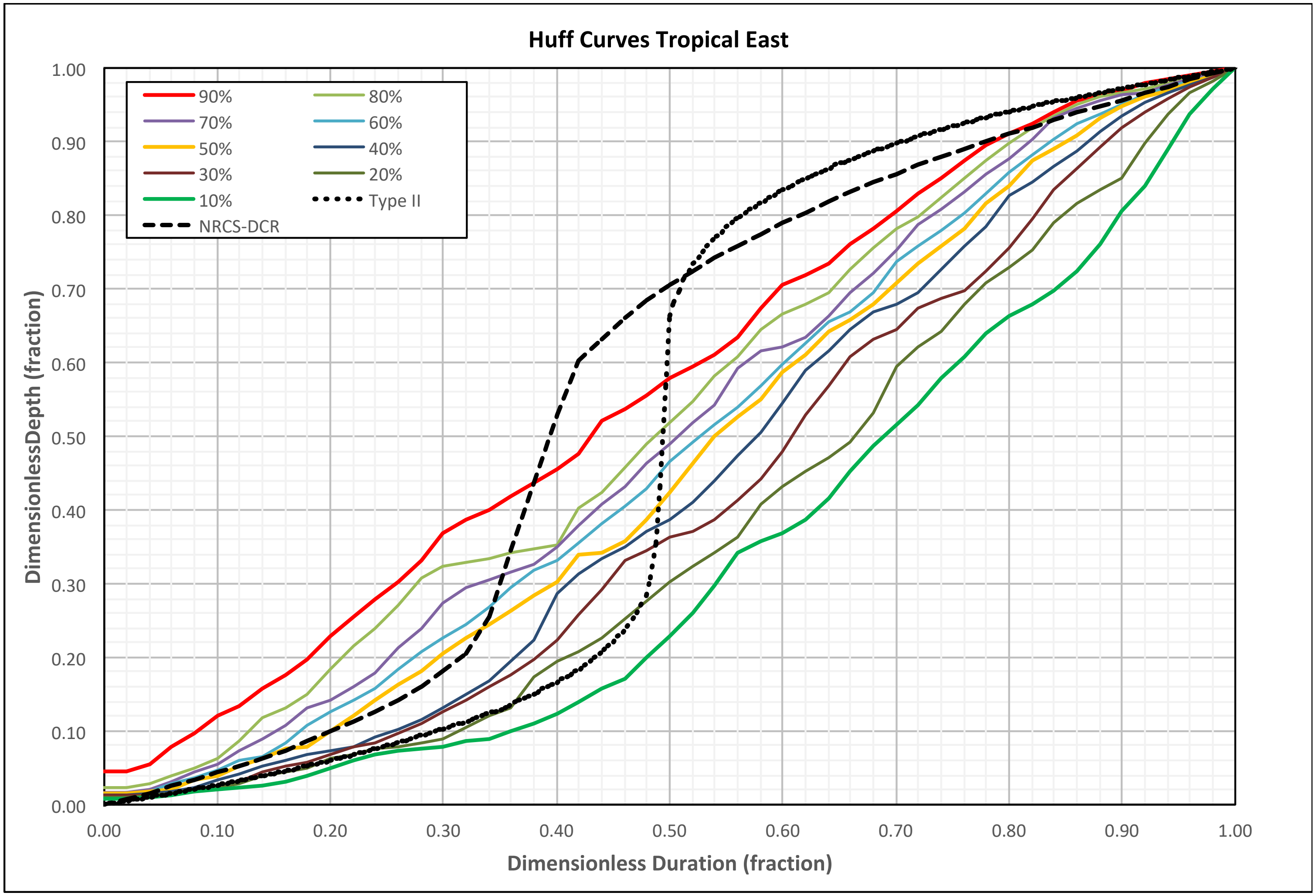

Figure 30. Raw Huff temporal curves for tropical storms east of the Appalachian Crest

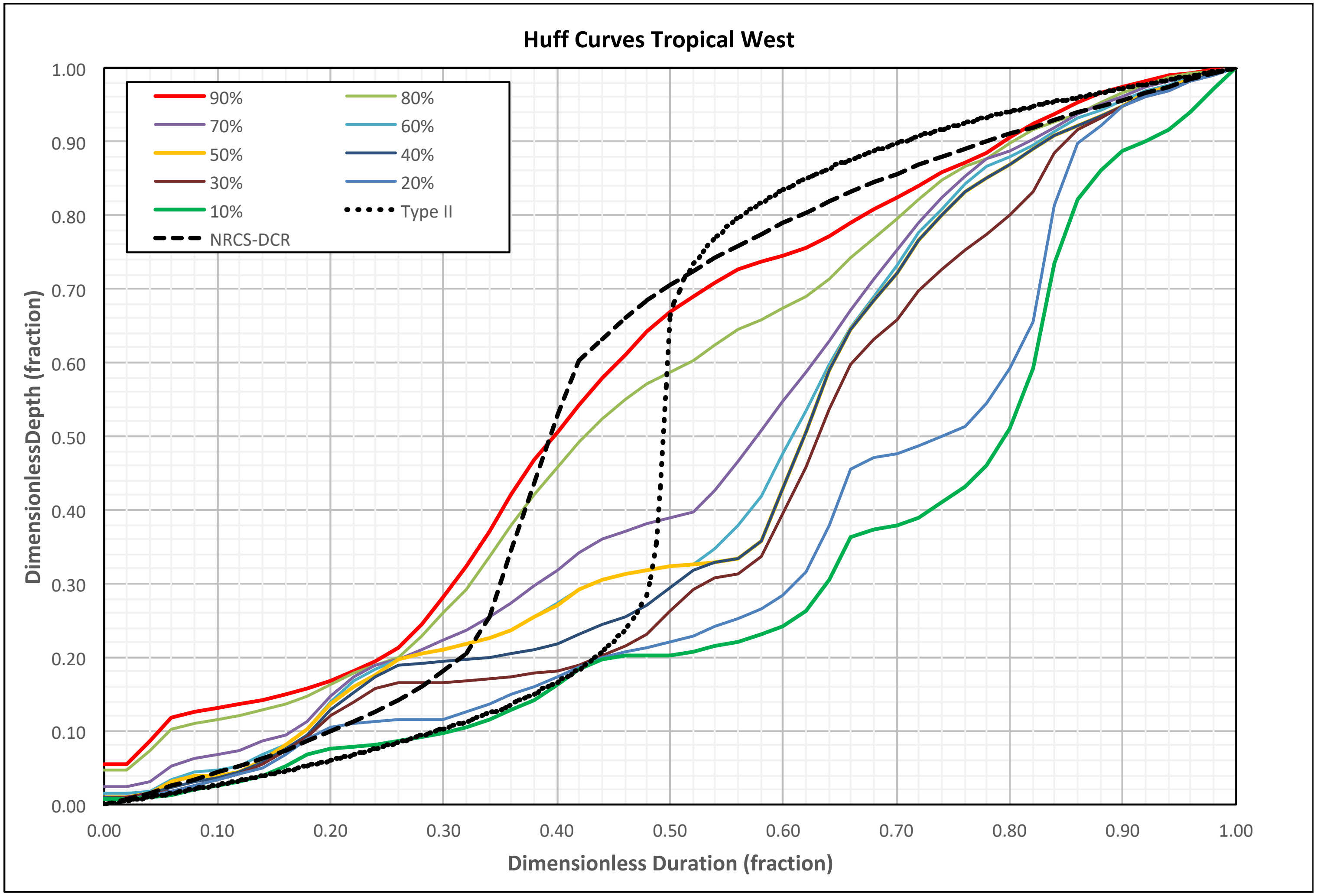

Figure 31. Raw Huff temporal curves for tropical storms west of the Appalachian Crest

3.0 Meteorological Description of Recommended Temporal Patterns

Each of the recommended temporal patterns were derived through visual inspection, comparisons, and discussions. This was completed by separating each storm by storm type (local, general, tropical) and location (east or west of the Appalachian Crest), then plotting the values as shown in Section 3. The recommended temporal patterns reflect the meteorological conditions that produce each storm type. Therefore, it is useful to understand the meteorology associated with each temporal pattern.

3.1 Local Storms West of the Appalachian Crest

For regions west of the Appalachian Crest, local storms are usually one of two types, either a thunderstorm developing in-place and interacting with topography or a Mesoscale Convective Systems (MSC). A typical MCS begins as an area of thunderstorms over regions to the west and north. As these storms begin to form, the predominantly westerly winds aloft move them in a generally eastward direction. The storms often undergo rapid development as they encounter increasingly warm and humid air from the Gulf of Mexico, usually associated with the low-level jet (LLJ) 3,000-5,000 feet above the ground. The area of thunderstorms will often form a ring around the leading edge of the mesoscale high and continue to intensify, producing heavy rain, damaging winds, hail, and/or tornadoes. An MCS will often remain at a constant strength as long as the LLJ continues to provide an adequate supply of moisture. The storms often move through the region during the evening or early morning hours from the west/northwest at rapid speeds. This is reflected in the temporal patterns as well, with the majority of the rainfall occurring within 6 hours for this particular storm type

Isolated thunderstorms in this region can produce some of the most significant short duration rainfall on record. These include storms such as Simpson, KY July 1939 and Glenville, WV August 1943 events. In these situations, extreme levels of moisture move into the region and are pooled along the topography where a combination of lift from atmospheric dynamics and topography can trigger severe storms and heavy rainfall. Again, these storms produce the most significant rainfall in 6 hours or less. The moisture source region for these storms is the Gulf of Mexico.

3.2 Local Storms East of the Appalachian Crest

For regions east of the Appalachian Crest, both isolated thunderstorms and modified MCSs can result in the local storm PMP. MCSs in this region are often modified by the topography of the Appalachians or through interaction with a front or remnant tropical moisture (Letkewitcz and Parker, 2010). In these situations, the intense rainfall can occur in separate bursts and last between 6 and 12 hours.

Isolated thunderstorms in this region can produce some of the most significant short duration rainfall on record. These include storms such as the Rapidan, VA storm of June 1995. In these situations, a very moist air mass moves into the region from the Atlantic Ocean. The moist air then requires a mechanism to cause lift in the air mass. This lift initiates the process of converting the moisture in the air to precipitation. Lift in these situations is caused by one or more of the following factors:

- Forced ascent as it encounters terrain
- Forces ascent as it encounters air masses with different density. This boundary between air masses with different densities is called a front or frontal boundary.
- Heating of the surface or lower levels of the atmosphere so that they are warmer than the air above. This results in positive buoyancy and rising air motion

Again, this storm type produces the most significant rainfall in 6 hours or less.

3.3 General Storms West of the Appalachian Crest

General storm patterns analyzed west of the Appalachian Crest showed a consistent pattern of accumulation through 24 hours. This is reflective of the meteorological environment associated with the general storm type. Moisture for these events is supplied by the Gulf of Mexico and is significantly altered by interactions with terrain in the region. The lift required to generate the rainfall is driven by the local topographic interactions as well as the thermodynamics associated with cold air aloft and frontal interactions at the surface. Because these factors can remain uniform over a large area during the storm events, general rainfall can occur for a significant period of time with similar intensities. These storms are most frequent in the fall and spring.

3.4 General Storms East of the Appalachian Crest

General storm patterns east of the Appalachian Crest are associated with frontal system either crossing the Appalachian or moving up the coast. Moisture for these events is supplied by the Atlantic Ocean. The lift required to generate the rainfall is provide by the frontal interaction as well as the topography of the Appalachians. These storms generally do not last as long as region west of the Appalachian crest because the storm pattern moves them out of the region quicker, but still produce significant rainfall over long durations and large area sizes. Again, these storms are most frequent in the fall and spring.

3.5 Tropical Storms West of the Appalachian Crest

Tropical systems west of the Appalachian Crest are significantly weaker than their counterparts to the east. This is a result of the storms having to move a long distance from their original source (either the Gulf of Mexico or Atlantic Ocean) and the fact that they have interacted with topography by the time they reach the region. This limits the amount of moisture available and the storm dynamics to convert moisture to rainfall. Therefore, the most intense rainfall with this storm type generally lasts less than 24 hours.

3.6 Tropical Storms East of the Appalachian Crest

Tropical systems east of the Appalachian Crest are the result of direct tropical system landfall in the region. In some cases the storms skirt the coastline moving south to north across the entire region (e.g. Hurricane Floyd September 1999) while at other times the storms may move east to west across the region. Each of the patterns can produce extreme rainfalls. The storms moving east to west into the region are also enhanced by interaction with the Appalachian Mountains. In all cases, moisture is supplied by the Atlantic Ocean. Intense rainfall can last 24 hours or longer with this storm type, especially when storms move south to north across the region.

4.0 Temporal Distribution Outfall Curves

A total of twenty-four temporal distribution curves were developed as part of this study with 12 curves utilized in the portion of Virginia west of the Appalachian Crest and 12 curves utilized in the portion of Virginia east of the Appalachian crest. The curves are organized into three time durations based on the Local, General, and Tropical storm types. When applying these temporal patterns, the user should determine whether the basin being analyzed is east or west of the Appalachian crest, then apply the appropriate curve by storm type.

The 24-hour curves were broken into two distinct types (A & B) as shown in Figures 31-36 in this section. The 24-hour "A" curves should be utilized when the 12-hour controlling PMP value differs from the 24-hour controlling PMP value meaning rainfall occurred within the controlling storm event after the 12-hour period. The 24-hour "B" curves should be utilized when the 12-hour controlling PMP value matches the 24-hour controlling PMP value meaning no additional rainfall occurred within the controlling storm event after the 12-hour period.

The derivation of the values presented in Figures 31-36 started with visual inspections of the rainfall accumulation patterns of the analyzed storms. This was followed by the manual development of characteristic curves intended to best represent the rainfall accumulation patterns by storm type. An iterative approach, which included several discussions and evaluations internally with AWA personnel and with Virginia DCR, was used along with manual manipulation of the values to obtain the recommended curves. The cumulative values were derived to ensure they started at zero and ended at one and produced an accumulation curve, which matched the characteristic distribution. The incremental values were derived to ensure they produced an accumulation intensity that replicated the characteristic distribution.

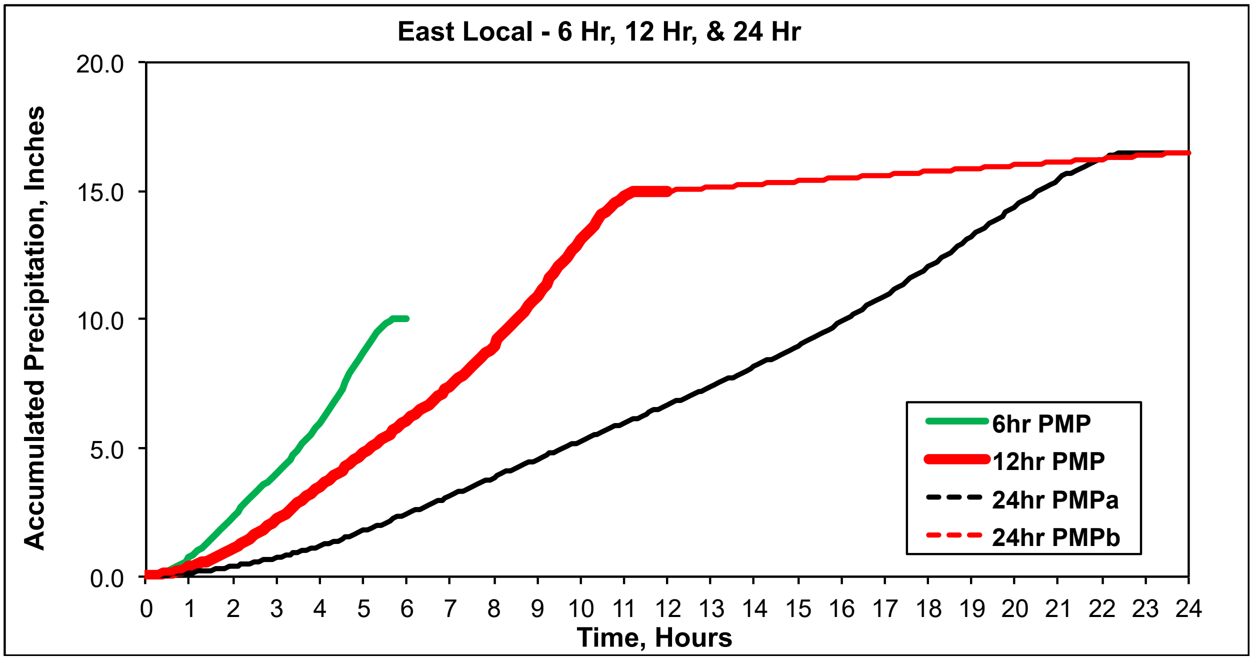

Figure 32. Local storm PMP temporal distribution curve for locations east of the Appalachian Crest

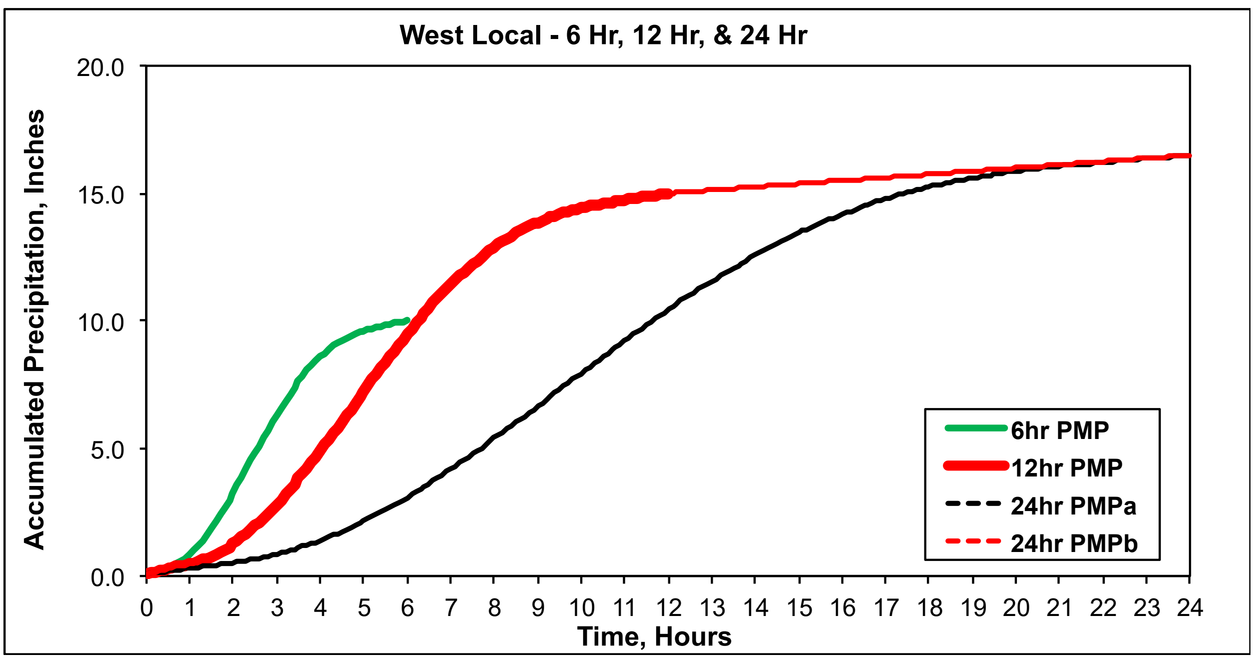

Figure 33. Local storm PMP temporal distribution curve for locations west of the Appalachian Crest

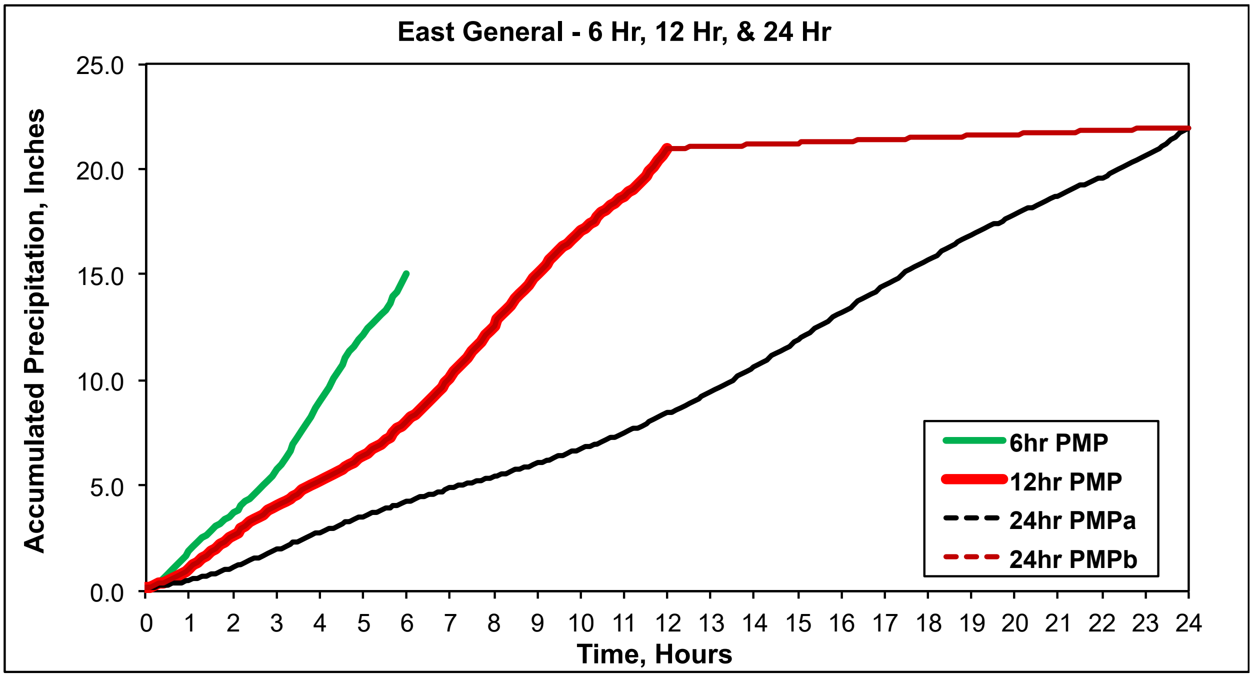

Figure 34. General storm PMP temporal distribution curve for locations east of the Appalachian Crest

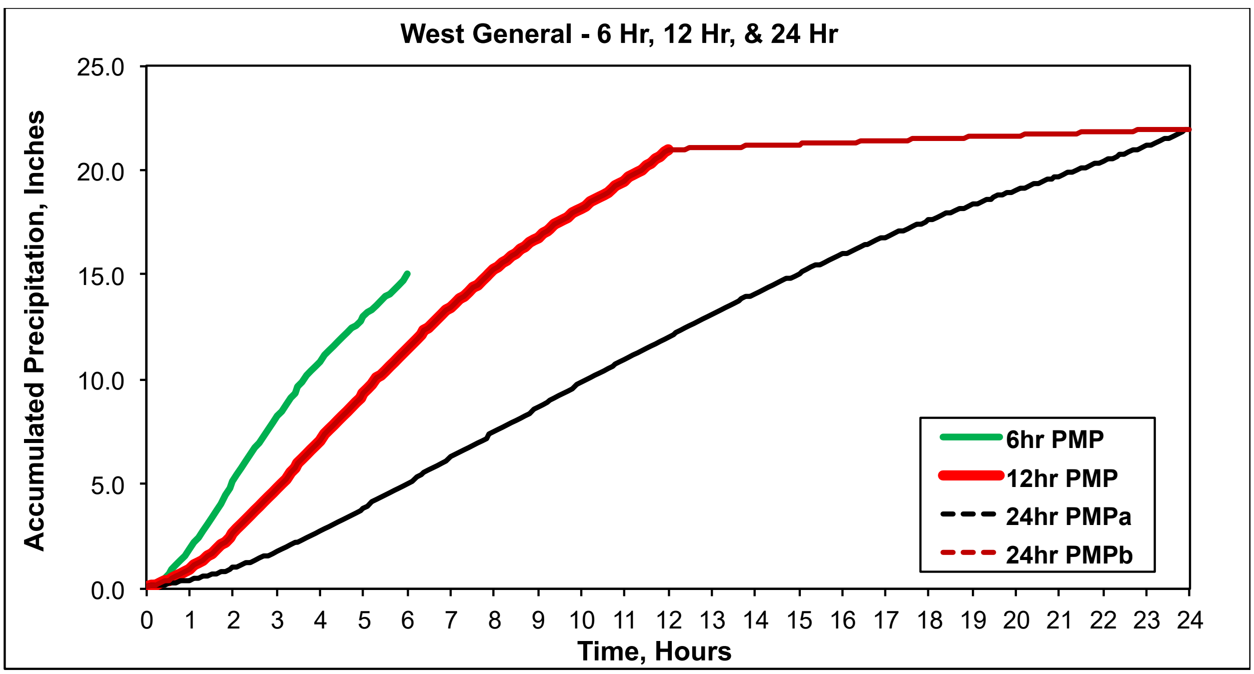

Figure 35. General storm PMP temporal distribution curve for locations west of the Appalachian Crest

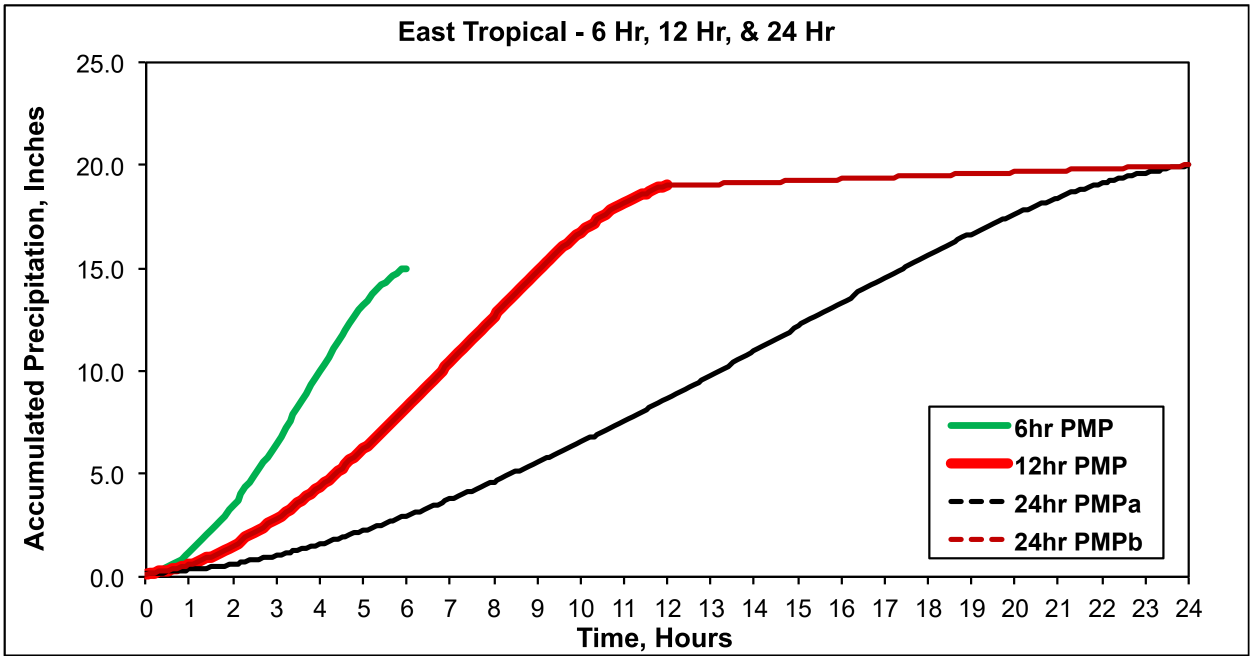

Figure 36. Tropical storm PMP temporal distribution curve for locations east of the Appalachian Crest

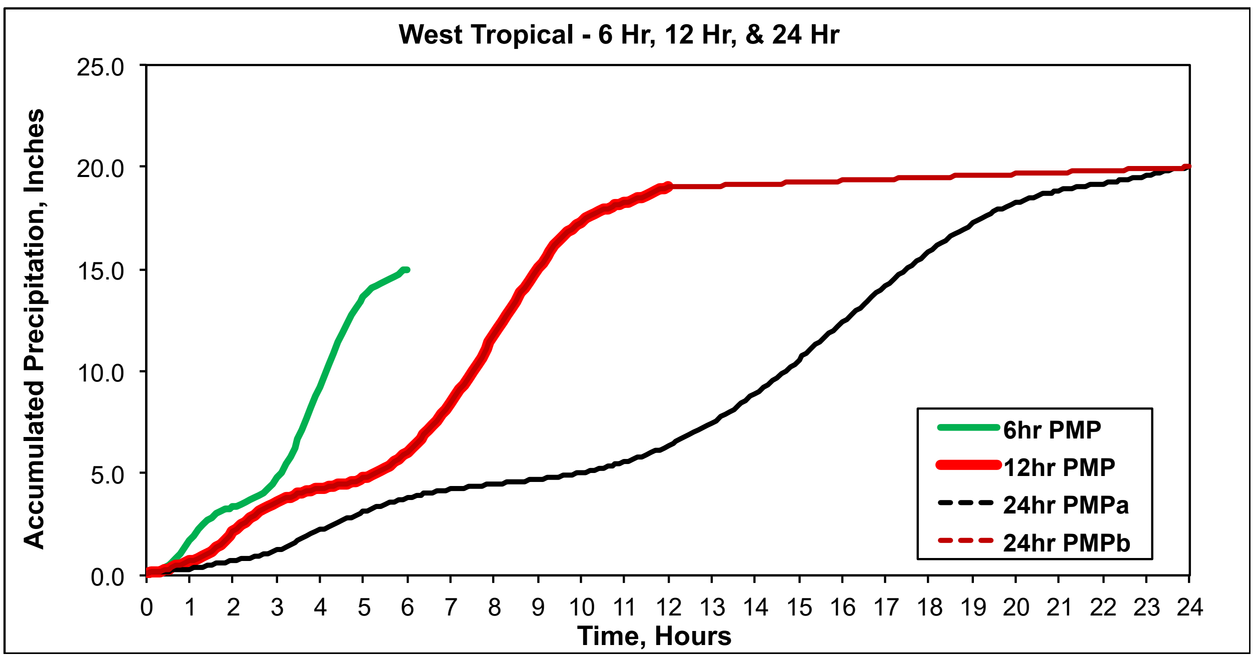

Figure 37. Tropical storm PMP temporal distribution curve for locations west of the Appalachian Crest

5.0 Application of Temporal Patterns to PMP Depths

Virginia DCR will provide guidance and training documents detailing how the temporal curves shown in Section 4.0 are to be applied in conjunction with the Commonwealth of Virginia PMP values / DCR Dam Safety Regulations. These documents should be consulted when applying the temporal curves discussed in this document to ensure proper application of the temporal patterns for a particular basin. Please note that any documents provided by DCR are considered “living documents” and could be updated at any time to include information that is more accurate. It is up to the user to consult / utilize the most up to date version of these two documents. Please consult DCR Dam Safety’s website at http://www.dcr.virginia.gov/dam-safety-and-floodplains/ to access said documents.

References

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Letkewicz, C.E., M.D. Parker, 2010: Forecasting the Maintenance of Mesoscale Convective Systems Crossing the Appalachian Mountains. *Wea. Forecasting*, **25**, 1179–1195.

Natural Resources Conservation Service (NRCS), Conservation Engineering Division. 2010, NRCS 5-point 24-hour dimensionless rainfall distribution for 24-hour events only *version 2.2.*

Virginia Department of Conservation and Recreation, Dam Safety Document, http://www.dcr.virginia.gov/dam-safety-and-floodplains/dcrdsdocs.

Appendix A

Temporal Analysis Excel Spreadsheet-provided via electronic format