Arizona Statewide Probable Maximum Precipitation (PMP), Improving HMR 49

*Edward M. Tomlinson, Ph.D., Applied Weather Associates, LLC**
*William D. Kappel, Applied Weather Associates, LLC**
Michael Johnson, Ph.D., P.E., Arizona Dept of Water Resources#
*Tye W. Parzybok, Metstat, Inc.^*
*Douglas M. Hultstrand, Metstat, Inc.^*

**Applied Weather Associates, LLC PO Box 680, Monument, CO 80132 (719) 488-9117*
#Arizona Department of Water Resources, Surface Water Division (602) 771-8649
^Metstat, Inc., 4764 Shavano Drive, Windsor, CO 80550 (970) 686-1253

Recent storm analyses and site-specific Probable Maximum Precipitation (PMP) studies completed in Arizona revealed the inadequacies of HMR 49 in properly representing storm characteristics and PMP throughout the region. To address the numerous issues associated with HMR 49, Applied Weather Associates (AWA) is conducting a statewide, storm based PMP project for the state of Arizona to replace HMR 49. AWA is working directly with a consortium of stakeholders, including Arizona DWR, various dam owners, the Department of Game and Fish, the state climatologist, and others in this important project.

HMR 49 was published in 1977 and is the oldest of the HMRs currently in use. More recent HMRs use updated storm data and PMP analysis procedures. HMR 49 used outdated methods and techniques, that have subsequently been improved through new understanding of meteorology and updated datasets. A major issue with HMR 49 is the lack of storm data used to develop the PMP values. Only a handful of storms were investigated during the development of HMR 49, none of which were analyzed using individual storm depth-area-duration (DAD) values. This combined with the fact that the document covers such a widely varying region both climatologically and topographically, explains the necessity for an update.

AWA has incorporated updated databases and procedures as part of several recently completed and current site-specific PMP projects. These improvements include, but are not limited to: updated storm databases (the newest HMR storm analyzed is from the mid-1990's), integrating the Storm Precipitation Analysis System (SPAS) with Next Generation Weather Radar (NEXRAD) to better spatially and temporally distribute rainfall, integration of GIS to analyze orographics and controlling topography, updated dew point climatology to better represent atmospheric moisture, and updated storm analysis techniques.

New storms analyzed as part of the Magma, Arizona site-specific PMP study as well as the Safford, Arizona site-specific PMP study and overlapping areas from HMR 59 were compared to values derived using methods in HMR 49. An extensive storm database constructed from these projects and other sources is being used to develop a database of storms that will be individually analyzed during the statewide PMP project. The storm list contains numerous storms in each climate division as well as each storm type (local convective, winter synoptic and decaying tropical) that affects Arizona. These storm analyses will allow for a storm based PMP to be developed for all points within the state of Arizona, much the same as was completed for the state of Nebraska in 2008.

Introduction

PMP values provided in HMR 49 (Hansen et al 1977) appear to be inaccurate and are in need of updating. The other HMRs produced using the same procedures as HMR 49 have been replaced by the NWS but there are no plans to replace HMR 49 or to produce any updates. The southwestern portion of the HMR 49 has been included in the HMR 59 (California) update. An updated statewide PMP analysis for Utah has been completed but Arizona, Nevada, New Mexico and the western portions of Colorado still have HMR 49 as the primary source for PMP values.

The technology exists to provide updates for regions within the HMR 49 domain. Any effort to provide a regional update such as for the state of Arizona needs to be comprehensive, incorporating updated storm data, storm Depth-Area-Duration (DAD) analyses for all major storm events for the various climatic regions within the southwestern United States, updated dew point analyses, and use state-of-the-science procedures and tools such as NEXRAD and GIS. HMR procedures, such as the orographic enhance factor (K-factor) procedure, are being carefully evaluated for reliability.

One of the products derived from the analyses of historic extreme rainfall events in Arizona are mass curves for each storm. These mass curves provide the temporal variation of rainfall during each storm event. Analyses of these mass curves by storm type, local and general, produces information on temporal rainfall distributions that can be analyzed to provide time distributions for use in modeling of both local and general storms statewide. The primary benefit of this analysis is time distributions are derived from actual rainfall events that have occurred within the study region. This approach does not rely on ratios or other assumptions to simulate the temporal distributions of storm rainfall.

The procedures used in completing a site-specific PMP study includes identifying historic extreme storms that could have occurred over the study basin; maximizing, transpositioning and elevation/barrier adjusting the rainfall amounts; and producing Depth-Area (DA) and Depth-Duration (DD) curves for the basin location. Enveloping curves for the largest rainfall amounts on both the DA and DD plots are completed. These envelope curves provide continuity among area sizes and continuity in time for rainfall values at the basin location. Regional or statewide studies also include analyses of the spatial distributions of the enveloped values determined over a grid or other spatial distribution method. This additional step provides added information on the horizontal variation of extreme rainfall events that result from different sets of storms used at differing locations and/or rainfall variations resulting from changes in available atmospheric moisture at the various locations. Hence regional or statewide PMP studies inherently incorporate not only the temporal and area size continuity analyses for individual locations but also incorporate spatial (horizontal) continuity analyses into the two dimensional maps of PMP values.

A storm search has been completed to identify all extreme rainfall storms that have occurred in Arizona including storms not identified in HMR 49 along with extreme rainfall events that have occurred since the publication of HMR 49. Additionally, the statewide PMP study has identified significant extreme rainfall storm events listed in HMR 49 that are appropriate for Arizona. Storm isohyetal and Depth-Area-Duration (DAD) analyses will be completed for extreme rainfall storm events deemed to be the most significant storms for PMP development at any location within the state. Extreme rainfall storms in much of the HMR 49 domain have not been systematically analyzed resulting in a large number of storms requiring analyses. The HMR 49 domain is shown in Figure 1.0.

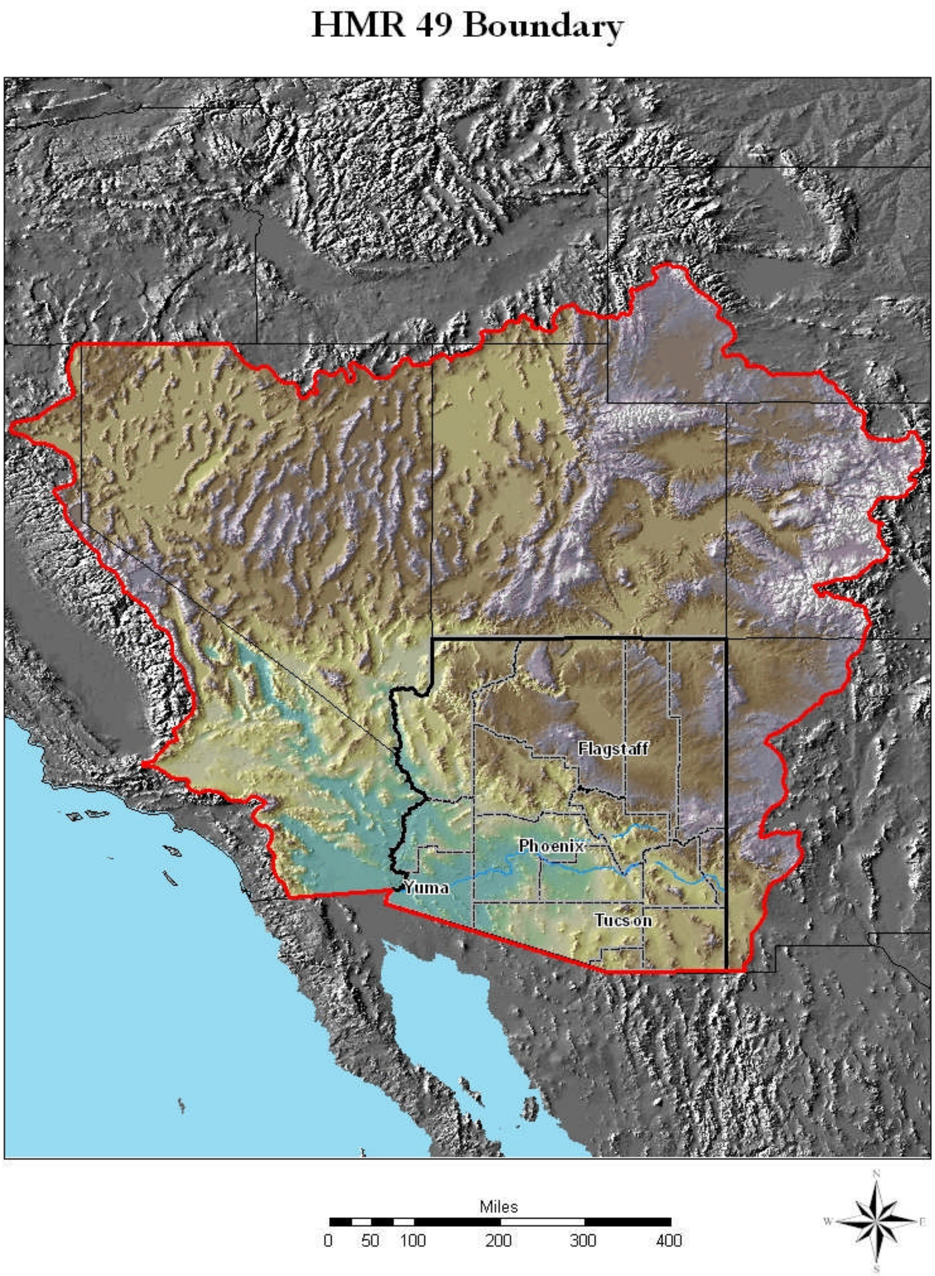

Figure 1.0	Coverage of HMR 49

PMP Background for Arizona

The site-specific studies recently completed in Arizona have produced reductions in PMP values for the basins studied. This may or may not be the case for other regions and individual basins around the state but in any case, an updated PMP analysis will provide increased reliability for PMP values. A statewide PMP study has recently been completed for Nebraska (Tomlinson et al 2008). The updated PMP maps incorporated many newer storms, as well as an updated maximum dew point analysis. The study used GIS to provide efficient and effective distributions of PMP values across the state. The new PMP maps provide continuity of PMP values across the state in both space and time which ultimately reflect the unique storm characteristics encountered across Nebraska. Such a study for Arizona is more complicated due to the varied climatic regions and significant topography. However, similar results to those in Nebraska can be achieved to provide reliable site-specific PMP values for every location across the state of Arizona.

HMR 49 covers a large area of the Intermountain West and Desert Southwest, including the entire state of Arizona, where climate and terrain vary greatly (see Figure 1.0). Because of the distinctive climate regions and significant topography, it is difficult to develop PMP values to accurately account for the complexity of the meteorology and terrain throughout the state. HMR 49 is the oldest of the current HMR series. An assessment of the storm database and procedures in HMR 49 identified significant issues. Among these are the lack of analyzed storm events, the age of the document and the procedures used.

The procedures used in HMR 49 for general storms are basically the same procedure used in HMR 36, "Probable Maximum Precipitation in California", and HMR 43, "Probable Maximum Precipitation, Northwest States" (HMR 49, Section 1.5). HMR 36 was replaced by HMRs 58 and 59 in 1999 (Corrigan et al 1999). HMR 43 was replaced by HMR 57 in 1994 (Hansen et al 1994). There has not been a replacement or update for HMR 49.

Storm Search and Analysis

The rainfall amounts associated with extreme rainfall storm events will be fully analyzed using the Storm Precipitation Analysis System (SPAS). The analyzed rainfall amounts will be adjusted throughout appropriate the climate zone (areas of meteorological, climatological, and topographical homogeneity) within the state of Arizona using standard procedures (Parzybok and Tomlinson 2006). This task will develop both maximization and transposition factors for each storm. A gridded analysis procedure will be used for geographic regions where appropriate with the contribution of each transpositioned storm applied across the grid. For orographically significant regions, a different approach may be taken to insure that orographic effects are addressed properly as they vary across mountainous terrain.

The largest of the adjusted rainfall amounts will be used to compute PMP values. Storm durations that are appropriate for hydrology specific to each climate zone of Arizona are being investigated and the final PMP values, both spatially and temporally, will be developed to best fit the hydrologic user's needs. Storm types that affect different area sizes and durations will be identified. Envelopment of the largest rainfall totals will be applied to insure spatial and temporal continuity of the final PMP values.

Storm maximization will be completed using the basic approach used in the EPRI Wisconsin/Michigan (Tomlinson 1993) and Nebraska statewide (Tomlinson et al, 2008) PMP studies. Following procedures used in these studies, instead of using the 12-hour persisting dewpoint analyses for storm moisture quantification for all storm types, average dew point values of durations consistent with the *actual* rainfall durations will be used. This approach is consistent with the procedure developed in the EPRI Michigan/Wisconsin and Nebraska studies to use dew point values averaged over the storm duration. A climatology of maximum 3-hour average, maximum 12-hour average and maximum 24-hour average dew points will be developed for the Southwestern United States to be used in the storm maximization and transpositioning procedures.

Significant Storm Events throughout Arizona

The approach taken in recent HMRs and the World Meteorological Organization (WMO) Manual is a storm based approach that uses historic extreme storms as the basis for PMP determination. The recent site-specific PMP study for the Magma FRS drainage basin (Tomlinson et al 2008) recognized that HMR 49 used only a relatively small number of storms for PMP development. It is very important to have an adequate database of storms for use in PMP studies along with as much storm information (including storm DADs) as possible. For storms that have occurred since the early to mid 1990's, NEXt generation RADar (NEXRAD) weather radar data contribute significantly to the spatial and temporal quality of storm analyses. Additionally, for domains that include distinctive topographic and climatic regions, such as the state of Arizona, an adequate storm database should be available for each distinctive region. Even for regions where extreme storm rainfall values are relatively small, it is important to have an adequate storm database to quantify the most extreme observed rainfall amounts and to ensure all possible storm types are captured.

Arizona has several distinct topographic and climatic regions. The storm database available for development of PMP in HMR 49 appears to have been lacking in both quantity (number of extreme storms) and quality (detailed storm rainfall analyses) for the various topographic and climatic regions statewide. As an example, the results of AWA's storm search for use in the Magma FRS drainage basin site-specific PMP study, combined with the storm search results of a PMP study AWA reviewed in the Safford area and an overall storm search within the entire southwestern United States for use in the statewide project shows how many storms are available in the region for consideration in developing the storm based PMP values (Figure 2.0). In contrast, Figure 3.0 displays the locations of the storms used to develop HMR 49. Notice how sparce the coverage of storms from HMR 49 is in relation to the varied climate and meteorological characteristics of the state.

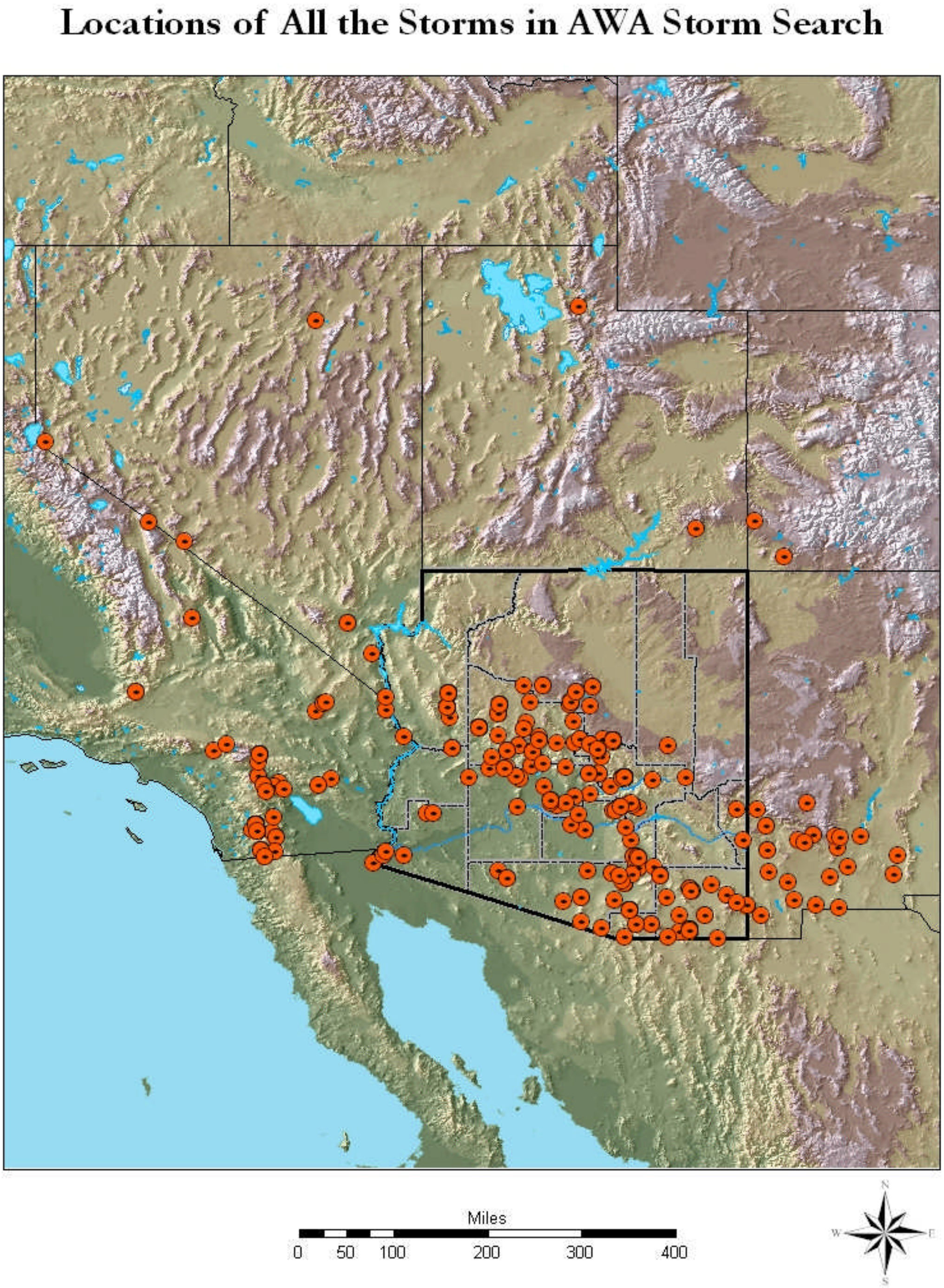

Figure 2.0 AWA combined storm search results within HMR 49's domain

Locations of All the Storms Used in HMR 49

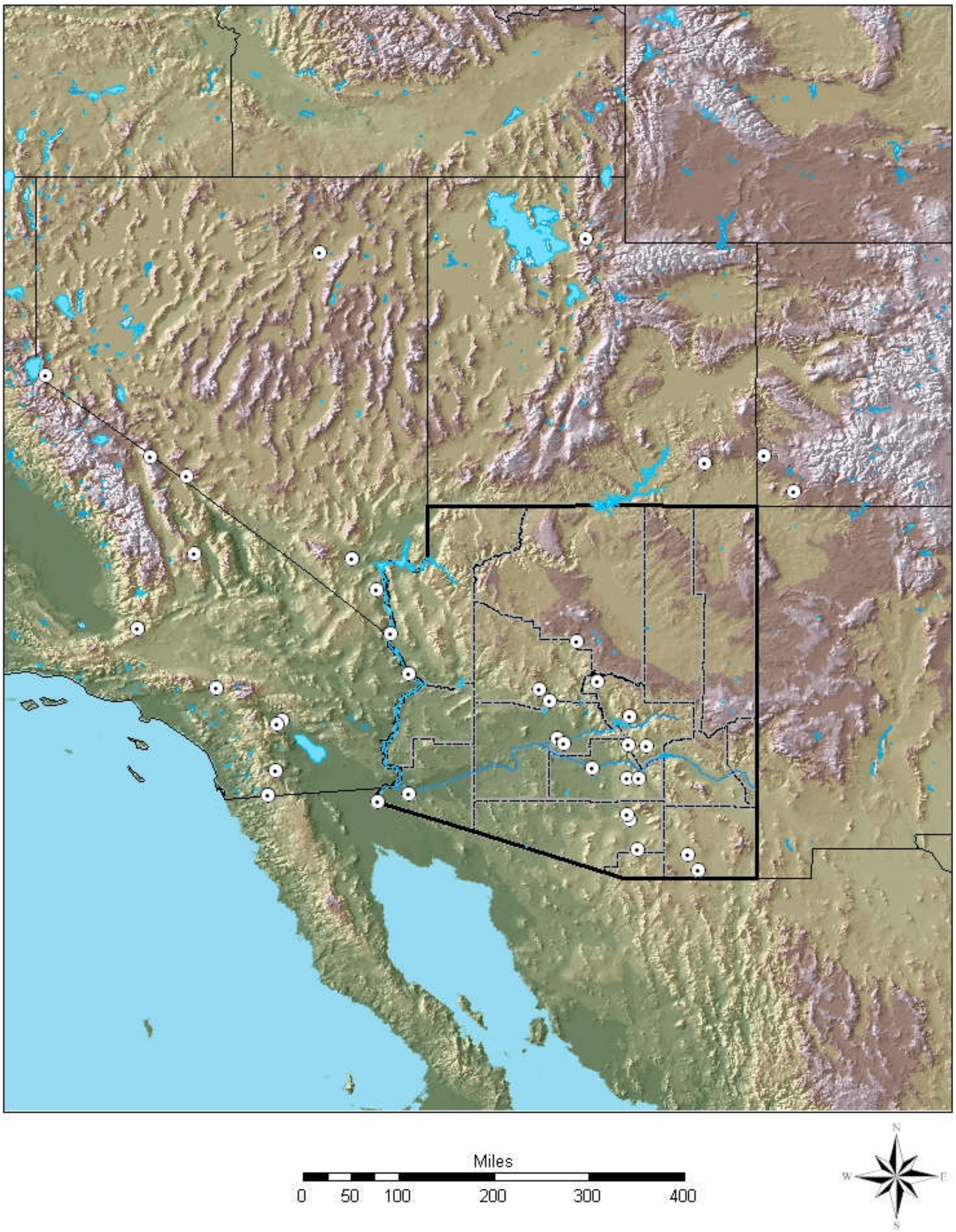

Figure 3.0 HMR 49 storm locations

Storm Maximization and Maximum Dew Point Maps

The storm based procedures used in the HMRs and the WMO Manual apply various adjustments to analyzed storm rainfall data for PMP determination. Once extreme storms have been identified and analyzed, a process called maximization is completed. The purpose of this procedure is to compute the "theoretical" maximum rainfall a storm could have produced had more atmospheric moisture been available for the storm to convert to rainfall. Historically in PMP studies, atmospheric moisture is quantified by computing the precipitable water (PW) contained in the air mass associated with the storm rainfall production. Since direct measurements of PW are very limited, PMP analyses have historically used surface dew point temperatures, along with the assumption that the air mass is saturated, to quantify PW. The maximization process identifies a surface dew point value that is representative of the air mass associated with the storm's rainfall production and determines the PW associated with that dew point. A climatology is used to determine the "maximum" dew point at the same location where the storm dew point was observed. After determining the PW associated with the maximum dew point, the ratio of maximum PW to storm PW is computed and becomes the maximization factor.

The same climatology maps of maximum dew points are used in the storm transpositioning process. Transpositioning computes the maximum rainfall a historic storm could have produced at other locations that are topographically and climatically similar, and then moves the storm to another location as if it had occurred there. This increases the number of extreme storm events that can be used in calculating the PMP values.

Dew Point and Storm Maximization

A couple of issues are associated with the determination of dew point values. Historically, 12-hour persisting dew point values have been used. A 12-hour persisting dew point is defined as the *lowest* dew point value that persists for a 12 hour period. It should be remembered that the dew point values are supposed to be representative of the moisture in the air mass associated with the rainfall. Using the lowest observed dew point vs. the average dew point may not be appropriate. Further, using a 12-hour duration vs. 3-hour or 24-hour duration more representative of the actual storm rainfall duration may not be appropriate. NWS has in HMRs 57 and 59 used 3-hour and 12-hour durations but continues to use persisting dew point values. Other site-specific and regional PMP studies have adopted the use of 6-, 12-, and 24-hour dew point values that use average vs. persisting dewpoint values to better quantify the atmospheric moisture associated with the rainfall production.

HMR 50 (a companion document to HMR 49) provides maximum dew point maps (Hansen and Schwarz 1981). There are two sets of maps, one for use with local storms and one for use with general storms. Both use 12-hour persisting dew points. An explicit discussion on how these maps were derived is not provided nor are discussions related to the differences in the values between local and general storms. There is a statement made that considerations of local and general storm situations suggested a difference of 2° to 3°F. The authors of HMR 50 did give a high level overview of the processes and stations used to develop their dew point climatology (HMR 50 Section 4.3), but it is greatly lacking in detail.

Evaluation of Orographic Enhancement and Depletion

HMR 49 uses a procedure that computes an orographic PMP component that is added to the convergent PMP. HMRs 57 (Columbia River Drainage) and 59 (California) use a K-factor multiplier to account for orographic increases in rainfall. Both of these procedures appear to have shortcomings.

Terrain effects on precipitation (orographic) are of immense importance in the western United States. Locally, precipitation tends to increase with increasing elevation (up to a few thousand feet, at least). This is true for both short-term events and for long-term averages. The National Weather Service in their more recent HMR reports uses an "Orographic Factor," or K-factor. This involves determining the "convergence" and "orographic" components of the precipitation field. An improved methodology would begin with an "extreme precipitation" gridded data set. Whereas long-term average ("climate") precipitation grids are available by month or year for many areas, up-to-date extreme precipitation grids are less common. As part of the Arizona PMP project, AWA will utilize the results of its SPAS storm analysis to derive the orographic adjustments appropriate for each part of the state. This will be based on actual storm characteristics instead of ratio or derived factors. Using actual storm characteristics is much more appropriate for storm analysis than are climate grids, because extreme storm events tend to have different spatial variations than average conditions. There is also potential to improve on the NWS approach by developing an improved method for estimating K-factors using GIS and the PRISM model (Daly et al 1997) in conjunction with the storm based analysis.

The next step would be to determine the least orographic areas in the state. This step begins with identification of air flow patterns during major storms. A trajectory model is very useful for estimating air flow and identifying which terrain barriers that are likely to be of influence. PRISM contains a trajectory model which could be used here along with the HYSPLIT trajectory model (Draxler and Rolph 2003). The result would be a more reliable procedure that could be verified using extreme rainfall storm data and potentially used in the computation of PMP values over orographically significant terrain.

Depth-Area-Duration Comparisons versus HMR 49 Ratios

The newer HMRs (i.e. all HMRs published after HMR 49) use Depth-Area-Duration (DAD) results from individual storm analyses in the determination of generalized PMP values. The more recent HMRs use the basic procedures provided in the World Meteorological Organization (WMO) PMP Manual, 1986. Storm DADs provide the maximum rainfall that was produced by the storm during various durations over various area sizes. Standard durations are 6-, 12-, 24-, 48-, and 72-hour durations. Shorter durations are often provided for local storms. Standard area sizes normally include 10-, 100-, 200-, 500-, 1000-, 5000-, 10000-, and 20000 square mile area sizes. For local storms, the larger area sizes are often not analyzed.

HMR 49 uses ratios to provide rainfall values for various durations and area sizes instead of using analyzed historic storm maximum rainfall depths for various durations and area sizes. These ratios are presented in various graphs and tables in HMR 49. The origin of these graphs and tables is not provided in HMR 49 and no working papers are available from the National Weather Service (NWS) Hydrometeorological Design Studies Center. Section 1.5 of HMR 49 states that depth-duration and depth-area variations were based on record storms but no further details are provided.

In order to get a sense of the variations between current processes used to derive DAD values and values that HMR 49 ratios would produce, direct comparisons were made with three extreme storm events analyzed by AWA during the Magma FRS site-specific PMP study (Yuma Valley 1977, Sols Wash 2000, Magma 2008). Additionally, comparisons were made with three HMR 59 analyzed storm events that occurred within the western domain of HMR 49. Two of these storms were compared as both local and general storms based on HMR 49 definition of local storm (3 hour or less duration). These were Yuma Valley 1977 and HMR 59 Storm 1018. AWA directly compared the analyzed storm DADs with the rainfall values derived from the HMR 49 local or general storm worksheet (HMR 49 Tables 6.1 and 6.3A). Comparisons were made for each standard duration and area size. For local storms, comparisons were made for the 1-, 2-, 3-, 4-, 5-, and 6-hour durations and for the 1-, 10-, 100-, 200-, and 500-square mile area sizes. For general storms, comparisons were made for the 6-, 12-, 18-, 24-, 48-, and 72-hour durations and 10-, 100-, 200-, 500-, 1000-, 2000-, and 5000-square mile area sizes.

The results of these comparisons proved to be very useful in quantifying the inadequacies of the HMR 49 ratio procedure for both local and general storms. Differences in analyzed storm DADs versus HMR 49 ratio derived DADs ranged from 128% larger to 51% smaller. Further, there was no consistent bias even within the same storm. At some durations HMR 49 results would be larger and at other they would be smaller. Another interesting result of this analysis is the fact that the variations are also dependent on storm characteristics. For example, a short duration local storm where the majority of the rainfall accumulates in the first hour (e.g. HMR 59 storm 1018) has as much greater variation from the HMR 49 derived rainfall amounts compared to a local storm where the rainfall accumulates more uniformly over the entire 6-hour period. This result is not surprising since HMR 49 ratios treat all local storms exactly the same and all general storms exactly the same, thereby completely missing the unique characteristics of each individual storm event.

The storm DAD based methodology explicitly analyzes each storm event and PMP values are based on analyzed storm rainfall values, explicitly accounting for varying storm characteristics. This procedure allows for all possible scenarios represented in the storm database that could produce a PMP type event at various area sizes and durations to be expressly captured and quantified.

HMR 49 derived DADs for local storms were constructed using only one rainfall value associated with a storm, the 1-hour 1-square mile rainfall value. Further compounding the error was the fact that this value was often derived using ratios of the total storm rainfall to what the author's of HMR 49 thought would represent the 1-hour rainfall. In the comparisons below, the actual 1-square mile 1-hour value is taken from the analyzed storm DAD table. For the general storms, the 24-hour 10-square mile analyzed storm rainfall value is used. Again, the same issue arises in HMR 49's treatment of the 10-square mile 24-hour value, as it was usually derived using a ratio method versus using the actual storm rainfall amount that fell in that time frame over that area size. Table 2. shows the comparison results for the four local storm events and Table 3. displays the comparison results for the four general storm events. Negative values in the *difference* tables indicate the HMR 49 derived rainfall value is smaller than the analyzed storm rainfall value while positive values in the *difference* tables indicate the HMR 49 derived rainfall value is larger than the analyzed storm rainfall value.

Table 2. Magma 2008 local storm comparison

Magma 2008 SPAS Analyzed Storm Depth-Area-Duration						
	1 Hour	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours
1 sq miles	**1.60**	**2.61**	**3.81**	**4.01**	**4.18**	**4.29**
10 sq miles	**1.60**	**2.57**	**3.58**	**3.96**	**4.09**	**4.24**
100 sq miles	**1.30**	**2.09**	**2.67**	**3.23**	**3.52**	**3.65**
200 sq miles	**1.16**	**1.88**	**2.51**	**2.96**	**3.24**	**3.36**
500 sq miles	**0.89**	**1.50**	**2.06**	**2.45**	**2.73**	**2.84**
1000 sq miles						
2000 sq miles						
5000 sq miles						

Magma 2008 HMR 49 Derived Storm Depth-Area-Duration						
	1 Hour	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours
1 sq miles	**1.6**	**1.82**	**1.94**	**2.00**	**2.05**	**2.08**
10 sq miles	**1.33**	**1.55**	**1.67**	**1.74**	**1.80**	**1.85**
100 sq miles	**0.78**	**0.97**	**1.11**	**1.18**	**1.27**	**1.31**
200 sq miles	**0.58**	**0.75**	**0.87**	**0.94**	**1.00**	**1.61**
500 sq miles	**0.37**	**0.47**	**0.56**	**0.64**	**0.70**	**0.73**
1000 sq miles						
2000 sq miles						
5000 sq miles						

Difference between Analyzed Storm DAD and the HMR 49 DAD						
	1 Hour	2 Hours	3 Hours	4 Hours	5 Hours	6 Hours
1 sq miles	**0%**	**-30%**	**-49%**	**-50%**	**-51%**	**-52%**
10 sq miles	**-17%**	**-40%**	**-53%**	**-56%**	**-56%**	**-56%**
100 sq miles	**-40%**	**-54%**	**-58%**	**-63%**	**-64%**	**-64%**
200 sq miles	**-50%**	**-60%**	**-65%**	**-68%**	**-69%**	**-52%**
500 sq miles	**-58%**	**-69%**	**-73%**	**-74%**	**-74%**	**-74%**
1000 sq miles						
5000 sq miles						
10000 sq miles						

Table 3. HMR 59 Storm 1017 general storm comparison

HMR 59 Storm 1017 Depth-Area-Duration					
	6 Hours	12 Hours	18 Hours	24 Hours	48 Hours
10 sq miles	**3.34**	**5.26**	**5.26**	**5.70**	**6.16**
100 sq miles	**3.27**	**5.17**	**5.17**	**5.53**	**6.03**
200 sq miles	**3.26**	**4.92**	**4.92**	**5.49**	**5.82**
500 sq miles	**2.89**	**4.53**	**4.53**	**5.02**	**5.28**
1000 sq miles	**2.60**	**4.01**	**4.01**	**4.44**	**4.81**
2000 sq miles	**2.11**	**3.16**	**3.16**	**3.52**	**3.85**
5000 sq miles	**1.55**	**2.10**	**2.10**	**2.47**	**2.88**

HMR 59 Storm 1017 HMR 49 Derived Storm Depth-Area-Duration					
	6 Hours	12 Hours	18 Hours	24 Hours	48 Hours
10 sq miles	**3.99**	**4.96**	**5.36**	**5.70**	**6.49**
100 sq miles	**3.59**	**4.51**	**4.89**	**5.23**	**6.03**
200 sq miles	**2.99**	**3.86**	**4.25**	**4.59**	**5.38**
500 sq miles	**2.63**	**3.47**	**3.84**	**4.18**	**4.97**
1000 sq miles	**2.32**	**3.11**	**3.51**	**3.79**	**4.59**
2000 sq miles	**2.03**	**2.79**	**3.15**	**3.48**	**4.27**
5000 sq miles	**1.59**	**2.32**	**2.66**	**2.99**	**3.78**

Difference between Analyzed Storm DAD and the HMR 49 DAD					
	6 Hours	12 Hours	18 Hours	24 Hours	48 Hours
10 sq miles	**19%**	**-6%**	**2%**	**0%**	**5%**
100 sq miles	**10%**	**-13%**	**-5%**	**-5%**	**0%**
200 sq miles	**-8%**	**-21%**	**-14%**	**-16%**	**-7%**
500 sq miles	**-9%**	**-23%**	**-15%**	**-17%**	**-6%**
1000 sq miles	**-11%**	**-22%**	**-13%**	**-15%**	**-5%**
2000 sq miles	**-4%**	**-12%**	**0%**	**-1%**	**11%**
5000 sq miles	**3%**	**10%**	**27%**	**21%**	**31%**

These results illustrate how poorly the ratio methodology used in HMR 49 compares with the analyzed storm rainfall amounts and its subsequent lack of reliability for use in calculating PMP. This was expressly recognized by the author's of the subsequent HMR reports, as they eliminated the ratio methodology and used the currently accepted practice of the storm based approach utilizing DADs.

Conclusions

Applied Weather Associates has conducted an assessment of the potential benefit of a statewide maximum precipitation (PMP) study for Arizona. A critical review of Hydrometeorological Report (HMR) 49 methodology and storm database was completed. Comparisons were made between the approach used in HMR 49 and the methodology used in more recent HMR publications as well as procedures and data used in recent regional and site-specific PMP studies.

The most obvious characteristic of HMR 49 is its age. The procedures used in HMR 49 for general storms are basically the same procedure used in HMR 36, "Probable Maximum Precipitation in California", and HMR 43, "Probable Maximum Precipitation, Northwest States" (HMR 49, Section 1.5). HMR 36 was replaced by HMRs 58 and 59 in

1999. HMR 43 was replaced by HMR 57 in 1994. There has not been a replacement or update for HMR 49.

But beyond its age, other significant shortcomings were identified. The storm database available for development of PMP in HMR 49 appears to have been lacking in both quantity (number of extreme storms) and quality (detailed storm rainfall analyses) for the various topographic and climatic regions statewide. An updated storm search for the statewide PMP project has identified a large number of potentially significant storms that should be included in PMP determination.

The newer HMRs (i.e. all HMRs published after HMR 49) use Depth-Area-Duration (DAD) results from individual storm analyses in the determination of generalized PMP values. These more recent HMRs use the basic procedures provided in the World Meteorological Organization (WMO) PMP Manual, 1986. Instead of using analyzed maximum storm rainfall depths for various durations and area sizes, HMR 49 uses ratios to provide rainfall values for various durations and area sizes. These are presented in various graphs and tables in HMR 49. This project compared the storm DADs constructed using these ratios to the results of storm analyses for five storms. Significant differences were identified with no consistent bias observed. The conclusion is that the ratio procedure in HMR 49 did not adequately replicate the spatial and temporal rainfall distributions of the storms evaluated. Given this significant problem, reliability of PMP values derived using the HMR 49 ratio procedure is highly questionable. Any effort to provide reliable PMP values for Arizona must replace the HMR 49 ratio procedure with actual storm DAD analyses. For storms that have occurred since the early to mid 1990's, NEXt generation RADar (NEXRAD) weather radar data contribute significantly to the spatial and temporal quality of storm analyses. When available, storm analyses should include NEXRAD data.

The storm based procedures used in the HMR and the WMO Manual apply various adjustments to analyzed storm rainfall data for PMP determination. Once extreme storms have been identified and analyzed, a process call maximization is completed. The purpose of this procedure is to compute the "theoretical" maximum rainfall a storm could have produced had more atmospheric moisture been available for the storm to convert to rainfall. HMR 49 uses the historically accepted practice of using 12-hour persisting dew point values for quantifying a storm's available atmospheric moisture and uses maximum12-hour persisting dew point values for storm maximization. Additionally, it distinguishes between 12-hour persisting dew point values for local and general storms. This is the only HMR that incorporates local and general 12-hour persisting dew point values and unfortunately does not provide explanations of the difference between the two values nor how the values are determined.

More recent HMR have incorporated dew point values based on various durations. Regional and site-specific PMP studies have incorporated average vs 12-hour persisting dew point values. This project includes an updated dew point analysis using average dew point values of various durations. HMR 50 is the companion document to HMR 49 and provides maps of maximum dew point values. A comparison was made in this assessment between return frequency values for maximum average dew point values for various return frequencies and the HMR 50 maximum 12-hour persisting dew point values. All show that the values used in HMR 50 are too low compared to using an average dew point representative of the actual storm duration. Therefore, in most situations, the HMR 50 analysis was missing the actual moisture associated with any particular extreme rainfall event. And more often than not, the storm maximization values are overly conservative, as a 1°F discrepancy in dew point temperatures causes and approximately 5% change in the maximization factor.

The last major issue evaluated was the of orographic enhancement procedure used in HMR 49 and in the new HMRs, HMRs 57 and 59 in particular. HMR 49 used a procedure that computes an orographic PMP component that is added to the convergent PMP. HMRs 57 and 59 use a K-factor multiplier to account for orographic increases in convergence PMP. Both of these procedures appear to have shortcomings. This analysis provides a recommended approach for providing improved reliability in the development of orographic enhancement factors that are more reliable and reproducible. At a minimum, a consistent procedure with the latest HMRs will be developed.

References:

Corrigan, P., Fenn, D.D., Kluck, D.R., and J.L. Vogel, 1999: Probable Maximum Precipitation Estimates for California. *Hydrometeorological Report No. 59*, U.S. National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Silver Spring, MD, 392 pp.

Daly, C., Taylor, G., and W. Gibson, 1997: The PRISM Approach to Mapping Precipitation and Temperature, 10th Conf. on Applied Climatology, Reno, NV, Amer. Meteor. Soc., 10-12.

Draxler, R.R. and Rolph, G.D., 2003: HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY Website (http://www.arl.noaa.gov/ready/hysplit4.html). NOAA Air Resources Laboratory, Silver Spring, MD.

Hansen, E.M., Schwarz, F.K., and J.T. Riedel, 1977: Probable Maximum Precipitation Estimates, Colorado River and Great Basin Drainages. *Hydrometeorological Report No. 49*, National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Silver Spring, MD, 161 pp.

__________ and F.K. Schwartz, 1981: Meteorology of Important Rainstorms in the Colorado River and Great Basin Drainages. *Hydrometeorological Report No. 50*, National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Silver Spring, MD, 167 pp.

___________, Fenn, D.D., Schreiner, L.C., Stodt, R.W., and J.F., Miller, 1988: Probable Maximum Precipitation Estimates, United States between the Continental Divide and the 103rd Meridian, *Hydrometeorological Report Number 55A*, National weather Service, National Oceanic and Atmospheric Association, U.S. Dept of Commerce, Silver Spring, MD, 242 pp.

__________, Schwarz, F.K., and J.T. Riedel, 1994: Probable Maximum Precipitation-Pacific Northwest States, Columbia River (Including portion of Canada), Snake River, and Pacific Drainages. *Hydrometeorological Report No. 57*, National

Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Silver Spring, MD, 353 pp.

House, P.K., and K.K. Hirschboeck, 1997: Hydroclimatological and Paleohydrological context of Extreme Winter Flooding in Arizona, 1993, *in* Larson, R.A., and Slosson, J.E., eds., Storm-Induced Geologic Hazards: Case Histories from the 1992-1993 Winter in Southern California and Arizona: Boulder, Colorado, Geological Society of America Reviews in Engineering Geology, Vol. XI, 27pp.

National Climatic Data Center (NCDC). NCDC TD-3200 and TD-3206 datasets - Cooperative Summary of the Day

Parzybok, Tye W., and Edward M. Tomlinson, 2006: A New System for Analyzing Precipitation from Storms, *Hydro Review*, Vol. XXV, No. 3, 58-65.

Tomlinson, E.M., 1993: Probable Maximum Precipitation Study for Michigan and Wisconsin, Electric Power Research Institute, Palo Alto, Ca, TR-101554, V1.

_________, Kappel W.D., Parzybok, T.W., Hultstrand, D., Muhlestein, G., and B. Rappolt, May 2008: Site-Specific Probable Maximum Precipitation (PMP) Study for the Wanahoo Drainage Basin, Prepared for Olsson Associates, Omaha, Nebraska.

___________, Kappel W.D., and T.W. Parzybok, February 2008: Site-Specific Probable Maximum Precipitation (PMP) Study for the Magma FRS Drainage Basin, Prepared for AMEC, Tucson, Arizona.

World Meteorological Organization, 1986: Manual for Estimation of Probable Maximum Precipitation.