Storm Distribution developed from World Curve Data and it's Potential Areal Application.

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Abstract: The determination and application of Probable Maximum Precipitation (PMP) has been an inherent part of designing major Reservoir Projects in both the Private and Federal sectors for over 50 years. Much attention has been given to identifying the magnitude, orientation, and probability of occurrence for PMP events. The rainfall distributions associated with these extreme magnitude events have been largely empirical in nature. The most common PMP distributions have been critically stacked sequences in which maximum PMP values for all shorter durations are encompassed in the design distribution. Legitimate questions can be raised regarding how conservative these critically stacked distributions are and whether there are better alternatives. A procedure for predicting Local Maximum Volume-Duration Curves will be explored in this paper.

In the Reservoir design process, the structure size and associated components are highly dependent on both the magnitude and distribution of the PMP event. The common perception has been that precipitation distributions for PMP sized events cannot be defined accurately due to a limited or lack of history of occurrence in the United States. This paper will present a limited focus on the magnitude of PMP events, however, the main emphasis will be to challenge some of the current perceptions on PMP precipitation distributions and their area applicability.

This paper will evaluate the findings from a study of the precipitation distribution developed from the Maximum Precipitation-Duration Events recorded around the world (World Curve). The World Curve has been available to the Hydrology community for at least twenty years but it appears that limited consideration has been given to using the World Curve information as a source for defining PMP rainfall distributions. This paper attempts to answer the important question of whether the critically stacked precipitation distribution developed from the World Curve data is applicable to any part of the United States.

Introduction

A prior paper and presentation focused on the development of a precipitation distribution developed from the World Record Maximum Volume-Duration Curve (World Curve). This paper will focus on the area of potential applicability for the precipitation distribution developed from the World Curve. A prediction procedure for determining Local Maximum Volume-Duration Curves (LMV-D Curves) will be tested.

Premises to be evaluated

This paper will address four basic premises as follows:

1) The Envelope Curve of the Maximum Volume-Duration values on the World Curve are the true upper limit values of precipitation that can be expected to occur anywhere in the world under current global climatic conditions.
2) Any Local Maximum Volume-Duration Curve (LMV-D Curve) that is parallel to the World Curve will have the same hourly distribution percentage (but a lesser total volume) as the World Curve.
3) Just as there are physical and meteorological upper limits on a global scale, similar physical and meteorological conditions exist on a local level and can be defined by Local Maximum Volume-Duration Curves (LMV-D Curves).
4) Sufficient data currently exists to tentatively define the LMV-D Curves for the area east of the 105th Meridian.

The first premise is somewhat self-explanatory. The maximum value for each duration is a world record but there are also numerous other measured rainfalls that approach the world record magnitude. This would be expected if there are physical and meteorological upper limits to precipitation for any duration. As remarkable as the World Curve precipitation values are, each duration has second, third and fourth ranked events that are nearly as large. Invalidation of the maximum value and substituting a second or third order value on the World Curve does not significantly change the curve. For example, if the 71.85 inches in 24 hours at Foc Foc on Reunion Island in January 1966 is invalidated, the 68.62 inches in 24-hours measured in Taiwan on July 31-August 1, 1966 (Typhoon Herb) can be substituted. The second outstanding characteristic of the World Curve is the remarkably smooth transition for succeeding durations that occurred at alternate locations and times. A first-order curve through the World Record Volume -Duration data gives a remarkable R^2 value of 0.9988. To further reduce any remaining skepticism, an envelope curve of all data points (excluding the 10-hour duration value from Muduocaidand, China) was used as the upper limit of expected rainfall for the Planet Earth. The envelope of the world record values is referred to as the "World Curve" for the remainder of this paper.

The second premise is a matter of simple mathematics. A LMV-D Curve that has a smaller total magnitude but the same slope (parallel) to the World Curve will have exactly the same percentage distribution for each comparable duration. This could be a very important relationship if it is observed that there are LMV-D Curves that are approximately parallel to the World Curve. Premises 3) and 4) will be evaluated in the remainder of this paper.

Conditions which support World Record and PMP Values

Before establishing the area of applicability of the World Curve distribution, there is a need to have a basic and common understanding of the meteorological, climatic and topographic processes that are likely to produce a PMP event in any specific locality. The following is a very abbreviated and non-inclusive listing of the more obvious factors that contribute to both intensity and volume of precipitation necessary to produce a PMP event:

- Temperature – a basic law of physics is that the warmer the air temperature, the more moisture the atmosphere can hold. This principle was used extensively in the development of PMP values in Technical Paper-40 (TP-40) and the Hydrometeorological Reports (HMR's) to maximize and transpose large historical precipitation events. Figure 1 taken from information in Table 2 of HMR-51 and other HMR sources clearly illustrates the importance of temperature as it relates to the amount of potential water that can be stored in an air column. Temperature also effects the amount of renewable water (inflow) in an air mass moving into a storm cell. The values in Figure 1 are based on 1000 mb pressure at sea level and adjustments are typically made for changes in elevation. The HMR reports were generally based on a relatively high 12-hour dew point temperature of 78 degrees Fahrenheit. The important factor to note here is that a column of the atmosphere at a dew point temperature of 78 degrees Fahrenheit at sea level can store approximately 3.35 inches of water that is available for precipitation. At a dew point temperature of 70 degrees Fahrenheit, the volume of water available for precipitation drops to approximately 2.27 inches.
- Proximity to large water bodies – As shown above, a single column of the atmosphere can only store (about 3.35 inches) a small percentage of the moisture needed to produce a PMP size precipitation event. The moisture must be continually replaced (inflow) during the storm event if PMP magnitude intensities and volumes are to be obtained. Precipitation events approaching 24-hour PMP levels are much more likely to occur near large water bodies. In the middle portion of the U. S., both the magnitude and probability of a PMP event diminishes with distance from the Gulf of Mexico or other large water bodies such as the Atlantic Ocean or Great Lakes.
- Topography – many people are surprised to learn that the maximum intensities and volumes of precipitation do not occur on the coast at sea level. The maximum intensities and volumes do tend to occur near large water bodies, but at some small distance inland at elevations between 3000 and 5000 feet. This is the elevation range where the most clouds routinely intersect with a coastal mountain range. This change in rainfall with elevation is called an orographic effect. Within the continental states (lower 48), this effect is prominent for those states that are west of the 105^{th} meridian. The orographic effect is minimal east of the 105^{th} meridian although a minor orographic effect is recognized in the Appalachian region.
- Stalled weather systems – A stalled weather system is not critical for producing a 24-hour PMP event in a coastal location but it helps. A slow moving hurricane can be wide enough to produce 24-hours of continual relatively high intensity rainfall without having a stalled or looped hurricane condition. Interestingly, the maximum observed rainfall events have not been caused by the larger hurricanes. Large hurricanes contain tremendous energy and seldom encounter an opposing force that slows or stalls the system. The largest rainfall events in coastal areas have occurred with moderate sized hurricanes that actually stalled. Hurricane Dennis in North Carolina in September 1999 is a good example of a moderate sized hurricane that produced extensive flooding over a very large area.

  For inland or land locked locations, moving weather systems simply are not wide enough or strong enough to produce 24-hour PMP size events. Two near-equal and powerful weather systems have to stall or very nearly stall with cell after cell of rainfall passing over the same point(s) to ever achieve 24-hour PMP volumes. In the area east of the 105^{th} Meridian, this prime condition occurs when a strong cold front collides with a warm moisture-laden front. The cold air settles to the surface and the warm moist air rises rapidly producing high intensity precipitation along the stalled front. There are probably no better examples of stalled weather systems than the May 30-31, 1935 Hale, Colorado storm and the October 10-11, 1973 Enid, Oklahoma storm. In terms of short duration intensities only (not overall volumes), the impact of stalled weather fronts are often greater than orographic effects.

- When evaluating 24-hour PMP events, the diurnal effect on storm intensities must be considered. The threat of severe high intensity precipitation is minimal at about sunrise because temperatures are at a minimum and barometric pressures tend to be at their daily maximum. The threat remains subdued until about noon because of a lag in heating the atmosphere. At about noon, the atmosphere begins to warm up rapidly. The peak time during the day for intense precipitation occurs in mid to late afternoon. There is a lag after dusk until about midnight where very high intensities can still be maintained. After midnight, there is a gradual decline back to minimum conditions. The chance for a 24-hour record or PMP event is dependent on the timing of prime conditions occurring during the peak time of the day.

We would expect and the data supports the fact that most of the World Record precipitation events occur in the tropical and semi-tropical regions of the globe near large water bodies in locations that have a prime orographic effect. All of the World Record values for durations of 18-hours or greater occur in the Indian Ocean near the equator at inland locations with ideal orographic influences. World Record values for shorter durations have occurred in unlikely locations including three values (Holt, Missouri, Smethport, PA and D'Hanis, Texas) within the area east of the 105^{th} Meridian. Of all the major factors that effect maximum volume-duration values, the only one that has a likelihood of changing in the next few centuries is global temperature. If global warming is a true phenomenon, we should begin to see a number of new World Record Volume-Duration values that are slightly above the current curve.

Storms of Six-hour or Greater Duration

Two different data sources are available for developing **Local Maximum Volume-Duration Curves (LMV-D Curves).** The first source, for durations of six-hours or greater, is the appendix in HMR-51. First published in 1978, HMR-51 contains information on 53 large storms used in the development of TP-40, HMR-51 and HMR-52. The earliest storm recorded in this data set occurred on September 10-13, 1878 in Jefferson Ohio. The most recent storm used in this data set occurred in 1972 in Zerbe, Pennsylvania. Other large storms that occurred during this same period were not used due to insufficient storm detail for shorter durations.

None of the events in the original HMR-51 database were fully instrumented and recorded. Even when recording gages were nearby, their records were often lost at some point during the event. Most data sets were from detailed "bucket survey" information supported by information from adjacent precipitation stations. **Forty-one of the 53 HMR-51 storms occurred prior to recording stations being present in the state of occurrence.** Any storm total in the data set can reasonably be questioned. The precipitation distribution within any given storm is subject to further questioning based on the nature by which the data was obtained. Nevertheless, the storms in the data set are quite similar in magnitude and other key characteristics and variables appear consistent from one event to another.
A caution is **"do not place too much reliance based on a single maximum value data point".** Long periods of record are not necessarily required for defining these events. Very few of the long duration, high intensity events occur but they have traditionally been studied and documented whenever and wherever they occurred. Stated alternately, we do not have the ultimate length of record needed with these type events but we do have a high degree of areal coverage with these types of records.

Included in the data set for this paper are three recent events, which occurred after the most recent event included in the HMR-51 database. The first is the Enid, Oklahoma storm on October 10-11, 1973. Enid, Oklahoma recorded maximums of 5.31 inches in one hour, 12.06 inches in three hours, and 13.87 inches was recorded in 6 hours (USGS open file report, 1974). An extensive Bucket Survey and radar imagery identified five locations that received 18+ inches and one cell that received 20 inches in a six to eight hour period. The storm dramatically displays one of the basic characteristics of inland PMP events, stalled weather systems. The second added event was the Alvin, Texas storm on July 25-26, 1979. This storm produced 42 inches in 24 hours (some sources report 43 inches in 24 hours). This represents 89 percent of the 24-hour PMP (47.1 inches) for this location. The distribution of this event was well defined by nearby recording instrumentation and supplemented by "bucket survey" information. The third storm, if proven accurately measured, is potentially the most dramatic. North Palm Beach, Florida on January 2, 1999 experienced 9.37 inches in one hour, 21.53 inches in 3 hours and 30.01 inches in 6 hours. The Palm Beach Florida event is especially valuable since it was captured on a recording precipitation gage. It also points out some issues associated with actually measuring a PMP or high intensity event and whether or not PMP events can be measured reliably. A good discussion of the issues associated with the measurement of this event can be found at:
http://www.srh.weather.gov/ftproot/topics/attach/html/ssd99-5.htm

Large long duration storms create many flooding problems and headlines. During the first 75 years of the Twentieth Century, large storms (near PMP size) were almost always defined and studied by an assortment of university, state and federal agencies. A great deal of bucket survey data was collected and documented. These studies often resulted in isohyetal maps and publications. The tendency has been to study any and all large events occurring within an area. Length or record is important but network density is not an issue. With a couple of exceptions, collection of "Bucket Survey" data on large events with durations of six or more hours has been done for about the last 125 years. From a statistical standpoint, a 125-year time frame is very short for defining PMP sized events but areal coverage during that period has essentially been 100 percent. More recently, state and federal agency budgets, a lack of experienced personnel and a general movement away from programs that require this type of information creates some doubt that near PMP sized precipitation events will automatically be studied in the future.

Storms of Short Durations (One to Three hours)

The second type of precipitation data used was for short duration (one to three hour) storm events. A maximum hourly data set based on National Oceanic and Atmospheric Administration (NOAA) data and developed by the NRCS National Water and Climate Center (NWCC) for use in testing the Revised Universal Soil Loss Equation (RUSLE) model, was available for use in this study. The maximum one-hour values for each state have been individually verified.

Maximum hourly data is a critical consideration of this document and one-hour values were included for analysis in developing this paper. The total precipitation amounts for these short duration events are much smaller and the storms tend to cover much smaller areas than the larger and longer duration storms. In reality, the maximum intensity, shorter duration events are rarely a part of a large longer-duration event. Traditional measurement of short duration, high intensity storm events is very different from measurement of longer duration events. The maximum one-hour precipitation for the area east of the 105^{th} Meridian ranges from about five to six inches near the Canadian border to approximately seven to ten inches near the Gulf. If these events are not part of much larger events, they may make the local paper but generally pass unnoticed. Unless they occur on a research project or as part of an operational network (flood warning, etc), they are seldom studied in detail. The NOAA network is relied upon to detect and measure a majority of this type of data, although there are a variety of secondary sources and the number of these sources has increased in recent times.

The maximum one-hour value is more important than the two or three-hour maximum value because the number of occurrences of maximum intensity rainfall events begins to decline very rapidly for durations in excess of one-hour. Quite simply, optimum conditions become more and more difficult to maintain as duration increases. More near maximum intensity one-hour events and progressively fewer large volume-duration events should be observed as the duration increases. **If optimum conditions could be maintained for extended periods, the maximum two-hour value on the World Curve would be twice the one-hour value**. However, even on the Envelope World Curve, the two-hour maximum of 22.6 inches is only 40 percent greater than the maximum one-hour value of 16.2 inches. The maximum one-hour and the maximum two-hour events for any region almost always occur in separate events. In many of the state records, the percentage increase in the two-hour over the one-hour is much less than 40 percent, which is caused partially by the limited period of record.

Two-hour and three-hour maximum volumes would be very helpful in verifying some of the information presented later in this paper. However, extracting these values would be a time consuming and expensive project. The NOAA network has not yet fully defined the two-hour and three-hour volume-durations as well as it have defined the one-hour data. The one-hour volume-duration (intensity) is by far the most critical of the short duration values and fortunately was the easiest to extract.

The NOAA network has only been in place for about 125 years. There were individual systems and stations that go back into the 1800's and some historical accounts of large events have been found and used where verifiable. Early data was all 24-hour data or data for storm totals. The hourly recording station portion of the NOAA network is generally much younger than even 100 years. Pennsylvania had the first hourly recording stations in 1900 followed by North Carolina in 1902. California joined the group in 1936 along with Texas and Montana in 1940. By 1947, 14 states had at least one hourly reporting station. All states had at least one hourly reporting station by 1948. Even though every state had at least one recording station by 1948, a vast majority of the NOAA station network still only reported 24-hour or total storm amounts. For all practical purposes, the hourly recording station network began in 1948. It should be noted that recorded hourly data was extremely limited at the time TP-40 was developed and less than 25 years of recording data for a limited number of stations was available at the time that HMR-51 and HMR-52 were developed.

An important concept of this paper is that the maximum one-hour precipitation at any location is bracketed by the World Curve on the upper side and the maximum one-hour ever recorded at that locality on the lower side. Even if the actual one-hour PMP has not yet been measured, the range of probable magnitude that can be expected for that location is narrowed. Information used in the development of this paper strongly suggests that maximum one-hour values close to the expected one-hour PMP for specific locations have been measured.

The NOAA hourly precipitation CD (TD3240, US Hourly Precipitation Data) contains all of the hourly-recorded NOAA data through 1998. The needed information for the one, two and three-hour values should be obtainable by querying the data set for each state. Unfortunately, the problem is much more complicated. The data on this CD is basically raw data that has been transferred to the CD without having the values individually verified. Two typical clues to bad data are large one-hour values without rainfall (or very limited rainfall) in the preceding hours or large one-hour values with limited or no rainfall after the event.

The NWCC hourly data set was developed from 30-minute data, which minimizes another problem with published hourly precipitation data. The data is normally reported on clock-hours. The data set from the NWCC was developed and verified based primarily on 30-minute data with fifteen-minute data being used where available. As an example of the difference that this can make, the maximum one-hour clock value on the CD was 6.45 inches between six p. m.and seven p. m. The thirty-minute data showed that 6.92 inches fell in a one-hour period between 5:30 p.m. and 6:30 p. m. The shorter the time increment, the greater the accuracy and magnitude of the resultant hourly data. The maximum recorded value from the NWCC database is given in Table 2 (Moore, 2003). The NWCC maximum one-hour data set developed for each state generally tends to closely match the longer duration values in the Appendix of HMR-51. The maximum one-hour value from the NWCC database for each state has application as a potential pivot point for defining the local LMV-D Curve.

<u>A Simple Model to aid in understanding shorter duration intensities</u>

The Simple Model presented herein is nothing more than a concept and is admittedly oversimplified. However, it can be useful in helping to define and understand the expected intensities for shorter durations such as one and two-hour events. The conceptual model is for discussion purposes only with no intent to predict actual hourly magnitudes. The maximum intensity in a storm cell can be represented by the hydrologist's concept of Inflow, Storage and Outflow. It has long been noted that a single storm rarely accounts for more than one or two maximum local volume-duration values. Maximum values for any duration tend to result from a maximum inflow rate plus depletion of stored precipitatable water. Regardless of the duration, when precipitatable water is completely depleted from the air column (storage), the storm exhibits a strong tendency to collapse or subside to very modest levels of intensity. Generally, after a large storm event collapses, several hours are required for the atmosphere to sufficiently recover and redevelop high intensities. Storms that collapse due to depletion of storage rarely reform in the same location and produce significant levels of precipitation.

Maximum storage or precipitatable water in an air column is indicated in Figure 1 as approximately 3.35 inches at 78 degrees dewpoint temperature at 1000 mb pressure at sea level (basic HMR-51 assumption). The 78-degree dewpoint temperature represents an average 12-hour value and may be somewhat higher for shorter durations. A reasonable estimate of maximum atmospheric moisture storage associated with maximum one-hour precipitation would be on the order of 4.0 inches of moisture at a dewpoint temperature of 82 degrees. This indicated storage value is for sea level conditions and will decrease somewhat with elevation and temperature as we move inland.

The process and actual rate of moisture inflow into a storm cell can be enormously complicated but there is also a lot of information available to give us a reasonable estimate of the historic integrated value. From the HMR-51 database, we have the very best estimates of six-hour, 10 square mile totals available. If we assume saturation at a dewpoint temperature of 78 degrees early in the six-hour duration, we can reasonably subtract approximately 3.35 inches of volume from the maximum observed six-hour totals listed in the appendix in HMR-51. Thrall, Texas as an example had 22.4 inches in a six-hour period. If we subtract 3.35 inches from the 22.4 inches and divide the resultant by 6 (hours), we get an average inflow rate of 3.18 inches per hour. Even though it may not have occurred in the Thrall storm, at some point we would expect that the maximum one-hour recorded intensity in the area of Thrall Texas to be at least 3.35 plus 3.18 or 6.53 inches in one-hour. This estimate is expected to be on the low side for this area because shorter duration events may have higher inflow rates and possibly higher dew point temperatures. As a matter of interest, the highest verified one-hour intensity for the state of Texas is 7.4 inches in one-hour. This application of the Simple Model is only intended as a quick way to estimate the upper and lower limits of the range for the expected maximum one-hour intensity.

The Simple Model can also be used to estimate the upper end of the range for one-hour intensity values for the area east of the 105th Meridian. Two World Record point values and the North Palm Beach values for shorter durations are also available within the study area east of the 105th Meridian. All three values have their supporters and doubters but are used here for illustration purposes. An upper limit assumption for short durations is that up to 4.0 inches of precipitatable water at 82 degrees dewpoint temperature can be stored in the air column. For North Palm Beach Florida, we would calculate a maximum inflow rate of 5.84 inches per hour based on the measured 21.53 inches in three hours. The world record point rainfall value of 30.8 inches in 4.5 hours at Smethport, Pennsylvania would indicate an inflow rate of 5.96 inches per hour. The world record of 22.00 inches in 2.75 hours at D'Hanis, Texas would indicate a maximum inflow rate of 6.55 inches per hour. The values calculated for all three extreme events are very similar in magnitude. Combining the maximum hourly rate ever recorded east of the 105th with the estimated precipitatable water at a dewpoint temperature of 82 degrees would give a maximum expected one-hour value of 6.55 inches plus 4.0 inches or **10.5 inches in one-hour**. This should be very close to the expected upper range of the one-hour intensity for the area east of the 105th Meridian under world record conditions. The largest recorded one-hour value that we have found in the study area is the 9.37 inches recorded at North Palm Beach, Florida although an unrecorded value of 10.0 inches at New Braunsfel, Texas is believed by many to be reliable.. The maximum one-hour intensity for most areas east of the 105th Meridian should be much less than the 10.5 inches that defines the upper limit under world record conditions. Most maximum one-hour values should be closer to the lower limit based on local conditions as defined by the Simple Model. We believe that the upper and lower limits defined by the Simple Model will effectively identify the range of maximum one-hour intensity events for the area east of the 105th Meridian.

The Simple model helps explain why the maximum two-hour volume is not twice the maximum one-hour volume. The maximum one-hour inflow rate plus the volume in storage in the atmosphere approximates the maximum one-hour volume. For the Thrall, Texas storm, the maximum one-hour volume could be estimated as 3.35 inches storage plus an average hourly inflow rate of 3.18 inches for a total of 6.53 inches. This is a somewhat low estimate but is used for illustration purposes. The maximum 2-hour value is estimated by one value of storage (3.35 inches) and two hours of inflow (3.18 inches / hour) for a total of 9.71 inches. The two-hour value of 9.71 inches is approximately 49 percent greater (not twice) than the one-hour value of 6.53 inches. While the simplified model would indicate that the two-hour value is 49 percent greater than the one-hour value, the World Curve and local distributions in this paper indicate that the two-hour value is closer to 40 percent greater than the one-hour value.

The rapid depletion of storage and storm collapse is important in understanding very short duration (less than one-hour) events. A prime example of such an event is the Holt, Missouri value of 12.0 inches in 42 minutes. Detailed information related to short duration high-intensity events is extremely difficult to obtain. Such events have to occur as the result of extraordinary inflow circumstances combined with complete storage depletion. Examples are water spouts, downbursts associated with hurricanes and occasionally from tornadoes. Large rainfall volumes are noted in minutes. In reality, such events are almost impossible to accurately measure and the catchments are often destroyed during the event. References have been made to the fact that none of the short duration events (less than one-hour) have ever been a part of a large-longer duration event. The special circumstances associated with these type events are simply not sustainable over an extended duration.

Point versus Areal Rainfall

Based on the 6000 stations in operation in 1957 and the period of record, NOAA estimated, based on statistical procedures of the time, that each station was essentially representative of rainfall for a 10 square mile area. PMP values in TP-40, HMR-51 and HMR-52 for all durations (except the one-hour in HMR-52) are based on 10 square miles as the minimum applicable area. Adjustments from point values to 10 square miles generally ranged from 10-20 percent over several HMR publications with 15 percent being near the average. All of the adjustment procedures are subjective at best. The actual areal adjustment is storm specific.

The 10 square mile minimum application area became a part of the NOAA culture and the NRCS culture. The density of the current recording station network is quite different from the original 6000 station network. Variable record lengths and changing locations make statistical analysis of gage representation extremely cumbersome. For the sake of proceeding with the analysis, we made the assumption that the maximum one-hour values taken from the current recording network represented 10 square mile values rather than point values. The assumption seems to fit well with other longer duration historical data used in this paper but may require future refinement.

Development of Local Maximum Volume-Duration Curves for the United States

The points of major interest on Figure 2 are the points for "U. S. Maximum". The points for the U. S. Maximums show more scatter than the World Curve values in part because there is a wide variety of limiting local conditions. There are several data points for California and the West Coast, where orographic influence, cooler water temperatures and successive west to east weather systems are dominant. There are some points representing Florida and the Gulf Coast where the hurricane influence is dominant. The remaining points are transitional between the Gulf of Mexico and land locked locations further inland where other processes begin to dominate.

West Coast Local Maximum Volume-Duration Curve (LMV-D Curve)

The California points can be separated out as being part of a unique data population (Figure 3). All but one of the California record-setting points are for durations of 48 hours or greater. Large California precipitation events are often characterized by a close succession of west to east weather fronts over a period of several days. Cyclical warmer moisture regimes associated with El Nino's along the West Coast are a somewhat unique feature in U. S. data. El Nino's effect weather patterns over all of the U. S. El Nino's usually produce especially notable increases in precipitation and resultant flooding along the western coastal ranges. Cooler Pacific waters and the fact that most of the West Coast is above 34 degrees North Latitude prevents West Coast locations from frequently approaching world record status in precipitation events. It takes a much longer period of time to fully define the upper limits of the LMV-D Curve in this climatic environment.

Figure 3 is a good example of **Local Maximum Volume-Duration Curve (LMV-D Curve**) that is still being slowly quantified. **It should also be noted that historical maximums for any duration never go down**, **they can only go up**. The historical data in Figure 3 is a good example of what we could call a "Youthful LMV-D Curve". The West Coast data is also a good example of the evolution of data accumulation needed to fully define the LMV-D Curve. We tend to define the short duration values (i.e. 1, 2, and 3-hour) first because many more short duration events normally occur. The data for the upper part of the curve should slowly move upward with the Campo, California data point remaining essentially fixed and serving as a pivot point. Given enough time (a very long time in this case), the definition of the curve may eventually approach a line that is parallel to the World Curve. **In contrast, physical reasons as to why a LMV-D Curve would ever exceed the slope of the World Curve could not be identified.**

Figure 3 data was discussed as though one LMV-D Curve might be applicable to all of the West Coast. The discussion is only intended as an example of a Youthful LMV-D Curve rather than a good data set for the West Coast. Based on temperature regime alone, it is expected that separate LMV-D Curves exist for the coastal areas of Southern California, Northern California, Oregon and Washington. There will be a number of very localized Inter-Mountain curves for the West. This paper will concentrate on the area east of the 105th Meridian where over 97 percent of NRCS earthen dams are located. If a separate effort to define the LMV-D Curves for the area west of the 105th Meridian is warranted, more specific identifications of LMV-D Curves are possible.

The Gulf Coast Local Maximum Volume-Duration Curve (LMV-D Curve)

Premise three was the concept that Local Maximum Volume-Duration (LMV-D) distributions east of the 105th Meridian are approximately parallel to the World Curve. Premise three is the critical aspect of this paper. Premise four explores the issue of whether there is enough data available east of the 105th Meridian to actually develop LMV-D Curves. The previously derived and assimilated data sources from this paper will be used to test premises three and four.

The same physical and meteorological conditions that limit World Record Volume-Duration values appear to limit Local Volume-Duration conditions. **The conditions that limit LMV-D values have existed for a long time**. Logic would indicate that the magnitude of LMV-D values should be less than World Curve values. For the area east of the 105th Meridian, the physical and meteorological conditions have been relatively stable for centuries, perhaps even dating from the last Ice Age. Fluctuations in climate in terms of centuries exist from time to time but those fluctuations have been relatively minor in the long-term picture. To say that the LMV-D curves are beginning to be defined **means that measurements of those values that will eventually define the curve have just begun.**

For the purposes of this paper, the definition of "Gulf Coast" includes all of Florida and the area within 50 miles of the Gulf Coast. This essentially matches the 47.1-inch, 24-hour PMP line in HMR-51. As discussed previously, the one-hour versus six-hour duration and longer data are from two entirely different data sources. Two one-hour values are shown on Figure 4. The 7.4-inch Texas value was the maximum Gulf Coast value from the state maximums (Moore, 2003), which included data through 1998. The 9.37 inch value was taken from the North Palm Beach, Florida storm of January 2, 1999. For most locations evaluated in this paper, there was a high degree of compatibility between the one-hour data and the six-hour and longer duration data.

Just as was noted in the West Coast data, the lower left-hand side of the curve (one-hour value) should act as a pivot point as more data is collected. Where the West Coast data represented a "youthful" LMV-D Curve, the Gulf Coast data (Figure 4) is a good example of a "mature" LMV-D Curve. The Gulf Coast data was defined over time very much like the West Coast data. The lower left-hand side of the curve (one-hour) is normally identified first in recording data because many maximum one-hour data points have been defined, especially in a prime environment like the Gulf Coast.

Because long duration events usually come from a different data source (evaluation of large individual storms), the right hand side of the curve (longer durations) may actually be quantified before the left-hand side of the curve is fully measured by the current recording network. As new maximum volume-duration values are added for longer durations, the upper end of the curve will slowly pivot upward around the better defined one-hour pivot point. In plotting historical data for LMV-D Curve purposes, only the maximum value for each duration is of interest. Some second and third order values for different durations have been plotted to illustrate that other events similar in magnitude to the maximum value have occurred. This repetition of maximum volume-duration values is one sign that there is some combination of local physical and meteorological conditions that form a local upper limit that consistently limits maximum values. Only the maximum value for each duration is used to actually define the historical Local Maximum Volume-Duration Curve.

If one considers the 9.37-inch value at North Palm Beach (or the ten inch value at New Braunsfel) as valid, the Gulf Coast LMV-D Curve is approaching a mature distribution. The historical data is approaching a straight-line relationship and it is approximating a line that is parallel to the World Curve. Three values that are above 38-inches have been identified in about a hundred plus years of record. Another hundred years of record will most likely produce a historical curve for the Gulf Coast that fully parallels the World Curve line. That curve may be slightly higher than the current curve indicated by historical data. **Remember that historical maximums can only go up**. Physically, there is no reason for the right (upper) end of the curve to ever exceed a line parallel to the World Curve. Additional records could move the pivot point up and flatten the slope of the LMV-D Curve back to that of the World Curve. **As a general statement, the slope of a mature LMV-D Curve should never exceed the slope of the World Curve**.

The premise that the Gulf Coast Curve will likely parallel the World Curve appears to be validated by the historic data in Figure 4. Throughout the development of this paper, an objective of developing a simple (and hopefully reliable) procedure for predicting LMV-D curves for any location east of the 105th Meridian was explored. The first procedure explored and ultimately accepted was based on intuitive logic. If the following two conditions exist, LMV-D Curves can be developed for any specific location east of the 105th Meridian:

- The published 24-hour PMP values for any location are approximately correct
- The LMV-D Curve for any location is essentially parallel to the World Curve

If these two conditions are met, we can use the 24-hour PMP value for a specific location and the World Curve Distribution to approximate the LMV-D Curve. Figure 5 shows the predicted LMV-D Curve for the Gulf Coast area. The predicted LMV-D Curve will always be parallel to the World Curve but lesser in magnitude. Using the local Gulf Coast 24-hour PMP (47.1 inches) and the World Curve distribution, we get a predicted LMV-D Curve (Figure 5) that exceeds the historical data but not excessively so. This would seem to be an ideal prediction for design purposes. The historical line may still go up over time so we would prefer a procedure that slightly over predicts the historical LMV-D Curve.

The historic Gulf Coast data on Figure 4 gives some interesting insight into PMP probabilities. Probability should consider both the frequency of occurrence of PMP sized events in a local area (Gulf Coast) and the likelihood that the event will occur within a specific design area. The 1979 Alvin storm occurred after TP-40 and HMR-51 were published. Thrall, Alvin and Yankeetown are three Gulf Coast events that approach 24-hour PMP status. All occurred under conditions of warmer temperatures and are located near a large water body. NOAA Technical Report 25 (Reidel, 1980) listed 40 storms for the entire area east of the 105th Meridian that produced more than 50 percent of the PMP sized event for their location and specific duration. There were 27 occurrences of more than 50 percent of the six-hour, 10 mi^2 PMP and 32 occurrences of more than 50 percent of the 24-hour, 10 mi^2 PMP. Obviously, some storms produced more than 50 percent of both the six and 24-hour, 10 mi^2 durations. Ten of the 27 six-hour duration storms and nine of the 32 24-hour storms exceeded 70 percent of the local PMP. Some additional large events have occurred since the 1980 publication date. We do not have an actual number but for the area east of the 105th Meridian there appears to be as many as one six-hour or longer near PMP (70 percent or greater) event somewhere in the area for every three to five years of record. We have always viewed PMP as something that rarely occurs. **This is a misconception, at least where 70 percent or more of PMP is involved.**

Near PMP or true PMP size events for durations of six hours or longer actually occur quite frequently in the area east of the 105th Meridian. The eyes or areas of maximum precipitation that closely approximate point rainfall values for these large events tend to cover relatively small areas. The climatic conditions along the Gulf Coast make it the most likely area east of the 105th Meridian to experience PMP size events. We have had three events (Alvin, Thrall and Yankeetown) within the Gulf

Coast area that were 82.2 to 89.2 percent of predicted 24-hour, 10 mi^2 PMP magnitudes. These three events have occurred within roughly 125 years of record. The eyes or areas of near maximum precipitation of these three near PMP size events collectively covered a total area of less than 100 square miles. The Gulf coast area as defined here covers an area of approximately 151,800 square miles. **The near PMP size event itself is not that rare (three near PMP events in about 125 years of record), it is the probability that it will hit your 10 square mile (or appropriate design area) that is rare.** Assuming that the three near PMP events actually were PMP events, a rough estimate of the historical probability that any specific Gulf Coast 10 square mile design area would be hit by a 24-hour PMP event would be (3 / 125 X 100 / 151,800) = 0.0000158. That value translates to an expected frequency of occurrence of once in (1.0 / 0.0000158) = 63250 years. This exercise is not intended to imply actual frequencies but rather to give a concept for considerations that should be a part of frequency calculations. It should be noted that as the design area increases above 10 square miles, the probability of occurrence increases and the associated frequency of occurrence decreases.

Evaluation of other Locations East of the 105th Meridian

Choosing additional local areas east of the 105th Meridian to test the process for developing LMV-D Curves identified some logistic problems with the data available. The HMR-51 database is site specific while the one-hour maximum data represents statewide maximums. The use of both databases as statewide data seems to give acceptable results. Further refinement of the data to more localized areas may ultimately be justified but the use of the data on a statewide basis appears to produce very good results.

Oklahoma

Oklahoma was chosen as the next test location because of the large number of hourly recording stations (over 150) and the identification of numerous large events (20 inches or greater). Most of Oklahoma resides between 34 and 37 degrees North Latitude. The center of the state is approximately 450 miles north of the Gulf of Mexico. The state has a somewhat uniform change in elevation from about 400 feet in the southeast corner to over 2000 feet in the panhandle with a maximum elevation of 4973 feet on Black Mesa near the western end of the panhandle. This provides some natural uplift for major storm events. Twenty two of the 32 storms east of the 105th Meridian that have produced 50 percent or more of 24-hour PMP for 10 mi^2 have occurred in this gradual uplift area west of the Mississippi River.

Major storms in the inland areas west of the Mississippi River are characterized by cold fronts from the northwest colliding with opposing warm-moist air from the Gulf of Mexico. The head on collision of two near-equal strength frontal systems results in a stalled frontal weather system. As the warm-moist air from the Gulf rapidly rises into the atmosphere, violent thunderstorms with high intensity rainfall are produced. Large storms are characterized by cell after cell of heavy rainfall passing over the same location along the stalled weather front. Movement of storm cells in this type storm is almost always from a southwest to northeast direction along the stalled frontal system.

Three large historic storms (Hallet, Cheyenne and Enid) account for all of the maximum Volume-Duration values above three hours (Figure 6). There are still second and third order values that are very near the maximum values. The historical data has a little more scatter than the Gulf Coast data but the tendencies are still apparent. The maximum Volume-Duration values tail-off after 12 hours. This change in slope at 12 hours duration is not indicative of a change in the LMV-D Curve. The break in slope does indicate two characteristics:

- The moisture supply associated with the distance from the Gulf is a restriction on longer duration events. As the distance from a sustainable water source increases, it becomes more difficult to maintain the moisture supply necessary to support longer duration events. The break in slope is a matter of insufficient length of record and not a change in the physical process.
- Larger 18 and 24-hour duration events will occur in the future when ideal storm circumstances will allow optimum conditions to exist for durations of 18 and 24 hours. The length of record simply has not been long enough to capture these longer duration events. Stated another way, it will take more than 100 years for the occurrence of a 24-hour PMP event in this locality. When combined with areal coverage, the occurrence of 24-hour PMP events in Oklahoma will be much less frequent than similar size events near the Gulf. If we bravely and optimistically assumed that one 24-hour PMP event covering 10 square miles would happen in the next 100 years (200 year of record), we could compute a very rough frequency for the likelihood that the PMP event would strike a specific 10 square mile design area. Using the 69903 square mile land area of Oklahoma, the probability would be (1 / 200 x 10 / 69903) = 0.000000715 or a frequency of once in 1,398,000 years (one in a million). Again, this is intended as a concept and not a prediction of actual frequency.

The historical LMV-D Curve shown on Figure 6 is a line that uses the Maximum one-hour value and the World Curve distribution (parallel to the World Curve) rather than a best fit through the Maximum Volume -Duration data. A best-fit line of the observed maximum volume-duration values would be very similar and are essentially parallel to the World Curve line for durations up through 12 hours. An important note is that the six-hour duration values for both Hallet and Cheyenne plot above the historical LMV-D Curve. All of the other maximum Volume-Duration values up through 12-hours plot very close to the expected line**.** The maximum one-hour data may move up slightly as additional data is collected. **Users should not be overly influenced by one data point above the line.** Remember all of the limitations related to using "bucket survey" data for longer duration storms. In this case, there are two events (Hallet and Cheyenne) for the six-hour duration event that both plot above the line so there is more reason for some concern. Basically, either the six-hour values are slightly too high based on measurement precision or the maximum values for the other durations will eventually move up to match the six-hour values as more data is collected. In either case, the historical data for Oklahoma up through 12-hour durations reflects an LMV-D Curve that is very nearly parallel to the World Curve.

Figure 6 again tests the proposition that the published 24-hour PMP and the World Curve Distribution can be used to safely approximate the local LMV-D Curve. The line constructed is specific for Hallet, Oklahoma since it represented the maximum historical data point. The predicted line again encompasses all historic data points including the two higher six-hour values. There is still some margin for historic values to increase. The premise of a LMV-D Curve parallel to the World Curve and the proposed prediction procedure for LMV-D Curves both seem to have worked very well for locations that are more than 400 miles from the Gulf of Mexico.

As a sidebar, the available data for all durations for the Enid and Hallet storms are shown in Figure 6. Both of these storms reflect the tendency of large events to collapse when they achieve an intensity that encounters the LMV-D Curve. Complete hourly data is available for the Enid storm. The maximum one-hour and two-hour intensities were high but less than maximums reflected by the Historical LMV-D Curve. The maximum three-hour Volume-Duration value for the Enid storm encountered the Historical LMV-D curve. The maximum Volume-Duration value for the fourth hour was also very near the Historical LMV-D Curve but then the storm collapsed. The Hallet data does not have historical data for Volume-Durations from one to five hours. However, it is known that the six-hour total of 18.4 inches reflects an average intensity of 3.04 inches per hour. The six-hour average rate at least is well below the Historical LMV-D Curve. The six-hour volume-duration value for the Hallet Storm encountered the LMV-D Curve. Somewhere between the six-hour and 12-hour Volume-Duration value, the Hallet Storm also collapsed. Again, the collapse of these large storms are characterized by storm intensities that exceed inflow rates and ultimately deplete moisture storage in the air column. At the point where air column storage is depleted (or dryed out), the storm will collapse. Both the Enid Storm and the Hallet storm each currently account for two of the maximum Volume-Duration values on the Oklahoma LMV-D Curve.

Iowa

The next location tested was Boyden, Iowa (Figure 7). Boyden is located above 43 degrees North Latitude and is approximately 1050 miles north of the Gulf of Mexico. Boyden has one of the rare six and 12-hour near PMP values for the northern latitudes. This station potentially represents the one exception from the NWCC database in which the one-hour volume-duration value plots above the predicted line. The NWCC database identifies a maximum one-hour value of 8.0 inches while the NOAA CD maximum for the same date and nearby location is only 4.0 inches. This 8.0-inch value meets all of the NWCC data tests for a valid point. The second order maximum value for Iowa is 6.6 inches in one-hour which fits much better with data from surrounding states and with the longer duration data available for Boyden, Iowa. This data point should be explored in greater detail to determine if it is reliable.

It is possible that the 8.0-inch value is a true point value with an associated 10 square mile value of approximately 6.8 inches (15 percent areal reduction). The 6.8-inch value would compare very favorably with the predicted value of 6.85 inches and the second order historical value of 6.6 inches. The historical large storm values for the six and 12-hour durations are also very close to the predicted line. Here is a case where the maximum measured two-hour and three-hour values would give us some additional guidance regarding the adequacy of the predicted line.

The predicted line still encompasses all of the historical data except for the current 8.0-inch estimate for the maximum one-hour. The predicted value does encompass the historical second order value of 6.6 inches. There is some indication of concern with the magnitude of the 24-hour PMP value at this location.

If the second order maximum one-hour data point is accepted, the LMV-D Curve for Boyden, Iowa is still approximately parallel to the World Curve. The six and 12-hour historical storm values still approximately parallel the World Curve values. Historical data is still lacking for the 18 and 24-hour duration values but time will eventually supply those values as well. Where Oklahoma has three or more occurrences of 20 + inches of rainfall, Iowa has only recorded one rainfall value greater than 20 inches. The number of occurrence of near PMP events continues to decline as one move farther north of the Gulf of Mexico. There is no indication from the Oklahoma and Iowa historic data that indicates there should be concern over **PMP events with durations in excess of 24-hours**. The historic data is surprisingly close to the predicted line using the 24-hour PMP and the World Curve distribution. This is a better data fit than was anticipated for this latitude.

Beaulieu, Minnesota

The northern most location evaluated was Beaulieu, Minnesota (Figure 8) located at approximately 47.3 degrees north latitude and is approximately 1300 miles north of the Gulf of Mexico. The maximum one-hour value of 5.80 inches plots just below the predicted one-hour value of 6.05 inches. The six-hour historical value is still slightly low at this latitude and the 12, 18, and 24-hour values have not yet been measured at this latitude. The one-hour maximum value fits well with the predicted line. The one-hour and six-hour values indicate that the data is gradually defining a line parallel to the World Curve. Time should produce values for the 6, 12, 18, and 24-hour durations much closer to the predicted line. The data fits well with what could be expected for this latitude given the combination of colder climate, moisture regime and period of record available. The time line to fully define the historical LMV-D Curve for this latitude is likely in terms of thousands of years rather than hundreds of years.

There appears to be clear evidence at all latitudes in the Mississippi Valley that the hypothesis that local distributions will approximately parallel the World Curve is valid. The concept of using the 24-hour PMP value and the World Curve distribution to safely predict LMV-D Curves also appears to be valid.

Tyro, Virginia

Tyro, Virginia east of the Appalachian Mountains was examined to further verify the hypothesis that local distribution curves approximately parallel the World Curve. Tyro, Virginia is located about 35-40 miles southwest of Charlottsville, Virginia at approximately 37.5 degrees North Latitude. The results for Tyro, Virginia are shown on Figure 9. For Tyro, the one-hour and six-hour values appear to parallel the World Curve. The 12-hour value is well above the other 2 data points and is very near the predicted LMV-D Curve for the location. The Tyro, Virginia data indicates that the maximum one-hour and six-hour values are not fully developed. With time, both the one-hour and six-hour data points should move up closer to the predicted line. In any case, the predicted LMV-D Curve encompasses all historical data points.

Smethport, Pennsylvania

Anyone who has studied PMP development has examined the July 17-18, 1942 storm at Smethport, Pennsylvania. The 4.5-hour and 12-hour point values of 30.80 and 34.50 inches respectively reported at Smethport represent World Record values on the World Curve. It is the 4.5-hour total of 30.80 inches which always creates concern and tends to defy explanation by traditional standards. Precipitation values that occurred outside the 4.5-hour maximum period are modest amounts and simply add to the very large 4.5-hour total. **The intense 4.5 hours of the Smethport storm has had the singular greatest influence on PMP development.** Many question whether or not the 4.5-hour total for Smethport is real. Smethport does have an orographic influence. The location could have also been subjected to dual moisture inflows from the Atlantic Ocean 250 miles to the east and the rain shadow of Lake Erie 70 miles to the northwest. The data exists and has been examined numerous times by meteorological experts without finding a conclusive reason to invalidate the 4.5-hour total. Most have concluded that the event either happened as reported or that it could have happened as reported.

The traditional arguments questioning the 4.5-hour total at Smethport always include temperature regime and distance from a large water body. The interpretation of the Smethport data is strongly influenced by a single point value. The 10 square mile, six-hour value drops to 24.7 inches and the six-hour, 100 square mile value is 16.4 inches. Other important issues raised by this paper also deserve new consideration in the debate over the validity of the Smethport data. Repetitive large values have been a characteristic of other sites evaluated in this paper. The second highest six-hour total in Pennsylvania was the six-hour 10-square mile value of 8.0 inches for Zerbe, Pennsylvania The nearest value of any consequence is located 240 miles southeast of Smethport at Ewan, New Jersey which reported a 10 square mile total of 20.1 inches in six-hours. Ewan, New Jersey is approximately 45 miles from the Atlantic Ocean. D'Hanis, Texas (Woodward Ranch) reported a point value of

22.00 inches in 2.75 hours and North Palm Beach, Florida reported 30.01 inches in 6 hours. These locations are 1200 and 1400 miles southwest and south of Smethport and located in much more favorable temperature and moisture conditions.

The maximum-recorded one-hour volume is a new piece of information that has not been considered in the past. The maximum recorded one-hour value of 7.09 inches for Pennsylvania compares very favorably with the predicted LMV-D Curve using the 24-hour PMP value for Smethport (Figure 10). The one-hour value does not compare favorably with either the 4.5-hour World Curve value or the six-hour or 12-hour, 10 square mile values from HMR-51. A line connecting the one-hour value with any of these values immediately intersects the World Curve values. In other words, it predicts a slope that is much greater than the slope of the World Curve when the one-hour value is used. **One must consider that either the one-hour value is far too small or the Smethport data is much too high**. The maximum one-hour value for Pennsylvania compares favorably with one-hour values in adjacent states. If anything, it is already higher than might be expected. One might ask why the one-hour data seems to be so compatible with longer duration data at other locations but not at the Smethport location. There are three frames of reference at the Smethport location which include the World Curve, the world record Smethport data, and the predicted LMV-D Curve as supported by the maximum one-hour volume. Two are compatible and one is not.

Comparison of the Critical Stacked World Curve Distribution with two Actual Near PMP events

The predicted intensities using the 24-hour PMP and World Curve distribution were compared to two large historic events to determine if the proposed procedure is indeed conservative. The Galveston, Texas District of the Corp of Engineers published the hourly storm data for the July 25-26, 1979 Alvin, Texas storm (Tropical Storm Claudette) as shown on Figure 11. Figure 11 shows the predicted LMV-D Curve for Alvin, Texas. The lower line on Figure 11 is the actual hourly rainfall distribution for the Alvin, Texas event. The Alvin, Texas storm was very nearly a uniform distribution. The Maximum Volume-Duration Curve (MV-D Curve) from the Alvin, Texas storm is also shown on Figure 11. At least in this case, the area between the predicted LMV-D Curve and the actual MV-D Curve represents the degree to which the Critically Stacked World Curve distribution combined with the local 24-hour PMP over predicted the largest historical near 24-hour PMP size event in our data base. The area between the actual storm MV-D Curve and the LMV-D Curve is quite large when the log-log scale is considered. The predicted maximum one-hour volume for Alvin, Texas based on the LMV-D curve was 10.0 inches while the observed maximum two-hour volume was 8.25 inches (1 a.m. to 3 a. m., C of E, 1980). The maximum one-hour volume based of Figure 3 (C of E, 1980) was approximately 4.25 inches. Alvin, Texas is not typical of the intensities found in many of the near PMP size events but it does illustrate that the potential degree to which the Critically Stacked World Curve distribution is capable of over predicting actual historical patterns.

The Enid, Oklahoma storm (Figure 12) was widely noted for its maximum intensities. The Enid storm was a large six-hour event. We will only look at the first six hours as compared to the predicted first six hours on the LMV-D Curve. There is still a significant safety factor between the predicted LMV-D Curve and the historical storm MV-D Curve. The predicted one-hour value was 7.79 inches compared to the actual maximum one-hour Volume-Duration value of 5.31 inches. Over prediction will always occur as long as the predicted LMV-D Curve encompasses all historical data points. This occurs because not all maximum volume-duration values for any location will occur in any single storm event. Only rarely do more than two maximum volume-duration values occur in any one historical storm event. That means that the predicted curve overestimates for all other durations. This is a typical result of using any critically stacked procedure that encompasses historical data. The degree of the safety factor can be modest as in the case of the Enid storm or it may be quite conservative as in the case of the Alvin storm.

Conclusions

Four premises related to the applicability of the Critically Stacked World Curve Distribution to the area east of the 105 Meridian were evaluated. All four premises were found to be either valid or at least worthy of further consideration. The premises tested and results were:

1) The envelope (World Curve) of the Maximum Volume-Duration values on the World Curve are the true upper limit values of precipitation that can be expected to occur anywhere in the world under current global climatic conditions. Until such time that new values begin to appear above the current World Record values, it is reasonable to assume that this premise is indeed valid.
2) Any Local Maximum Volume-Duration Curve (LMV-D Curve) that is parallel to the World Curve will have the same percent hourly distribution (but a lesser total volume) as the World Curve. The premise that LMV-D Curves are essentially parallel to the World Curve was tested at four latitudes and locations within the Mississippi Valley area east of the 105th Meridian. The results at the first three latitudes in the Mississippi Valley gave strong indications that the

historical volume-duration data was approximately parallel to the World Curve. The fourth location at the northern most latitude was less conclusive based primarily on the lack of time required to define the LMV-D Curve at that latitude. Two locations east of the Appalachian Range were also tested. The Tyro, Virginia location was less than conclusive but all historical values were encompassed with the proposed prediction procedure. The premise of a LMV-D Curve parallel to the World Curve did not work at all with the Smethport, Pennsylvania world record data.

3) Just as there are physical and meteorological upper limits on a global scale, there also exists Local Maximum Volume-Duration Curves (LMV-D Curves). This premise seemed to work very well for the Mississippi Valley locations and showed promise for the Tyro, Virginia site. The addition of the local maximum one-hour volume-duration value was a valuable addition to the longer duration database. Again, the premise seemed to work well at all site locations except Smethport, Pennsylvania. The theorem justifies additional study and consideration before dismissal.
4) Sufficient data currently exists to tentatively define the LMV-D Curves for the area east of the 105th Meridian. The data available for the analysis in this paper should justify this premise. There is much more applicable data available but a great deal of persistence will be required to identify the sources.

In addition to testing the four premises, a prediction procedure for estimating LMV-D Curves was also presented and tested. The procedure performed well at all test locations excluding Smethport, Pennsylvania. Test locations were chosen to test areal applicability and because of the presence of large record events at that location. The predicted values tended to parallel the local historical values and give a slightly conservative estimate. The prediction procedure for LMV-D Curves should be an extremely valuable tool for developing local rainfall distributions for use with 24-hour PMP events. No new data is required to implement this procedure since the only input requirement is the 24-hour PMP value from HMR-51. Localizing the data should be a rare issue since the primary input (24-hour PMP) has already been localized. In most cases, state boundaries are the most convenient local area to consider. The procedure for conversion of LMV-D Curve values to a rainfall distribution is discussed in an accompanying paper (Moore, 2003). The proposed procedure provides a uniform and consistent method for 24-hour PMP designs for the area east of the 105th Meridian that is based on PMP size events.

The proposed prediction procedure will give a conservative answer for all historical record events for all locations east of the 105th Meridian with the exception of the two world record events (Smethport and D'Hanis Texas). An earthen dam at D'Hanis Texas designed using this procedure would have actually passed the May 31, 1935 record event primarily because the actual storm duration was less than six hours. A similar earthen dam at Smethport, Pa designed using this procedure would have overtopped. Any test of these two events is somewhat judgmental since the actual maximum one-hour intensities are unknown.

Contrary to West Coast data where storm durations for large events are often in excess of 24 hours, east of the 105th Meridian there have been no recorded volume-duration values for duration in excess of 24 hours that approached the LMV-D Curve for that location. The conclusion is that designs for durations in excess of 24 hours are not applicable to the area east of the 105th Meridian. The east to west movement of the dominant PMP moisture source (hurricanes) and their rapid dissipation over landmasses accounts for the lack of large longer duration events.

Recommendations

1) The World Curve Volume-Duration data should be used for developing a critically stacked rainfall distribution for use with 24-hour PMP events. The distribution is more appropriate than any current distribution because it is developed from PMP sized events.
2) The distribution would be applicable to any area where the data exhibits a historical LMV-D Curve that is approximately parallel to the World Curve. The historical data (LMV-D curves) for the area east of the 105th Meridian displays a strong tendency to parallel to the World Curve.
3) Further time and resources should be devoted to evaluate data needs identified in this document. Maximum one-hour data should continue to be monitored on a regular systematic basis (say every 5 years) to identify any new maximum values. There is also an opportunity to identify the two-hour and three-hour historical maximums from the RUSLE data set using the current NWCC protocol. For six-hour or longer durations, only new maximum volume-duration values need to be collected.
4) The procedures used for the area east of the 105th Meridian can very likely be applied to areas in the Western U. S. if the need justifies the necessary resources.
5) The North Palm Beach, Florida data needs to be confirmed or invalidated. If validated, the rainfall volumes recorded indicate a higher PMP value (than the current 47.1-inch value) would be warranted for South Florida.

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Figure 1: Available Water verses Dew Point Temperature

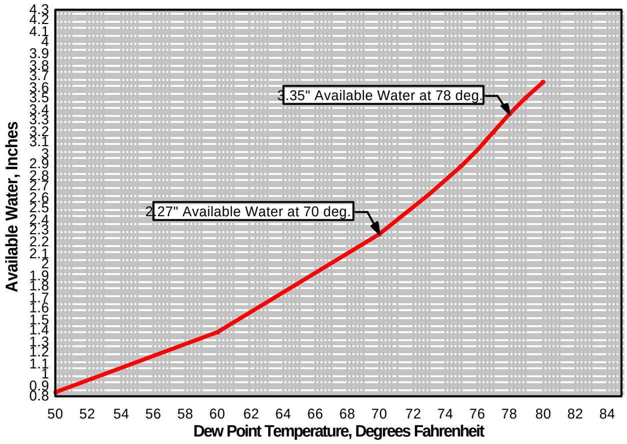

Figure 2: Maximum Observed Point Rainfall as a Function of Duration

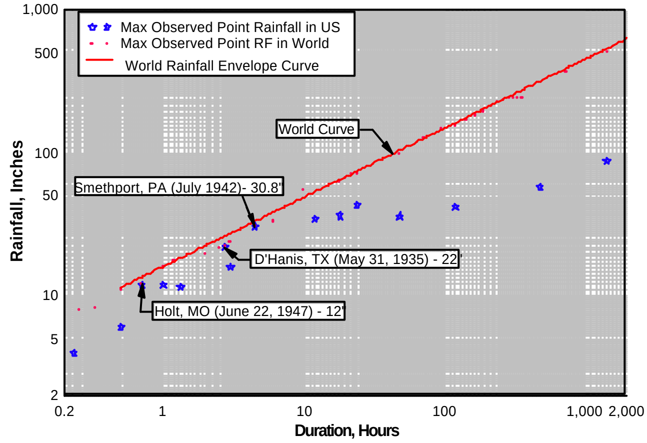

Figure 3: World Curve & West Coast Observed Rainfall-Duration Data

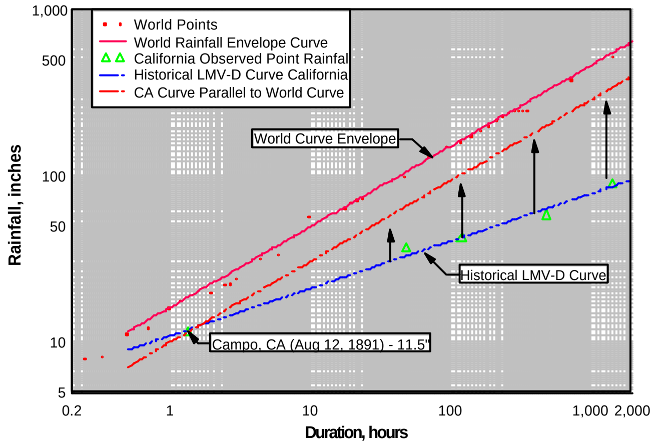

Figure 4: Rainfall Volume - Duration; World & Historical US Gulf Coast

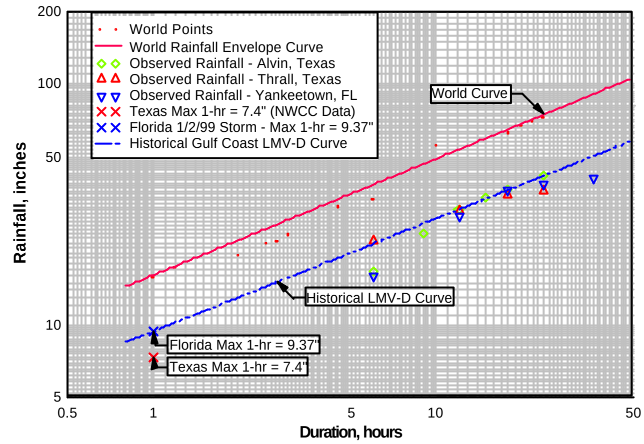

Figure 5: Rainfall Volume - Duration, World & Historical US Gulf Coast

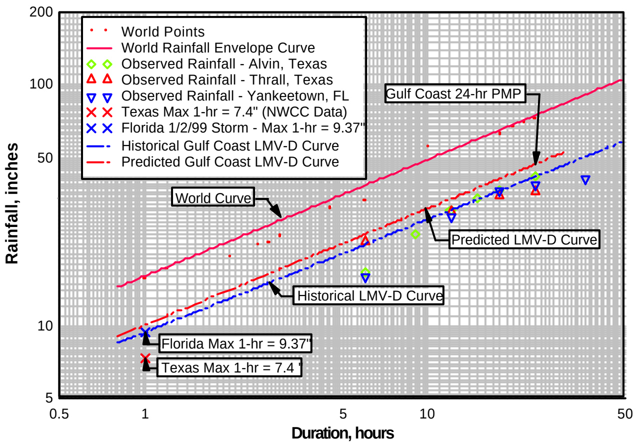

Figure 6: Rainfall Volume - Duration; World & Historic Oklahoma

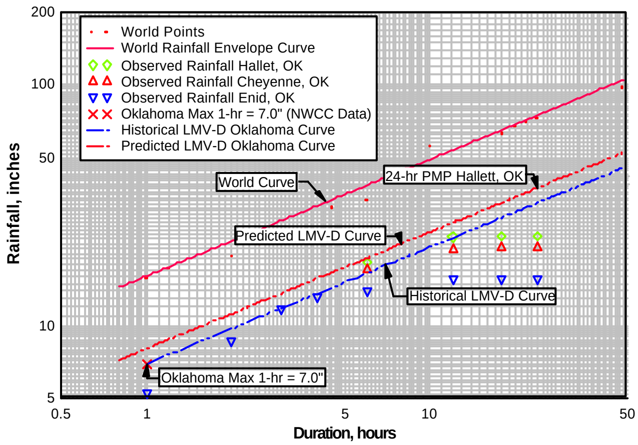

Figure 7: Rainfall Volume - Duration; World and Boyden, Iowa

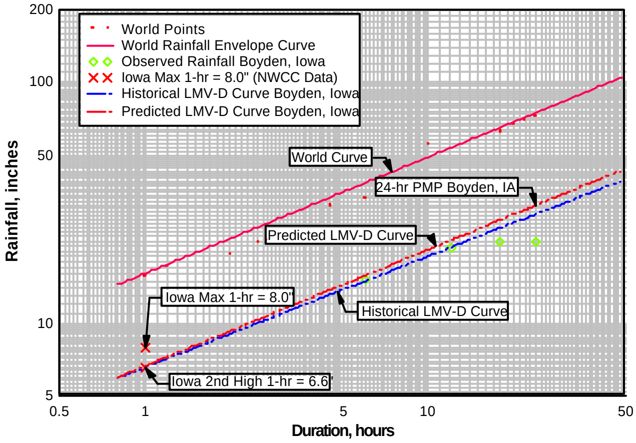

Figure 8: Rainfall Volume - Duration; World and Beaulieu, Minnesota

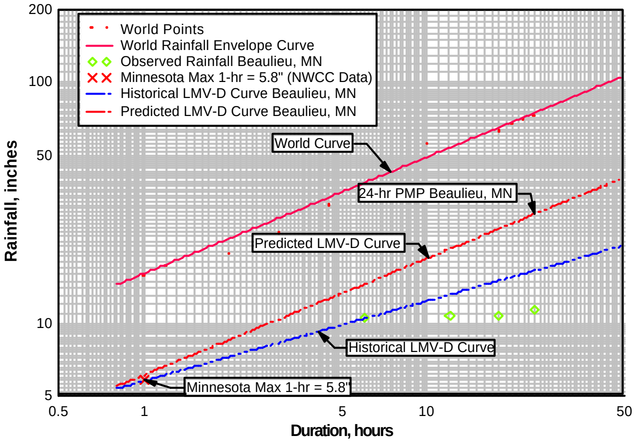

Figure 9: Rainfall Volume - Durations; World and Tyro, Virginia

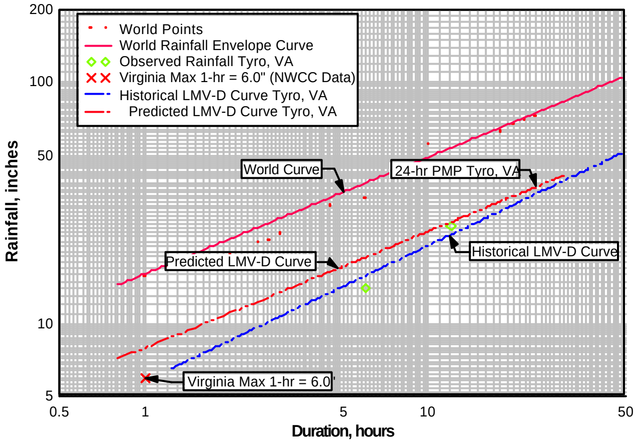

Figure 10: RF Volume - Duration; World & Smethport, Pennsylvania

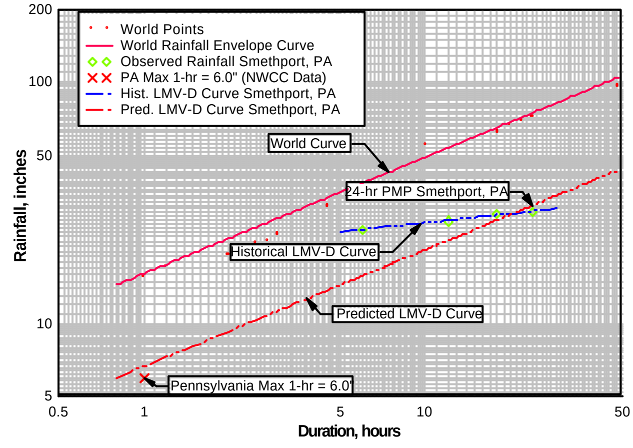

Figure 11: July 25-26, 1979 Storm - Alvin, Texas

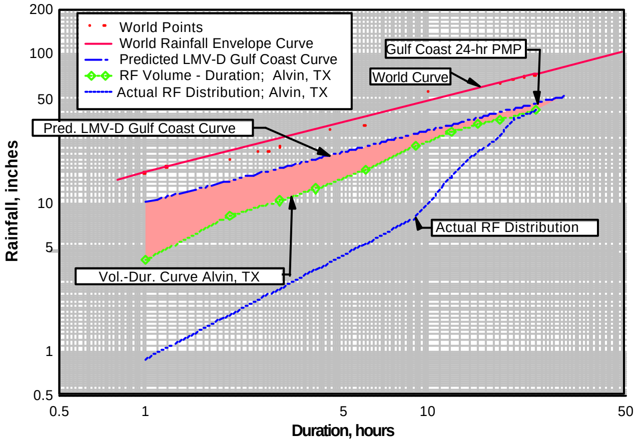

Figure 12: October 10, 1973 Storm - Enid, Oklahoma