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Final Report
Review of the Extreme Precipitation Analysis Tool (EPAT), Phase II: Independent Meteorological Review
DQ#: PEA-1402

Introduction

Applied Weather Associates has completed a technical review of the Extreme Precipitation Analysis Tool (EPAT) for the Dam Safety Branch of the Colorado State Engineer's Office. The development of an extreme precipitation analysis tool using geographic information system (GIS) technology was initiated in 2005. It was recognized that the GIS based tool could potentially provide objective analysis results for use in determining extreme rainfall values for individual drainage basins. The intent of this initiative was to objectively determine extreme rainfall values using procedures applied in the NOAA Hydrometeorological Reports (HMRs). These procedures have been refined and used in site-specific Probable Maximum Precipitation (PMP) studies for individual drainage basins. EPAT was developed to automate the site-specific PMP (SSPMP) methodology.

The purpose of this EPAT review was to evaluate how effective the tool performs in applying SSPMP determination procedures in an objective, meteorologically accurate, reliable and reproducible manner. EPAT was evaluated to determine that the extreme rainfall values produced are consistent with historically observed extreme rainfall events and that calculated extreme rainfall values are physically possible for a given watershed location as required by the definition of PMP. Results produced by the GIS based tool must be physically possible based on combinations of storm characteristics that produce the most extreme rainfall values possible while insuring that unrealistic assumptions or inconsistent combinations of parameters are not allowed. The review evaluated the effectiveness of the tool to objectively, consistently and reliability produce PMP values for individual watersheds using the storm based approach for determining site-specific PMP values.

During the evaluation of the spatial and temporal envelopment process in EPAT, an error was found in some of the EPAT data related to spatial rainfall accumulation. Analysis of EPAT rainfall spatially showed several instance where rainfall accumulations increased with increasing area size at the same duration, i.e. the 100-square mile 24-hour rainfall was larger than the 10-square mile 24-hour rainfall over a given location. It could not be determined from the data provided whether this was an issue related to the EPAT storm analysis process or the application process. A detailed discussion and examples are provided a part of Appendix A of this review.

The process employed by EPAT to calculate basin average precipitation uses a simplified weighted average methodology based on the total area covered by a given storm and the area covered by each incremental isohyetal. This process does not take into account variations in rainfall accumulation spatially between know data points and between given isohyetal increments. Therefore, significant amount of precipitation are missed and left out of the analysis. This is exaggerated the larger the storm domain being analyzed and the more extreme the rainfall gradients are across that domain. Appendix B provides a discussion of the procedure used for calculating basin-average precipitation in EPAT.

The following tasks were completed in this review:

Task 1 Familiarization with EPAT
The EPAT v4.2 program and EPAT Phase I deliverables were reviewed in order to thoroughly understand how EPAT works and to identify errors and concerns.

Task 2 Evaluate the EPAT Storm Library
The completeness of the extreme rainfall events included in the EPAT storm library was reviewed. Spatial and temporal characteristics of the storm data included in the EPAT Storm Library were reviewed for completeness, reliability and accuracy.

Task 3 Evaluate In-place Maximization and Transposition Procedures
The in-place maximization factors for each storm in the EPAT Storm Library were evaluated. In addition, the storm transposition procedures were reviewed to access the reliability of horizontal and vertical adjustments.

Task 4 Evaluation of the EPAT Procedures
All EPAT procedures with respect to current PMP science and practice, including accuracy and reliability of calculations, were evaluated. Each procedure was reviewed and compared to procedures used in recent PMP studies. Evaluations and verifications of calculations and procedures included evaluating in-place maximization factors, moisture transposition factors, re-evaluation of transposition limits, re-evaluation of storm orientations, inflow vectors, and storm isohyetal patterns.

Task 5 EPAT Rio Grande Dam Drainage Basin Evaluation
EPAT v4.2 rainfall depth, area and duration results for the Rio Grande Dam drainage basin were evaluated using storms in the AWA storm analysis database from site-specific PMP studies in Colorado and from the Arizona statewide study. The results were compared to the EPAT results. Comparisons and discussion are provided to explain and detail the differences.

Task 6 Recommendations for EPAT Modification
Based on the results of the review, AWA has made recommendations for potential EPAT modifications to improve the science and reliability of the program for use by the DSB. Outdated and incorrect procedures have been identified and replacement procedures recommended where possible.

Discussion

Task 1

The EPAT v4.2 program and EPAT Phase I deliverables were reviewed to provide a thorough understand of how EPAT works and to identify errors and concerns. The review took an objective and methodological approach. Individual EPAT procedures were identified and compared with standard procedures used in National Weather Service HMR PMP development, and in site-specific and regional PMP studies. Although the procedures developed in EPAT were storm based, many did not follow standard accepted PMP development procedures or applied the procedures in inconsistent ways. Task 4 identified these non-standard procedures as well as the inconsistencies.

The EPAT software was run and found to perform as designed. AWA exercised the software and found that it consistently produced extreme rainfall values for individual watersheds with a some exceptions. There were a few test runs that resulted in crashes of the EPAT application – and the test runs could not be completed. For several test runs within the San Luis Valley (37.75° N, 106°W) using a circular test basin shapefile at various area sizes (1 through 500 mi^2), the tool crashed with an "unspecified error". It is not clear on what caused this error. However, the EPAT software indicated it was "Rotating rainfall features…" for storm #31 San Luis, indicating there was an issue with transposing/orienting the isohyetal pattern for this storm to the basin locations in the San Luis Valley. A similar error occurred for a circular test basin in El Paso County (39°N, 105°) for storm #75 Penrose/Beaver Creek, although this error only occurred at the 500 mi^2 area size.

EPAT requires the ESRI ArcGIS version 9.1 to operate. ArcGIS 9.1 was released May, 2005 and updated to version 9.2 in June, 2006. The current version of ArcGIS Desktop is version 2 and was released July 2013, with new versions being released approximately once a year. ArcGIS version 9.1 has been long outdated, is difficult to obtain, and cannot be installed on the same workstation as current version of ArcGIS. The Visual Basin code used to design EPAT is not compatible with the current version of ArcGIS in its current form. ESRI states ""VBA no longer provides the best toolset for customizing ArcGIS and is not included in the default installation", suggesting plans to no longer support Visual Basin languages for development. For these reasons, from a technical perspective, EPAT is currently outdated and would necessitate a significant effort to update the code to allow the application to function concurrent with today's GIS software.

Task 2
The EPAT library was evaluated for both completeness in identifying all extreme storm events that could influence PMP values for watersheds in Colorado along with evaluating spatial and temporal characteristics of the storm data for completeness, reliability and accuracy. The storm parameters were evaluated to ensure that all required parameters are included. Storms in the library must include comprehensive rainfall data and state-of-the-science storm rainfall analyses with sufficient spatial and temporal detail to provide accurate and reliable input to the GIS tool. Site-specific PMP studies procedures were evaluated for consistency with accepted procedures. The application of these procedures was evaluated from an atmospheric science prospective, consistency with accepted SSPMP study procedures, and as well completeness of documentation. Task 4 provides a summary of the review of storms in the EPAT library.

Task 3
The in-place maximization factors for each storm in the EPAT Storm Library were evaluated. Since the in-place maximization factors are linear multipliers in the development of PMP values, they must be consistently determined using accepted procedures. Many non-standard procedures and inconsistent procedures have been identified. In addition, the storm transposition procedures

were reviewed to access the reliability of horizontal and vertical adjustments. Explicitly adjustments for varying topography, storm centering and elevation adjustments were evaluated.

The use of the Colorado State University Report 97-1 and other analyses to help delineate similar transposition regions as discussed in the EPAT Phase 1 Report Section 2.4.1 was appropriate and is based on meteorological and topographical considerations. However, the final application of where to move storms and how to utilize these data needs extensive re-evaluation and refinement. In general, the transposition limits applied to most of the storms are not supported by current understanding of meteorology and topographical interactions and therefore do not provide the level of conservatism needed for PMP development for all regions covered by EPAT.

In addition, because topography within even these refined transposition zones varies greatly over short distances, the currently accepted methodology of the orographic transposition factor (OTF) to quantify the effects of topography would need to be employed. The OTF methodology has been used to derive PMP values in the Lewis River site-specific PMP study, the Arizona statewide PMP study, the Susitna-Watana site-specific PMP study, and the ongoing Wyoming and Tennessee Valley Authority studies. The HMR 55A storm separation method (SSM) has been shown to be highly subjective, is not based on observed data, and not reproducible and is therefore not recommended for use.

The explicit transposition limits applied in EPAT can produce extreme gradients of values and discontinuities across boundaries and at adjacent locations. This issue is addressed in the HMRs by applying manual smoothing of the PMP values and by applying an areal reduction factor (ARF) and depth-duration (DD) ratio across larges regions. This introduces its own set of issues by implicitly letting storms influence regions far beyond their intended transposition limits. In additions, in regions with topographically significant terrain, regionalized ARF and DD ratios are not appropriate and instead should be evaluated on a storm-by-storm, location specific basis. In recent PMP studies (e.g. Arizona statewide) which employed the OTF, the discontinuities were address through the gridded development of PMP and the envelopment process which allows several different storms to influence PMP at a given location at each duration. It should be noted that significant gradients in PMP values can exist over short distances where topography has an extreme effect on rainfall. Therefore, in some regions having large gradients in PMP values between locations can be warranted.

A summary of the results are provided in the Task 4 discussions.

Task 4

All EPAT procedures with respect to current PMP science and practice, including accuracy and reliability of calculations, were evaluated. Results from Task 2 and Task 3 evaluations of the EPAT Library and in-place maximization are presented under Task 4 since they all related to how EPAT procedures produce PMP values. Each procedure was reviewed and compared to procedures used in recent PMP studies. Evaluations and verifications of calculations and procedures include evaluations of the calculation of in-place maximization factors, moisture transposition factors, re-evaluation of transposition limits, re-evaluation of storm orientations, inflow vectors, and storm isohyetal patterns. EPAT procedures that are current and applied appropriately are identified. Outdated and incorrect procedures have been identified and update procedures are recommended where appropriate. These are presented in expanded outline format.

General Comments

During the evaluation of the spatial and temporal envelopment process in EPAT, an error was found in some of the EPAT data related to spatial rainfall accumulation. Analysis of EPAT rainfall spatially showed several instances where rainfall accumulations increased with increasing area size at the same duration, i.e. the 100-square mile 24-hour rainfall was larger than the 10-square mile 24-hour rainfall over a given location. It could not be determined from the data provided whether this was an issue related to the EPAT storm analysis process or the application process. A detailed discussion and examples are provided as part of Appendix A of this review.

The process employed by EPAT to calculate basin average precipitation uses a simplified weighted average methodology based on the total area covered by a given storm and the area covered by each incremental isohyetal. This process does not take into account variations in rainfall accumulation spatially between know data points and between given isohyetal increments. Therefore, significant amount of precipitation are missed and left out of the analysis. This is exaggerated the larger the storm domain being analyzed and the more extreme the rainfall gradients are across that domain. Appendix B provides a discussion of the procedure used for calculating basin-average precipitation in EPAT.

1.0 EPAT storm library

1.1 Completeness

- 1.1.1 76 storms included
- 1.1.2 Some relatively small storms
- 1.1.3 Storms outside Colorado not included
- 1.1.4 Storm rainfall center locations not included[1]

Problem Statement

For a storm based deterministic PMP evaluation, it is imperative that the storm set used to derive the PMP values is inclusive of all potential storms that could influence PMP. The EPAT report included 76 unique storm events. This should be an adequate number of events, assuming all storms which could control PMP values at various area sizes and durations are included. However, some storms which have been shown to control PMP values in PMP studies within and immediately adjacent to the state of Colorado were not included (e.g. Bluff, UT 2001, John Day, OR 1969, Gibson Dam, MT 1964, Springbrook, MT 1921, and Warrick, MT 1906). For example, Figure 1 shows the HMR 55A transposition limits for the Gibson Dam storm. The storm was clearly transpositioned to the northern mountains of Colorado, yet this storm was not used in EPAT. This storm is extremely important for PMP in mountainous regions where it is considered to be transpositionable. The list of potential storms which should be included not currently in the EPAT library is shown in Table 1. Each of these storms has already been analyzed by the US Army Corps of Engineers (USACE), National Weather Service (NWS), Bureau of Reclamation (USBR) or Applied Weather Associates (AWA).

An additional concern with the EPAT storm library is that several of the storms are significantly smaller than other storms and therefore are not required to be in the storm library. Table 2 listed the storms which after initial investigations are not of PMP magnitude and can be removed from the storm library. The criteria used to determine whether a storm was recommended to be

[1] The EPAT storm library does include the coordinates for all 76 storm centers (not clear if these are actual true “rainfall centers” or how these were used). The table is located in **StormLibrary.mdb\StormCenters**. However, this table is “not used in EPAT, can be ignored” pg.425. Therefore, thiit was unknown how and if this information was used.

removed from the EPAT library were based on two main factors. First, the magnitude of the point rainfall listed in relation to other extreme rainfall in similar areas (transposition regions) were compared. Storms that would not control PMP values even after the largest allowable adjustments are applied were removed. Next, storms were compared to PMP in areas were previous work has shown which events control PMP and how those values compare to the rainfall amounts listed. Events removed were much smaller and would not control PMP values even after all adjustments were applied. In its current form, including these storms is not a problem other than adding computational time. However, if the EPAT process is updated using gridded rainfall analyses, all storms in the EPAT library would need to be analyzed in a gridded format, adding unnecessary cost and effort if smaller storms are included. Therefore, storms which are not important for PMP development should be removed from the library in order to avoid unnecessarily analyzing relatively small storm events.

Effect on EPAT

Having an incomplete EPAT library leads to not producing reliable PMP values at locations where the missing storms are transpositionable.

Recommendation

The storm library should be modified to add appropriate storms not previously included as well as add storms that have occurred since EPAT development. Storms that will not contribute to PMP values should be identified and eliminated. Identifying the storms to be deleted and storms to be added would take approximately one week. Adding the required new storm analyses to the EPAT library would take two months. Storms would be added in the format required for EPAT and provide all of the information required.

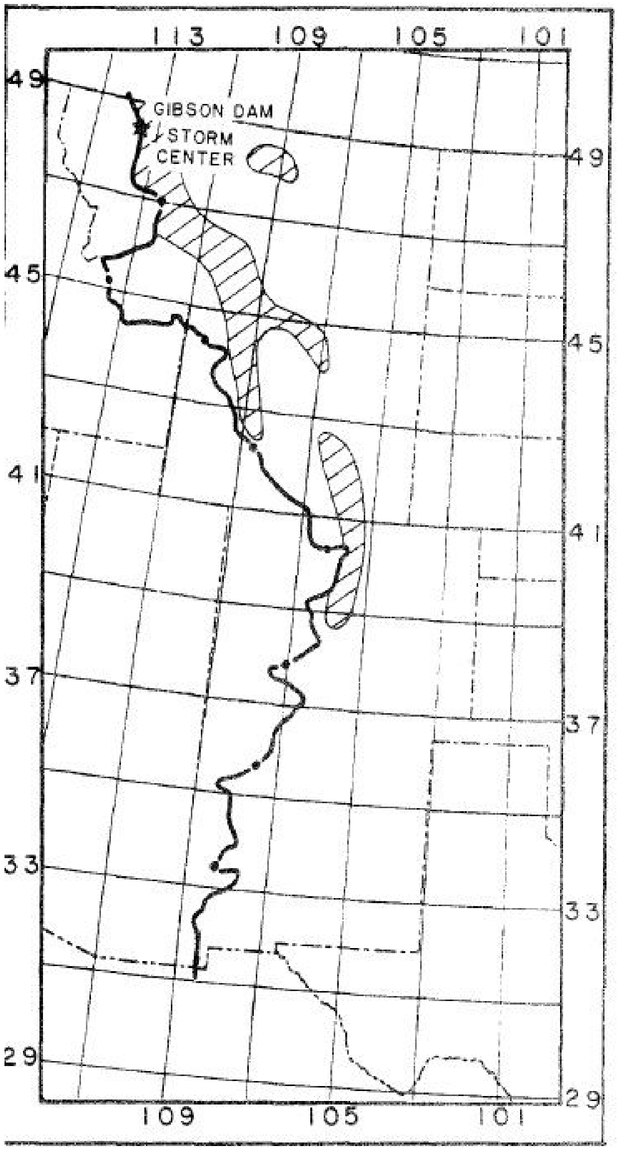


Figure 8.3.--Transposition limits for Gibson Dam, MT storm (75) of June 6-8, 1964.

Figure 1: HMR 55A transposition limits of the Gibson Dam June 1964 storm

Table 1: Potential storms to be included in expanded Colorado PMP analysis

Storm Name	State	Lat	Lon	Elevation	Year	Month	Day	Maximum Point Rainfall	Precipitation Source
GREELEY	NE	41.550	-98.533	2000	1896	6	4	12.30	MR 4-3
ROCIADA	NM	35.867	-105.333	7743	1904	9	26	7.90	SW 1-6
WARRICK	MT	48.067	-109.650	4123	1906	6	6	13.30	HMR 55A stor
CLAYTON	NM	36.333	-103.100	4719	1914	4	29	9.60	SW 1-16
MEEK	NM	33.683	-105.183	5224	1919	9	15	9.50	GM 5-15B
SPRINGBROOK	MT	47.367	-105.750	2687	1921	6	18	14.60	HMR 55A stor
SAVAGETON	WY	43.846	-105.804	5056	1923	9	27	17.56	SPAS 1325
PORTER	NM	35.200	-103.283	4120	1930	10	9	9.90	SW 2-6
HALE	CO	39.6125	-102.2625	3700	1935	5	30	18.00	SPAS 1295
MCCOLLEUM RANCH	NM	32.167	-104.733	5783	1941	9	20	21.20	GM 5-19
PRAIRIEVIEW	NM	33.117	-103.200	3855	1941	5	20	8.40	GM 5-18
RANCHO GRANDE	NM	34.950	-105.100	5600	1942	8	29	8.00	SW 2-29
BUFFALO GAP	SK	49.100	-105.270	2600	1961	5	30	10.50	SK 5-61
HOLLY	CO	37.7125	-102.4042	4100	1965	6	16	19.18	SPAS 1293
GLEN ULLIN	ND	47.304	-101.388	1723	1966	6	24	12.87	SPAS 1324
CLYDE	TX	32.479	-99.479	2000	1981	10	10	23.23	SPAS 1184
CHEYENNE	WY	41.354	-104.819	6236	1985	8	1	7.15	SPAS 1213
PARKMAN	SK	49.710	-101.910	2080	1985	8	3	14.86	SK 8-85
SPIONKOP CREEK	AB	49.270	-113.890	4415	1995	6	5	11.51	ALTA 6-95
VANGUARD	SK	49.922	-107.210	2487	2000	7	3	15.29	SPAS 1077
OGALLALA	NE	41.125	-101.717	3215	2002	7	6	14.92	SPAS 1033
CALGARY	AL	51.156	-114.721	4500	2013	6	20	15.00	SPAS 1320
BOULDER	CO	40.015	-105.265	5313	2013	9	8	20.41	SPAS 1302

Table 2: Storms from the EPAT library not required for PMP development

HDR Storm Number	Storm Name	State	Lat	Lon	Year	Month	Day	EPAT Total Storm Rainfall
2	CLIFTON	CO			1999	7	24	2.01
9	STEAMBOAT SPRINGS	CO			1921	6	14	3.00
19	DELTA	CO			1993	8	10	4.00
20	DELTA	CO			1993	8	10	4.00
38	PALMER DIVIDE	CO			1938	9	2	4.00
39	RATON	NM			1938	9	2	4.00
52	COLORADO SPRINGS	CO			1985	7	19	6.50
54	DEADMAN HILL	CO			1989	8	1	2.80
55	NORTHEAST EL PASO COUNTY	CO			1996	7	18	3.50
56	NORTHWEST ELBERT COUNTY	CO			1996	7	18	3.00
57	NORTHWEST EL PASO COUNTY	CO			1996	7	18	3.50
58	EL PASO COUNTY	CO			1996	8	1	5.00
59	FREMONT COUNTY	CO			1996	8	1	1.50
60	FREMONT COUNTY	CO			1996	8	8	4.00
62	COLORADO SPRINGS	CO			1998	7	30	6.00
63	CUSTER/PUEBLO COUNTIES	CO			1998	8	25	4.00
64	ARVADA	CO			2000	7	16	3.50
65	BERTHOUD	CO			2001	7	12	3.00
66	COLORADO SPRINGS	CO			2001	8	31	6.00
67	GOLDEN	CO			2004	6	8	4.00
68	KEN CARYL	CO			2004	6	24	4.00
69	COLORADO SPRINGS	CO			2004	7	16	3.00
70	FOUNTAIN	CO			2004	7	16	3.50
71	PUEBLO	CO			2004	7	16	3.50
72	FREMONT COUNTY	CO			2004	7	16	3.00
73	EL PASO COUNTY	CO			2004	8	5	2.50
74	CASTLEWOOD CANYON	CO			2006	7	2	7.00
75	PENROSE	CO			2006	7	5	6.00
76	RAMPART RANGE	CO			2006	7	6	3.00

2.0 Storm rainfall analyses

2.1 Rainfall analyses not standardized
2.2 Some taken from SSPMP studies
2.3 Some from previous NWS analyses
2.4 Some from HDR storm reconstruction
2.5 Rainfall was smaller in many storms compared with refined rainfall analyses
2.6 Rainfall amounts sometimes based on uncalibrated weather radar estimates

Problem Statement

Adequate analysis of a storm to include spatial, temporal, and magnitude of rainfall is required for proper PMP evaluation. The analyses of rainfall patterns used in EPAT are inconsistent. The use of radar reflectivity data to analyze the rainfall magnitudes was completed using a unique procedure. No development discussions or references for the procedure are provided. The HDR storm reconstruction process is not described and has not been independently evaluated or peer reviewed. Therefore, accuracy of these storm analyses is unknown without further evaluation. Use of rainfall patterns/information from previous USACE, USBR, and/or AWA studies should be acceptable. However, the digitization and spatial representation of these previously analyzed rainfall patterns may not be adequate for use in detailed analyses and PMP development. There is a lack of information available on the reliability and completeness of the spatial and temporal patterns in properly representing the rainfall from the USCAE, USBR, and HDR.

For proper analysis in orographically significant terrain, hourly rainfall information on a high resolution grid is required to be able to properly analyze the data and quantify the rainfall. These data are often not available from USACE and USBR storm analyses and the HDR process of analyzing storms is not presented. One alternative would be to use AWA's Storm Precipitation Analysis System (SPAS). SPAS has been used to analyzed more than 300 storm events since 2002. SPAS results have been extensively peer reviewed by several boards of consultants and accepted for use in deriving PMP values in all studies since 2002. SPAS rainfall analyses are more accurate because it utilizes a more sophisticated methodology to spatially distribute rainfall among data points and temporally distribute daily and supplemental rainfall observations. The use of a basemap climatology (usually a monthly mean or precipitation frequency climatology) more accurately reflects how rainfall has accumulated over the same region being analyzed during past rainfall events. This allows for data driven spatial interpolation based on rainfall patterns. In addition, more robust data mining is undertaken during SPAS analyses to ensure all data (hourly, daily, supplemental, bucker survey, etc) are included. Because these data have various levels of reliability, extensive QC is employed in the SPAS process. Finally, SPAS does not simply employ a weighted average of each isohyetal pattern like EPAT. Therefore, the more accurate representation of the spatial variability of rainfall magnitude is captured and quantified. This is a major reason why SPAS analyzed storms are often significantly larger than EPAT analyses over the storm domain analyzed.

Understanding and quantifying how rainfall associated with the PMP accumulates over a given duration (e.g. 1-hour, 6-hours or 72-hours) is essential to the modeling of the Probable Maximum Flood (PMF). A comparison of six storm events and their temporal distributions a defined in EPAT was compared to the temporal distributions calculated from SPAS for the same storms. Magnitude comparisons were made based on five durations (10-minute, 30-minute, 1-hour, 6-hour, and total storm). Note, local storm temporal distributions in EPAT were linearly interpolated to 5-minute time steps because actual 5-minute data were not available. For comparison purposes, SPAS hourly data were linearly interpolated to 5-minute time steps using procedures outlined in the EPAT documentation. Durations compared were the maximum 10-

minute, 30-minute, 1-hour, 6-hour, and total storm magnitudes at the storm center (Figure 2). Discussions on each of the six storms are provided below.

Big Thompson, CO July 1976					
Time	10-min	30-min	1-hr	6-hr	Total
SPAS 1231.1	0.62	1.86	3.72	9.48	12.52
HDR ID50	1.10	3.30	6.61	12.28	14.00

Blanding, UT August 1968					
Time	10-min	30-min	1-hr	6-hr	Total
SPAS 1249	0.17	0.51	1.02	3.42	6.67
HDR ID25	-	-	3.14	4.41	6.00

Big Elk Meadows May 1969					
Time	10-min	30-min	1-hr	6-hr	Total
SPAS 1253	0.16	0.48	0.96	3.54	20.02
HDR ID49	-	-	0.95	3.55	19.00

Plum Creek, CO June 1965					
Time	10-min	30-min	1-hr	6-hr	Total
SPAS 1293.4	0.81	2.43	4.86	11.88	14.25
HDR ID47	0.86	2.58	5.16	11.34	13.00

Opal, WY August 1990					
Time	10-min	30-min	1-hr	6-hr	Total
SPAS 1264	0.92	2.76	5.52	7.14	7.16
HDR ID17	1.10	2.75	4.75	7.00	7.00

Cheyenne, WY August 1985					
Time	10-min	30-min	1-hr	6-hr	Total
SPAS 1213	0.69	2.07	4.14	7.14	7.15
HDR ID53	1.11	2.80	4.45	7.00	7.00

*** 1249 and 1253 are general storms, HDR did not generate 5-min data

Figure 2: Comparison of rainfall accumulations between EPAT and SPAS

Big Thompson, CO:
Timing was based on storm observers notes, USGS report and HMR reports. HDR used the CSU report and USBR/COE report for the temporal distribution in EPAT. SPAS ended up with a total storm value of 12.52", this is similar to the 12.50" excepted in HMR55A. HDR used a total storm precipitation amount of 14.00".

Big Elk Meadows, CO:
Timing was based on the closest official NCDC hourly station (Boulder no2) to Big Elk Meadows, climatological reports, and HMR55A. HDR used the CSU report and USBR/COE report for the temporal distribution in EPAT. SPAS ended up with a total storm value of 20.02", close to the bucket survey report of 20.00". HDR used a total storm precipitation amount of 19.00". HDR classified this storm as a General Storm type, they did not create 5-minute temporal data.

Opal, WY:
Timing was based on observation report (Corrigan and Vogel) and NOAA Atlas 14 temporal distribution. The NWS PFDS 6-hour temporal distribution data for the semi-arid US was used to create an hourly station at Opal, WY. The 6-hr 10% first quantile distribution was scaled to two hours and used to distribute the 7.00". HDR used an external report and an HMR report for the temporal distribution in EPAT.

Blanding, UT:
Timing was based on storm observers' notes, USGS report and Utah Water Resources Laboratory reports. HDR used the CSU report and USBR/COE report for the temporal distribution in EPAT. SPAS ended up with a total storm value of 6.67", close to a bucket survey report of 6.50" recorded at an ungauged location. HDR used a total storm precipitation amount of 6.00". HDR classified this storm as a General Storm type, they did not create 5-minute temporal data.

Plum Creek, CO:
Timing was based on official NCDC hourly stations, USGS and USBR reports, and climatological reports. HDR used the CSU report and USBR/COE report for the temporal distribution in EPAT. SPAS DAD zone 4 ended up with a total storm value of 14.25". HDR used a total storm precipitation amount of 13.00".

Cheyenne, WY:
Timing was based on the closest official NCDC hourly station (Cheyenne), climatological reports, and largely a USGS report. HDR used the CSU report and newspaper report for the temporal distribution in EPAT. SPAS ended up with a total storm value of 7.15". HDR used a total storm precipitation amount of 7.00".

Effect on EPAT
PMP values produced by EPAT using storm rainfall analyses in the EPAT library are not reliable because of inaccuracies in storm rainfall analyses.

Recommendation
Each storm used for PMP determination should be evaluated in detail to determine the adequacy of the original analysis. Most, if not all, of the storms important for PMP development have subsequently been analyzed on a gridded basis for PMP work that has occurred since EPAT was completed. Using this peer reviewed storm database will provide significant increases in PMP reliability. One or more storms in the EPAT library will need to be re-analyzed to provide reliable rainfall information. To verify, update, and complete the storm analyses would take two months.

3.0 In-place maximization

3.1 Inflow vectors were not used to identify storm representative dew point values

3.2 Storm representative dew point values were not standardized

- 3.2.1 12-hour persisting values sometimes used
- 3.2.2 3-hour persisting values sometimes used
- 3.2.3 Average dew point values for various duration used from some SSPMP studies
- 3.2.4 Dew point values appear to be 1000mb values not adjusted to storm center elevation
- 3.2.5 Upwind barrier to moisture inflow not accounted for
- 3.2.6 All maximization calculations appear to use maximum 12-hour persisting dew point maps

Problem Statement
The process of in-place maximization is required in PMP development to adjust observed storm rainfall amounts to their upper limit. This calculation step is critically important for PMP development. The process of calculating the in-place maximization factor is explicitly detailed in HMR 55A, Section 5.2. This calculation procedure has been refined during subsequent PMP studies (e.g. Nebraska statewide PMP, Tomlinson et al. 2008; Tarrant Regional Water District, Kappel et al. 2012; Ohio statewide PMP, Tomlinson et al. 2013; Arizona statewide PMP, Tomlinson et al. 2013; Wyoming statewide PMP (in progress)). In addition, the climatological data sets used for maximization have been updated in other PMP studies (e.g. Nebraska statewide PMP, Tomlinson et al. 2008; Tarrant Regional Water District, Kappel et al. 2012; Arizona statewide PMP Tomlinson et al. 2013; Wyoming statewide PMP (in progress)). EPAT did not follow accepted procedures as outlined in the HMRs and other PMP studies and did not

use consistent and appropriate climatological data sets for maximization. The information provided in Appendix A of the EPAT report provides some information regarding the data used to calculate in-place maximization factor. The information provided shows that the in-place maximization factors were not calculated correctly, did not follow the procedures described in the HMRs or subsequent PMP studies. No explicit inflow vectors were defined. No explicit time frame of observations used to determine the storm representative dew point values are provided. Inconsistent durations were used. Inconsistent maximum dew point climatologies were used. In some cases, it appears that an inadequate number of stations were used to determine the storm representative dew point values. No accounting for elevation at the original storm elevation was applied. No accounting for upwind/intervening barriers was applied.

Effect on EPAT

EPAT does not accurately calculate the in-place maximization factors for many if not all storms. Therefore, the determination of in-place maximization factors is incorrect and the resulting maximized storms do not produce reliable PMP values.

Recommendation

Determination of reliable in-place maximization factors for each storm is critical for PMP determination. Each maximization factor should be re-evaluated to determine an accurate and reproducible value. Storm inflow vectors should be determined for each storm and used for both in-place maximization and storm transposition. The in-place maximization factor for most, if not all, of the storms important for PMP development have subsequently been analyzed during other PMP studies. Utilizing these peer reviewed maximizations is recommended. Assuming the original EPAT rainfall analysis was accurate, applying the corrected in-place maximization factors within the current EPAT architecture would be straightforward. However, because of the numerous other issues within EPAT, this is not recommended. To verify, update, and complete the appropriate in-place maximizations would take two months.

4.0 Storm transpositioning

4.1 Storms transpositioning appears to use storm center location instead of transpositioned inflow vector

4.2 Transpositioning appears to be done using maximum 12-hour persisting dew point maps

4.3 Transpositioning done only within very small climate zones

4.4 Reasoning for transpositioning appears to be inconsistent and not fully documented

4.5 Use of the same transposition procedure for General and Local Storms (contrary to HMRs)

4.6 Validity of the 7500/8500 ft climate zone boundary

Problem Statement

Storm transposition limits

The process of storm transpositioning trades space for time in the storm library as most watersheds have not experienced a PMP-type event during the available period of record. However, the definition of transpositionability is that a storm event has to be similar meteorologically and have similar topography between the original location and the target location. This is described in HMR 55A, Section 8.0, with specific example delineations discussed further in 8.2.1, 8.2.2.1, and 8.2.2.2. EPAT performed an extensive evaluation of transposition zones across the area covered by EPAT. This evaluation was comprehensive and well developed. However, the definition of the transposition zones in EPAT implies false precision not supported by current understanding of storm mechanisms and interactions with moisture and topography. Geographic regions where storms with similar characteristics can occur are much larger along Colorado’s Front Range, as well as over higher elevations in the Colorado Rocky Mountains. Storm transposition limits should be expanded over larger areas, while accounting for differences in moisture availability and topographic influences. The transposition limits applied to many storms are more restricted than transposition limits in HMR 55A and subsequent PMP studies. As an example, Figure 3 displays the transposition limits of the Cherry Creek, May 1935 event from HMR 55A. This storm was transpositioned over a much greater region than was applied in EPAT. Because this process is subjective and many uncertainties exist, a more conservative approach should be applied. Thereby storms should be moved over greater distances unless and until data is available to support a more refined analysis. Current transposition limits of each of the storms relevant for PMP development are listed in Table 3, with recommended transposition limits listed immediately next to those from EPAT. This table includes AWA's preliminary transposition limits recommendations. These are made after a first look at each storm, knowledge of a given storm's meteorology/topography, how the storm was transpositioned in other PMP work (if available), and it's relation to the climate zones provided in the document. The transposition limits would be refined after further analysis and potentially result in restructuring of the climate/transposition zones. AWA's recommended transposition limits may be significantly different from what was used in EPAT, primarily because many storms will be moved over much greater distances, i.e. have expanded transposition limits.

In addition, EPAT has elevation limits applied to storm transposition on the east and west side of the Continental Divide, using the 8,500 foot elevation on the east side and a 7,500 foot elevation on the west side. The reasoning behind this is based on several paleoflood and historic flood investigations which investigated the primary cause of major floods (either snow melt driven or rainfall driven) below and above these elevations. This is a good first approximation of transposition limits. However, more detailed investigation and proper quantification of the meteorological processes which result in these delineations should have been involved and discussed. This would have allowed for more appropriate transpositioning of storms near these boundaries and a more appropriate transition of PMP depth in these regions. Finally, as has been discussed in several HMRs and site-specific PMP studies, general storms have different meteorology (both storm dynamics and moisture) than local storms. Section 8.2.1 of HMR 55A discusses the different transposition considerations which were applied by storm type. Therefore, it is required that the transposition limits of the two storm types should be analyzed separately and applied specific for each storm type. Further, variations within each storm type occur east and west of the Continental Divide. Therefore, transposition limits should further be defined by location in relation to the Continental Divide and moisture source availability.

Effect on EPAT

Constrained transposition limits have been applied to several of the storms important for PMP development in EPAT. Therefore, resulting PMP values produced by EPAT for watersheds do not consider the larger number of transpositioned storms used in other PMP studies.

Recommendation

A re-evaluation of transposition limits of storms important for PMP should be completed. Updated understanding of the storm dynamics, rainfall patterns, and their relation to topography and moisture inflow should be considered to better quantify transposition limits. The results should provide an updating set of transposition limits for PMP development. This re-evaluation and application would take one month.

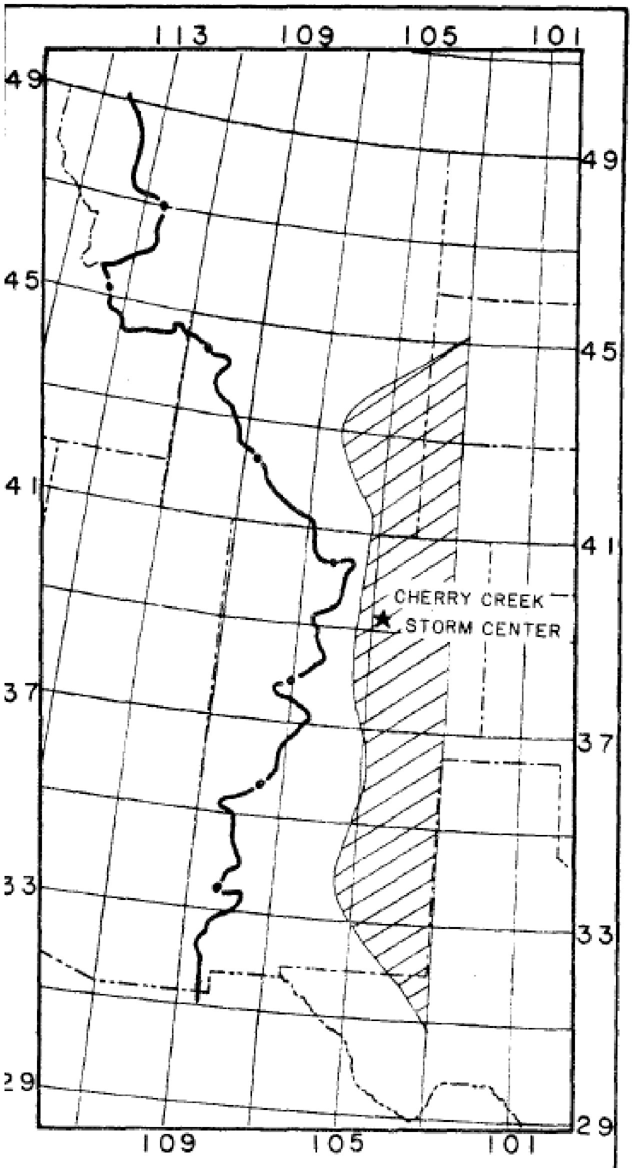


Figure 8.4.--Transposition limits for Cherry Creek, CO storm (47) of May 30-31, 1935.

Figure 3: HMR 55A transposition limits of the Cherry Creek May 1935 storm

Table 3: Transposition limits from the EPAT library and recommended transposition limits

HDR Storm Number	Storm Name	Storm Type	Transposition Zones	Recommended Transposition Zones
1	PLACERVILLE	LOCAL	6b, 6c	Portions of 6a, 6b, 6c, 7, 8, 9
3	COLORADO NATL MONUMENT	LOCAL	7, 8, 9	Portions of 6a, 6b, 6c, 7, 8, 9
4	DALLAS CREEK	LOCAL	6b, 6c	Portions of 6a, 6b, 6c, 7, 8, 9
5	GRAND JUNCTION 4W	LOCAL	7, 8, 9	Portions of 6a, 6b, 6c, 7, 8, 9
6	DINOSAUR 2E	LOCAL	7, 8	Portions of 6a, 6b, 6c
7	GLENWOOD SPRINGS	LOCAL	6a, 6b, 7	6a, 6b, 6c, Portions of 7, 8, 9
8	COLLBRAN	LOCAL	6a, 6b, 7	Portions of 6a, 6b, 6c, 7, 8, 9
10	MESA VERDA	LOCAL	9	Portions of 6a, 6b, 6c, 7, 8, 9
11	GATEWAY	LOCAL	7, 8	Portions of 7, 8, 9
12	MORGAN	LOCAL	7, 8	Portions of 7, 8, 9
13	MORGAN	LOCAL	7, 8	Portions of 7, 8, 9
14	COLORADO NATL MONUMENT	LOCAL	7, 8, 9	7, 8, 9
15	SWEETWATER	LOCAL	6a, 6b	Portions of 6a, 6b, 6c, 7, 8, 9
16	JIM CREEK	LOCAL	6a	Portions of 6a, 6b, 6c
17	OPAL	LOCAL	7	Portions of 7, 8, 9
18	RIFLE	LOCAL	8	Portions of 6a, 6b, 6c, 7, 8, 9
21	WESTERN COLORADO	GENERAL	6a, 6b, 7, 8	Portions of 6a, 6b, 6c, 7, 8, 9
22	GLADSTONE	GENERAL	6c	Portions of 6b, 6c
23	PALISADE LAKE	GENERAL	6c	Portions of 6b, 6c
24	PYRAMID	GENERAL	6a	Portions of 6a, 6b
25	BLANDING	GENERAL	9	Portions of 6a, 6b, 6c, 7, 8, 9
26	DOVE CREEK	GENERAL	9	Portions of 6b, 6c, 8, 9
27	DURANGO	GENERAL	6c	Portions of 6b, 6c, 8, 9
28	WOLF CREEK	GENERAL	6c	Portions of 6b, 6c, 8, 9
29	SAGUACHE	LOCAL	5, 6c	Portions of 5, 6a, 6b
30	SOUTH CENTRAL	GENERAL	5	Portions of 5, 6a, 6b
31	SAN LUIS	LOCAL	5	Portions of 5, 6a, 6b
32	SAN LUIS VALLEY NORTH	LOCAL	5	Portions of 5, 6a, 6b
32	SAN LUIS VALLEY SOUTH	LOCAL	5	Portions of 5, 6a, 6b
34	PENROSE	LOCAL	4b, 4c, 4d, 4e	Portions of 2a, 2b, 2c, 2d, 4a, 4b, 4c, 4d, 4e
35	SAVAGETON	GENERAL	2c, 2d	Portions of 2c, 2d, 2b, 4b
36	CHERRY CREEK	LOCAL	2b, 4b, 4e	Portions of 2c, 2d, 4b, 4c, 4d, 4e
37	GENOA	LOCAL	2b, 4b, 4e	Portions of 2c, 2d, 4b, 4c, 4d, 4e
39	RATON	LOCAL	2b, 4b, 4e	Portions of 2c, 2d, 4b, 4c, 4d, 4e
40	GENESEE	LOCAL	2c, 2d	Portions of 2c, 2d, 4b, 4c, 4d, 4e
41	SOUTH BOULDER CREEK	LOCAL	2c, 2d	Portions of 2c, 2d, 4b, 4c, 4d, 4e
42	MASONVILLE	LOCAL	2d	Portions of 2c, 2d, 4b, 4c, 4d, 4e
43	LAKE GEORGE	LOCAL	4a	Portions of 2a, 2c, 4a, 4d
44	REDSTONE CREEK	GENERAL	2b, 2c, 2d, 4b	Portions of 2c, 2d, 4b, 4c, 4d, 4e
45	RYE	GENERAL	2a, 2b, 2c, 2d, 4a, 4b, 4c, 4d, 4e	Portions of 2a, 2b, 2c, 2d, 4a, 4b, 4c, 4d, 4e
46	RATON MESA	GENERAL	2b, 4b, 4e	Portions of 2b, 2c, 2d, 4b, 4c, 4d, 4e
47	PLUM CREEK	LOCAL	2b, 4b	Portions of 2b, 2c, 2d, 4b, 4d, 4e
48	FALCON	LOCAL	2b, 4b	Portions of 2b, 2c, 2d, 4b, 4d, 4e
49	BIG ELK MEADOWS	GENERAL	2a, 2b, 2c, 2d, 4a, 4c, 4d, 4e	Portions of 2a, 2c, 4a, 4d, 4e
50	BIG THOMPSON	LOCAL	2d	Portions of 2a, 2c, 4a, 4d, 4e
51	FRIJOLE CREEK	LOCAL	4c, 4e	Portions of 2b, 2c, 2d, 4b, 4d, 4e
53	CHEYENNE	LOCAL	2d	Portions of 2b, 2c, 2d, 4b
61	FORT COLLINS	LOCAL	2c, 2d	Portions of 2b, 2c, 2d, 4b

Storm Adjustment Calculations

The process followed to perform the transposition and the associated calculations do not follow standard procedures as described in the HMRs (e.g. HMR 55A Section 8.4.2 and subsequent PMP studies (e.g. Tomlinson et al. 2008, Tomlinson et al. 2013, Kappel et al. 2014). This includes not using a storm inflow vector representing direction and distance from the original storm location to the storm representative dew point location, then moving that vector to the location of interest and calculating the transposition factor based on the upwind end of the transposition vector. The EPAT process does not account for intervening barriers in the transposition calculation. These can play a significant role in moisture availability difference between two locations and must be accounted for in regions with significant topography. Further, the transposition calculation applied in EPAT uses the 12-hour persisting dew point climatologies from HMR 50 or HMR 55A. However, several of the storm representative dew points used average dew point values and used various durations. Using these along with a 12-hour persisting climatology is inconsistent and considered not correct. The state of the practice in PMP development is to use a maximum dew point climatology value that most closely represent when approximately 90% of the rainfall accumulated during the main rainfall period. In all AWA PMP studies since 2008, updated 100-year recurrence interval maximum dew point climatologies for 3-, 6-, 12-, and 24-hour durations are used. Regardless, the same duration climatology is required in the calculation as the duration of the storm representative dew point. Extensive discussions on why this is required are included in the Nebraska statewide PMP study (Tomlinson et al. 2008) and the Arizona statewide PMP study (Tomlinson et al. 2013). Finally, it should be noted that the process in HMR 55A of applying 1/2 the moisture adjustment for general storm is not state of the practice and was not applied in any previous or subsequent HMRs or PMP studies.

Effect on EPAT

Rainfall values calculated by EPAT are inaccurate. This is a result of incorrect transposition factor being calculated because inconsistent dew point climatologies are used and the fact that moisture inflow barriers were not accounted for. These moisture inflow vectors should be used for moisture transpositioning. The moisture transpositioning process should also include moisture adjustments for elevation and for upwind barrier moisture depletion, and/or variations in topographic influence.

Recommendation

Inflow moisture vectors should be used in the transposition of each storm. The storm elevation moisture adjustments, upwind barrier moisture depletion, and effects of topography should be included in the transposition calculations. These can either be calculated directly on an individual storm basis using the storms moisture inflow vector or they are captured in the OTF calculation process. Barriers must be accounted for, as they remove some amount of moisture below their elevation for some distance downwind. This application would take three months. Extensive modification of EPAT would be required to incorporate the expanded transposition limits along with elevation and upwind moisture adjustments. As part of the transposition process, effects of topography on both storm center location and isohyetal shape should be included. The current EPAT procedure does not include either of these. Extensive expansion of the procedure is required, accompanied by significant rewriting of the GIS code, which would take a significant amount of time.

5.0 Storm centering

5.1 Storms are transpositioned with centers over the thalweg of the basin

5.2 Storms are centered over various locations along the thalweg

Problem Statement

Storms transpositioned to a watershed are constrained in EPAT to have centers over the thalweg of the basin. This is a constraint on storm centering that has not been applied in any other PMP studies. Centers for transposition storms are generally positioned over upslope regions within a watershed, not over the lowest portions of the watershed. Guidance for the placement of storm centers over the basin is often obtained from climatological rainfall analyses. For basins in topographically significant regions, the PMP rainfall accumulation would be influenced by that topography, so that there would be limitation to where the storm center would occur, i.e. mountainside versus valley floor. This is based on meteorological interactions with topography both within the basin and upwind of the basin. An orographic transposition factor procedure (the

OTF) has been developed in recent site-specific and statewide PMP studies that incorporates climatological rainfall analyses (e.g. Tomlinson et al. 2011, Tomlinson et al 2013). This procedure determines rainfall on a gridded basis over the watershed. In the OTF process, the PMP depth in topographically significant regions are calculated on a grid by grid basis and the spatial distribution naturally results from that process. Initially, it will reflect the precipitation frequency climatology patterns. However, historic storm patterns which have occurred over a basin (if available) can also be used to spatially distribute the PMP rainfall. Then, whichever pattern(s) produce the greatest runoff becomes PMF.

Effect on EPAT

Although the centering of the storm over thalweg will in general create the largest volume of rainfall within the basin boundaries, it does not usually represent a physically possible storm centering.

Recommendation

Since the centering of the storm over the thalweg is not a physically possible storm centering location for most basins, it should not be a requirement in the EPAT storm transposition procedure. Other centering procedures should be considered using historic storm isohyetal and climatological patterns. The level of effort to evaluate and recommend a storm centering procedure is estimated to be two weeks

6.0 Storm isohyetal orientation

6.1 Low level wind is mandated to stay parallel to the thalweg

6.2 The rainfall pattern is 40-90 degrees to the right of the low level wind

6.3 Low level wind vector is determined by the mean basin orientation

Problem Statement

EPAT documentation includes some discussion on the relationship between isohyetal orientation and the low level wind inflow. The procedure requires that the low level wind stay parallel to the thalweg. Although low level wind directions are modified by the terrain, the overall wind direction in the lower atmosphere is determined by pressure gradient forces of the larger synoptic weather pattern. The low level winds and rainfall accumulation pattern will be dependent on the within-basin topography and upwind terrain interactions. These are inherently reflected in the precipitation frequency climatologies used to calculate the OTF or in explicit barrier evaluations and site-specific basin studies. Therefore requiring that the low-level wind be parallel to the thalweg is not supported by considering the larger overall weather situation. Such a constraint has not been applied in previous or subsequent HMRs or PMP studies. Recent site-specific and statewide PMP studies (e.g. Tomlinson et al. 2011, Tomlinson et al. 2013, Kappel et al. 2014) have incorporated a procedure that provides isohyetal shapes based on climatological analyses. For basins which have experienced extreme storms, the isohyetal shape of that storm can be used. In non-orographic regions, orientation is accounted for in the HMR 52 application manual or by investigating patterns of past events. In topographically significant terrain, the GIS application spatially distributes the PMP rainfall throughout a given basin based on the precipitation frequency climatology used or past rainfall events over the basin. Use of precipitation frequency climatologies to spatially distribute rainfall in topographically significant terrain is recommended in HMR 57 Section 15 and HMR 59 Section 13.

Effect on EPAT

Since the rainfall pattern is required to be at an angle to the inflow wind direction, and the inflow wind direction is required to be parallel to the thalweg, the rainfall isohyetal pattern can never be aligned with the overall basin orientation. This constraint limits the maximum rainfall volume that can fall within the basin boundaries.

Recommendation

Re-evaluation of the storm isohyetal pattern orientation over basins should be completed. The storm orientation should be patterned after historic storm events or a climatology of rainfall analyses over the basin. The level of effort for this re-evaluation is estimated to be 2 to 3 weeks.

7.0 Areal reduction

7.1 Figure from HMR 49 used without any validation

7.2 Circular pattern used for some point rainfall observations without discussion

7.3 Areal reduction: EPAT incorrectly applies HMR 55A general storm ARFs to local storms

Problem Statement

Areal reduction factors have historically been used to determine rainfall amounts over various area sizes given a 24-hour point rainfall. While use of areal reduction factors may be reasonable over relatively flat terrain, use of areal reduction factors in mountainous areas can produce large errors. HMR 49 contains a figure that provides areal reduction factors. The procedure used to determine these area reduction factors is not provided. The reliability of these areal reduction factors is suspected to be very low. For individual thunderstorms, a circular rainfall pattern is used without any discussion on how the pattern was determined or any references for prior use (e.g. Storm #31 San Luis 1957). In addition, EPAT incorrectly applied the general storm ARFs to local storms. EPAT uses areal reduction factors only for point rainfalls. The orographic transposition procedure used in some recent site-specific and statewide PMP studies assumes that the areal reduction factors for both the in-place location and the study basin are similar. This is a required assumption for a storm to be considered transpositionable from one location to another. This assumption is currently being evaluated and quantified during ongoing PMP studies for the state of Wyoming and Tennessee Valley Authority. Calculation of ARFs is a dynamic calculation using the OTF process and would be unique to each basin and each storm transpositionable to that basin. Although, it should be noted in the OTF calculation process, the background data used in the calculation, the storm's original gridded rainfall data and the precipitation frequency climatology are static in the data base, and are queried as needed for a given location.

Effect on EPAT

The use of areal reduction factors in the mountainous terrain of Colorado is not reliable. Furthermore, the use of area reduction factors from HMR 49 introduces additional uncertainty since it is not known how these areal reduction factors were developed. In addition, neither the use of a circular pattern of homogeneous rainfall nor the use of the general storm areal reduction factors for local storms can be justified. The result is that the volume of rainfall produced by the EPAT PMP values does not provide reliable estimates of rainfall over individual watersheds.

Recommendation

The use of individual areal reduction factors should be re-evaluated for use over the mountainous terrain of Colorado. Other procedures for the transposition of storms over orographic regions should be investigated. This re-evaluation should take approximately 2 weeks.

8.0 No orographic storm separation method applied to account to the effects of topography on historic storms

Problem Statement

EPAT does not have a procedure to address differences in to the topographic influence between the original storm locations and the basin being studied. The National Weather Service in developing HMR 55A, HMR 57 and HMR 59 recognized that significant variations in rainfall magnitude and spatial patterns occur over topographically significant terrain. The storm separation method (SSM) was developed to address these spatial and magnitude variations. Although ideally one would like to separate a storm into its two components, convergence only (FAFP) and orographic (k factor), this is not possible given the current data available and meteorological understanding. This is because the data used to define these values in topographically significant terrain is affected by topography and therefore it is unknown what that rainfall amounts and patterns would have been without topography. Therefore, the SSM is highly subjective, not based on historic data and is not reproducible. It is not recommended that EPAT incorporate the storm separation method. The SSM is discussed here only as reference to the procedure used in HMR 55A for addressing topographic influences. Neither the FAFP nor orographic enhancement factors are recommended.

Effect on EPAT

EPAT that does not have a procedure for addressing differences in rainfall production associated with topographic influences between the original locations of the storms in the study basin. Since terrain plays a very important role in determining the magnitude and spatial distributions of rainfall, a procedure should be included to address terrain differences. Use of the SSM is not recommended. Use of the orographic transposition factor used in recent site-specific and statewide PMP studies should be investigated. Incorporation into the current EPAT GIS procedures would be very difficult at best.

Recommendation

EPAT should include a procedure for addressing topographic influence differences between the locations where storms historically occurred in the study basin. Storm isohyetal pattern orientation is dependent on several factors, including upper level winds and basin topography. The rainfall patterns for individual basins are reflected in the rainfall climatology. Procedures using gridded rainfall data together with climatological maps have been shown to address topographic differences. Evaluation of this procedure along with other methods should be investigated. Incorporating the OTF process into the current EPAT GIS may not be possible and would probably take more effort than to just program it from scratch using the current methods employed in several other studies. This investigation would take approximately one month.

9.0 No enveloping of spatial or temporal storm data

Problem Statement

EPAT bases the development of PMP values on the largest of single storm transpositionable to basin. Various storms in the EPAT library can contribute to PMP values at different area sizes and durations. EPAT retains the timing of various storms as they are transpositioned to the basin. The standard procedure in PMP studies is to use the rainfall amounts associated with various storms adjusted to the basin to provide rainfall amounts. Therefore, because EPAT only evaluates a single storm for each run for a basin, it is likely that rainfall efficiencies at certain area sizes or durations were not adequately represented by that single event. To account for this, the process of envelopment is employed. This process fills in portions of the rainfall curve where rainfall efficiency may have not been at a maximum. This is not applied in the EPAT process. The timing or mass curves of various storms of a specific type are evaluated to provide the most critical timing of PMP rainfall when evaluating the resulting flood. Evaluation of the spatial and temporal envelopment (or lack thereof) in EPAT is given in Appendix A.

Effect on EPAT

By only allowing a single storm to represent PMP at a time, spatial envelopment is not occurring, unless the storm controlling PMP for a given basin was truly efficient at all area sizes/durations relevant for a given basin. Similarly, using the timing associated with a discrete event may result in certain durations associated with that event not having the most critical timing. A separate issue associated with using the timing from discrete events is that the most critical timing for the

PMP storm may not be provided. It may be that the timing from one storm applied to the rainfall from a different storm would result in a larger PMF for a given basin. This is not addressed in EPAT.

Recommendation

Investigation into spatial envelopment should occur to ensure proper conservatism is reached in the EPAT process. Calculated rainfall for a given basin must be a conglomeration of several of the most extreme events adjusted to that basin of the same storm type as if they could have all occurred over that basin together in space and time. For the temporal consideration, timing or mass curves from various storms of the same storm type should be considered and provided to apply to each location by storm type. This should provide a conservative temporal accumulation of rainfall that represents a worst-case scenario based on actual temporal patterns of several past storms of the same storm type.

10.0 Elevation adjustment (9%/1000')

Problem Statement

The elevation of a storm location has a direct influence on the amount of atmospheric moisture available for rainfall production. Calculation of the amount of moisture reduction should be completed during the in-place maximization process where the amount of precipitable water is removed from the atmosphere below the elevation of the storm location. The amount of moisture removed is based on the 1000mb storm representative dew point value. In the general range of storm representative dew point values used for storm maximization in Colorado (~55-75 degrees), the reduction of atmospheric moisture varies between 8% and 11% per 1,000 feet. The discussion of the elevation adjustment applied to a storm's available moisture as discussed in Section 7.5 of the EPAT report utilizes the guideline from HMR 57 and 59. However, these adjustments don't begin until reaching an elevation of 6,000 feet for local storms. This does not take into account the enhancing effect of topography on rainfall. More importantly, evaluations of the effects of topography on rainfall production can be explicitly quantified using the OTF. This has been applied in AWA PMP studies since 2011 (e.g. Tomlinson et al. 2011, Tomlinson et al. 2013, Wyoming statewide PMP (in progress), and Tennessee Valley Authority regional PMP (in progress)). HMR 55A applies only one half of the moisture elevation adjustment to general storms (Section 8.4.2.2). The application of one half of the elevation moisture adjustment was not used in any previous HMR's or site-specific PMP studies, nor has it been used in any subsequent studies including HMRs 57 and 59. It should not be used in EPAT. Explicit elevation moisture adjustments in site-specific and statewide PMP studies are made using lookup tables and explicit calculations.

Effect on EPAT

Application of the 9% decrease per 1,000 feet above 6,000 feet across the entire domain for both local storms and general storms is a deviation from its application in the HMRs. In addition, this value can be explicitly calculated for all storm maximizations. There is no need to apply a generalized ratio.

Recommendation

Explicit calculation of the elevation moisture adjustment should be completed for all storms. This can be accomplished by following moisture transposition calculation steps or through application of the OTF calculation. Use of the OTF explicitly accounts for elevation differences between the original storm location and the grid cell location being compared. This is captured in the precipitation frequency climatology. In areas where topography isn't the controlling factor (i.e. eastern plains of Colorado), explicit calculation of the elevation of the original storm locations versus the new basin location to the nearest 100 feet would be used. In addition, an analysis of intervening barriers would be performed. It is recommended that this procedure not be incorporated in the current version of EPAT, as doing so would take more time and effort than utilizing the current process starting from scratch. Recalculation of this factor for all storms important for PMP development would take two months.

Task 5

EPAT v4.2 rainfall depth, area and duration results for the Rio Grande Dam drainage basin were evaluated using storms in the AWA storm analysis database from site-specific PMP studies in Colorado and from the Arizona statewide study. Results were compared with EPAT results. Comparisons and discussion are provided to explain and detail the differences. A comprehensive discussion is provided below:

Overview

AWA produced site-specific gridded PMP values for the Rio Grande Dam basin at the 1-, 6-, 12-, 24-, 48-, and 72-hour durations for the general and local storm types. The next section describes the procedure followed for the calculation of the gridded PMP values with results provided in the following section. Basin-specific PMP values were also calculated for the Rio Grande Dam basin using the Colorado Extreme Precipitation Analysis Tool (EPAT). The EPAT PMP results are also provided.

The Rio Grande Dam basin is defined as a drainage area of 160.75 mi^2 above the Rio Grande dam on the upper Rio Grande River in Southwestern Colorado (Figure 4). The basin lies within San Juan and Hinsdale counties on the east side of the Continental Divide. The basin has an average elevation of 11,616 feet within the high altitude highly orographic terrain of the San Juan Mountains.

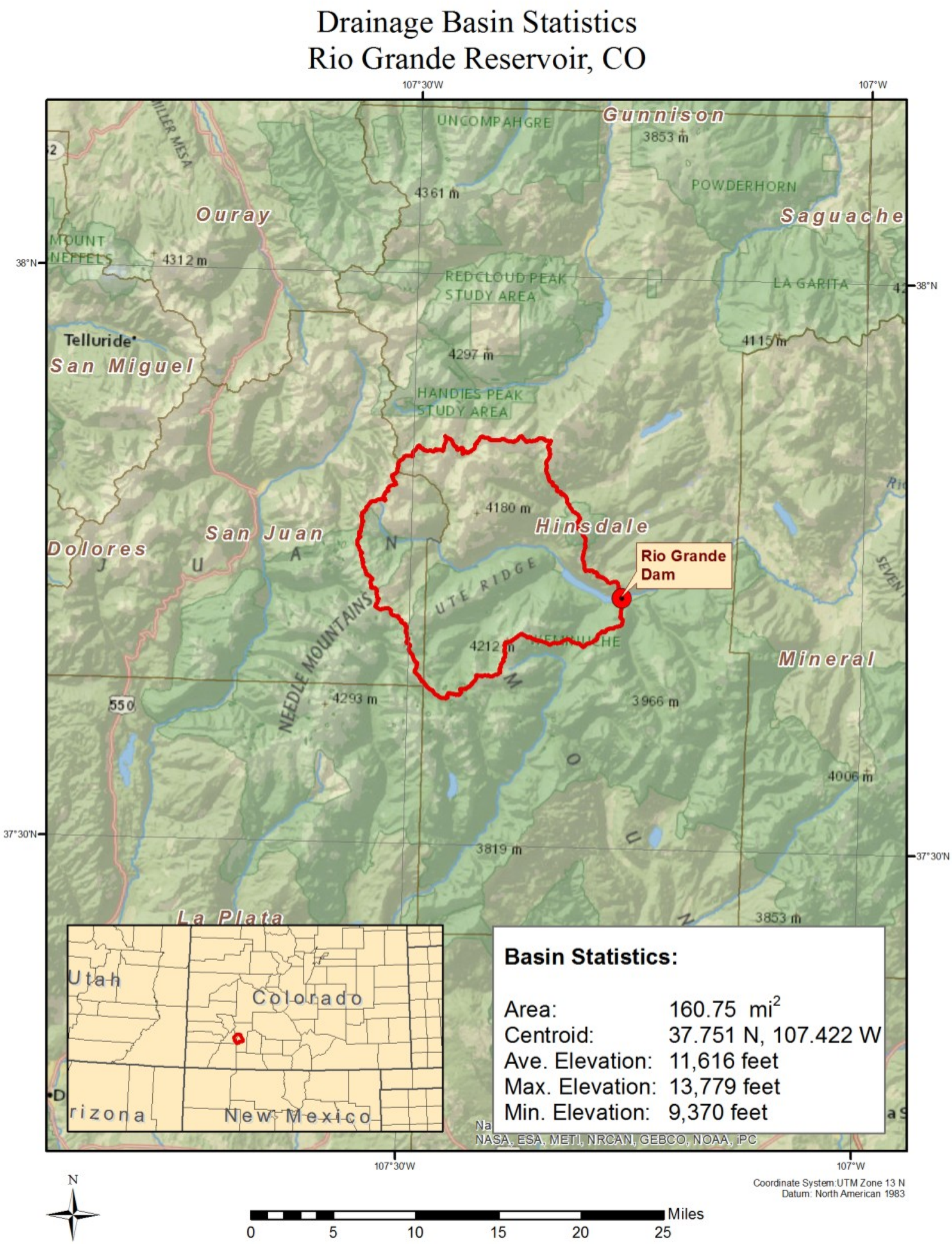


Figure 4: Rio Grande Dam basin statistics

Procedure

Storm List

A short list of significant historical rainfall events was determined for the general and local storm types.. Each of these events met the criteria of occurring in locations that were topographically and climatologically similar to the Rio Grande Reservoir drainage basin, and therefore considered transposable to the basin. The list of transposable storms is shown in Table 4. All station name identifiers refer to the name location associated with the largest SPAS analyzed DAD storm center. Many of the SPAS storms used in this analysis have several DAD zones. This SPAS DAD zone location may not be the one used in this analysis. Note that the SPAS DAD zones used from the storms in Arizona are the ones which occurred over the mountains of southwest Colorado or in region directly transpositionable to the Rio Grande basin. For example, the December 1966 storm was place-named "Junipine" due to the largest storm center (DAD zone 1) which occurred at Junipine, AZ. This storm center is not transposable to the Rio Grande basin; however, the same event produced a significant storm center over southwest Colorado (DAD zone 4) which was used for the Rio Grande analysis.

Table 4: List of SPAS analyzed storm events transposable to the Rio Grande Dam basin

SPAS Storm Number	Storm Name	SPAS DAD Zone	State	Lat	Lon	Year	Month	Day	Total Storm Rainfall	Elevation	Analyzed Storm Duration	Moisture Inflow Vector	Storm Type
General Storms:													
1075	NORMA REMNANTS	DAD zone 4	CO	37.5620	-106.8791	1970	9	3	5.95	12,433	120	SW @ 445	general
1107	WAGON WHEEL	DAD zone 1	CO	37.6630	-106.9380	1911	10	4	7.88	12,500	120	SW @ 350	general
1137	YOUNG	DAD zone 5	AZ	37.0958	-106.6292	1965	11	22	7.00	11,406	144	SSW @ 420	general
1141	JUNIPINE	DAD zone 4	AZ	38.9875	-106.9125	1966	12	4	14.94	12,520	144	SW @ 1,285	general
1144	MT ORD	DAD zone 3	AZ	35.1113	-108.1958	1916	1	14	8.45	8,688	168	WSW @ 32	general
1149	COOKS MESA	DAD zone 4	AZ	37.5400	-106.8700	2007	11	30	6.69	12,058	49	SSW @ 470	general
1150	BEAR SPRING	DAD zone 2	AZ	34.0380	-111.4880	1978	2	27	15.52	7,000	96	S @ 100	general
1241	DEER CREEK DAM	DAD zone 2	UT	41.6300	-111.9700	2010	10	25	4.74	5,741	96	SW @ 325	general
1266	CONRAD RANCH	DAD zone 1	UT	40.5900	-111.5900	1979	10	20	5.78	9,700	72	WSW @ 30	general
Local Storms:													
1131	BLUFF	DAD zone 1	UT	37.2550	-109.5750	2001	8	14	6.28	4,900	6	S @ 190	local
1249	BLANDING	DAD zone 1	UT	37.8258	-109.5425	1968	8	1	6.67	10,367	72	SW @ 240	local

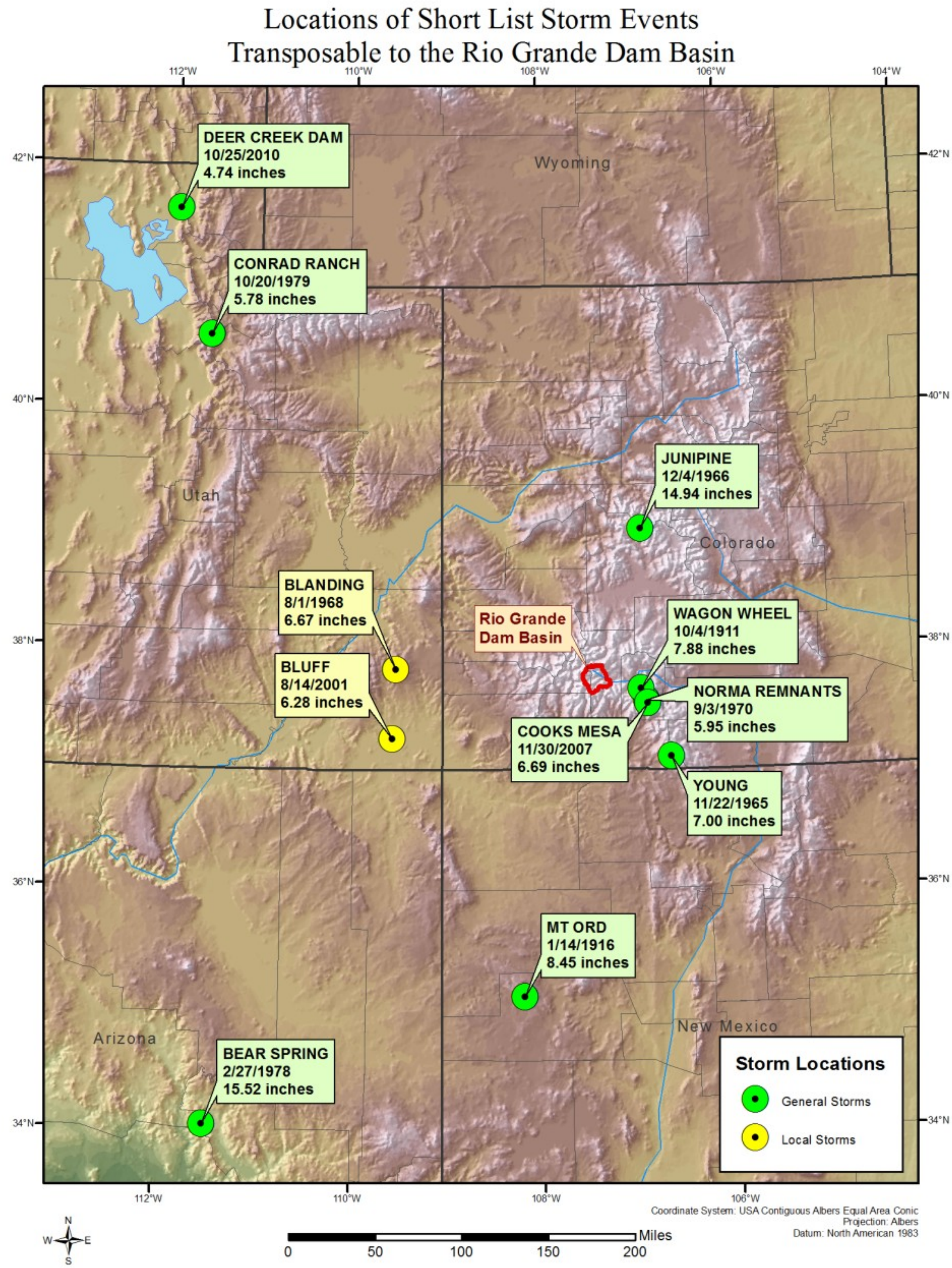


Figure 5: Locations of analyzed storms in proximity to the Rio Grande Reservoir drainage basin

Nine general storm events and two local storm events were identified for transposition to the basin. Each of these events was analyzed using SPAS. SPAS produced rainfall depths for each analyzed duration at areal increments up to the maximum storm areal extent. An example of the DAD table for the December, 1966 (Junipine, AZ) storm is shown in Table 5.

Table 5: SPAS 1141 DAD zone 4 table for the December, 1966 Junipine, AZ storm.

Storm 1141 - December 2, 1966 (0800 UTC) - December 8, 1966 (0700 UTC) MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)												
	Duration (hours)											
Area (mi^2)	1	3	6	12	24	36	48	72	96	120	144	Total
0.27	1.02	1.88	3.25	4.67	7.14	10.24	12.04	12.58	13.91	14.94	14.94	14.94
1	0.98	1.85	3.16	4.61	6.92	9.92	11.60	12.14	13.46	14.43	14.43	14.43
10	0.97	1.70	2.95	4.16	6.90	9.73	11.38	12.05	13.04	14.23	14.23	14.23
25	0.92	1.59	2.69	3.93	6.66	9.45	11.03	11.66	12.64	13.55	13.71	13.71
50	0.86	1.49	2.50	3.67	6.08	8.74	10.56	11.17	12.11	12.99	13.10	13.10
100	0.75	1.36	2.29	3.54	5.69	8.22	9.79	10.50	11.48	12.31	12.31	12.31
150	0.63	1.33	2.18	3.24	5.32	7.60	9.38	10.05	10.93	11.75	11.79	11.79
200	0.62	1.29	2.06	3.18	5.07	7.32	8.59	9.83	10.63	10.82	11.56	11.56
300	0.59	1.18	2.01	2.93	5.02	7.20	8.43	9.37	9.51	10.30	11.17	11.17
400	0.53	1.14	1.87	2.84	4.72	6.64	8.29	8.92	9.47	10.12	10.78	10.78
500	0.53	1.11	1.77	2.78	4.60	6.51	8.02	8.54	9.43	10.11	10.39	10.39
1,000	0.48	0.96	1.65	2.47	4.11	6.15	7.39	7.99	8.83	9.37	9.58	9.58
2,000	0.40	0.83	1.47	2.25	3.69	5.22	6.58	7.19	8.02	8.25	8.59	8.59
5,000	0.22	0.66	1.19	1.83	3.07	4.41	5.41	5.93	6.67	6.86	7.16	7.16
10,000	0.19	0.51	0.95	1.46	2.44	3.67	4.37	4.79	5.45	5.60	5.87	5.87
20,000	0.17	0.38	0.71	1.05	1.79	2.61	3.20	3.54	4.06	4.21	4.47	4.47
39,752	0.09	0.23	0.38	0.73	1.13	1.69	2.12	2.15	2.15	2.84	2.84	2.84

Storm Maximization

For each duration, the rainfall depth for the area of the Rio Grande Dam basin (160 mi^2) is interpolated between the 150 mi^2 and 200 mi^2 depths. Each of the SPAS-analyzed depths is maximized in-place. The in-place maximization factor (IPMF) is calculated as:

$$IPMF = \frac{W_{p,max}}{W_{p,rep}}$$

where,

$W_{(p,max)}$ = precipitable water for the maximum dew point
$W_{(p,rep)}$ = precipitable water for the representative dew point

For general storms, the climatological maximum dew point duration was 24-hours, 12-hours for the Blanding, UT storm, and 3-hours for the Bluff, UT storm. The IPMF was held to a maximum of 1.50. The dew point temperatures and IPMF for each storm is listed in Table 6.

Table 6: In-place maximization factors with storm representative and climatological maximum dew points for each event.

SPAS Storm Number	Storm Name	SPAS DAD Zone	State	Storm Rep Dew Point	Climo Max Dew Point	In Place Max Factor	Moisture Inflow Vector	Storm Type
General Storms:								
1075	NORMA REMNANTS	DAD zone 4	CO	75.0	77.0	1.16	SW @ 445	general
1107	WAGON WHEEL	DAD zone 1	CO	68.0	74.0	1.50	SW @ 350	general
1137	YOUNG	DAD zone 5	AZ	64.0	65.0	1.11	SSW @ 420	general
1141	JUNIPINE	DAD zone 4	AZ	68.0	70.0	1.16	SW @ 1,285	general
1144	MT ORD	DAD zone 3	AZ	57.0	60.0	1.22	WSW @ 325	general
1149	COOKS MESA	DAD zone 4	AZ	63.5	65.0	1.12	SSW @ 470	general
1150	BEAR SPRING	DAD zone 2	AZ	58.5	60.5	1.16	S @ 100	general
1241	DEER CREEK DAM	DAD zone 2	UT	59.0	64.5	1.41	SW @ 325	general
1266	CONRAD RANCH	DAD zone 1	UT	55.0	64.0	1.50	WSW @ 300	general
Local Storms:								
1131	BLUFF	DAD zone 1	UT	77.5	81.0	1.20	S @ 190	local
1249	BLANDING	DAD zone 1	UT	76.5	79.0	1.16	SW @ 240	local

In the case of the Junipine storm of Dec, 1966, the storm representative location is over the Pacific Ocean. A +2σ sea surface temperature (SST) climatology was used in lieu of a dew point climatology for this event. The substitution of SST climatology for dew point climatology is consistent with procedures developed by the NWS (e.g. HMR 57) and previous work by AWA (e.g. Tomlinson et al. 2013).

Moisture Transpositioning

The moisture available to the storm center location due to the climatological maximum dew point at the moisture source location differs from the moisture available to the basin location. Figure 6 illustrates the moisture inflow vector for the Conrad Ranch, UT, of 1979 storm. The moisture inflow vector is 300 miles from the west-southwest direction with a storm representative location in central Nevada. The same vector is applied to the basin location resulting in a transposed dew point location in Northern Arizona.

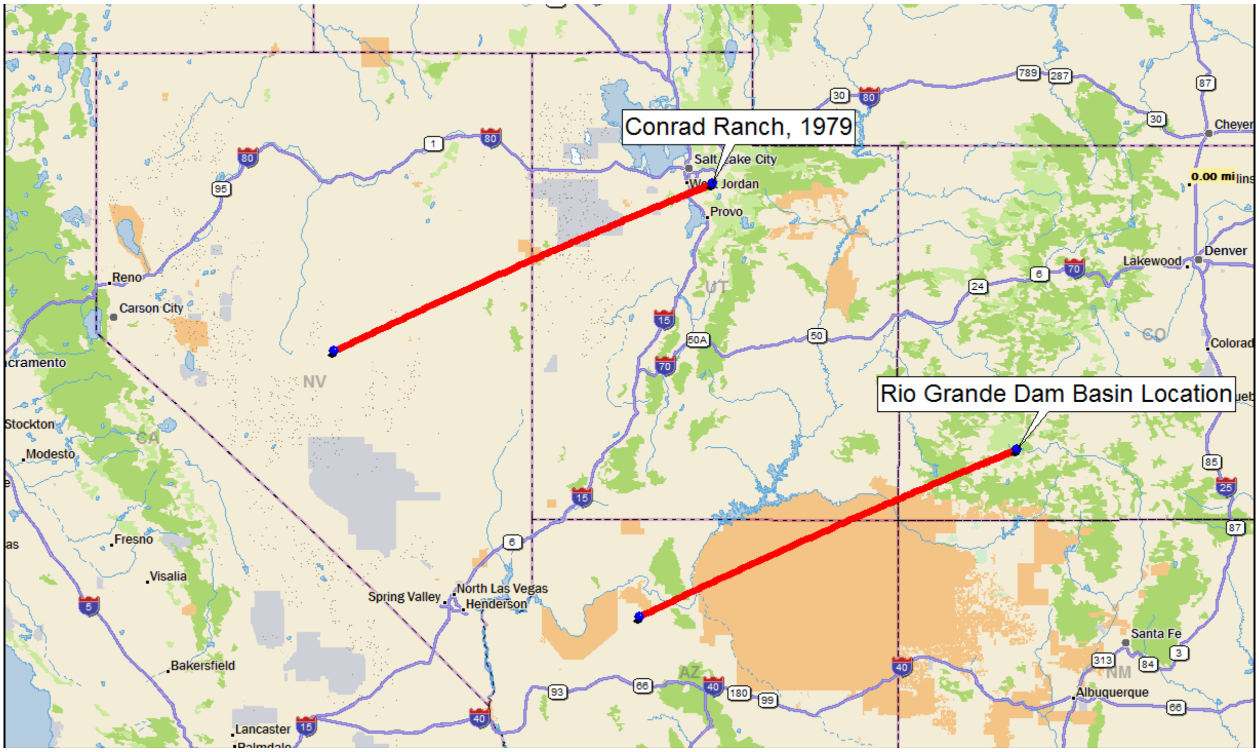


Figure 6: Moisture inflow vector for the Conrad Ranch, 1979 storm

This difference is quantified in the moisture transposition factor (MTF). The range in MTF values is effectively constant across a basin extent of this size, negating the need of a gridded analysis of the MTF. The MTF is calculated by taking the ratio of moisture for the climatological maximum dew point at the basin centroid location to the moisture for the climatological maximum dew point at the storm center location:

$$MTF = \frac{W_{p,trans}}{W_{p,max}}$$

where,

$W_{(p,trans)}$ = precipitable water at the target location
$W_{(p,max)}$ = precipitable water at the storm center location

The MTF accounts only for changes in moisture due to different locations along the horizontal plane. Differences due to elevation area accounted for during orographic transpositioning, described in the next section.

Orographic Transpositioning

The orographic transpositioning factor (OTF) quantifies the orographic effect on rainfall at the basin location in reference to the original storm location. The orographic effect addresses changes in rainfall due to topography including upward deflection, temperature changes due to anabatic/adiabatic processes, and rainshadow effects. To account for the diverse topography over the basin, a gridded approach is applied to the quantification of the orographic rainfall component.

Using a GIS, a gridded network was created over the basin extent at a resolution of 90 arc-seconds, or 0.025 x 0.025 decimal degrees, resulting in 88 evenly spaced grid points. Figure 7 shows the 88 grid cells over the drainage basin, each cell with an approximate area size of 2.36 square miles.

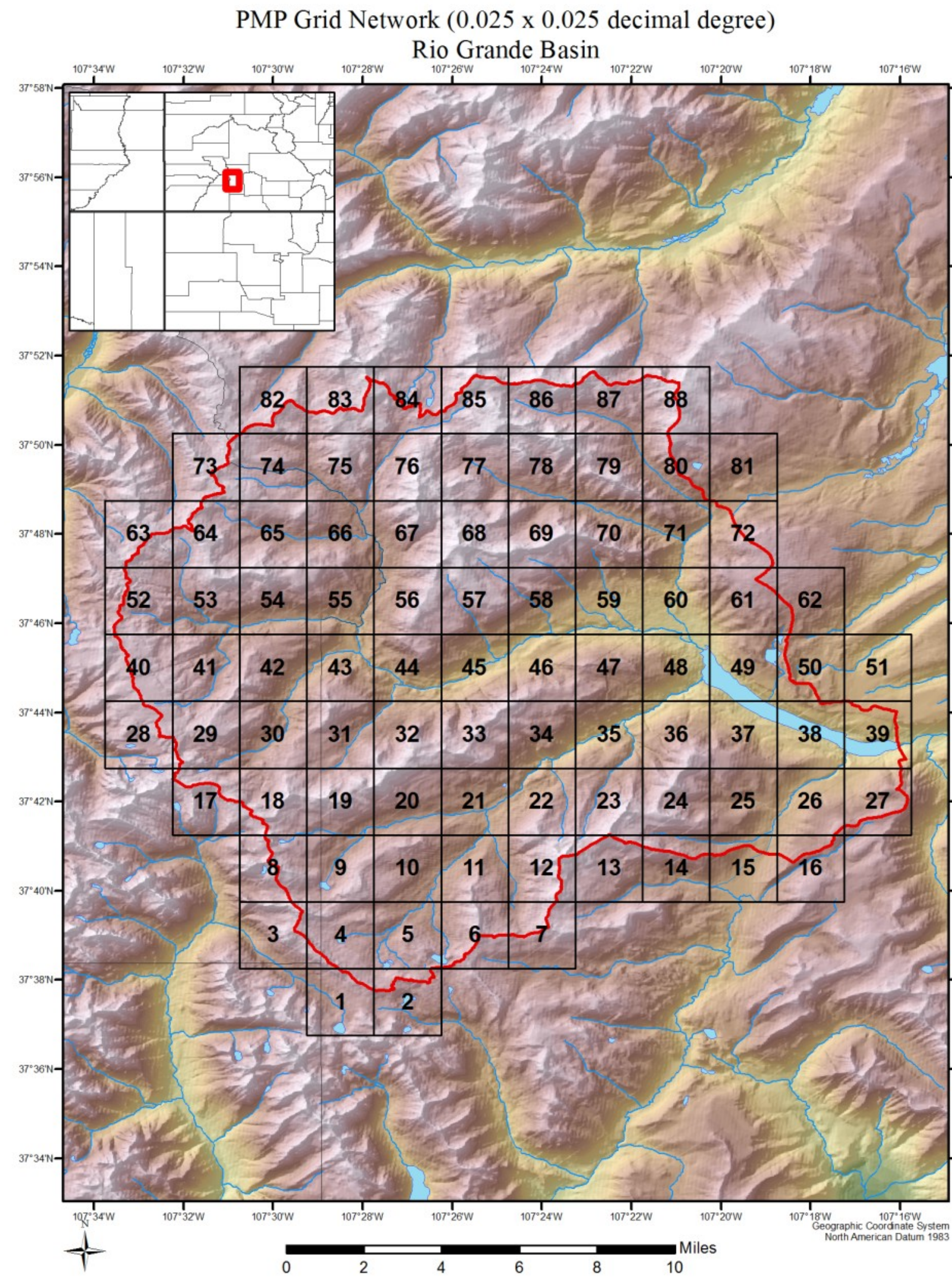


Figure 7: PMP grid network over the Rio Grande Dam basin.

Each storm center was transpositioned to each of the 88 grid points and the resulting OTF was calculated for the grid point locations. The OTF is quantified by taking the ratio of depths from a 24-hour precipitation frequency climatology at the basin grid point location to the storm center location. The most recent and comprehensive available precipitation frequency climatology is published as NOAA Atlas 14 Volume 5 (Bonnin et al. 2011) for the Utah, New Mexico, and Arizona storm centers and Volume 8 (Perica et al. 2013) for the Colorado storm centers and basin grid points.

To adequately encompass the return frequency of typical extreme precipitation events, the 10-, 25-, 50-, 100-, 200-, 500-, and 1,000-year return period precipitation depths are used. Linear regression is applied to the storm center precipitation frequency depths using the SPAS DAD precipitation to determine the orographically adjusted rainfall at each grid point location for the given storm. The ratio of orographically adjusted rainfall at each grid point to the rainfall at the storm center is the OTF:

$$OTF = \frac{P_o}{P_i}$$

where,

P_o = orographically adjusted rainfall (target)
P_i = SPAS-analyzed in-place rainfall

An example of OTF values for the Conrad Ranch, UT event is shown in Figure 8. In general, higher OTF values are produced over upwind slopes at higher elevations while the lower values are produced in valleys and downwind slopes.

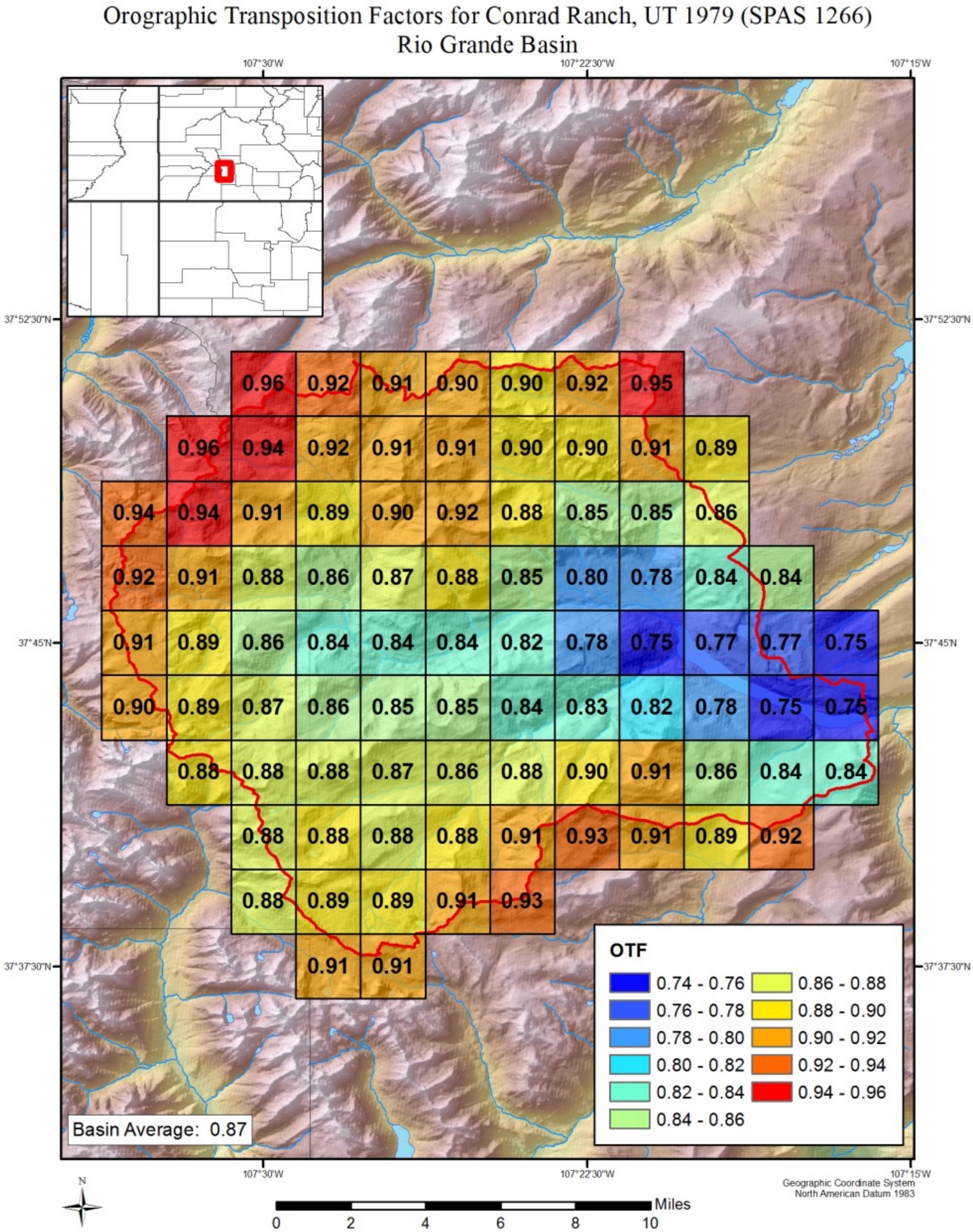


Figure 8: Basin OTF values for the Conrad Ranch, UT of 1979 event

Total Adjustment Factors and PMP Calculations

The product of the IPMF, MTF, and OTF is a total adjustment factor (TAF) that can be applied to the SPAS analyzed 160 mi^2 rainfall depth at each duration to determine the gridded total adjusted rainfall for each storm.

Table 7 lists the IPMF, MTF, average gridded OTF, and the resulting average gridded TAF calculated for each analyzed storm. The actual TAF for each grid is applied to the durational SPAS-analyzed rainfall at the basin area size to determine the total adjusted rainfall for each storm.

Table 7: Average basin total adjustment factors (TAF) for each storm.

SPAS Storm Number	Storm Name	SPAS DAD Zone	State	IPMF	MTF	OTF (average)	TAF (average)	Moisture Inflow Vector	Storm Type
General Storms:									
1075	NORMA REMNANTS	DAD zone 4	CO	1.16	1.00	1.01	1.17	SW @ 445	general
1107	WAGON WHEEL	DAD zone 1	CO	1.50	0.97	0.80	1.16	SW @ 350	general
1137	YOUNG	DAD zone 5	AZ	1.11	0.90	0.51	0.51	SSW @ 420	general
1141	JUNIPINE	DAD zone 4	AZ	1.16	1.13	0.88	1.15	SW @ 1,285	general
1144	MT ORD	DAD zone 3	AZ	1.22	0.90	1.17	1.28	WSW @ 325	general
1149	COOKS MESA	DAD zone 4	AZ	1.12	0.97	0.77	0.84	SSW @ 470	general
1150	BEAR SPRING	DAD zone 2	AZ	1.16	0.86	0.57	0.57	S @ 100	general
1241	DEER CREEK DAM	DAD zone 2	UT	1.41	1.55	1.01	2.21	SW @ 325	general
1266	CONRAD RANCH	DAD zone 1	UT	1.50	1.53	0.87	2.00	WSW @ 300	general
Local Storms:									
1131	BLUFF	DAD zone 1	UT	1.20	0.98	1.10	1.29	S @ 190	local
1249	BLANDING	DAD zone 1	UT	1.16	1.03	0.75	0.90	SW @ 240	local

Once the gridded total adjusted rainfall depths are determined for each storm at each duration, they are compared to all other analyzed storms of the same type (general or local). The largest total adjusted rainfall value becomes the PMP depth for that grid point.

Results

The final gridded PMP depths are averaged over the basin and summarized in Table 8 for general storms and in Table 9 for local storms.

Table 8: Basin average general storm PMP

	Rio Grande Gridded PMP Summary - General Storms					
	1-hour	6-hour	12-hour	24-hour	48-hour	72-hour
Basin Average	1.36	4.12	5.83	7.41	10.52	11.43
Basin Max.	1.50	4.53	6.41	8.15	11.61	12.61
Basin Min	1.16	3.52	4.98	6.34	8.94	9.71
Source Storm	SPAS_1241_2	SPAS_1241_2	SPAS_1266_1	SPAS_1266_1	SPAS_1141_4	SPAS_1141_4

Table 9: Basin average local storm PMP

	Rio Grande Gridded PMP Summary - Local Storms					
	1-hour	2-hour	3-hour	4-hour	5-hour	6-hour
Basin Average	3.70	3.92	3.98	4.01	4.02	4.04
Basin Max.	4.46	4.73	4.81	4.84	4.85	4.88
Basin Min	3.36	3.56	3.62	3.64	3.65	3.67
Source Storm	SPAS_1131_1	SPAS_1131_1	SPAS_1131_1	SPAS_1131_1	SPAS_1131_1	SPAS_1131_1

Theoretically, for a given duration, different storms can drive PMP at different grid points across the basin domain. For the Rio Grande Dam basin, three different general storms control PMP values, with one local storm controlling PMP values. For general storm PMP, the Deer Creek Dam, UT, 2010 storm is the source for the 1-hour and 6-hour durations; the Conrad Ranch, UT, 1978 storm is the source for the 12-hour and 24-hour durations; and the Junipine, AZ, 1966 is the source for the 48-hour and 72-hour durations. For local storm PMP, the Bluff, UT, 2001 storm is the source at all durations up to 6-hours.

EPAT Evaluation

EPAT was used to calculate general storm and local storm PMP over the Rio Grande basin. A basin track was digitized along the Rio Grande River and used as input for EPAT along with the same 160 mi^2 basin outline shapefile that was used in the AWA PMP analysis. The number of runs along the basin track was set at 10. Figure 10 shows the main interface screen for the EPAT run of Rio Grande Dam basin.

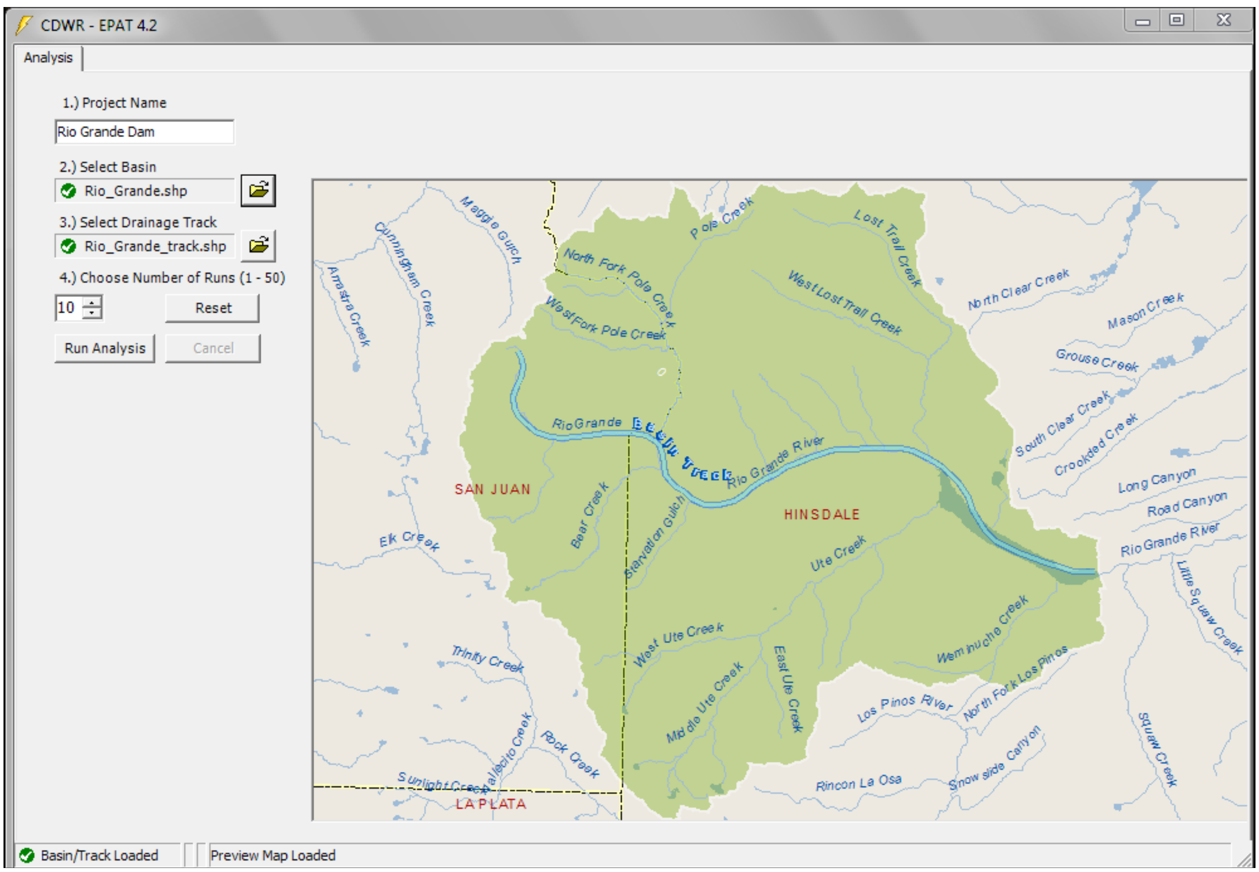
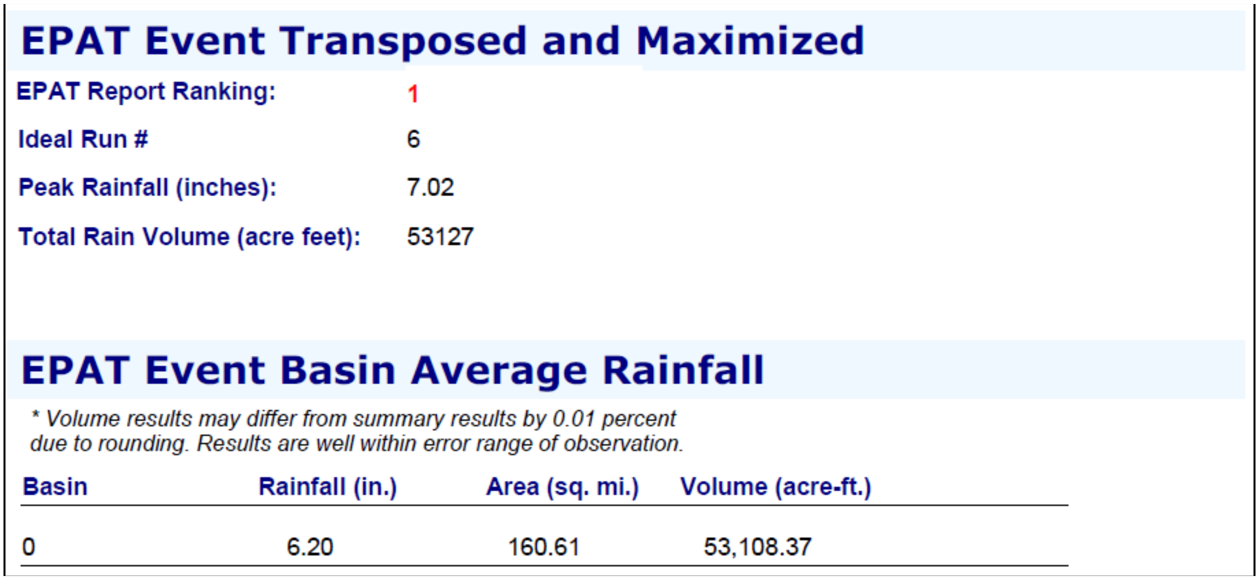


Figure 10: Main EPAT interface for Rio Grande Dam PMP analysis

EPAT storm 23: Palisade Lake, CO, 1927 provided the source for the basin average general storm PMP of 6.20" over an 84-hour duration.



EPAT Event Transposed and Maximized

EPAT Report Ranking:	1
Ideal Run #	6
Peak Rainfall (inches):	7.02
Total Rain Volume (acre feet):	53127

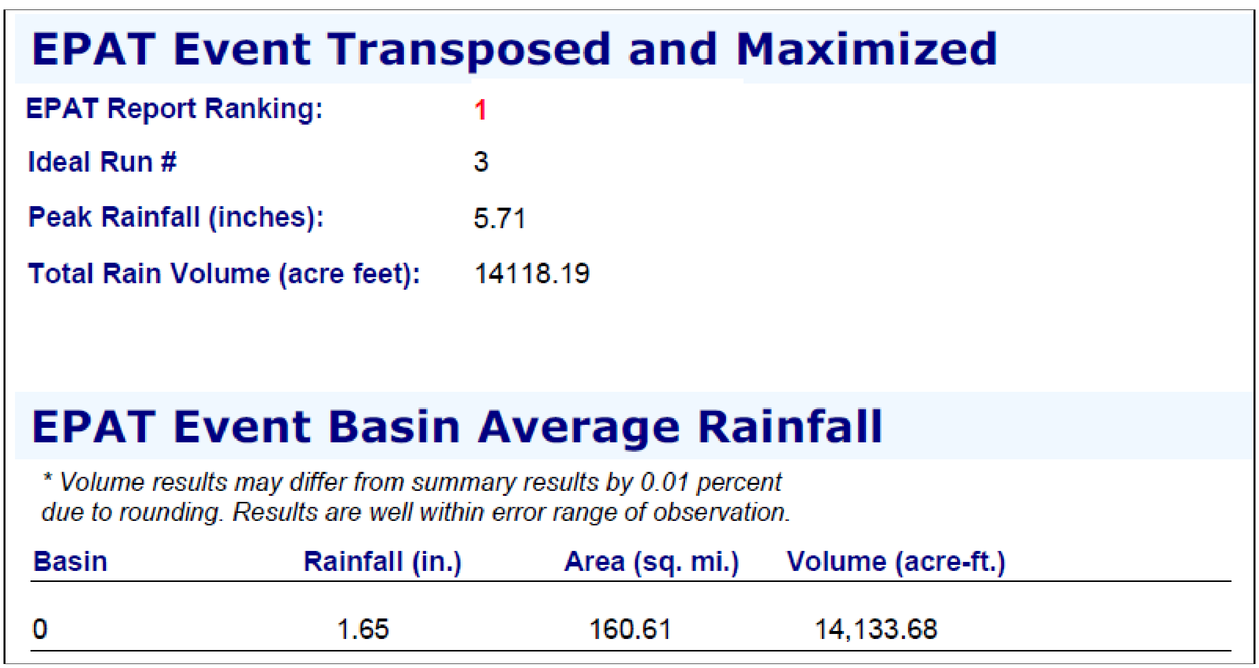
EPAT Event Basin Average Rainfall

** Volume results may differ from summary results by 0.01 percent due to rounding. Results are well within error range of observation.*

Basin	Rainfall (in.)	Area (sq. mi.)	Volume (acre-ft.)
0	6.20	160.61	53,108.37

Figure 11: EPAT general storm PMP #1 ranked event - Palisade Lake, CO, 1927

Storm 28: SW CO/Wolf Creek, CO, 1993; storm 27: SW CO/Durango, CO, 1972; and storm 22: San Juans/Gladstone/Silverton, CO, 1911 were also evaluated for general storm PMP and ranked #2, #3, and #4, respectively, and contributed to PMP at various general storm durations.
For local storm PMP, the #1 ranked event was storm 1: Placerville, CO, 2001, with a basin average PMP of 1.65" over a 1.5-hour duration.



EPAT Event Transposed and Maximized

EPAT Report Ranking:	1
Ideal Run #	3
Peak Rainfall (inches):	5.71
Total Rain Volume (acre feet):	14118.19

EPAT Event Basin Average Rainfall

** Volume results may differ from summary results by 0.01 percent due to rounding. Results are well within error range of observation.*

Basin	Rainfall (in.)	Area (sq. mi.)	Volume (acre-ft.)
0	1.65	160.61	14,133.68

Figure 12: EPAT local storm PMP #1 ranked event – 1.5-hr RADAR event, CO, 2001

Storm 4: Dallas Creek, CO, 1999 and storm 29: Saguache, CO, 1999 were also evaluated for local storm PMP and ranked #2 and #3, respectively, and contributed to PMP at various local storm durations.

Table 10 compares the basin average and basin maximum general and local storm PMP between the EPAT and AWA analyses. The general storm PMP is listed for the 24-hour duration. The local storm PMP is listed for the 1-hour duration. For each of these durations, the EPAT storm temporal distribution percent reduction was applied to the full duration PMP for each of the EPAT ranked storms to determine the largest value.

Table 10: Comparison of EPAT and AWA basin PMP depths for general storms (24hr) and local storms (1hr)

Rio Grande Basin (160.5 sqmi)

	EPAT Basin Analysis Results					
	PMP (Basin Average)	PMP (Max.)	PMP Duration (hours)	Source Storm	# of Runs	Ideal Run
General	4.37	4.85	24	22 - Gladstone, Oct 1911	10	5
Local	1.31	4.09	1	29 - Saguache, Jul 1999	10	4

	AWA Site-Specific Analysis Results			
	PMP (Basin Average)	PMP (Max.)	PMP Duration (hours)	Source Storm
General	7.41	8.15	24	SPAS 1266 - Zone 1 - Conrad Ranch, UT, Oct 1979
Local	4.01	4.84	1	SPAS 1131 - Bluff, UT, Aug. 2001

Appendix C evaluates each of the Task 4 problem statement procedures in reference to the EPAT versus AWA PMP calculations for the Rio Grande basin.

Task 6

Based on the results of the review, AWA has made recommendations for potential EPAT modifications to improve the science and reliability of the program for use by the DSB. Outdated and incorrect procedures have been identified and replacement procedures recommended where possible. These have been listed in Task 4 but are consolidated under Task 6 discussions.

EPAT storm library

Recommendation

The storm library should be modified to add appropriate storms not previously included as well as add storms that have occurred since EPAT development. Storms that will not contribute to PMP values should be identified and eliminated. Identifying the storms to be deleted and storms to be added would take approximately one week. Adding the required new storm analyses to the EPAT library would take two months. Storms would be added in the format required for EPAT and provide all of the information required.

Storm rainfall analyses

Recommendation

Each storm used for PMP determination should be evaluated in detail to determine the adequacy of the original analysis. Most, if not all, of the storms important for PMP development have subsequently been analyzed on a gridded basis for PMP work that has occurred since EPAT was completed. Using this peer reviewed storm database will provide significant increases in PMP reliability. One or more storms in the EPAT library will need to be re-analyzed to provide reliable rainfall information. To verify, update, and complete the storm analyses would take two months.

In-place maximization

Recommendation

Determination of reliable in-place maximization factors for each storm is critical for PMP determination. Each maximization factor should be re-evaluated to determine an accurate and reproducible value. The in-place maximization factor for most, if not all, of the storms important for PMP development have subsequently been analyzed during other PMP studies. Utilizing these peer reviewed maximizations is recommended. To verify, update, and complete the appropriate in-place maximizations would take two months.

Storm transpositioning
Recommendation
A re-evaluation of transposition limits of storms important for PMP should be completed. Updated understanding of the storm dynamics, rainfall patterns, and their relation to topography and moisture inflow should be considered to better quantify transposition limits. The results should provide an updating set of transposition limits for PMP development. This re-evaluation and application would take one month.

Storm centering
Recommendation
Since the centering of the storm over the thalweg is not a physically possible storm centering location for most basins, it should not be a requirement in the EPAT storm transposition procedure. Other centering procedures should be considered using historic storm isohyetal and climatological patterns. The level of effort to evaluate and recommend a storm centering procedure is estimated to be two weeks

Storm isohyetal orientation
Recommendation
Re-evaluation of the storm isohyetal pattern orientation over basins should be completed. The storm orientation should be patterned after historic storm events or a climatology of rainfall analyses over the basin. The level of effort for this re-evaluation is estimated to be 2 to 3 weeks.

Areal reduction
Recommendation
The use of individual areal reduction factors should be re-evaluated for use over the mountainous terrain of Colorado. Other procedures for the transposition of storms over orographic regions should be investigated. This re-evaluation should take approximately 2 weeks.

No orographic storm separation method applied to account to the effects of topography on historic storms

EPAT should include a procedure for addressing topographic influence differences between the locations where storms historically occurred in the study basin. Procedures using gridded rainfall data together with climatological maps have been shown to address topographic differences. Evaluation of this procedure along with other methods should be investigated. This investigation should take approximately one month.

No enveloping of spatial or temporal storm data
Recommendation
Timing or mass curves from various storms should be considered and provided to the hydrologist for use in computing the probable maximum flood.

Elevation adjustment (9%/1000')

Recommendation
Explicit calculation of the elevation moisture adjustment should be completed for all storms. This can be accomplished by following moisture transposition calculation steps or through application of the Orographic Transposition Factor calculation. Recalculation of this factor for all storms important for PMP development would take two months.

These recommendations are to address individual issues associated with errors and/or inconsistencies found in the EPAT review. Recommendations associated with the update of the EPAT library are straightforward and will address issues associated with the shortcomings of both the inclusiveness of the library for extreme storms as well as the completeness of storm parameters. Many of the other recommendations should adequately address problems found in the EPAT review. Other issues such as storm centering and orographic transposition are more complicated. It is unclear if the current EPAT architecture can adequately accommodate updates in these procedures.

The remaining areas of Colorado not covered in EPAT can be including for complete statewide PMP determination. Several storms need to be added to the storm library, mainly from the eastern plains of Colorado through the western Great Plains to approximately 2,500 feet elevation. This would be a straightforward process because of all of the storms have already been analyzed as part of the Nebraska and Wyoming statewide PMP studies. The majority of the work would involve setting up the grid and adjusting each storm as appropriate to each location.

Appendix A- EPAT Spatial and Temporal Envelopment Analysis

Overview

It was requested that AWA evaluate EPAT's use of observed storm data for the distribution of PMP over time and space instead of using envelopment procedures. The suggested procedures were outlined through notes in the PDF titled "2014-03-07 Concept for Evaluation of Enveloping.PDF". For a hypothetical basin location, the change in PMP depths over space and time could be calculated and plotted to aid in illustration and determination of the need for envelopment.

Basin Setup and PMP Calculation

Ten basin centroid locations were chosen across the EPAT analysis domain (Figure A.1). The basin locations were chosen to provide a broad representation of the various EPAT climate transposition zones. Basin #3 was located at the Rio Grande basin centroid. Beyond those criteria, the basin locations were located arbitrarily. At each location, hypothetical basin areas were produced in ArcMap as shapefiles in at the 1-, 5-, 10-, 25-, 50-, 100-, 250-, and 500-sqmi area sizes (Figure A.2). These basins were created as concentric circles centered on each of the 10 basin location centroids. A basin track shapefile was digitized inside the circle for each basin shapefile. The basin track bisected the circle diagonally.

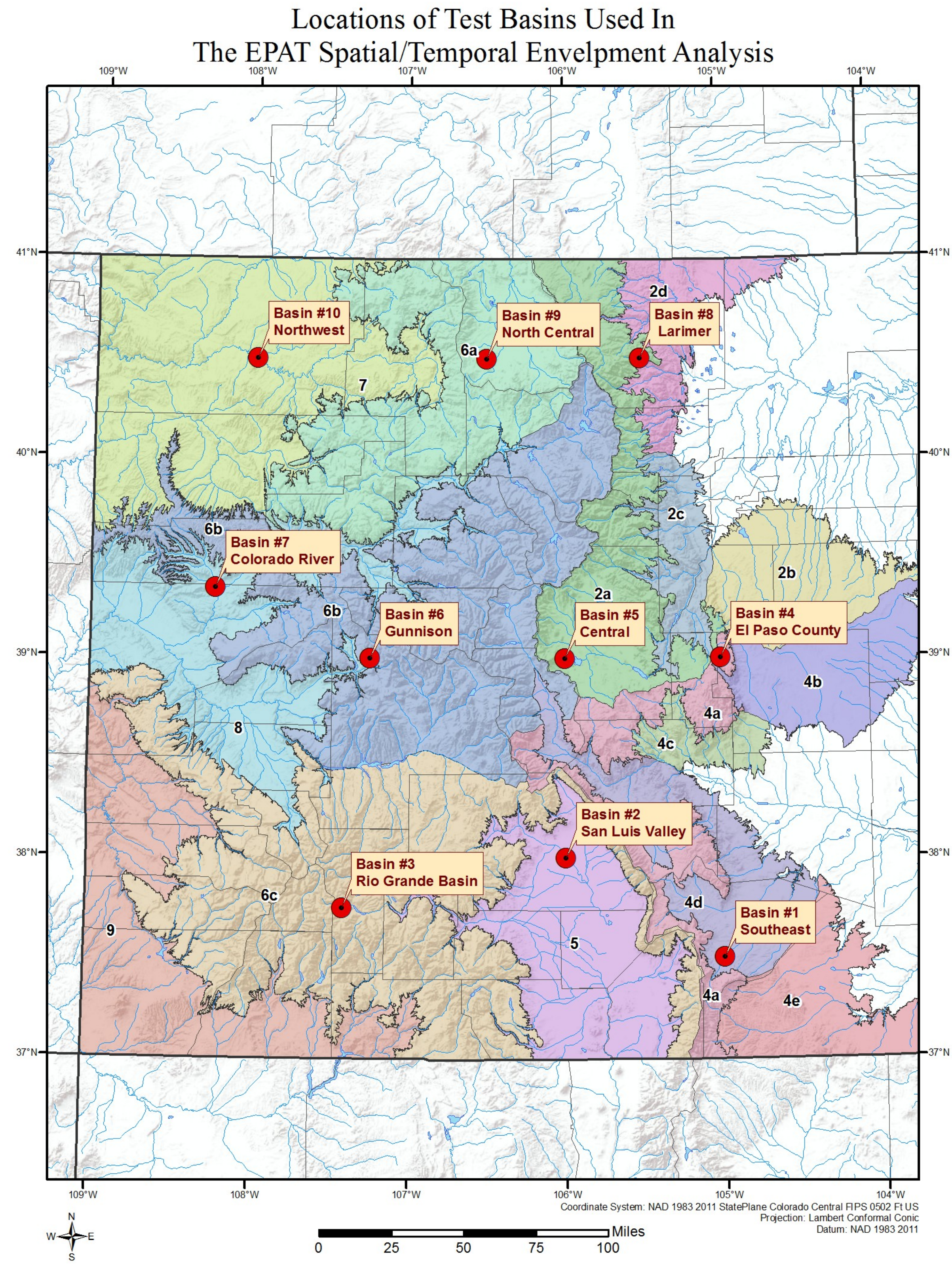


Figure A.1: Locations of sample basins for envelopment analysis

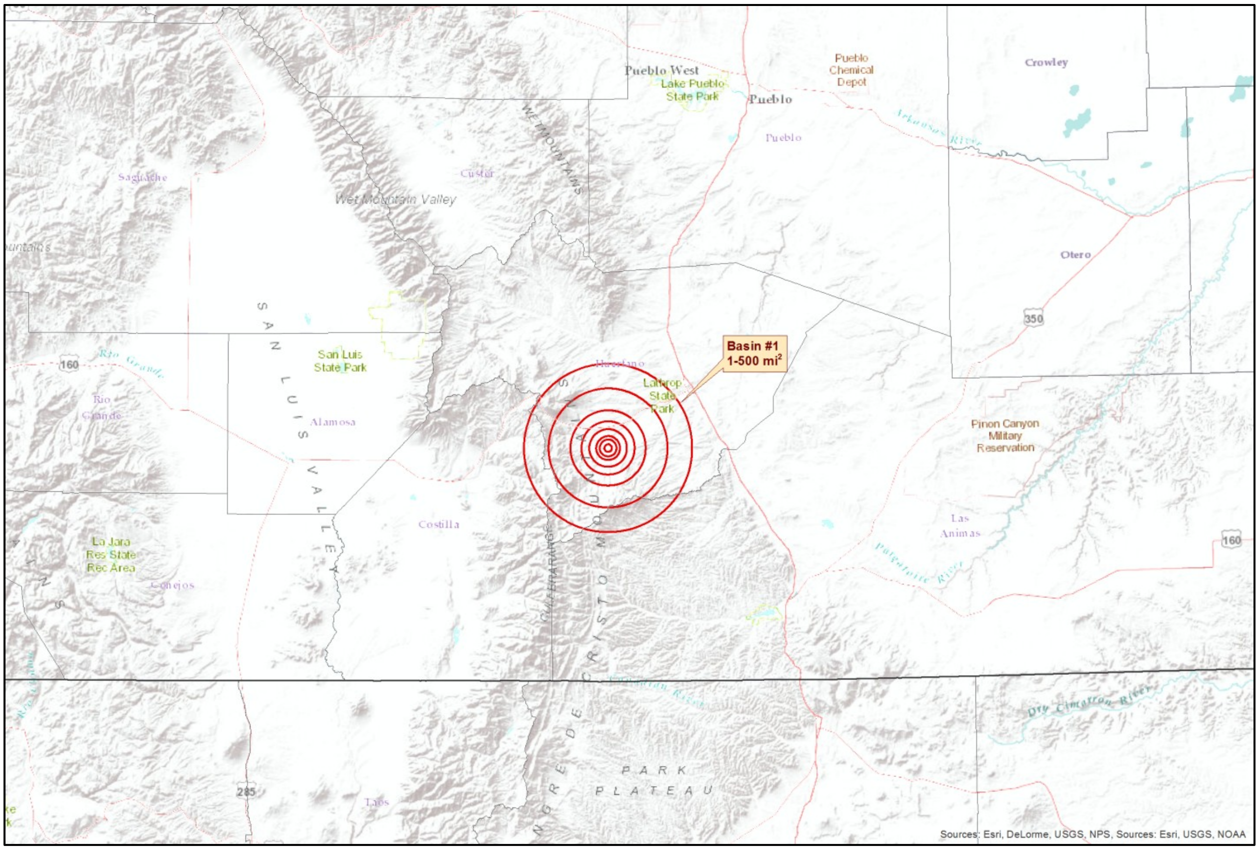


Figure A.2: Sample concentric basin areas 1 through 500 mi^2

EPAT was run for each of the eighty basin/basin track shapefiles pairs and the PMP output files were recorded. One run (the basin centroid) was chosen as an input parameter for 'Number of Runs'.

An Excel spreadsheet was created for each of the ten basin locations and was used to calculate and plot the spatial and temporal rainfall distributions.

Spatial Envelopment Analysis

Procedure

The basin average PMP versus basin area was plotted for the 1 mi^2 through 500 mi^2 area sizes. A single duration was chosen for the spatial envelopment analysis: the 1-hour PMP duration was used for local storms and the 24-hour PMP duration was used for general storms.

EPAT provides only the total storm basin average PMP along with accumulated temporal adjustment factors at 1-hour intervals for general storms, and 5-minute (and some 1-minute) intervals for local storms. 1-hour and 24-hour depth-duration relation factors were calculated for each storm by taking the accumulated adjustment factors and converting them to incremental adjustment factors within an Excel spreadsheet. A moving 1-hour sum window was then applied to each local storm's 5-minute incremental adjustment factors to determine the largest consecutive time steps over a 1-hour period. A similar 24-hour window was applied to each general storm's 1-hour incremental adjustment factors to determine the largest consecutive time steps over a 24-hour period. The 1-hour factors were also determined for each general storm to be used in the temporal envelopment analysis. Table A.1 shows the maximum 1-hour and 24-hour depth-duration relation factors for the general storms.

Table A.1: Maximum depth-duration relation factors for EPAT general storms

STORM ID	STORM NAME	24-HOUR RELATION FACTOR	1-HOUR RELATION FACTOR
21	Western Colorado	0.32	0.03
22	San Juans/Gladstone/Silverton	0.95	0.08
23	Palisade Lake	0.42	0.04
24	Pyramid	0.57	0.06
25	Blanding, UT	1.00	0.52
26	SW CO / Dove Creek	0.94	0.19
27	SW CO / Durango	0.64	0.06
28	SW CO / Wolf Creek	0.49	0.03
30	S. Central	0.42	0.02
35	Savageton	0.57	0.09
44	Redstone Creek	0.73	0.27
45	Rye	0.62	0.28
46	Raton Mesa	0.71	0.08
49	Big Elk Meadows	0.56	0.05

The 1-hour factors were applied to each controlling storm's basin average total storm PMP depth to determine the 1-hour PMP at each basin area size. The same process was used for general storms at the 24-hour duration. Figure A.3 shows the depth-area plot for 1-hour local storm PMP at the basin #1 location. Figure A.4 shows the depth-area plot for the 24-hour general storm PMP at the basin #1 location. A dashed green envelopment line is manually added to help illustrate envelopment between area sizes. Depth-area plots for the remaining nine basin locations area provided in the attached spreadsheets.

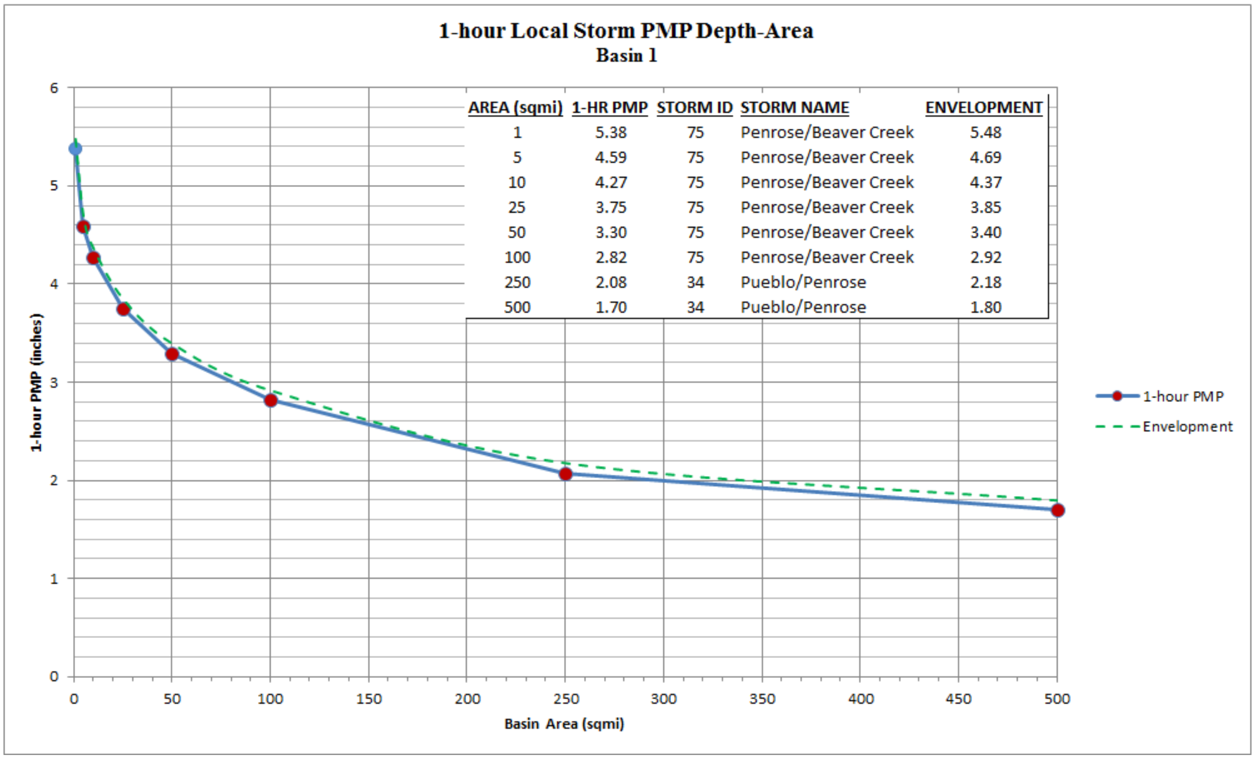


Figure A.3: Local storm 1-hour PMP depth-area curve

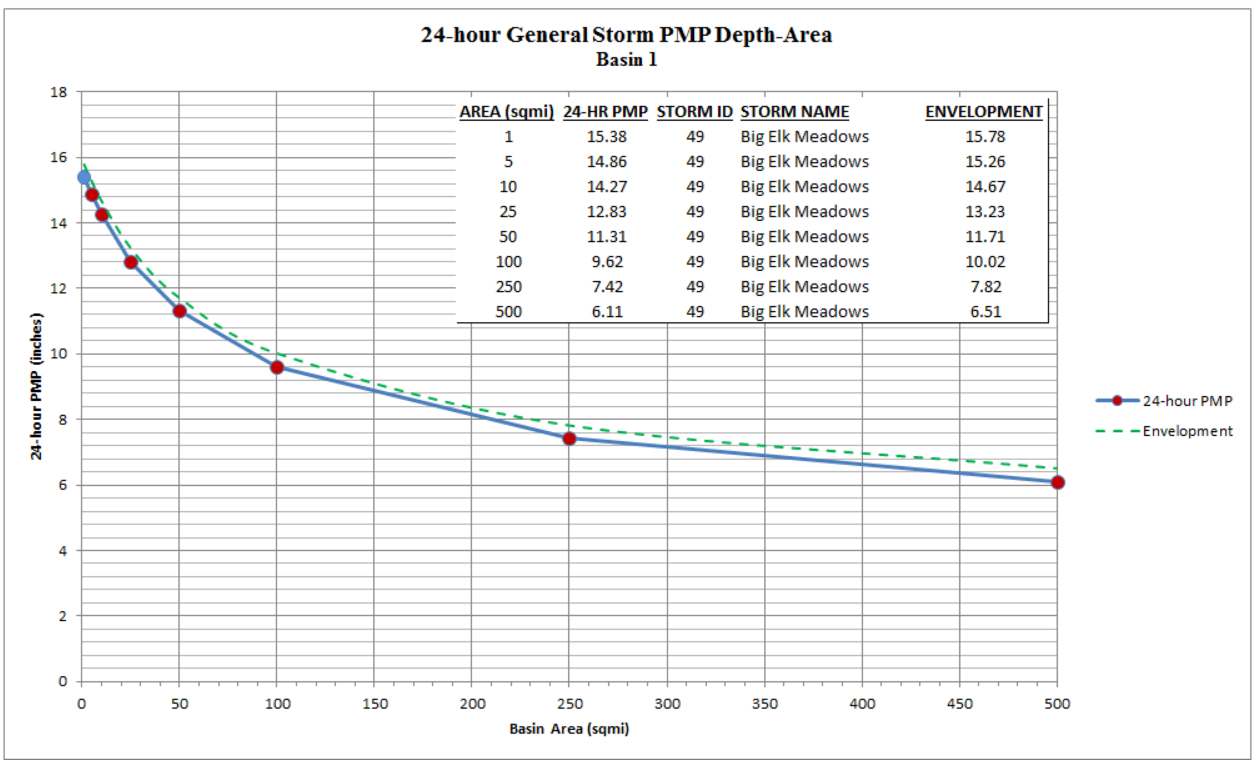


Figure A.4: General storm 24-hour PMP depth-area curve

Discussion:
In each of the 10 basin location cases, there was only one, or a maximum of two, PMP driver storms. The depth-area curve was fairly smooth in every case. The manual envelopment curve only accounts for minimal/negligible increases in PMP due to curve smoothing. However, if significantly more than eight incremental area sizes were analyzed (e.g., at every 10 mi^2 increment), the depth-area curve may show more dramatic steps between area sizes. To accomplish an analysis for each 10 mi^2 increment, for example, would require the creation of 50 separate basin shapefiles for each location, then a separate EPAT analysis for each. An analysis at this resolution would not be feasible within the constraints of this evaluation.

A larger database of storms would inevitably contribute to greater depth-area smoothing.

Temporal Envelopment Analysis

Procedure

For local storms, the peak rainfall intensity (in/hour) curves are plotted for durations up to 2-hours in 5-minute increments for each driver storm. For general storms, the rainfall intensity (in/hour) is plotted for durations up to 72-hours in 1-hour increments. A constant area size of 10 mi^2 was used for local storms and 100 mi^2 was used for general storms.

The peak rainfall intensity was determined by applying the accumulated 5-minute (or 1-hour for general storms) depth-duration reduction factors, in descending order, to the maximum 1-hour basin average.

The peak rainfall intensity versus time plot for 10 mi^2 local storm PMP at the basin #1 location is shown in Figure A.5. The intensity versus time plot for 100 mi^2 general storm PMP at the basin #1 location is shown in Figure A.6. A manually drawn envelopment curve is shown as a red dashed line. The intensity over time plots for the other nine basin locations are included in the attached spreadsheets.

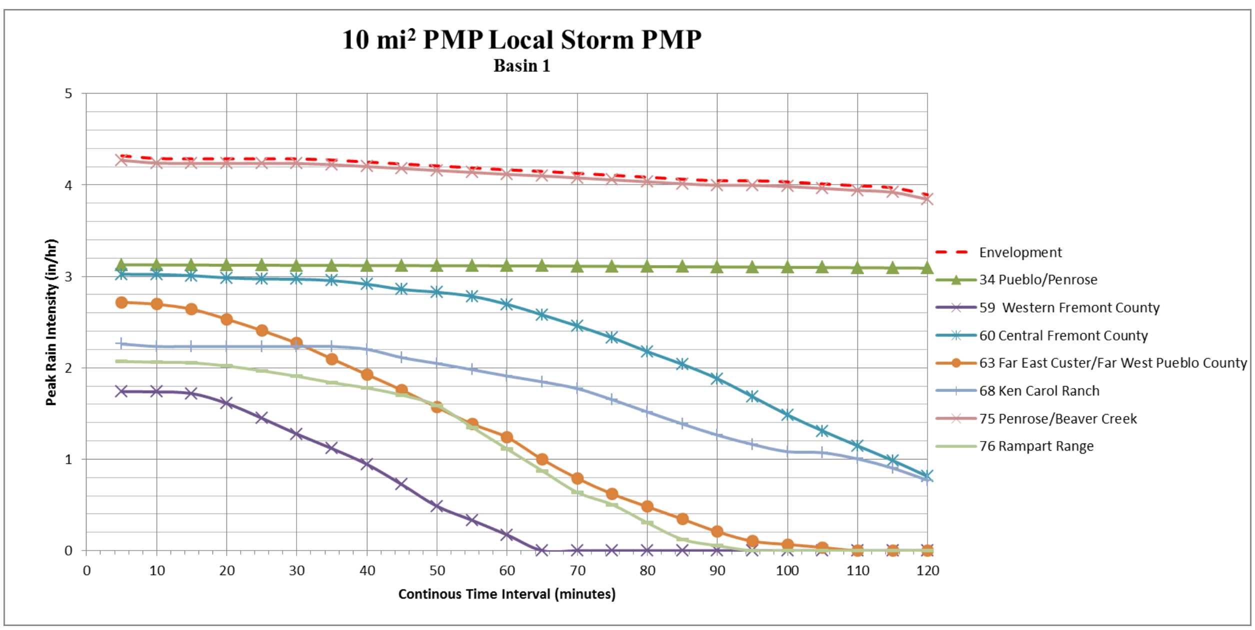


Figure A.5: Peak rainfall intensity (in/hr) over time for 10 mi^2 PMP local driver storms

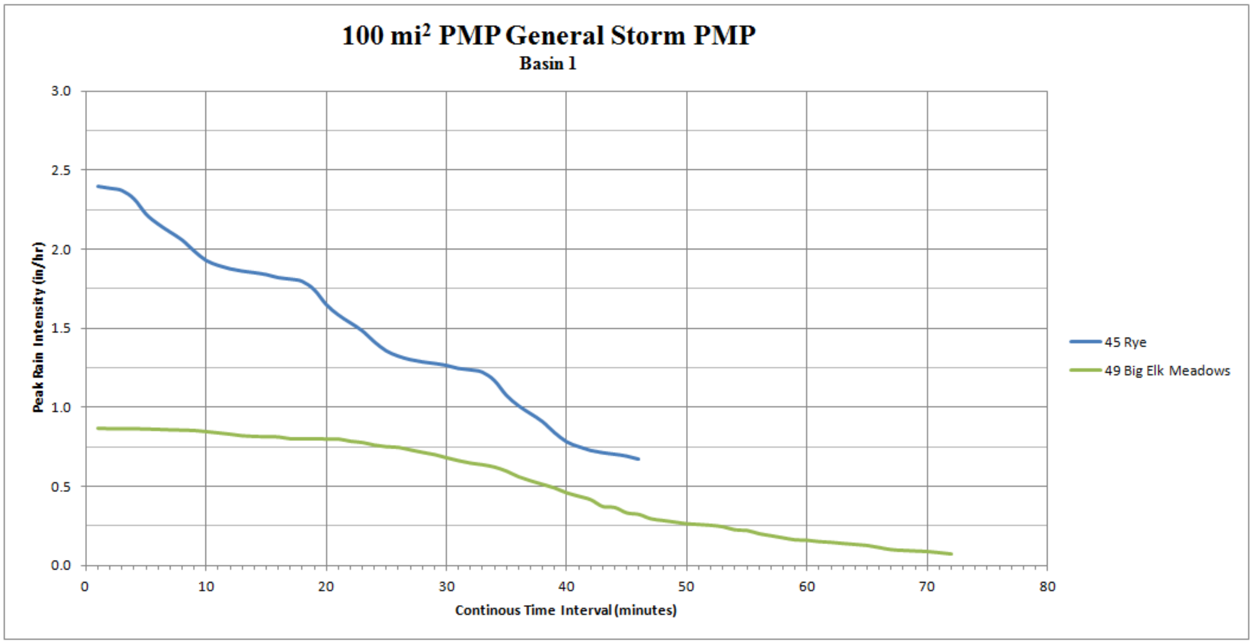


Figure A.6: Peak rainfall intensity (in/hr) over time for 100 mi^2 PMP general driver storms

Discussion:
Based on the results of this analysis, it appears that temporal envelopment may contribute to a significant increase in EPAT rainfall values.

Several of the intensity/time plots show the need for envelopment. In some cases the maximum controlling storm changes at longer durations, indicating the need for smoothing over the transition. An example is local storm values at basin location #10. In some cases, such as local storm values at basin location #5, there does not appear to be a sufficient storm sample with only two events that both end at 90-minutes. Theoretically, the 120-hour PMP should be a non-zero magnitude.

Notes/Errors:

There were a few issues/errors that arose during the analysis.

- EPAT crashed with an unspecified error for all analyses run on the basin #2 location, therefore no values and no envelopment analysis was completed at this location. It is not clear on what caused this error. However, the EPAT software indicated it was "Rotating rainfall features…" for storm #31 San Luis, indicating there was an issue with transposing/orienting the isohyetal pattern for this storm to basin #2.
- EPAT crashed with an unspecified error for the 500 mi^2 run on the basin #4 location, therefore no values and no envelopment analysis was completed at this location at the 500 mi^2 area. It is not clear on what caused this error. However, the EPAT software indicated it was "Rotating rainfall features…" for storm #75 Penrose/Beaver Creek, indicating there was an issue with transposing/orienting the isohyetal pattern for this storm to basin #4.
- At basin location #6, the only controlling general storm, #21 Western Colorado, produced basin average total storm rainfall values that increased with area size up to 100 mi^2, where basin average rainfall should decrease with area (see values below). This storm also was the sole driver at basins #7 and #10, and decreased with area at those locations,

as would be expected. It is not known what is causing the increase in rainfall with area at basin #6.

Table A.2: Rainfall accumulation for 24-hours at various area sizes for EPAT storm #21

	AREA (sqmi)							
STORM	1	5	10	25	50	100	250	500
21	4.50	4.51	4.46	4.55	4.67	4.73	4.51	4.10

- A similar rainfall increase with area also occurred at basin location #8 with storm #45 Rye between 1 mi^2 and 5 mi^2.

Table A.3: Rainfall accumulation for 24-hours at various area sizes for EPAT storm #45

STORM	1	5	10	25	50	100	250	500
45	9.65	9.88	9.52	8.80	7.97	6.79	5.43	4.76

Appendix B- Description of the EPAT Procedure for Calculating Basin Average Rainfall

The process to determine the basin average rainfall is handled by several subroutines. These include code lines 663-725, 2261-2317, 2805-2913 and 3667-3727. The actual calculations are all performed within the EPAT software and are not transparent during the analysis or included in the output. The EPAT source code notes state that:

1) The basin average rainfall considers the intersection of any rainfall polygons as well as the absence of any rainfall polygons intersecting each basin.
2) Average rainfall is calculated using a weighted average based on maximized rainfall in the basin and the geometric area of the intersection as a percentage of the basin's total area.
3) The basin average rainfall formula can be expressed as (the sum of each rainfall feature intersecting a sub-basin * (area of intersecting rainfall in sub-basin / total sub basin area).

Test runs of sample basins showed that this approach is consistent with basin average rainfall values reported in the EPAT output. The following example calculated basin average rainfall for Storm #29 Saguache, CO 1999 over the Rio Grande Basin (160.6 sqmi).

Table B.1: Rainfall accumulation for 24-hours at various area sizes for EPAT storm #21

Rainfall Polygon	**Maximized Rainfall R (in)**	**Rainfall Area A_r (mi^2)**	**Basin Area A_b (mi^2)**	**Weighted Rainfall = R* (A_r / A_b)**
1	1.79	32.98	160.61	0.37
2	2.62	30.14	160.61	0.49
3	3.47	23.25	160.61	0.50
4	4.59	3.48	160.61	0.10
			Basin Average (sum) =	**1.46**

The basin average maximized rainfall is computed as 1.46”

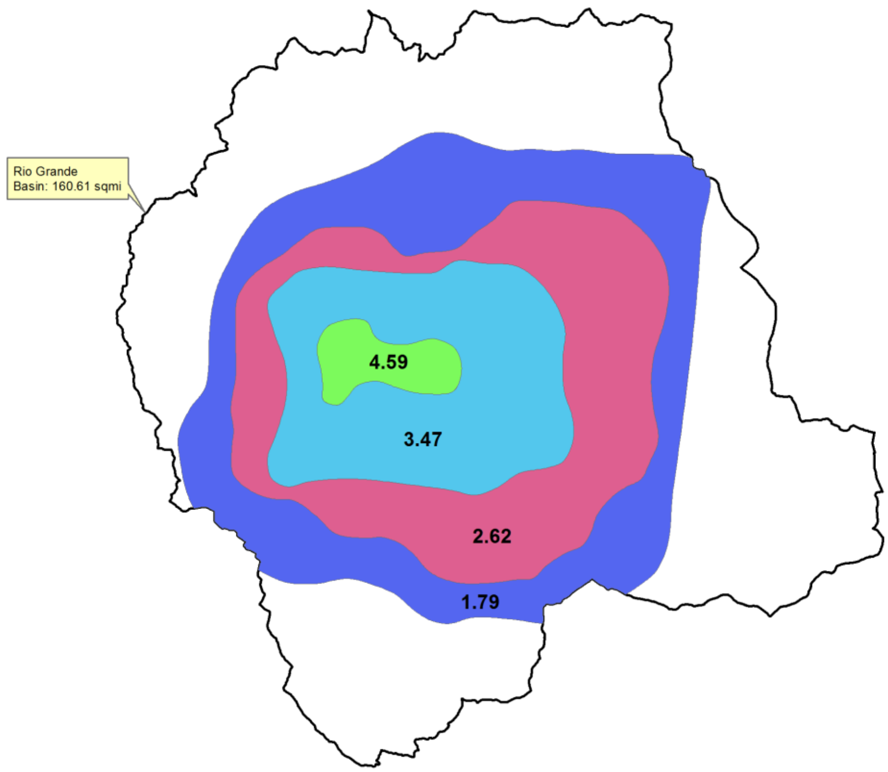


Figure B.1: Storm #29 isohyetal pattern shapefile clipped to the Rio Grande basin with rainfall depths associated with each polygon

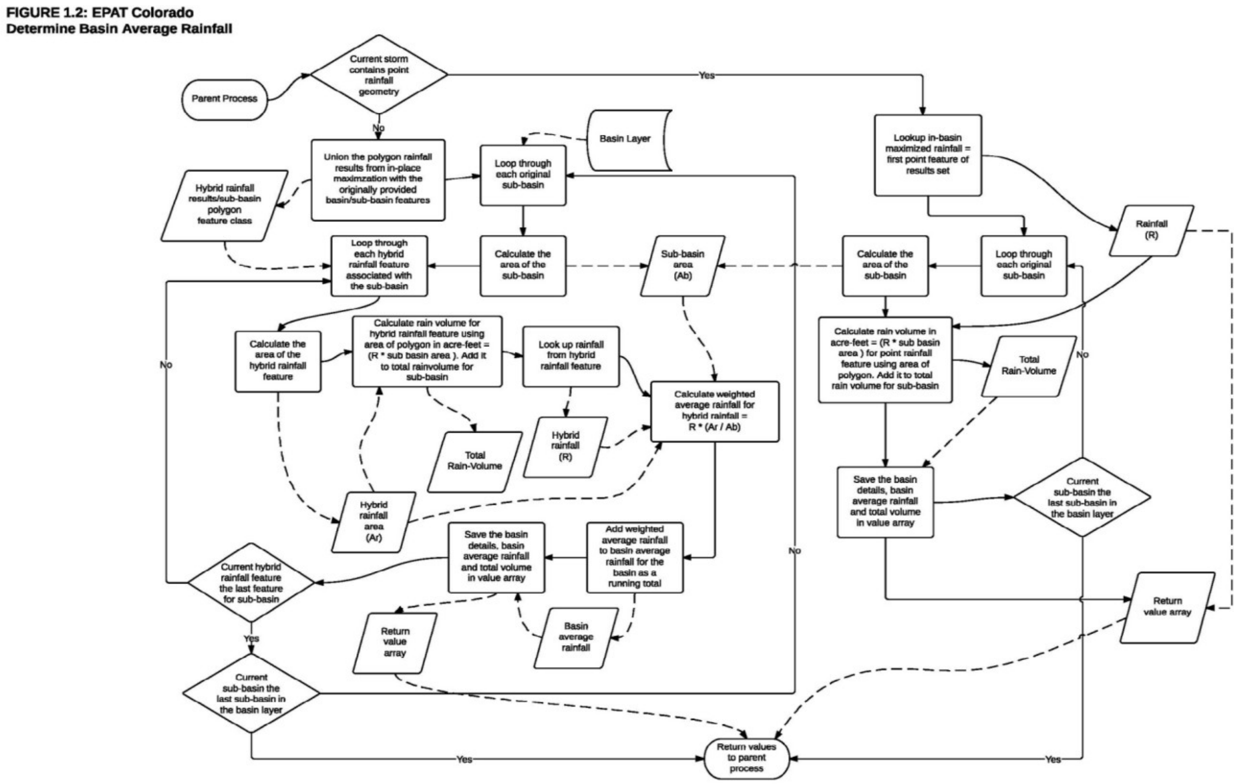


Figure B.2: Flowchart for the process for basin average rainfall calculations (from the EPAT Technical Report Appendix E, page 411)

There is an inherent issue with the storm rainfall spatial data existing as shapefiles made up of stacking polygons attributed with rainfall depths, or isohyets, in that the rainfall depth associated with the area of a given isohyetal polygon is discrete for that area, and does not change. In reality, the change in rainfall over space is continuous. EPAT presents rainfall as discrete values over space, potentially under-representing the amount of rainfall that actually occurred. Many storms in the EPAT library have very few isohyets, or a highly simplified pattern, which would enhance the issue of lack of continuity and mask the true spatial variation. Some storms, such as #31 and #38 have only one isohyet, showing no change in rainfall over space whatsoever.

Furthermore, the isohyetal polygons are spatially limited to the extent of the original hard-copy isohyetal pattern from which they were digitized. These often only extend outward to an extent limited by subjective means. For instance, storm #46 extends only out to the 5” isohyet. All rainfall data beyond the 5” isohyet are not included in the analysis. If this storm were placed over a large basin so that the entire basin was not covered by the pattern, all the area beyond the 5” isohyet would be considered to have no rainfall, resulting in basin average that is too low. In reality, the rainfall occurring beyond the extent represented by the shapefile could potentially significantly contribute to basin rain volume.

An alternative to the shapefile approach to represent spatial rainfall data would be raster or gridded rainfall datasets, assuming the rainfall grid creation process is reliable (i.e. reviewed and accepted data collection, processing interpolation methods, etc.). Gridded data allows for a continuous representation of values over space, and would allow for greater precision and accuracy when calculating basin/areal averages. Ideally, gridded rainfall datasets would be produced for each storm in the library with a tested and approved analysis system such as SPAS. Alternatively, the existing isohyetal patterns could be easily spatially interpolated to raters using a variety of interpolation tools within a GIS.

Appendix C- Rio Grande Basin Examples

The following procedures (from Task 4) are applied to the EPAT PMP analysis for the Rio Grande basin and compared with the AWA site-specific gridded PMP analysis for the basin.

1: List the storms missing from the EPAT analysis.

Table C.1 lists the AWA SPAS-analyzed storms used in the Rio Grande PMP analysis. Two of these storms were included in the EPAT storm library: General storm SPAS 1107 Wagon Wheel, CO Oct. 1911 (EPAT #22 San Juans/Gladstone/Silverton) and local storm SPAS 1249 Blanding, UT Aug. 1968 (EPAT #25 Blanding). However, Storm #25 Blanding, UT Aug. 1968 was considered a general storm in the EPAT storm library.

Table C.1: AWA storms used in the Rio Grande PMP study

SPAS Storm Number	Storm Name	SPAS DAD Zone	State	Year	Month	Day	Lat	Lon	Storm Type	EPAT Storm?
General Storms:										
1075	NORMA REMNANTS	DAD zone 4	CO	1970	9	3	37.56	-106.88	general	no (different center)
1107	WAGON WHEEL	DAD zone 1	CO	1911	10	4	37.66	-106.94	general	Storm ID #22
1137	YOUNG	DAD zone 5	AZ	1965	11	22	37.10	-106.63	general	no
1141	JUNIPINE	DAD zone 4	AZ	1966	12	4	38.99	-106.91	general	no
1144	MT ORD	DAD zone 3	AZ	1916	1	14	35.11	-108.20	general	no
1149	COOKS MESA	DAD zone 4	AZ	2007	11	30	37.54	-106.87	general	no
1150	BEAR SPRING	DAD zone 2	AZ	1978	2	27	34.04	-111.49	general	no
1241	DEER CREEK DAM	DAD zone 2	UT	2010	10	25	41.63	-111.97	general	no
1266	CONRAD RANCH	DAD zone 1	UT	1979	10	20	40.59	-111.59	general	no
Local Storms:										
1131	BLUFF	DAD zone 1	UT	2001	8	14	37.26	-109.58	local	no
1249	BLANDING	DAD zone 1	UT	1968	8	1	37.83	-109.54	local	Storm ID #25 (GS)

2: Compare SPAS storm analysis to EPAT storm library data for common storms.

Figure C.1 compares the EPAT #22 Gladstone isohyetal pattern (Source: USBR/HMR) with the SPAS 1107 gridded rainfall. SPAS did not use the anecdotal 8.05" observation near Gladstone, still the rainfall values were an average of 33% higher with the center focused farther to the east.

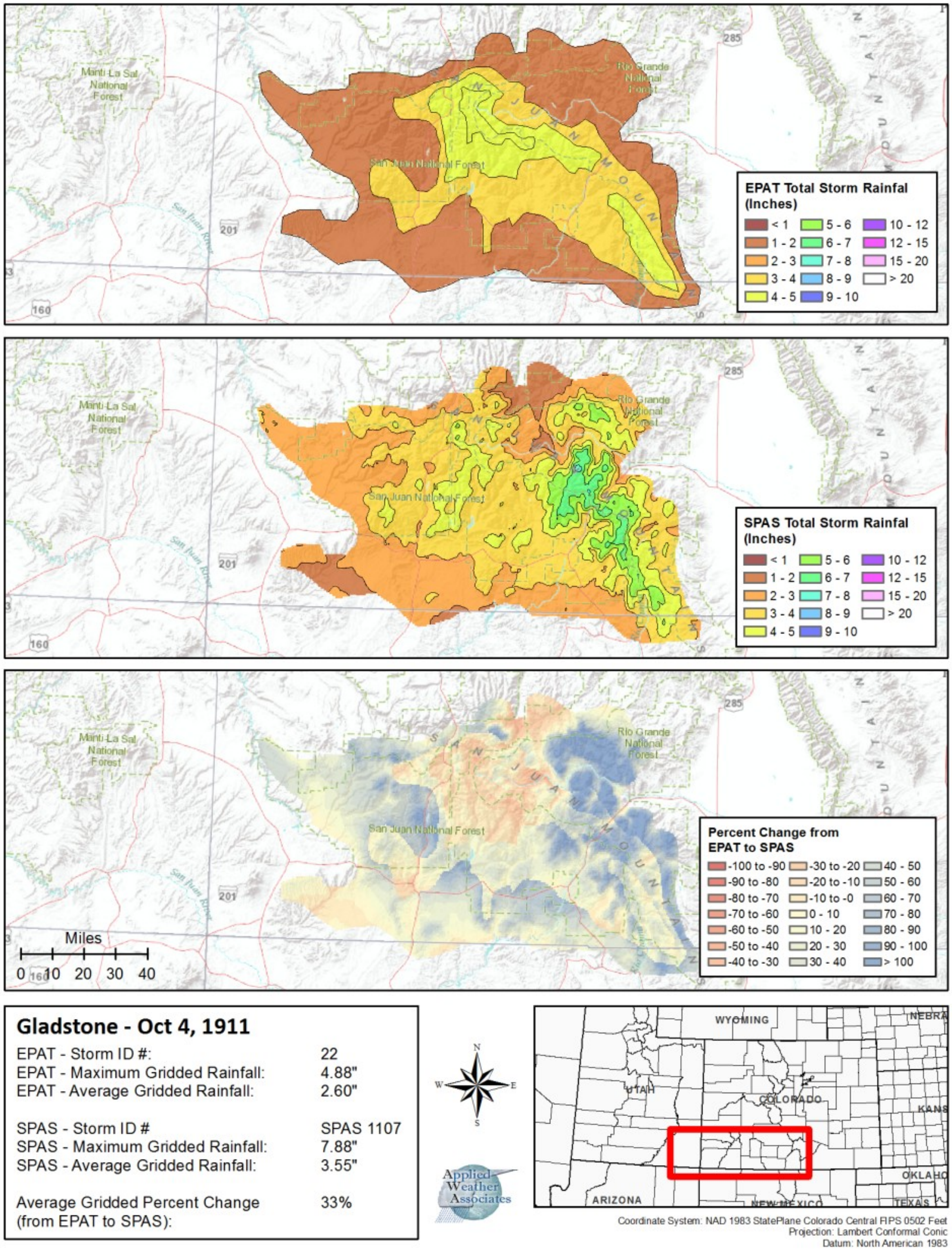


Figure C.1: EPAT vs SPAS comparison of storm isohyetal patterns: Gladstone, CO 1911

Figure C.2 compares the EPAT #22 Gladstone isohyetal pattern (Source: CSU report) with the SPAS 1249 gridded rainfall. The SPAS analysis was based on hourly data, daily data, and previously analyzed isohyetal pattern. An hourly station was placed at Blanding, UT based on timing and magnitude information from NCDC Utah Hourly Precipitation Data report. AWA has a high degree of confidence in the station based results, and spatial pattern is dependent on PRISM basemap (similar to USGS isohyetal). Note, a report by Utah State University "Flood Damage Mitigation in Utah" and USGS state that Utah has a record amount of 2.10" for 1-hour at Blanding for August 1968. The Blanding hourly data from NCDC has 1.03" for maximum 1-hr duration during August 1, 1968.

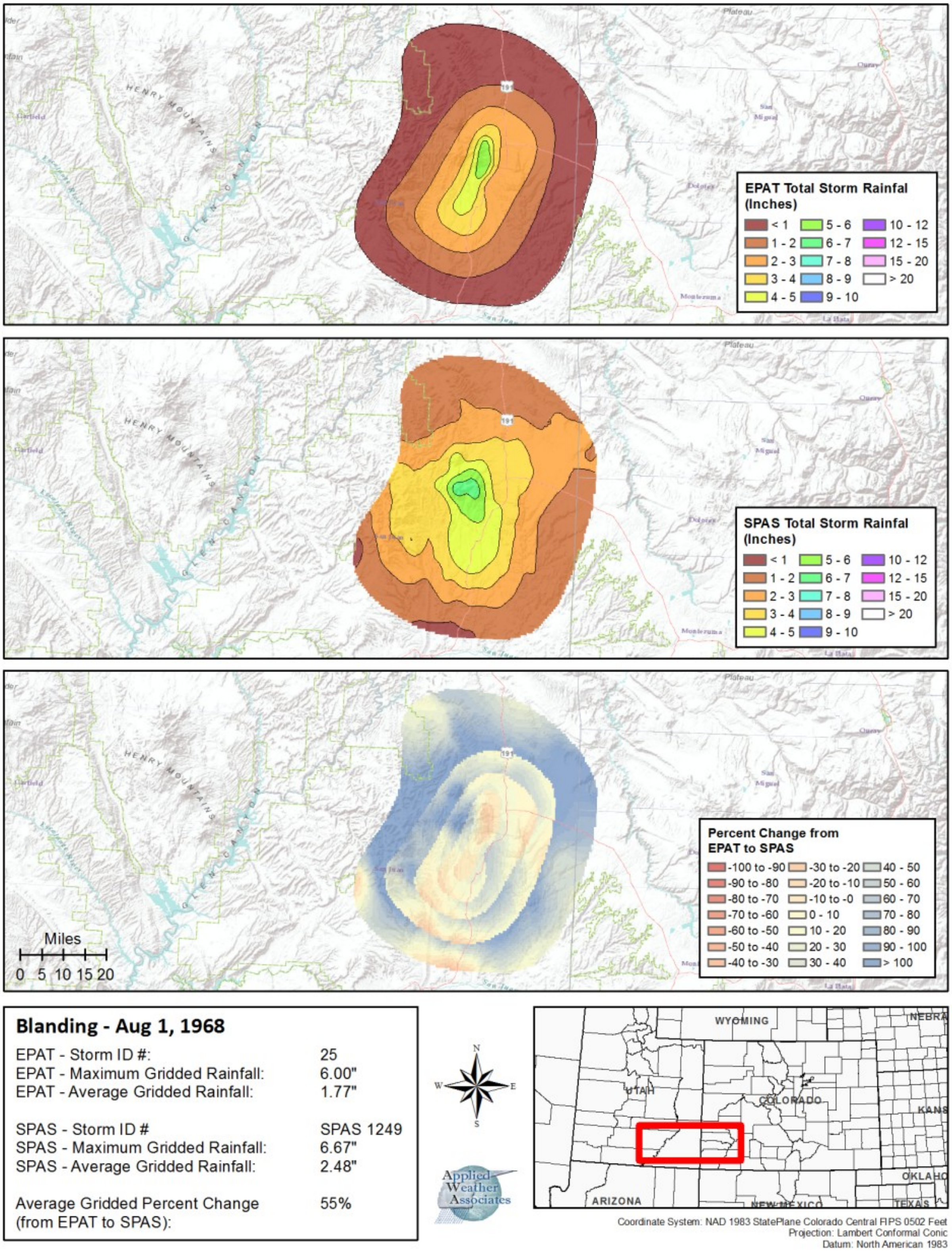


Figure C.2: EPAT vs SPAS comparison of storm isohyetal patterns: Blanding, 1968

3: Evaluate storm maximization.

Table C.2 compares the in-place maximization factors for the two common storms, Gladstone and Blanding. In addition, the EPAT #26 SW CO/Dove Creek storm was compared with SPAS 1075 DAD zone 4. Although the storm centers are in different locations, they are from the same Hurricane Norma remnant moisture source, and should have comparable maximizations. The SPAS 1075 moisture source lies over the ocean so +2σ SSTs are used in lieu of dew point temperatures. Both studies cap IPMF at 1.50 in accordance with HMR procedures and this constraint is applied to SPAS 1107.

The in-place maximization factors differ significantly between the two analyses. There are numerous contributing factors to this such as the difference in dew point climatologies, interpretation of moisture source locations, and the absence of elevation adjustment in EPAT. These differences are discussed in depth in Task 4. The most significant difference is with the EPAT #22/SPAS 1107 Gladstone/Wagon Wheel maximization. EPAT calculates the IPMF at 1.03 while AWA calculates it as 1.55 (held to 1.50). The lack of EPAT elevation adjustment is a major contributor to the difference, as this is a very high elevation event at ~12,000'. This storm is ranked #4 in the EPAT PMP output. If the AWA maximization of 1.50 were used by EPAT, the Rio Grande PMP would be increased by 47% without any other considerations.

Table C.2: SPAS and EPAT in-place maximization factors

SPAS Storm Number	Storm Name	SPAS DAD Zone	State	Moisture Inflow Vector	AWA Td (°F)	AWA PWI (in)	AWA IPMF	EPAT Td (°F)	EPAT PWI (in)	EPAT IPMF	Storm Type	EPAT STORM ID
1075	NORMA REMNANTS	DAD zone 4	CO	SW @ 445	76.8	3.14	1.16	73.7	2.68	1.45	general	Storm ID #26
1107	WAGON WHEEL	DAD zone 1	CO	SW @ 350	73.8	2.73	1.50	70.0	2.26	1.03	general	Storm ID #22
1249	BLANDING	DAD zone 1	UT	SW @ 240	79.2	3.44	1.16	74.2	2.76	1.24	local	Storm ID #25

4: Evaluate storm transposition limits and values.

Of the AWA analyzed storms transposed to Rio Grande basin, only #22 Gladstone 1911 and #25 Blanding 1968 are included in the EPAT storm library. Of these two storms, only #22 Gladstone is transposed to the basin. The Rio Grande basin lies fully within EPAT climate zone 6c. The #25 Blanding storm is only considered transposable to zone 9 within EPAT, excluding it from transposition to the Rio Grande basin. In addition to #22 and #25, EPAT transposes and ranks storms #1, #4, #23, 27, 28, and #29 as PMP contributors to the Rio Grande basin. Of these, AWA recommends #29 Saguache not be transposed to zone 6c. This storm produced the highest EPAT 1-hour local storm PMP depths for the basin. AWA recommends storms #3, #5, #6, #7, #8, #10, #15, #16, #18, #21, and #26 be transposable to at least portions of zone 6c and should be further investigated to determine the transpositionability to Rio Grande basin specifically.

Table C.3 compares the transposition factors for the only storms commonly transposed by both EPAT and AWA. The AWA orographic adjustment is the basin average gridded OTF based on the ratio of basin location NOAA Atlas 14 climatology to storm location. The moisture adjustment is based on the ratio of basin location precipitable water (from 24-hour maximum dew point climatology) at basin centroid to the storm location. The EPAT moisture adjustment calculated the same way but uses the EPAT PWI seasonality grids. The elevation adjustment is a 9% reduction for every 1,000' increase. The 20% orographic reduction for the AWA transposition of SPAS 1107 is due to SPAS storm center location lying ~35 miles east of the EPAT storm center where the NOAA Atlas 14 precipitation is higher. The table also predicts the

EPAT transposition factors for the Blanding event if it had been transposed to the Rio Grande basin.

Table C.3: SPAS and EPAT transposition factors.

SPAS Storm Number	Storm Name	SPAS DAD Zone	State	Transposition Zones	Recommended Transposition Zones	AWA Orographic Adjustment (average)	AWA Moisture Adjustment	AWA Total Adjustment (average)	EPAT Elevation Adjustment	EPAT Moisture Adjustment	EPAT Total Adjustment	Storm Type	EPAT STORM ID
1107	WAGON WHEEL	DAD zone 1	CO	6c	6b, 6c	0.80	0.97	**0.78**	1.03	1.00	**1.03**	general	Storm ID #22
1249	BLANDING	DAD zone 1	UT	9	6a, 6b, 6c, 7, 8, 9	0.75	1.03	**0.77**	0.73	1.00	**0.73**	local	Storm ID #25

5: Storm centering

The AWA PMP analysis does not use storm centering methods so no direct comparison to EPAT can be made in this respect. The nature of the precipitation climatology-based spatial distribution of rainfall in combination with the SPAS gridded depth-area analysis prohibits the need for storm centering. Ten runs were specified as input for EPAT in the above comparisons, allowing for ten data points along the thalweg.

6: Storm isohyetal orientation

The AWA gridded PMP analysis does not use storm isohyetal orientation methods so no direct comparison to EPAT can be made in this respect. In the case of the Rio Grande basin, the high degree of circularity of the basin diminishes the importance of isohyetal orientation as the basin average rainfall would not significantly differ with orientation.

7: Areal reduction

The Rio Grande basin lies in areal reduction zone W which applies a factor of 0.55 to a 160 mi^2 basin at the six-hour duration. However, all of the ranked storms in the EPAT PMP output for the Rio Grande basin were 2D isohyetal pattern storms. Since none were point rainfall storms, no areal reduction factors were applied or needed.

Similarly, areal reduction factors were not used or needed in the AWA analysis because explicit depth-area-duration values are determined by the gridded SPAS analysis.

Although no areal reduction factors are applied in the analysis, at the total storm duration (33-hours) the EPAT areal reduction factor for 160 mi^2 can be calculated at 0.90 for the #22 Gladstone 1911 isohyetal pattern clipped to the basin. The SPAS DAD table can be used to estimate an areal reduction of factor 0.80 for the basin area for AWA SPAS analyzed version.

8: Storm separation method

The HMR 55A storm separation method is not applied in the EPAT or AWA PMP analysis and no comparisons were made in this respect.

9: Spatial and temporal envelopment

No traditional-manual smoothing to produce spatial or temporal envelopment curves are applied to the EPAT analysis. AWA PMP methods to apply envelopment in that any storm transpositionable to a given grid point can control PMP values at each duration. Therefore, each grid point at each duration could be controlled by a different storm (whichever produces the largest total adjusted rainfall value). The EPAT methods allows for multiple storms to control PMP at various areas and durations, however only one storm can control for the entire basin, therefore spatial and temporal variations that might exist if other storms where allowed to control PMP values simultaneously re lost in the analysis. Appendix A provides a detailed analysis for a series of 80 test basins to quantify and visualize the distribution of PMP over space and time for ten separate locations across the EPAT domain.

10: Elevation adjustment

An elevation adjustment of 9% decrease per 1,000 foot increase in elevation is applied within the EPAT analysis. The change in elevation is determined from subtracting the elevation at the storm's largest isohyetal polygon centroid from the basin average centroid. The Rio Grande average basin elevation is 11,600 feet resulting in a reduction for most storms. In contrast to a linear elevation adjustment, the AWA approach attempts to capture the comprehensive effect of orographic effects on rainfall, not only between the source of the storm and the basin, but within the basin itself. This distinction is particularly important for basins in complex terrain with extreme variations in elevation such as the Rio Grande basin.

The Gladstone, 1911 storm is the only storm commonly transposed and adjusted between both PMP tools. The values are shown in table C.3 in section 4. EPAT applies a 3% increase due to a slight reduction in elevation between the Gladstone center and the basin average elevation. This is done despite the fact that much of the area inside the basin is actually above the Gladstone storm center elevation of 11,954 feet (Figure C.3). Conversely, the AWA analysis applies an average of a 20% reduction due to the precipitation climatology showing consistently greater precipitation production at the SPAS 1107 center than each grid point within the basin. It's also important to note that the EPAT isohyetal places the storm center on the western basin boundary while the SPAS analysis places the storm center ~35 miles to the east.

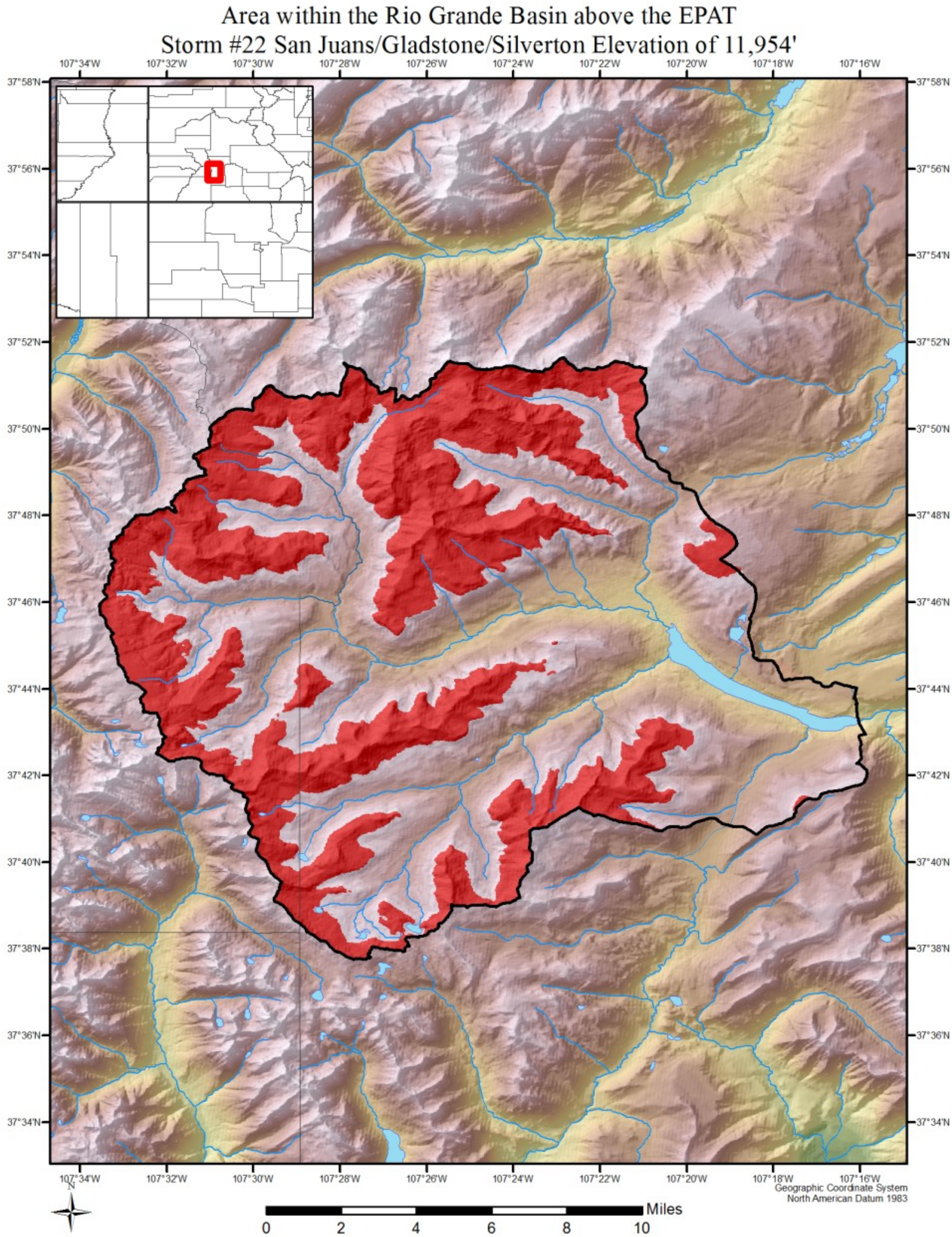


Figure C.3: Area within the Rio Grande basin above the Gladstone 1911 storm center elevation