Real-time Average Recurrence Interval Rainfall Maps for the U.S.

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ABSTRACT

Describing floods in terms of an average recurrence internal (ARI) or "return period" (100-year) has been used for decades to convey the rareness of major flooding events. However, describing the intensity of heavy rainstorms in a similar manner has not been as routine, but provides an equally good perspective of extreme rainfall events. Although the ARI of rainfall does not necessarily equate to a flood of the same ARI, ARI maps of rainfall provide an excellent indicator of flooding potential. Plus, real-time ARI maps of rainfall provide forecasters and media outlets a critical alternative to stream gauge information during rain-induced flooding events, especially considering flooding can often destroy or cause stream gauges to malfunction.

The concept of ARI rainfall mapping has been used in recent government documents pertaining to extreme rainstorms. However, this paper/presentation will introduce the concept of real-time ARI rainfall maps, a new tool for conveying the magnitude of heavy rainfall events to the public. This is especially important as society and infrastructure become increasingly more vulnerable and impacted by extreme rainfall events, making timely, accurate and informative rainfall information paramount to protecting property, saving lives and efficiently managing water. Expressing the rarity (or commonness) of rainfall in terms of an ARI provides an objective and useful perspective of the rainfall that most people understand, even for those not familiar with the rainfall in a particular area. Real-time ARI rainfall maps provide a new and powerful means for the media to communicate where the rainfall is most unusual and most apt to produce flooding.

The rainfall-to-ARI conversion is based on official rainfall frequency data published by the National Atmospheric and Oceanic Administration (NOAA) together with high-resolution (1 km x 1 km) gauge-adjusted radar rainfall from Weather Decision Technologies, Inc. (WDT) and the National Weather Service (NWS). The rainfall-to-ARI process is highly computational given the millions of grid cells that comprise the contiguous U.S. domain, but software has been optimized in to operate in a highly reliable, fast and redundant data center. Depending on the extent of rainfall across the country, a contiguous U.S. ARI map is processed in 4-8 minutes on a multiple-processor Linux computer. Operational ARI maps/grids are available within 25 minutes of their valid time and converted into a number of common formats. Once ARI maps for discrete periods (e.g. last 24-hours) are created, maps of the maximum ARI over a given period of time (e.g.

72-hours) can easily be created. These so-called maximum ARI maps/grids have the unique ability of portraying the ARI of a storm event, regardless of when the heaviest rainfall occurred across an area.

An overview of rainfall frequency estimates as well as 6- and 24-hour ARI maps, including several case studies, animations and real-time examples will be presented.

Introduction

Describing floods in terms of a "return period" (e.g. 100-year) has been used for decades to convey the rareness of major flooding events. However, describing the intensity of heavy rainstorms in a similar manner has not been as routine but provides an equally good perspective of extreme rainfall events. In order to compute the "return period" of a flood, pre-existing flood frequency statistics and a measure of the flood (i.e. peak discharge) need to be available at a specific location along a river or stream. Unlike flood frequency statistics, which are only available at gauged locations along rivers and streams, rainfall frequency statistics are available at any location in the United States.

The frequency and magnitude of rainfall is critically important to engineers, hydrologists and others involved in designing hydrologic structures, such as storm sewers, retention ponds, dams and levees. To meet this need, NOAA's National Weather Service Hydrometeorological Design Studies Center (HDSC) has been responsible for creating and publishing rainfall frequency atlases (e.g. 100-year 24-hour rainfall depth) for the United States since 1953. In 2003, the HDSC began updating the rainfall/precipitation frequency values for regions of the country as part of a series of atlases known as NOAA Atlas 14 (Bonnin, 2004). NOAA Atlas 14 not only provided updated information but also established clearer terminology.

The use of the term "return period" has been criticized for leading to confusion in the minds of decision makers and the public. "Return period" is sometimes misinterpreted as implying that the associated magnitude of a rain event is only exceeded at regular intervals. In other words, it is misunderstood that a 100-year event should only occur every 100 years. Therefore to clarify the meaning, NOAA Atlas 14 uses the term "average recurrence interval" or ARI to describe frequency. The ARI, which is in units of years, is defined as the average, or expected, period of time between exceedances of a given rainfall amount over a given duration and location. For example, suppose five inches of rain in 24 hours at a particular location is equivalent to an ARI of 100 years. This means five inches of rain in 24 hours is expected to occur, <u>on average</u>, every 100 years at this location. Since the ARI is an average, a similar or even larger, rainfall amount could occur again this year, next year or any other year. The ARI can be also be approximated as a probability or percent chance of occurring in any given year. For example, a 100-year ARI could also be expressed as having a 1 in 100 chance or a 1 percent chance of occurring in any given year. Table 1 converts the different terminologies.

ARI (years)	Probability of occurrence in any given year	Percent chance of occurrence in any given year
1000	1 in 1000	0.1%
500	1 in 500	0.2%
100	1 in 100	1%
50	1 in 50	2%
20	1 in 20	5%
10	1 in 10	10%
5	1 in 5	20%
2	1 in 2	50%
1	1 in 1	100%

Table 1. Three common ways of expressing the frequency ("return period") of events.

Although rainfall frequency estimates have been available since the 1950s, they have been largely overlooked as a means of translating actual rainfall observations into an ARI and instead used primarily for the design of infrastructure. This translation has been hampered by the generalized, hard-copy maps of rainfall frequency estimates buried in government documents. Before an ARI can be computed for a given rainfall depth and duration, a tedious interpolation of known rainfall frequency estimates needs to be drawn from the rainfall frequency maps. This is changing since rainfall frequency estimates from NOAA Atlas 14 are available online and as Geographic Information System (GIS) compatible files (Parzybok and Yekta, 2003). Access to reliable rainfall measurements at locations of interest is perhaps another reason that has hampered more frequent calculations of ARIs associated with rainfall amounts. However, given today's radar-adjusted rainfall products and the plethora of rain gauge observations/networks, observed rainfall amountsare no longer lacking in most parts of the United States. Real-time rainfall maps and observations are available from a number of on-line sources, including CoCoRaHS, Meteorological Assimilation Data Ingest System (MADIS), and the NWS (to name a few.

Given the government-issued rainfall frequency atlases and observed rainfall, climatologists and hydrometeorologists have computed the ARI of major rainstorms for purposes of insurance claims, media requests and post-storm reports. For example, according to a study conducted by the Peachtree, GA NWS Forecast office, the rainfall across portions of northern Georgia during the period September 20-21, 2009 was in excess of a 10,000-year rainfall event (Belanger, 2010). The heavy rainfall resulted in epic flooding, which according to the United States Geological Survey (USGS) was a 500-year flood in parts of Cobb and Douglas counties (Shepherd, et. al. 2010). The ARI of rainfall does not necessarily equate to a flood of the same ARI. The degree of flooding from heavy rainfall depends on the rainfall intensity, duration, topography, soil conditions, ground cover, basin size and infrastructure design. Floods can be caused by heavy rain, spring snowmelt, dam/levee failure and/or limited soil absorption. Rain associated with a 1 to 5 year ARI can cause significant urban flooding since most urban storm water systems are designed for 1-10 year ARI rainfall events. ARIs for highway and other transportation infrastructure typically vary from 10 to 25. However, it is a near certainty that rainfall associated with ARIs greater than 100-year will cause major flooding, regardless of anything else. Dams and levees are generally designed for rainfall ARIs much larger than 500 years, but can be compromised during ARIs of 100-500+ year events.

There have been countless other cases where point rainfall values have been translated into an ARI, but computing the ARI for a number of points across an affected area for the same storm provides a unique sense of both the magnitude and spatial extent of the storm. Until recently, maps of this nature were not created due to the extensive calculations necessary.

To our knowledge, the spatial depiction of rainfall in terms of an ARI is something first done by Goodridge et al. in the Historic Rainstorms in California document, published in August 1997 by the California Department of Water Resources (Goodridge, 1997). The Historic Rainstorms document contains a comprehensive storm catalog. Each storm is documented by a brief discussion, observed rainfall amounts and a map of rainfall amounts coupled with contours of ARI (Figure 1). The ARI contours have the unique capability to clearly and objectively convey the severity of rainfall, even to those not familiar with rainfall in California.

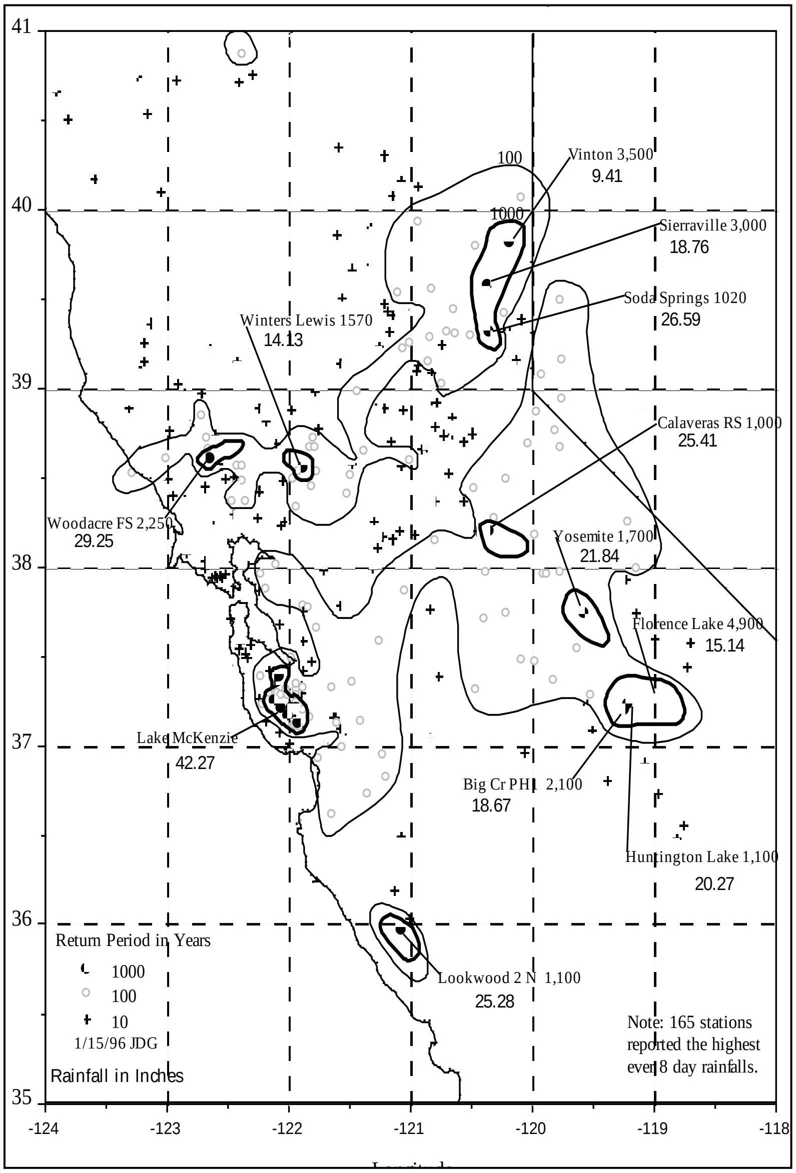


Figure 1. Total storm rainfall map for central California for the period December 19-27, 1955 from Historic Rainstorms in California. Rainfall values shown in call outs, while symbols and contours depict ARI (Goodridge, 1997).

A web search turned up one international instance of extreme rainfall depicted as a map of ARI in New Zealand. The High Intensity Rainfall Design System (HIRS), developed by New Zealand's National Institute of Water and Atmospheric Research, was used to develop an ARI map of rainfall associated with an extraordinary rainstorm on February 14-17, 2004 (National Institute of Water and Atmospheric Research, 2010). The storm produced widespread flooding and extensive infrastructure damage in the lower North Island (Figure 2.) Although the storm event lasted four days, the ARI map depicts the ARI of the maximum 24-hour rainfall during the 4-day storm period. The map shows large areas where rainfall exceeded ARIs of 150 years.

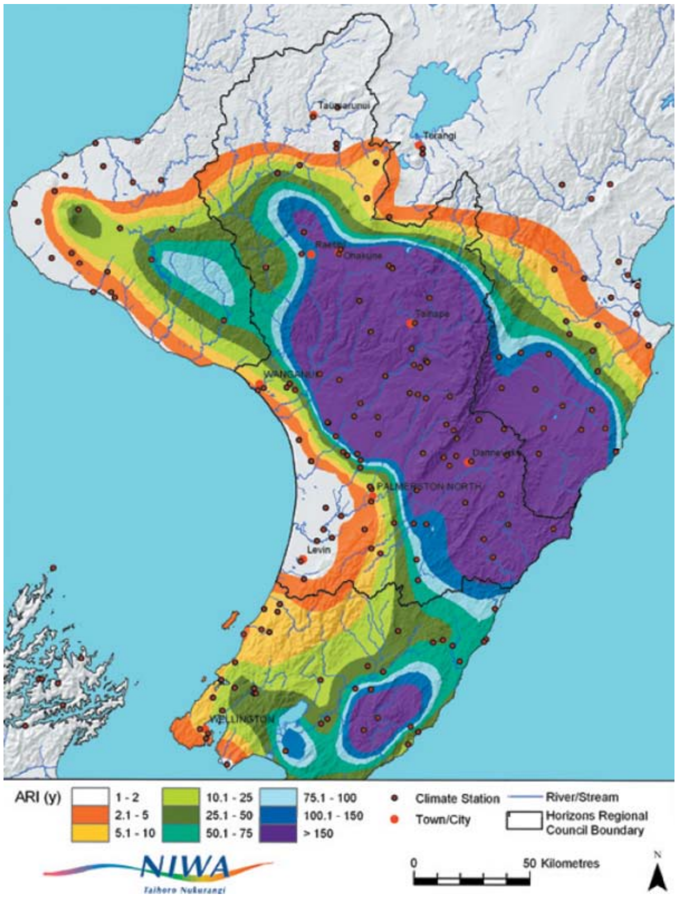
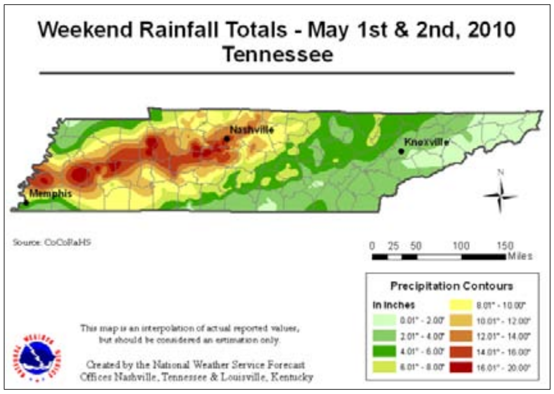


Figure 2. Average Recurrence Interval (years) of the maximum rainfall in a 24-hour period during the period February 17-24 2004 storm across the North Island of New Zealand (Natural Hazards Centre, 2004).

More recently, maps of the ARI of rainfall have been created to convey the rareness of two major rainfall events in the United States. The ARI maps were created by the National Oceanic and Atmospheric Administration (NOAA) National Weather Service for the May 1-2, 2010 epic flood event across western and middle Tennessee. The map of the 48-hour rainfall average recurrence intervals (Figure 3) indicated a large area of 1000+ ARIs.

Similarly, NOAA created a 4-day ARI map of the rainfall (and melted snow) associated with the record-breaking rain and snow (generally above 5,000 feet elevation) event across Arizona during the period January 19-23, 2010. The map was published as part of a Local Service Assessment by the Weather Forecast Offices in Arizona, Las Vegas, NV and the Colorado Basin River Forecast Center in Salt Lake City, UT (NOAA, 2010).



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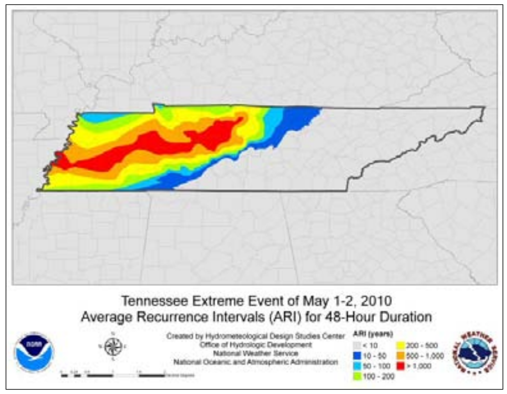

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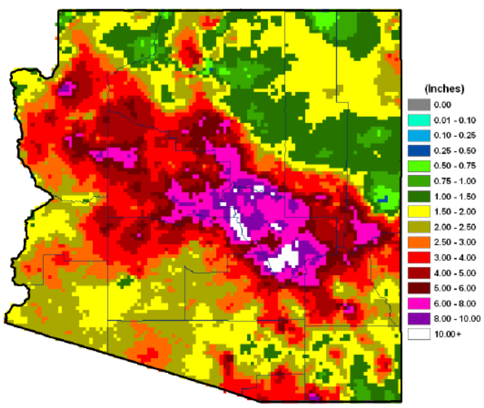
Figure 3. Two day rainfall totals (a) and the associated ARI (b) for Tennessee during the epic rain and flooding event of May 1-2, 2010 (Nashville, Tennessee National Weather Service Forecast Office, 2010).



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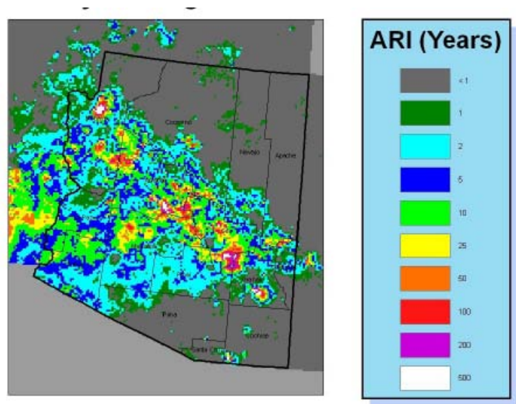

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Figure 4. (a) Total rainfall for the period 18-23 January 2010 across Arizona and the corresponding (b) ARI map from the NWS Local Service Assessment (NOAA, 2010).

Rainfall Frequency Estimates

Before the ARI of a specific rainfall event can be ascertained, ARIs must first be computed using historical rainfall data collected by long-term climatological weather stations. It is generally understood that one can estimate reliable ARIs twice that of the length of the rainfall record. For example, the analysis of 50 years of historical rainfall data can confidently result in ARIs up to 100 years. In order to estimate rainfall frequency estimates for rarer ARIs, a regional frequency analysis approach is used, which leverages historical rainfall data from a cluster of stations to confidently extend the ARIs well beyond the period of record of any given station (Hosking and Wallis, 1997). The approach "trades space for time" and has been widely used in recent rainfall frequency atlases, including NOAA Atlas 14.

In 2003, HDSC began updating the old, out-dated rainfall frequency atlases published in the 1950s, 1960s and 1970s as different volumes of NOAA Atlas 14 (Bonnin, 2004). NOAA Atlas 14 is based on a much larger and longer sample of observed rainfall data than was available for previous atlases, therefore reducing the uncertainty of the rainfall frequency values (Bonnin, et al., 2003). Eventually, NOAA Atlas 14 will cover the entire United States, but currently the Southwest, Ohio River Basin and Surrounding States, California, Hawaii, Pacific Islands, Puerto Rico and the U.S Virgin Islands have updated precipitation frequency estimates as volumes 1, 2, 3, 4 and 5 respectively. Figure 5 shows a map of current NOAA Atlas 14 projects and areas included in future volumes of NOAA Atlas 14.

Some states and local governments have funded development of their own state, city or regional rainfall frequency analyses, but NOAA publishes the nation's de-facto standard rainfall frequency values for the United States (Bonnin, et al., 2003).

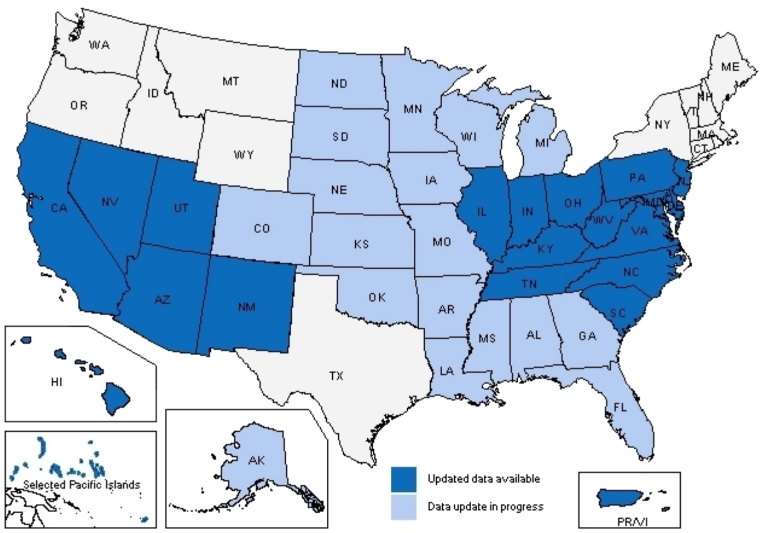


Figure 5. Map of current NOAA rainfall frequency projects and areas already included in NOAA Atlas 14 Volumes 1-5 as of January 2011. Light blue areas will have updated rainfall estimates in 2011-2012. (http://hdsc.nws.noaa.gov/hdsc/pfds/index.html)

NOAA Atlas 14 is a web-based document and all of its associated gridded data are available through the Precipitation Frequency Data Server. (Parzybok and Yekta, 2003). Those areas not already updated by NOAA Atlas 14 are covered by older precipitation frequency documents, such as Technical Paper 40 (eastern U.S.) and NOAA Atlas 2 (western U.S.) for durations less than 24-hours and Technical Paper 49 (entire U.S.) for longer (up to 10-days) durations. (U.S. Weather Bureau 1964; Hershfield, 1961; Miller et. al., 1973). NOAA Atlas 14 contains rainfall frequency estimates for durations as short as 5-minutes to as long a 60-days, and ARIs from 1-year to 1000-year.

In order to create seamless ARI maps of the continental U.S., the precipitation frequency estimate maps from the older atlases were digitized and converted into a format, resolution and projection consistent with those from NOAA Atlas 14. In a GIS, grids of rainfall frequency estimates were merged into seamless rainfall frequency grids for 24- and 6-hour durations and ARIs from 1-year to 1000-year, thus providing the basis for translating rainfall into an equivalent ARI for anywhere in the country.

Rainfall Data

To attain the unique perspective of ARIs across the U.S., one must also acquire rainfall values for all locations in the Continental United States (CONUS). There are a growing number of on-line sources of rainfall maps/grids, including the National Weather Service and Weather Decision Technologies, Inc. (WDT). Gridded NWS rainfall data can be accessed from http://water.weather.gov/precip/ as shown in Figure 6. Meanwhile, Figure 7 is a CONUS map of precipitation from WDT. The NWS gauge-adjusted radar-estimated precipitation data is available at a spatial resolution of 4 km x 4km, while from WDT it is available at 1 km x 1 km. Both are available every one hour.

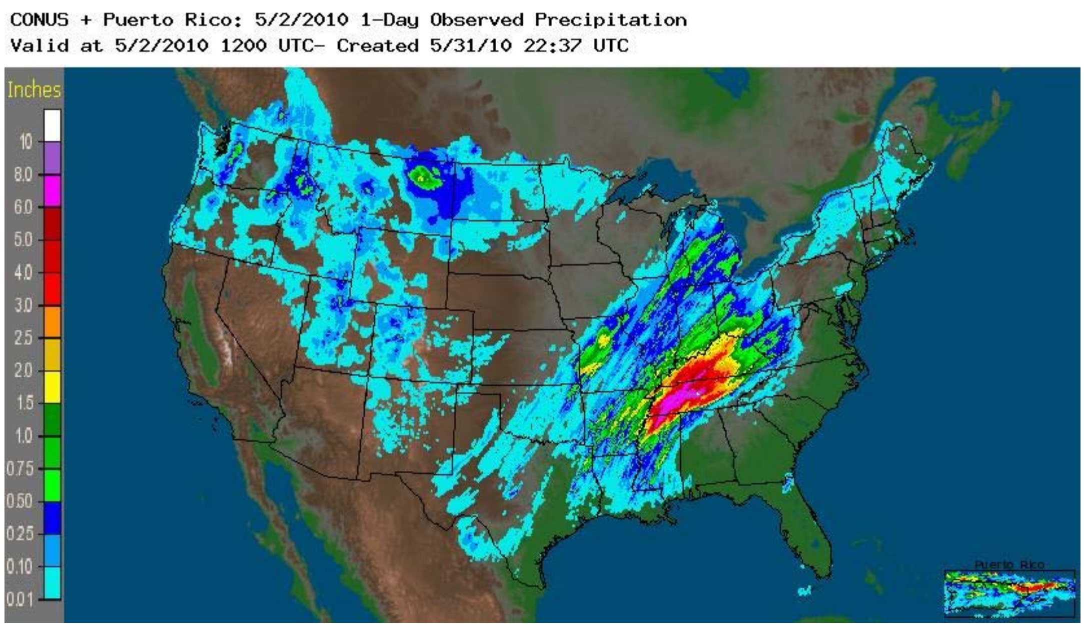


Figure 6. NWS gauge-adjusted radar-estimated 24-hour observed rainfall ending at 12 UTC on May 2, 2010.
(URL: [http://water.weather.gov/precip/index.php?yday=1302696000&yday_analysis=0&layer[]=0&layer[]=1&layer[]=4&timetype=D&loctype=STATE&units=engl&timeframe=current&timeYYYY=2010&timeMM=5&timeDD=2&product=observed&loc=conus](http://water.weather.gov/precip/index.php?yday=1302696000&yday_analysis=0&layer[]=0&layer[]=1&layer[]=4&timetype=D&loctype=STATE&units=engl&timeframe=current&timeYYYY=2010&timeMM=5&timeDD=2&product=observed&loc=conus))

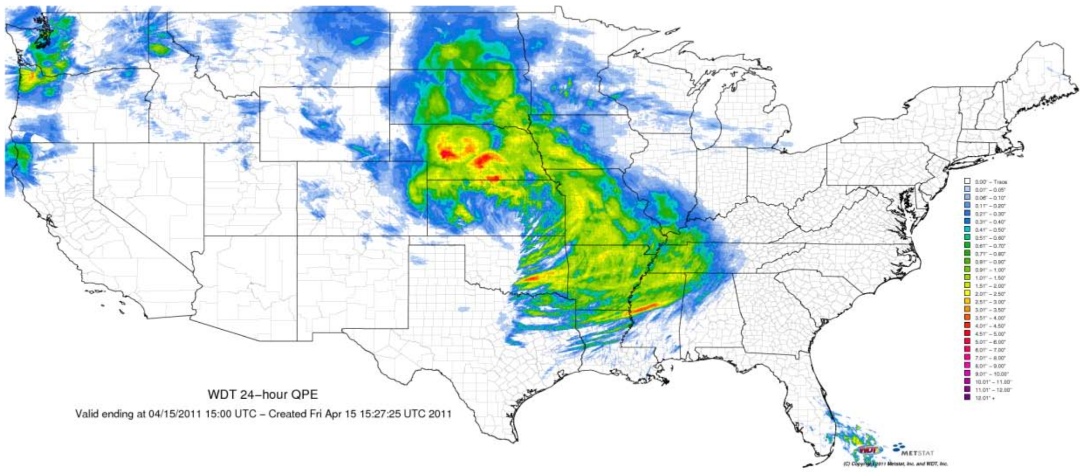
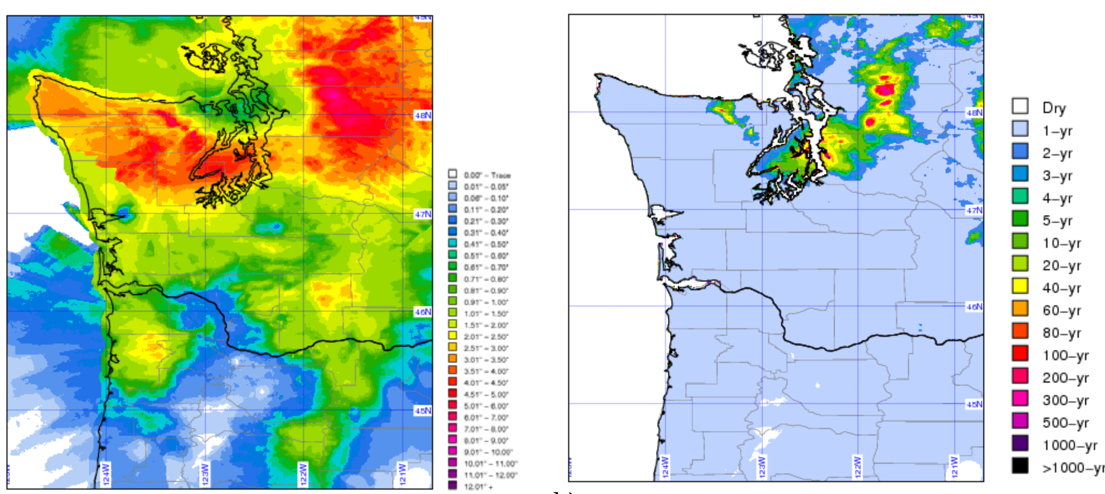


Figure 7. High-resolution WDT gauge-adjusted radar-estimated 24-hour observed rainfall ending at January 10, 2010 at 2100 UTC.

The rainfall-to-ARI conversion is especially sensitive to erroneous rainfall data, so it is of critical importance to have good-quality rainfall data. Erroneously high rainfall data will be amplified in the ARI product and result in ARI values that are spatially inconsistent and hence cause a "bulls eye" on the ARI map. It has only been within the past decade that gauge-adjusted radar-estimated rainfall has become reliable enough to support computations like ARI. For areas of complex terrain, particularly in the western United States, radar-based rainfall estimation still suffers from radar beam blockages, but new technologies like the Storm Precipitation Analysis System (SPAS) offers new ways to blend radar and climatologically-based rainfall estimation to produce seamless rainfall grids across any terrain (Parzybok, 2010). Figure 8 depicts a rainfall event as modeled by SPAS across the rugged terrain of the Pacific Northwest that produced ARIs in excess of 80 years in parts of the northern Cascades of Washington.



a) b)

Figure 8. SPAS-produced visualization shows 24-hour rainfall in inches (a) across western Washington and northwestern Oregon ending December 12, 2010 22 UTC and (b) resulting ARI in years.

Rainfall to ARI Conversion

ARI grids/maps are created by translating each grid cell of rainfall across the CONUS into an ARI given the ARI statistics at each grid cell. The rainfall to ARI conversion uses proprietary software but begins with summing up rainfall for a desired duration (e.g. 24-hours). Given an observed rainfall amount, duration and location (e.g. 2.00 inches in 24 hours at a grid cell near Phoenix, Arizona), the corresponding ARI is computed by determining bounding ARIs of the observed rainfall amount. For instance, according to NOAA Atlas 14 Volume 1, the 24-hour rainfall for a 5-year ARI at Phoenix is 1.81 inches, while the 10-year ARI is 2.14 inches. Using the bounding ARIs (5 and 10 years) and rainfall frequency estimates (1.81 and 2.14), the ARI of the observed rainfall amount is interpolated. In this example, a 24-hour 2.00 inch rainfall value at Phoenix is equivalent to an ARI of 7.9 years.

The rainfall-to-ARI process is highly computational given the millions of grid cells that comprise the CONUS domain, but software has been optimized in to operate in a highly reliable, fast and redundant data center. Depending on the extent of rainfall across the country, a CONUS ARI grid/map, based on gauge-adjusted radar estimated rainfall, is processed in 4-8 minutes on a multiple-processor Linux computer. The ARI map is available within 25 minutes of its valid time. In other words, a CONUS ARI map for 24-hours ending at 1200 UTC would be available by about 1225 UTC. As shown in Figure 9, a free 24-hour CONUS ARI map, based on gridded NWS precipitation data, is available daily from METSTAT.com.

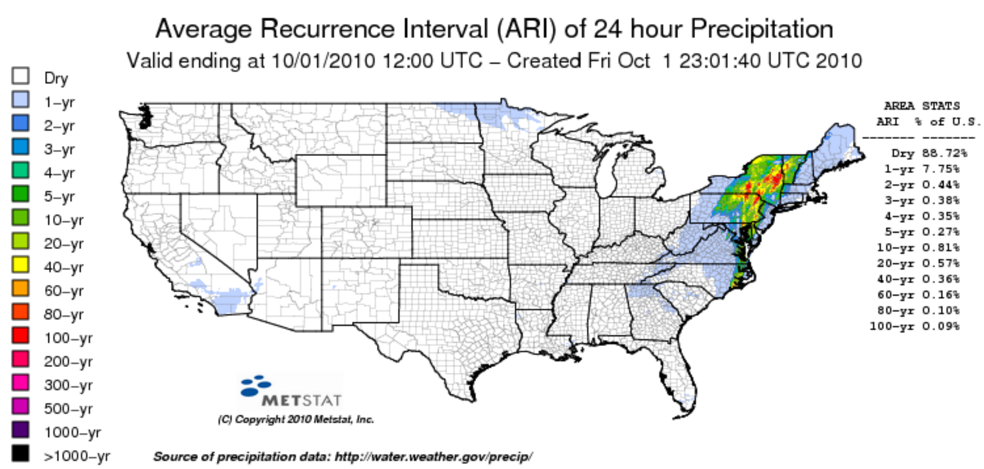


Figure 9. METSTAT produced 24-hour ARI map based on gridded NWS rainfall data ending at 12 UTC on October 1, 2010. (Available at: http://www.metstat.com/)

Once ARI maps for discrete periods are created (e.g. January 8, 2011 1100 UTC through January 2, 2011 1200 UTC), grids/maps of the maximum ARI over a given period of time (e.g. 72-hours) can easily be created. These so-called maximum ARI maps have the unique ability of indicating the maximum ARI, regardless of when it exactly occurred for a storm event. Maximum ARI maps better depict the ARI history of a "storm" than an instantaneous ARI map since the maximum ARI occurs at different times and places as the storm passes through a region. Figure 10 shows the maximum 6-hour ARI for the U.S. based on high-resolution gauge-adjusted radar rainfall from WDT during the period September 30, 2010 through October 1, 2010, a period of particularly wet weather across the northeastern United States.

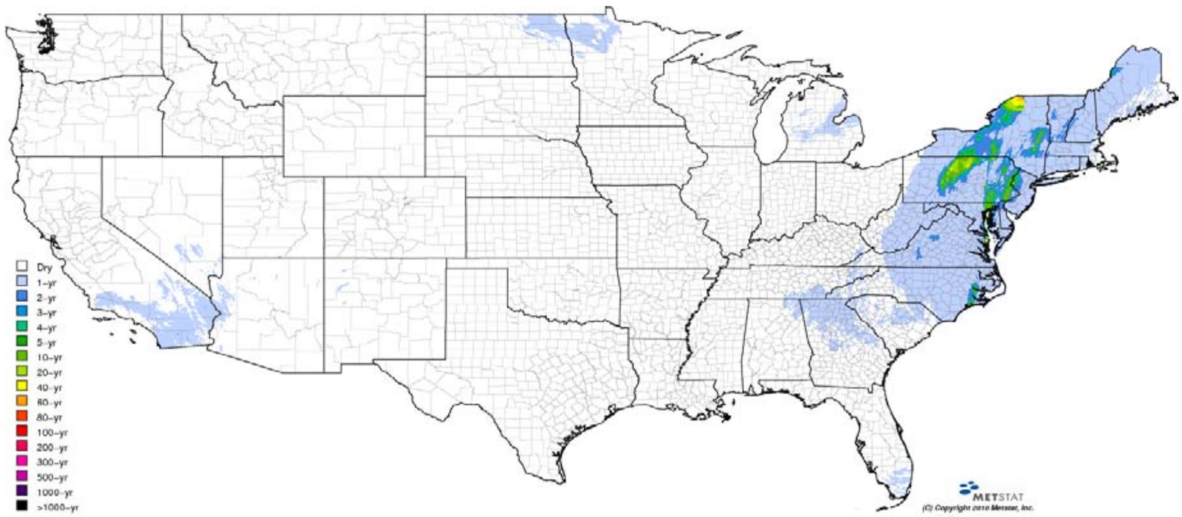
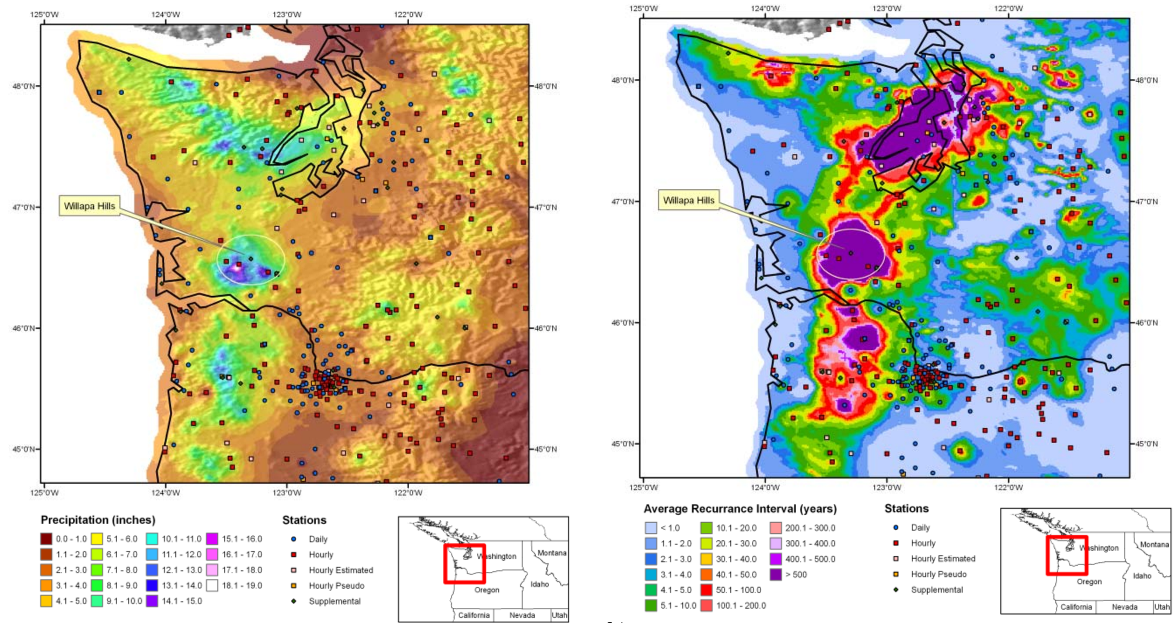


Figure 10. METSTAT produced maximum 6-hour ARI based on high-resolution gauge-adjusted radar rainfall from WDT during the period September 30, 2010 through October 1, 2010, a period of particularly wet weather across the northeastern United States.

Case Studies

Willapa Hills, December 2007

Two powerful storms brought extremely heavy rain and high winds to the Pacific Northwest during early December 2007. The intense low pressure areas fed an "atmospheric river" of very moist tropical air into the region. Orographic lifting caused copious amounts of rain to fall across western Oregon and Washington. Several rivers in northwestern Oregon and western Washington surpassed major flood stages. Rainfall intensities at 12- and 24-hours were particularly intense. Figure 11 shows the maximum 24-hour rainfall amounts during a five day period. Twenty-four hour rain values approached twenty inches in the Willapa Hills region, which equated to an ARI of 500+ years.

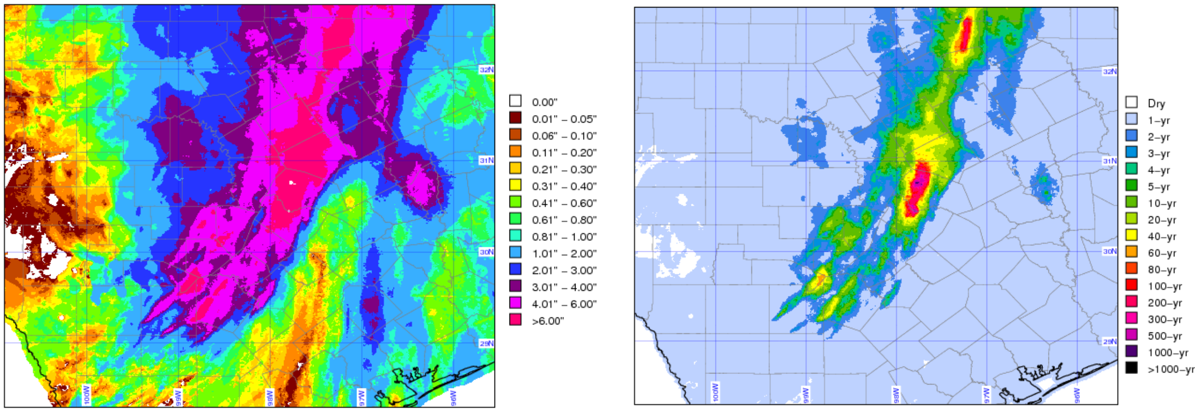


a) b)

Figure 11. METSTAT produced maximum 24-hour rainfall (a) and the resulting ARI (b) for an "Atmospheric River" event across western Washington and northwestern Oregon during the period December 1-5. 2007. The hardest hit areas were the Willapa Hills in southwestern Washington where up to 18 inches of rain fell, which equated to an ARI of 500+ years.

Tropical Storm Hermine

Tropical storm Hermine moved ashore just south of Brownsville, Texas on September 6, 2010. Although the storm packed a light punch when it moved ashore, its moist, tropical air mass unleashed heavy rainfall across Texas. The storm and its moist air mass slowly moved over San Antonio and into central Texas late on September 7th, then into Oklahoma on the 8th and 9th. The storm's flooding caused eight deaths and nearly two million dollars in damage. Figure 12 shows a 24-hour snapshot of rainfall and the associated ARI. Rainfall across central Texas reached 13 inches, which equated to an ARI of about 300 years.



a) b)

Figure 12. (a) 24-hour rainfall (in inches) across central Texas associated with the remnants of Tropical Storm Hermine, and (b) the associated ARI, in years. Up to 13.20 inches of rain in 24 hours equated to an ARI of >300 years.

September 2009 Northern Georgia Flood

The combination of low-level moist flow from the Atlantic Ocean and moist southwest flow above that from the Gulf of Mexico, coupled with terrain enhancement, caused slow moving thunderstorms to occur over northern Georgia for several days (NOAA, 2009). The extreme rainfall caused catastrophic flooding across northern Georgia on September 18-23, 2009. The most intense rain occurred during a 24-hour period from September 20-21 when 10 to 20 inches of rain fell. The flooding claimed eleven lives and caused over $250 million in property damage (NOAA, 2009). Figure 13 shows the distribution and magnitude of rainfall and the corresponding ARI for the 24-hour period ending at 1200 UTC on September 21, 2009. Technical Paper 40 on provides ARI up to 100 –years, but we extrapolated ARIs to 500 years for purposes of gauging the severity of the rainfall. As noted earlier, Belanger (2011) calculated 24-hour rainfall associated with this storm exceeded the 10,000-year ARI in places.

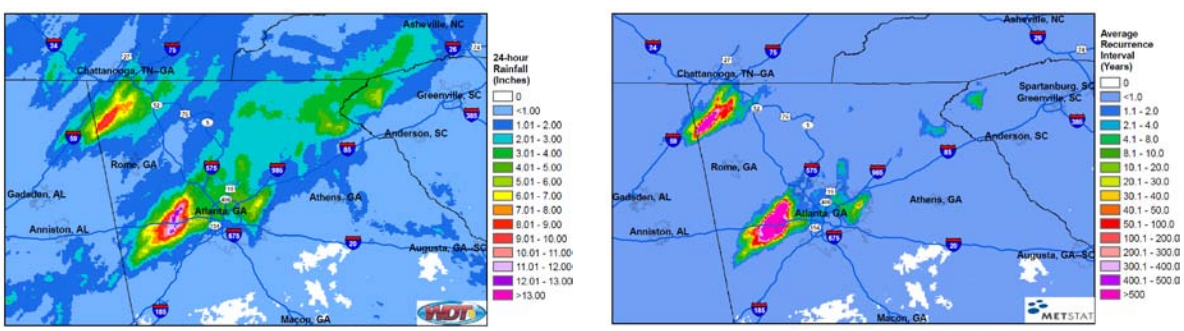


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Figure 13. (a) Total 24-hour rainfall, in inches, ending on September 21, 2009 1200 UTC and (b) corresponding ARI in years.

Conclusions

Descriptions of floods in terms of "return periods" have been used for decades to convey the rareness of major flooding events. While similar descriptions of heavy rainstorms have not been as common, they provide an equally useful perspective on extreme rainfall events. Hampered by lack of known ARIs, rain gauge data and computational computing power, ARIs of specific events have not been routinely computed. Given the recent availability of real-time rainfall data and pre-existing rainfall frequency statistics, however, the natural evolution has been to create maps depicting the ARI of rainfall in real-time. Use of official rainfall frequency atlases in conjunction with observed rainfall grids/maps provides an objective and powerful means of conveying the rareness (or commonness) of rainfall, even to those not familiar with the rainfall of the area. Maximum ARI maps for a defined duration depict the ARI of a "storm" since the maximum ARI occurs at different times and places as the storm pass through a region.

The information conveyed via an ARI map has been illustrated in post-storm studies, but real-time ARI maps of rainfall provide a new and powerful tool that benefits a number of disciplines. Having the capability of seeing ARIs of rainfall in near real-time is an important part of determining how to respond, and puts the rainfall into a perspective (ARI, probability or percent chance) that is understood by most people. Real-time ARI maps can help city and flood control district planners and engineers determine the intensity of downpours with which storm water drainage systems and other structures are designed to cope. In addition, real-time ARI maps could provide forecasters with a critical alternative to stream gauge discharge frequency estimated during extreme events. This is especially significant because flooding can often wipe out or cause stream gauges to malfunction. In fact, the flooding in Georgia during September 2009 was so severe that 20 percent of the stream gauges failed (NOAA 2009). Although the ARI of rainfall does not necessarily equate to the same ARI of flooding, if the ARI of rainfall (based on radar-estimated and/or gauge precipitation) were available, it would have provided a critical alternative for inferring the situation as the flooding unfolded.

A near real-time 24-hour ARI map for the continental United States is available at http://www.metstat.com. The ARI map, which is based on 24-hour NWS gauge-adjusted radar rainfall data, is routinely updated three times per day, at approximately 11am (16Z), 2pm (19Z) and 6pm (23Z) Eastern Standard Time which coincides with the updates of the observed precipitation available at http://water.weather.gov/precip/. A portion of an extensive ARI map/grid archive, dating back to 1999, is available online.

Future Work

Efforts are underway to expand ARI mapping to Puerto Rico and Hawaii, but the immediate focus is on providing additional durations and various area sizes. The ARI maps discussed thus far represent point rainfall values and do not reflect the ARI of differing area sizes. Hydrologists, in particular, would find the ARI of a real rainfall to be more useful than point rainfall ARIs. However, in order to ascertain the ARI of areal rainfall amounts, it is necessary to know the actual areal rainfall depth and frequencies. The areal rainfall depth can be easily computed, but areal rainfall frequencies are more difficult to come by. Existing point rainfall frequency estimates from NOAA can be converted into areal estimates via an Areal Reduction Factor (ARF), however reliable ARFs for all areas of the United States are not available. NOAA is in the process of updating the ARFs for the United States, but the project results are not scheduled to be available until 2012 (Hydrometeorological Design Studies Center, 2011). Until then, ARFs published in the existing precipitation frequency documents (NOAA Atlas 2 and Technical Paper 40) may be used to produce ARFs of rainfall for common area sizes (e.g. 10, 20, 50,100, 200, 500 square-miles).

Acknowledgements

Thank you to Geoff Bonnin, Chief Hydrologic Science and Modeling Branch at National Weather Service, for the decade of inspiring and rewarding work at the Hydrometeorological Design Center where I gained my unique wealth of rainfall frequency knowledge. The real-time ARI capability could not have evolved as it has without the confidence and support of Weather Decision Technologies, Inc. Thank you to Michael Eilts of WDT for the years of trust, collaborative support and gauge-adjusted radar-estimated precipitation data for testing, development and now an operational product.

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