JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 54, No. 5 AMERICAN WATER RESOURCES ASSOCIATION October 2018

Assessment of the Extreme Rainfall Event at Nashville, TN and the Surrounding Region on May 1–3, 2010

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Research Impact Statement: The maximum rainfall totals for some durations during the May 1–3, 2010 storm event at Nashville, TN exceeded the 1,000-year rainfall values from NOAA Atlas 14 warranting a reevaluation of design storms.

ABSTRACT: This paper analyzes the May 1–3, 2010 rainfall event that affected the south-central United States, including parts of Mississippi, Tennessee, and Kentucky. The storm is evaluated in terms of its synoptic setting, along with the temporal distributions, and spatial patterns of the rainfall. In addition, the recurrence interval of the storm is assessed and the implications for hydrologic structure designs are discussed. The event was associated with an upper-level trough and stationary frontal boundary to the west of the rainfall region, which remained quasi-stationary for a period of 48 h. Heavy rainfall was produced by two slow-moving mesoscale convective complexes, combined with abundant atmospheric moisture. Storm totals exceeding 330 mm occurred within a large elongated area extending from Memphis to Nashville. Isolated rainfall totals over 480 mm were reported in some areas, with NEXRAD weather radar rainfall estimates up to 501 mm. An extreme value analysis was performed for one- and two-day rainfall totals at Nashville and Brownsville, Tennessee, as well as for gridded rainfall estimates for the entire region using the Storm Precipitation Analysis System. Results suggest maximum rainfall totals for some durations during the May 1–3, 2010 event exceeded the 1,000-year rainfall values from National Oceanic and Atmospheric Administration Atlas 14 for a large portion of the region and reached up to 80% of the probable maximum precipitation values for some area sizes and durations.

(KEYWORDS: flooding; meteorology; precipitation; statistics.)

INTRODUCTION

On May 1–3, 2010, record-breaking rainfall dramatically affected the region surrounding Nashville, Tennessee. These rains led to severe flash flooding in the city and river basin flooding, particularly on the Cumberland River. The flooding caused 26 deaths in Tennessee and Kentucky, but the hardest hit area was Nashville (National Weather Service 2011). The storm broke previous record rainfall totals for a large portion of the south-central United States (U.S.). Prior to this event, the most extreme rainfall records in this region were associated with tropical cyclones, such as Hurricane Frederic in 1979 and Hurricane Katrina in 2005 (Durkee et al. 2012). This storm stands out, not only because it exceeded previous rainfall records by substantial margins but also because it was initiated by a midlatitude cyclone that interacted with extremely high atmospheric moisture

Paper No. JAWRA-17-0076-P of the *Journal of the American Water Resources Association* (JAWRA). Received July 5, 2017; accepted April 29, 2018. © 2018 American Water Resources Association. **Discussions are open until six months from issue publication**.

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Citation: Keim, B.D., W.D. Kappel, G.A. Muhlestein, D.M. Hultstrand, T.W. Parzybok, A.B. Lewis, E.M. Tomlinson, and A.W. Black. 2018. “Assessment of the Extreme Rainfall Event at Nashville, TN and the Surrounding Region on May 1–3, 2010.” *Journal of the American Water Resources Association* 54 (5): 1001–1010. https://doi.org/10.1111/1752-1688.12657.

levels. A number of studies have examined various aspects of this significant and impactful storm. The storm's physical mechanisms were explored by two studies (Moore et al. 2012; Moore et al. 2015), while others investigated the synoptic environment (Durkee et al. 2012), forecasting difficulties (Lynch and Schumacher 2014), and potential enhancement due to climate change (Lackmann 2013). However, a detailed analysis of the rareness of this storm and its implications for hydrological planning and risk management in the hardest hit areas has not been completed.

The May 2010 flood event that resulted from these record rains established the new flood of record for most of the Cumberland River (U.S. Army Corps of Engineers 2010). The flooding nearly overwhelmed the locks and dams along the river. At Cordell Hull Dam near Carthage, Tennessee, water was within 0.05 m of overtopping the lock gates (U.S. Army Corps of Engineers 2010). A similar situation occurred at Old Hickory Dam immediately upstream of Nashville, where water was within 0.16 m of overtopping the lock wall (U.S. Army Corps of Engineers 2010). Given the vicinity of Old Hickory to Nashville, overtopping of the lock gates would have resulted in a crest approximately 1.22 m higher in Nashville itself (U.S. Army Corps of Engineers 2010). Therefore, it is important to consider this storm event for future infrastructure development in the region, especially hydrologic structure designs. Given the extreme nature of the storm and its impacts, this paper (1) summarizes the meteorological conditions associated with the storm, (2) describes the spatial pattern and temporal distribution of the rainfall, (3) discusses the implications for probable maximum precipitation (PMP) studies, and (4) assesses this storm's recurrence interval using extreme value statistics.

This study adds to a growing list of case study papers on heavy rainfall, including Caracena and Fritsch (1983) on the Texas Hill Country Flash Floods of 1978, Leathers et al. (1998) on the rain on snow floods of January 1996 in North-Central Pennsylvania, Keim (1998) on the record rainfalls during the coastal storm in Maine in October 1996, Changnon and Kunkel (1999) who examined the rainstorms and flooding of July 1996 in Chicago, and Wang et al. (2016) who performed an attribution study of the Louisiana flood of August 2016, among many others. This storm is also one of several impressive rainfall events that have occurred across the Eastern U.S. over the past 8–10 years, including in South Carolina (October 2–4, 2015), West Virginia (June 23–24, 2016), Ellicott City, Maryland (July 30, 2016), and Hurricane Harvey's rains in southeastern Texas (August 25–31, 2017) (see the list of reports from the Hydrometeorological Design Studies Center at http://www.nws.noaa.gov/oh/hdsc/aep_storm_analysis/). Collectively, this assemblage of recent heavy rainfall events does raise the question whether global climate change is having an impact on the heavy rainfall climatology of the region. Two recent papers did note that climate change enhanced the probability for such events to occur, e.g., in Louisiana in August 2016 (van der Wiel et al. 2017) and during Hurricane Harvey in Texas (van Oldenborgh et al. 2017).

METEOROLOGICAL SETTING OF STORM

At 1200 UTC on May 1, 2010, the entire eastern half of the U.S. was in some way under the influence of an occluded midlatitude cyclone with its associated surface low pressure center anchored over North Dakota, Minnesota, and southern Manitoba, Canada (Figure 1). A warm front extended across the Great Lakes into southern New England, with an associated cold/stationary front extending over the Mississippi River Valley. Precipitation was ongoing across western Tennessee and Kentucky. At this time, the Nashville region and much of the southeastern U.S. was within the warm sector of the storm system.

The next set of images at 1200 UTC on May 2 shows that the center of low pressure migrated slowly southeastward, and the trailing cold front only advanced eastward modestly. The slow movement of the surface front was associated with the stagnant 500 mb pattern characterized by winds parallel to the frontal boundary. Rainfall was enhanced by the propagation of a series of 500 mb shortwave troughs that moved over the Nashville region on May 1 and 2 and initiated a pair of slow-moving mesoscale convective complexes (MCCs). Most of the rain fell during these two calendar days. By May 3, the cold front had moved eastward past Nashville, ending the rainfall over the Nashville region. Little rainfall was produced by the secondary cold front that followed closely behind.

While the overall synoptic setting of the storm was not particularly unusual, the quasi-stationary nature of the storm, combined with very high precipitable water levels that originated over the Caribbean and Gulf (Higgins et al. 2011; Lynch and Schumacher 2014), were unusual. An extremely moist atmospheric air mass was in place that originated from the Caribbean and Gulf of Mexico, as shown in Figure 2 by the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) atmospheric trajectory model (Draxler and Rolph 2014; Rolph 2014). This model can be used to determine the source region of an air particle using a backward trajectory over a period of days, which in this case is stepped back in time over 72 h. This flow regime from the Caribbean, termed the

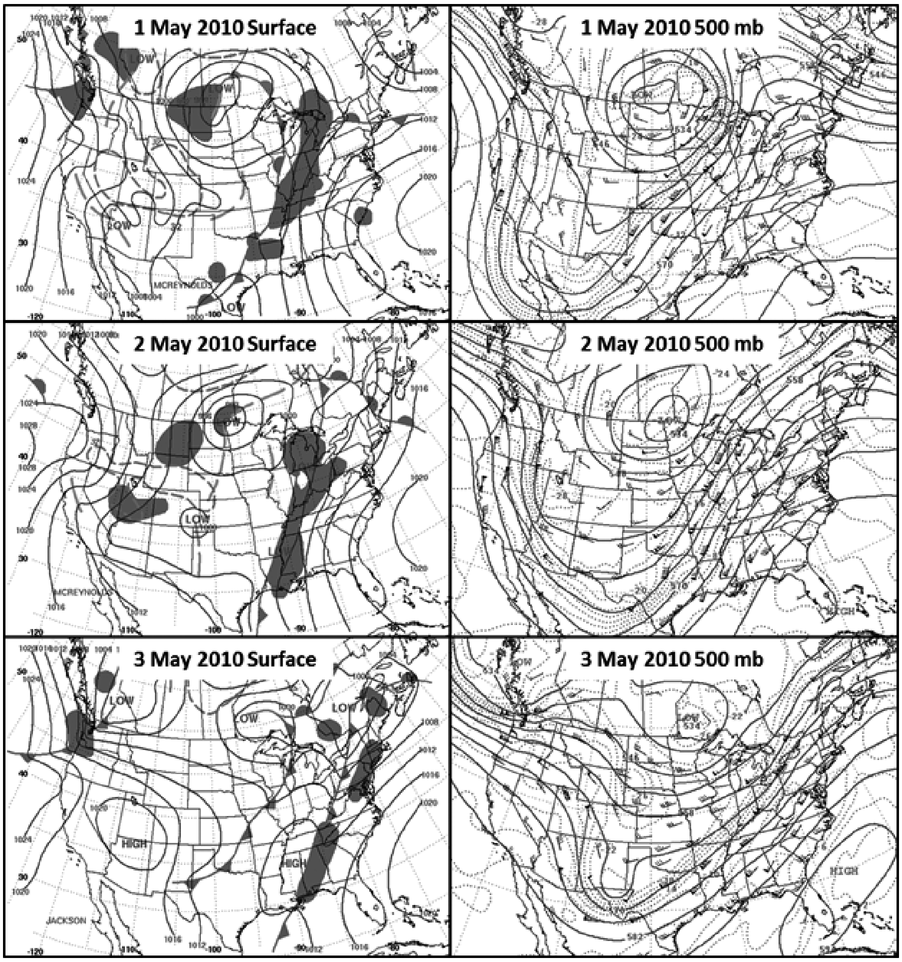

FIGURE 1. Composite weather maps depicting surface atmospheric pressure (solid lines), areas of precipitation (shaded), and frontal positions (left column) and 500 millibar (mb) heights (solid lines), temperature (dashed lines), and wind barbs depicting wind speed and direction (right column) at 1200 UTC (0700 EST) for May 1–3, 2010. Maps are adapted from the Daily Weather Map series provided by the National Oceanic and Atmospheric Administration's (NOAA) Hydrometeorological Prediction Center.

Maya Express by Dirmeyer and Kinter (2009), is one of several types of "atmospheric rivers" (Mahoney et al. 2016) that are responsible for rapid moisture transport from tropical regions to the midlatitudes. The highest precipitable water values ever observed in 60 years of records were measured at both Jackson, Mississippi and Nashville, Tennessee on May 1–3, 2010. This rare combination of events allowed the historic flooding event to unfold. For a more detailed synoptic analysis of the storm, refer to Durkee et al. (2012).

SPATIAL AND TEMPORAL PATTERNS OF RAINFALL

The primary hydrometeorological rainfall analysis tool used in this study is the Storm Precipitation Analysis System, or SPAS (Parzybok and Tomlinson 2006). SPAS is a gridded rainfall analysis software package that combines all available rainfall data, including rain gauge data (daily, hourly, and subhourly), supplemental/bucket survey rainfall data, dynamically calibrated NEXRAD weather radar data, and climatological basemaps, to produce a high-resolution, spatially continuous gridded analysis of rainfall amounts. Rainfall values are produced at time intervals as short as five minutes, and at spatial scales as fine as 1 km^2 (Parzybok and Tomlinson 2006). The system is designed to reproduce the spatiotemporal pattern of a rainfall event across a region. It provides highly accurate estimates of rainfall values between rainfall observation locations, thereby allowing for an accurate representation of accumulated rainfall in both space and time across the rainfall domain. In our database of storms across the U.S., the Nashville storm is No. 1208, which appears in several of the figures used in this paper.

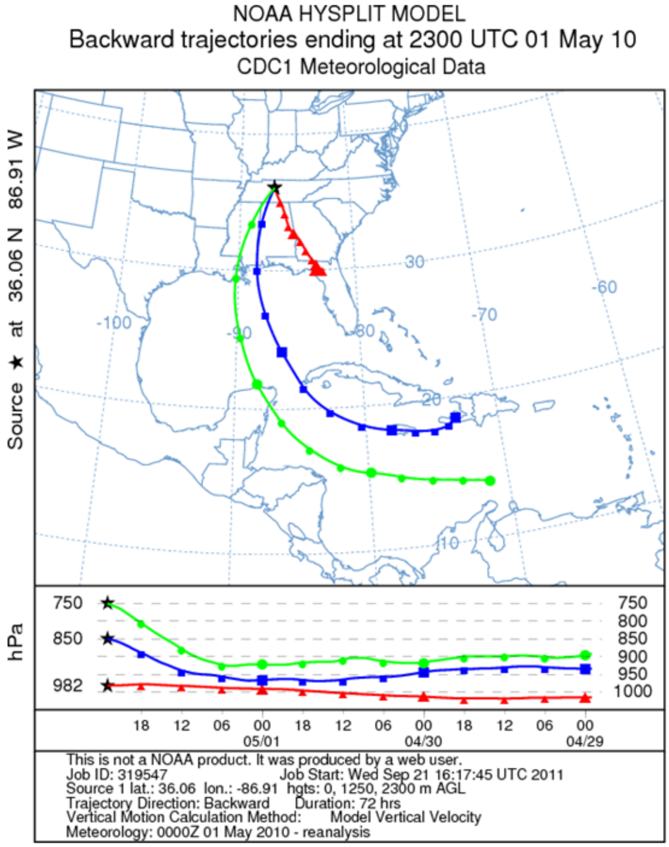

FIGURE 2. HYSPLIT backward trajectory for the May 1–3, 2010 rainfall event near Nashville, Tennessee, showing the source region for the moisture-rich air mass in place during the storm. Data are from the NOAA's Air Resources Laboratory. HYSPLIT, HYbrid Single-Particle Lagrangian Integrated Trajectory.

Additional details on the SPAS system are found in Parzybok and Tomlinson (2006).

While rainfall totals exceeding 125 mm were observed from northern Mississippi to central Kentucky, the heaviest rainfall produced by this storm system was concentrated in an elongated band extending from Memphis to Nashville (Figure 3). The analyzed rainfall fell from May 1 at 0100 UTC to 3 May at 1200 UTC. Storm totals exceeded 330 mm for most of the area in this band. Even higher precipitation totals were nested within the band, including storm totals of over 480 mm at multiple locations. The SPAS analysis produced a storm maximum rainfall total of 501 mm at 36.06°N and 86.91°W, or about 6 km north-northeast of Camden, Tennessee. This location is the storm center for this event.

An hourly time series of rainfall from May 1 at 0100 UTC to May 3 at 1200 UTC at the storm center shows several intense short-duration rainfall periods, imbedded within two longer periods of heavy rainfall (Figure 4). The timing of the two waves of heavy rainfall corresponds to the passage of two upper-level shortwaves and associated MCCs. The first wave of rain began on May 1 at 1100 UTC and ended about 0100 UTC on May 2, with two hourly accumulations that exceeded 25 mm. The first wave produced over 250 mm of rain. The second wave of rain on May 2 began after 1200 UTC and ended around 2300 UTC, with three hourly accumulations that exceeded 25 mm. The second wave produced an additional 200 mm of rain.

HYDROLOGIC DESIGN APPLICATION

To quantify the magnitude and extent of the rainfall, a depth–area–duration table was generated for the storm event using SPAS. The maximum average depth of precipitation at various time durations was computed for area sizes up to 129,500 km^2 (50,000 mi^2) surrounding the storm center (Table 1). The nontraditional area sizes in km^2 are used here to maintain continuity with other hydrometeorological publications used in the U.S. (i.e., U.S. Army Corps of Engineers 1973; Schreiner & Riedel 1978 storm studies). This type of analysis is very important for assessing hydrological impacts, because it provides the volume of rainfall that fell over various area sizes during the storm. This analysis shows that an average of 197 mm of rain fell across a region of 129,500 km^2 (50,000 mi^2) over a 60-h period — an area larger than the entire state of Tennessee. In addition, 416 mm of rainfall fell over an area of 5,180 km^2 (2,000 mi^2) over the same duration, and 118 mm was the absolute one-hour rainfall maximum, which fell at latitude 35.61°N and 89.26°W, near Brownsville in western Tennessee. The impressive amount of rain that fell over such a large area compounded by the extreme rainfall intensity over short time durations help to explain why this event caused such catastrophic flooding throughout the region.

To further demonstrate how impressive these rainfall totals are for the region, they are compared to PMP estimates from *Hydrometeorological Report No. 51* (Schreiner and Riedel 1978) for varying durations and area sizes. PMP as defined by Corrigan et al. (1999, 5) is "theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of the year." As such, rainfall values even approaching PMP estimates would suggest a very rare storm. The 48-h/ 25,900 km^2 (10,000 mi^2) and the 48-h/51,800 km^2 (20,000 mi^2) rainfall values are found to be

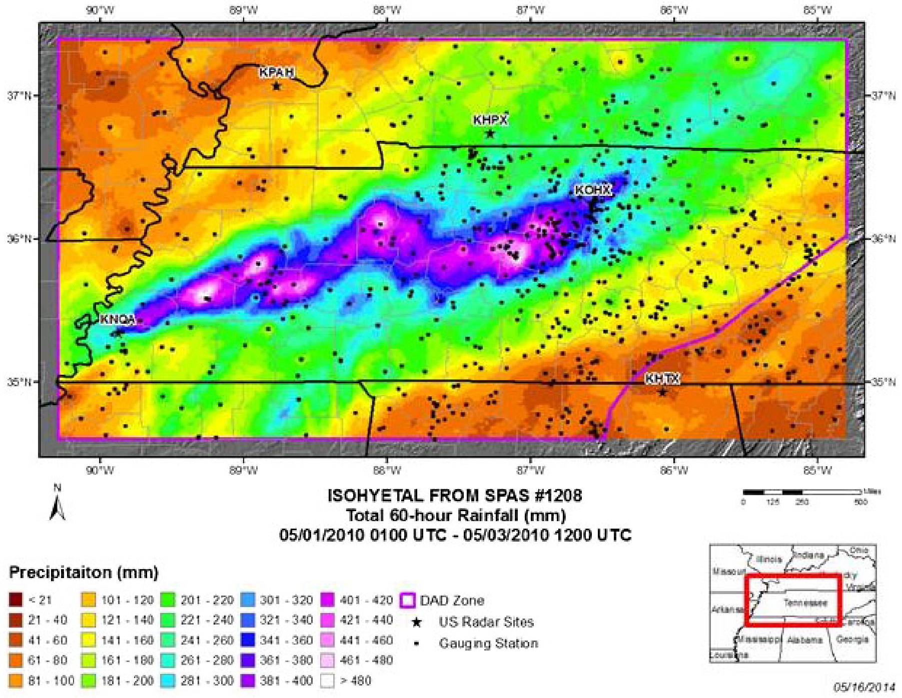

FIGURE 3. Sixty-hour rainfall totals for May 1 (0100 UTC) to May 3 (1200 UTC) 2010 in millimeters. The rainfall isohyetal pattern is generated by the Storm Precipitation Analysis System (SPAS).

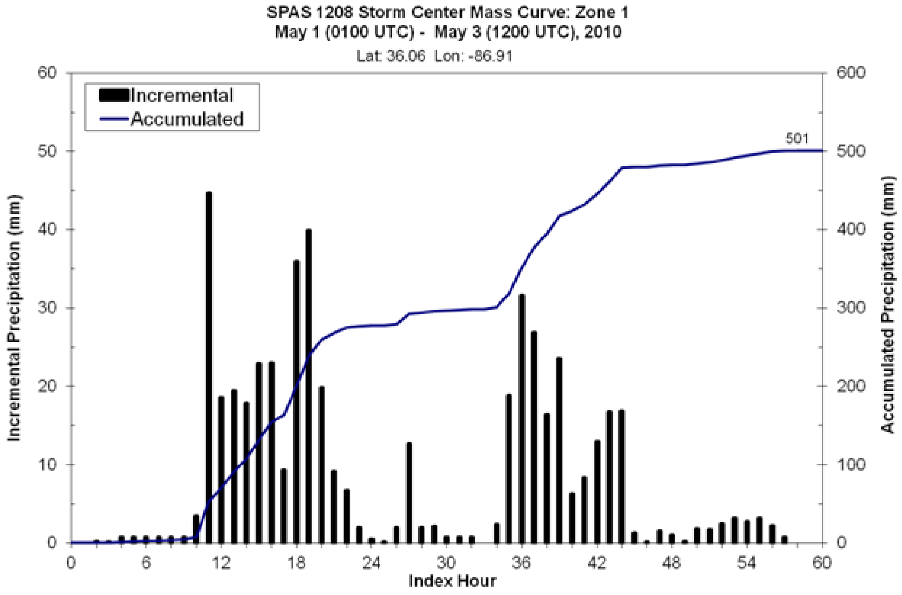

FIGURE 4. Hourly accumulations and incremental rainfall at the May 1–3, 2010 Nashville storm center from the SPAS analysis beginning on May 1, 2010 at 0100 UTC and progressing for 60 h.

approximately 80% of the PMP values for the region (Schreiner and Riedel 1978). This gives testament to the unusual nature of this storm. This has utility because PMP is one of the most important parameters used to develop design criteria for dams and evaluate existing structures for dam safety.

In the determination of PMP values, not only are rare storms analyzed but they are also maximized to estimate how much more rainfall could have been produced if the maximum amount of atmospheric moisture had been available to the storm at the time of its occurrence. This process, called storm

TABLE 1. Maximum areally averaged depths of precipitation at 1-, 3-, 6-, 12-, 18-, 24-, 36-, 48-, and 60-h durations for areas from 1.0 to 129,500 km^2 generated from the SPAS analysis for May 1, 2010 (0100 UTC) to May 3, 2010 (1200 UTC) Nashville storm.

		Maximum Average Depth of Precipitation (mm) May 1 (0100 UTC)–May 3 (1200 UTC) 2010								
		Duration (h)								
Area (km^2)	**Area (mi^2)**	**1**	**3**	**6**	**12**	**18**	**24**	**36**	**48**	**60**
1.0	0.4	118	227	389	451	466	467	492	499	501
2.6	1.0	116	224	383	445	458	460	485	492	494
26	10	113	224	380	440	456	459	484	486	494
65	25	109	219	372	434	449	452	480	484	489
130	50	103	210	359	424	437	440	474	478	483
259	100	94	196	336	404	420	422	465	470	475
389	150	91	187	321	390	407	408	455	466	469
518	200	87	181	309	381	395	401	451	460	465
777	300	80	171	294	368	383	388	440	453	458
1,036	400	75	164	281	358	372	379	429	448	453
1,295	500	71	157	270	343	364	371	428	442	449
2,590	1,000	58	134	228	319	337	343	416	428	433
5,180	2,000	45	106	188	282	304	321	399	410	416
12,950	5,000	35	76	133	235	262	278	359	376	381
25,900	10,000	25	58	96	188	214	219	310	330	334
51,800	20,000	17	41	74	138	161	182	260	280	283
129,500	50,000	8	22	40	81	104	117	168	194	197

maximization, requires that the atmospheric moisture actually associated with the storm system be quantified using surface dew point temperature observations (World Meteorological Organization 2009). This dew point temperature value is known as the storm representative dew point (Schreiner and Riedel 1978). To maximize the rainfall, a climatological maximum dew point temperature is determined for the same location where the storm representative dew point was observed. The 100-year return period maximum dew point temperature is often used for the maximum dew point temperature value (e.g., Kappel et al. 2014, 2015a).

Using methods provided by the World Meteorological Organization (2009) PMP Manual, the storm representative dew point temperature location for this storm was determined to be 31.50°N and 90.00°W, approximately 360 miles south-southwest of the storm center. It is inappropriate to use dew point values within the area of rainfall production, as dew point temperatures under these conditions do not always reflect the incoming air mass. This location was determined to best represent the atmospheric environment that contributed to the event's rainfall production. A parcel trajectory model (HYSPLIT; Draxler and Rolph 2014) was used to assist in identifying this location and timing ahead of the storm from which to select the dew points (Figure 2). Surface dew point temperature observations surrounding the storm representative dew point location were collected and the 12-h average dew point temperature value was determined by averaging observed dew point temperature values from the following weather stations: Jackson, Mississippi (KJAN); McComb, Mississippi (KMCB); Hattiesburg, Mississippi (KHBG); and Slidell, Louisiana (KASD). From these stations, the storm representative dew point was determined to be 24.0 °C.

To determine PMP values like those provided in *Hydrometeorological Report No. 51* (Schreiner and Riedel 1978), storms are "maximized" to increase the storm's rainfall to its full potential based on the largest possible dew point for the time of year in which the storm occurred, plus or minus a window of time of two weeks from the occurrence date of the storm. In this case, the 100-year 12-h recurrence interval value for maximum dew point temperatures in the southeastern U.S. from Tomlinson et al. (2013) was used to maximize this storm. The 100-year 12-h recurrence interval value was determined to be 25.0 °C. Assuming a saturated atmosphere, these dew point temperatures (storm representative dew point temperature of 24.0 °C and the 100-year return period dew point temperature of 25.0 °C) correspond to precipitable water values of 72 and 78 mm, respectively (U.S. Department of Commerce 1951). Using procedures recommended by the World Meteorological Organization (2009) PMP Manual, these two values produce a maximization factor of 1.08 (78 mm/72 mm), which indicates that in a worst-case scenario, this storm could have produced 8% more rainfall than it did, assuming the maximum level of moisture was available to the storm for rainfall production and the storm dynamics remained constant. In hydrologic design, these larger values (Table 1 values multiplied by 1.08) would be used to represent this storm at the location of occurrence, and then the storm could be transposed to other locations and modified according to the World Meteorological Organization (2009) guidelines. Factoring in maximization and transposition, recent site-specific PMP analysis have shown that the inclusion of this storm impacts PMP estimates for parts of the south-central U.S. (Tomlinson et al. 2013; Kappel et al. 2014, 2015a, b).

RECURRENCE INTERVALS

Recurrence intervals are often calculated for an event for different time durations, typically ranging from hours to days (i.e., see Keim 1998). This often leads to confusion because the recurrence interval values vary depending on the duration that is being examined. For example, the 100-year return period calculated for a 24-h duration is not the same as the 100-year return period calculated for a one-day duration (Hershfield 1961). Return periods calculated for 24-h durations are determined from the greatest 24-h rainfall that occurred during an event, which is derived from hourly rainfall observations that are passed through a moving window and can span calendar days. However, the number of sites that record hourly rainfall observations is limited. Therefore, it is common to calculate return periods for observational day durations, which are collected at a larger number of sites and therefore provide improved spatial coverage of an event. However, using observational day data limits the amount of temporal analysis that can be applied to the data. Conveniently, SPAS provides hourly rainfall values for each grid cell for the duration of the event, allowing for both a thorough temporal analysis and a complete spatial analysis of the storm's recurrence intervals. In this analysis, both SPAS data combined with regional data from *NOAA Atlas 14* (NA14) Volume 2 (Bonnin et al. 2006) are used in one analysis and individual station data are analyzed in another.

With both datasets, an extreme value analysis was performed for the entire region using quantile estimating methods identical to those used in the current Precipitation Frequency Atlas of the U.S. (NA14) Volume 2. The quantile estimates in NA14 were determined using annual maximum series (AMS) rainfall data, which are converted to represent partial duration series (PDS) data. AMS data were used in conjunction with L-moment analysis and the generalized extreme value (GEV) distribution (Hosking 1990; Stedinger et al. 1993; Hosking and Wallis 1997). L-moments are defined as expectations of certain linear combinations of order statistics (Hosking 1990). They are analogous to conventional moments with measures of location (mean), scale (standard deviation), and shape (skewness and kurtosis). The GEV distribution is a mathematical form that incorporates Gumbel's Type I, II, and III distributions for maxima (Stedinger et al. 1993). The parameters of the GEV distribution are the ξ (location parameter), α (scale parameter), and k (shape parameter). The Gumbel, Type I, is obtained when $k = 0$. For $k > 0$, the distribution has finite upper bound at $\xi + \alpha/k$ and corresponds to the Type III distribution for maxima that is bounded from above (Stedinger et al. 1993). Stations with records of sufficient length (30 years for daily stations and 20 years for hourly stations) extending up to December 2000 were used in NA14 (Bonnin et al. 2006) and this criterion was used here. The stations were grouped into small regions and the appropriate distribution function among the GEV family of distributions was determined for each region using goodness-of-fit tests. Once determined, the appropriate distribution was used to fit the AMS and generate quantile estimates at each station, which are then adjusted to represent precipitation frequency estimates via a PDS (Bonnin et al. 2006).

The quantile estimates were spatially interpolated to produce continuous quantile estimates for the entire region. To determine the recurrence intervals for the extreme rainfall event in the Nashville region, quantile estimates for recurrence intervals of two years through 1,000 years were extracted from NA14 for the center of each SPAS grid cell for the 24-h period with the heaviest rainfall. The SPAS rainfall values were translated into average recurrence intervals based on where they fell in the spectrum of recurrence interval estimates from NA14. Results are presented in Figure 5. A significant area in central Tennessee and part of northern Alabama has 24-h maximum rainfall recurrence intervals of 1,000 years or more, surrounded by progressively larger areas exceeding the 500- and 100-year recurrence intervals.

To further put this rainfall event into perspective, the recurrence intervals for rainfall totals at the stations of Nashville and Brownsville, Tennessee at one- and two-day durations were determined, and compared with the recurrence intervals of previous heavy rainfall events at these sites. Note that the Nashville and Brownsville analyses were an "at-site" statistical analysis, whereas the comparison between SPAS data and NA14, previously discussed, provided spatially continuous recurrence intervals based on a regional analysis. Nashville has a rainfall record of 74 years, while at Brownsville there are 109 years of

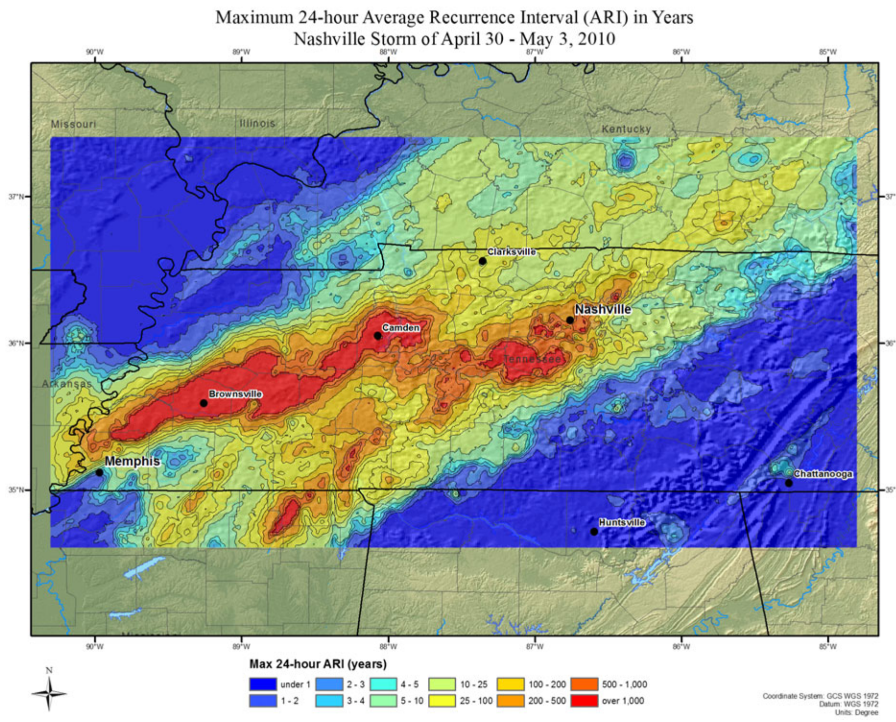

FIGURE 5. The maximum 24-h recurrence intervals in years generated from hourly SPAS rainfall values for the May 1–3, 2010 Nashville storm.

data. Nashville was chosen because it is the location of the historic flooding and Brownsville, Tennessee was chosen because it is located near the area that received the maximum precipitation during the event. The recurrence intervals for the top five largest events at each location for one- and two-day durations are displayed in Tables 2 and 3. Again, the recurrence interval estimates were determined based on the GEV distribution, which was the best fit for both locations. For all four instances, the largest rainstorm on record occurred during this 2010 event. In Nashville, the recurrence interval for the storm at the one-day duration was nearly 800 years (Table 2). In addition, the first and third highest one-day rainfall events occurred on May 2 and May 1, respectively. When calculated for the two-day duration, the rainfall total is 345 mm, which is over twice the magnitude of the previous largest two-day rainfall event at Nashville produced by the remnant of Hurricane Frederic in September 1979. The recurrence interval for the storm at Nashville was determined to be almost a 14,000-year event, and greatly exceeds the recurrence interval for any other two-day duration storm. This recurrence interval is extrapolated well beyond the Nashville period of record and as a result, this return interval must be interpreted judiciously; however, the rarity of this event does punctuate just how large of an outlier this storm is relative to the other rainfall events at Nashville. The one-day maximum rainfall event at Brownville is also produced by the May 2010 event at 406 mm (Table 3). This value is also over twice the value of the previous largest storm on record. The recurrence interval at Brownsville is over 900 years for the one-day duration. Due to its location further west, the majority of the rain fell at Brownsville on May 1, 2010.

TABLE 2. Top five heaviest one- and two-day rainfall events at Nashville, Tennessee with estimated recurrence interval for each storm event.

Top 5	One-day precipitation (mm)	GEV (years)
May 1, 2010	184	792
September 13, 1979	168	308
June 4, 1998	161	205
May 6, 1984	129	35.3
March 12, 1975	120	21.2
	Two-day precipitation (mm)	**GEV (years)**
May 1, 2010	345	13,833
September 13, 1979	170	33
June 4, 1998	154	18
May 6, 1984	153	17.8
March 12, 1975	152	17.0

Notes: GEV, generalized extreme value.
Period of record for this station extends from January 1940 to December 2013.

TABLE 3. Top five heaviest one- and two-day rainfall events at Brownsville, Tennessee with estimated recurrence interval for each storm event.

Top 5	**One-day precipitation (mm)**	**GEV (years)**
May 1, 2010	406	929
December 25, 1987	185	38.0
January 29, 1956	170	27.1
October 6, 1910	152	17.7
March 17, 1919	152	17.7
	Two-day precipitation (mm)	**GEV (years)**
May 1, 2010	457	1,093
December 25, 1987	226	34.8
January 8, 1930	208	24.2
January 29, 1956	202	21.6
November 29, 2001	194	18.1

Note: Period of record for this station extends from September 1895 to December 2013.

The two-day recurrence interval at Brownsville is over 1,000 years.

SUMMARY AND CONCLUSIONS

The heavy rainfall event of May 1–3, 2010 was caused by the interaction of two upper-level shortwave troughs with a stationary front and abundant atmospheric moisture that persisted in the region for nearly 48 h. This storm produced record amounts of rainfall and caused catastrophic river flooding in Mississippi, Tennessee, and Kentucky. The highest rainfall totals from the event occurred along a band from just north of Memphis to Nashville, and set one- and two-day rainfall records throughout the region, exceeding previous records set by the remnant of Hurricane Frederic in 1979 by over 100%. The maximum 24-h rainfall totals during the period of May 1–3, 2010 exceeded the 1,000-year rainfall estimates in a large portion of the region. Rainfall values for the region for some durations and drainage area sizes fell within 80% of NOAA PMP estimates (Schreiner and Riedel 1978) and are controlling (sets the upper limit) of updated PMP values in several recent site-specific and region PMP studies (e.g., Kappel et al. 2014). After factoring in maximization and transposition of this storm, our data show that recent site-specific PMP analyses would indeed be impacted in other parts of the south-central U.S. by this storm. This storm was a remarkably efficient rain producer; PMP maximization found that this storm in a worst-case scenario would have only produced 8% more precipitation than the event that actually occurred. While this efficiency is impressive, it is important to recognize that greater rainfall totals are theoretically possible in the region and to account for that possibility in future hydrological planning and risk management.

There is clearly a need to continue to analyze both old and new storms to further understand and refine our understanding of PMP across the U.S. and beyond. The implications are that dam design across the U.S. is either over- or underengineered. The only way to make this determination is through PMP analysis, which is frequently conducted on a site-specific basis — in other words for only a single watershed and dam at a time. As such, results (varying rainfall amounts over varying area sizes for durations from 1 to 60 h) from this storm can be used as candidate values in PMP analysis, along with similar information from other storms. With that in mind, the methods used in this paper also provide a framework for analysis of other storms of varying shapes and sizes relevant in the world of PMP — down to sizes of less than 1 km^2 to well over 50 km^2. However, we note that these analyses are only as robust as the data quantity and quality available. Furthermore, Kunkel et al. (2013) and van der Wiel et al. (2017) suggest that impacts of climate change also be considered in such analyses.

ACKNOWLEDGMENTS

This paper was supported by NOAA Grants NA080AR4320886 and NA13OAR4310183. Original datasets are from the National Oceanic and Atmospheric Administration.

LITERATURE CITED

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