State of Colorado
Department of Natural Resources
Division of Water Resources
Office of the State Engineer
Colorado Dam Safety

GUIDELINES FOR THE USE OF REGIONAL EXTREME PRECIPITATION STUDY (REPS) RAINFALL ESTIMATION TOOLS

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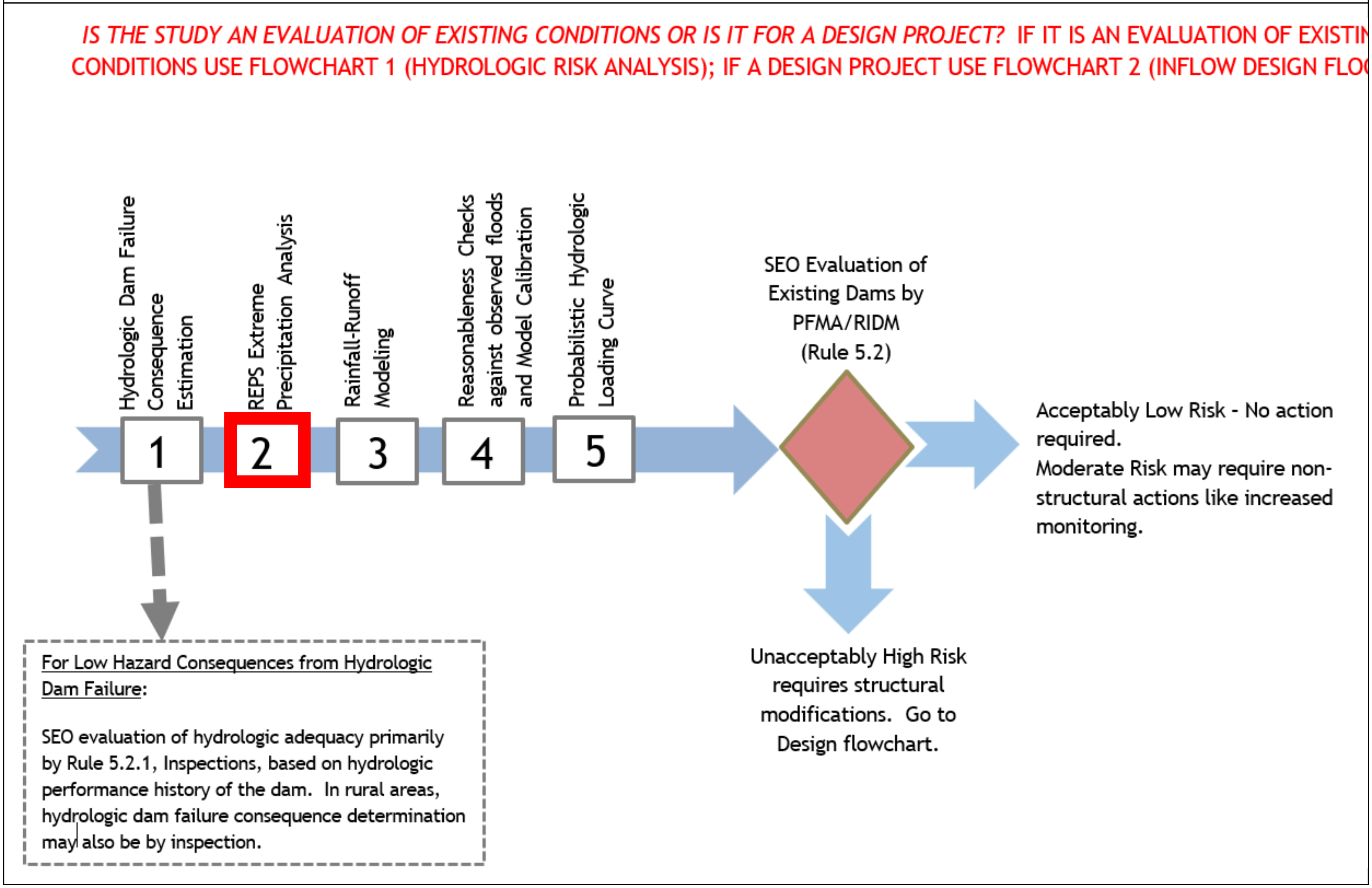
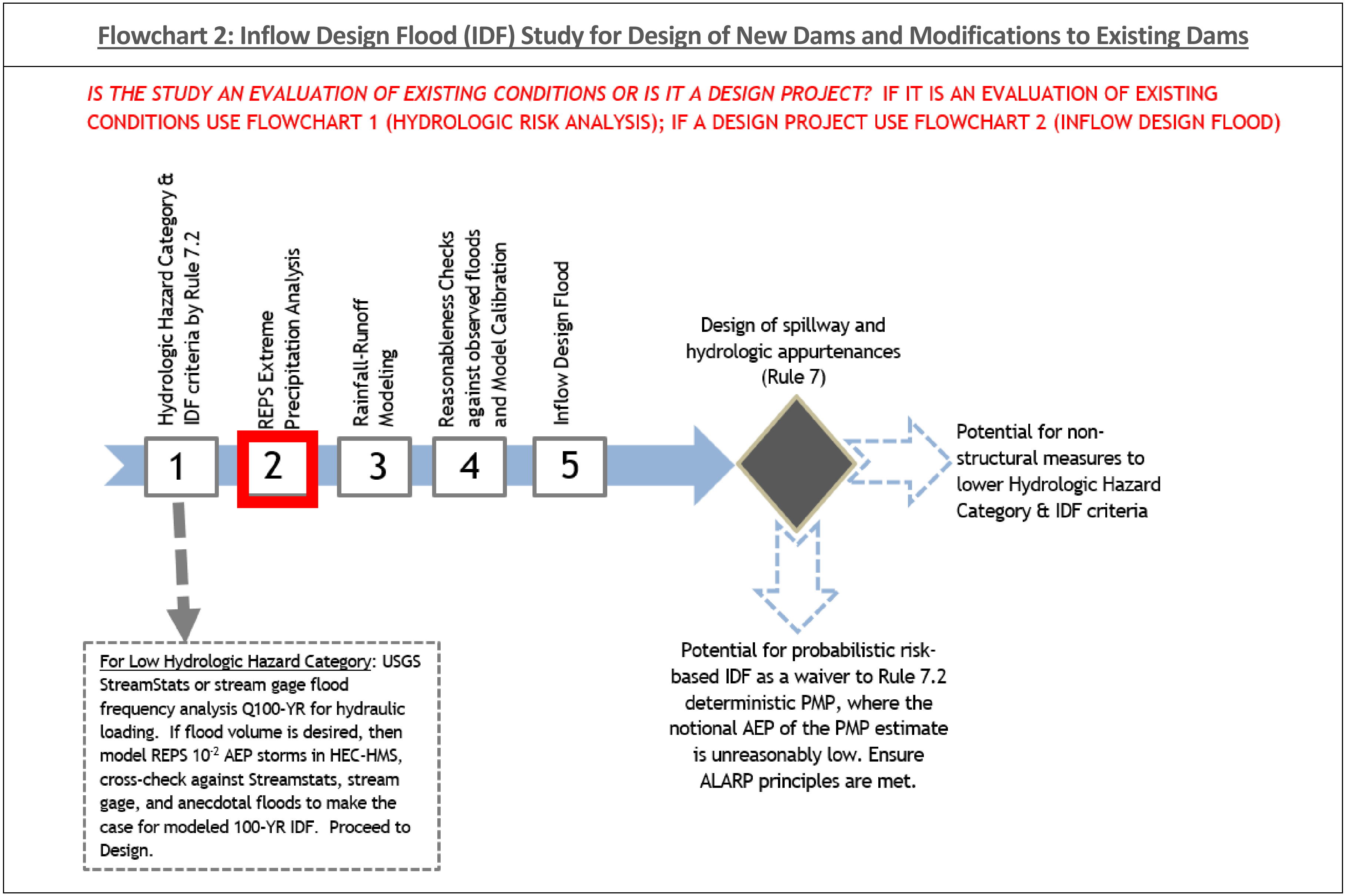
https://dwr.colorado.gov/services/dam-safety

Flowchart 1: Hydrologic Risk Analysis for Hydrologic Adequacy of Existing Dams



Colorado Dam Safety Hydrologic Risk Assessment process for hydrologic adequacy of existing dams. **REPS rainfall estimation is Step 2 in process (highlighted in red).**



Colorado Dam Safety Inflow Design Flood process for design of spillways & hydrologic appurtenances. **REPS rainfall estimation is Step 2 in process (highlighted in red).**

TABLE OF CONTENTS

Section 1. Introduction

1.1 **REPS Background & Documentation:** The Colorado and New Mexico Regional Extreme Precipitation Study (REPS) was a multi-year effort (2016-2018) to update probable maximum precipitation (PMP) estimates, extreme precipitation frequency (PF) estimates, storm temporal patterns, and stochastically-generated areal reduction factors for Colorado and New Mexico. PMP and PF tasks were supported by dynamical weather modeling by NOAA. REPS was conducted using the best available science and practice and was overseen by a robust project review board of more than 20 federal, state, and academic scientists to ensure credibility. REPS required complex analyses, which were presented to the PRB at seven quarterly workshops and reviewed thoroughly. Such a study requires many assumptions and decisions. These were documented to the fullest extent possible to ensure transparency and repeatability. **Full REPS study documentation is available at the following Google Drive link:**

https://drive.google.com/open?id=1BwS5VLnQ6_5N_NWjfgbLUPV42Ietex4n

Any attempt at estimating PMP or extreme PF is subject to future improvements in science and data. REPS extreme precipitation estimates, together with subsequent updates, are considered by Colorado Dam Safety to be the best available information for hydrologic design and analysis of dams in Colorado. Together REPS PMP and PF provide powerful tools for safe and efficient spillway and dam design.

1.2 **Related Guidelines:** REPS rainfall estimation is one step in Colorado Dam Safety's two main hydrologic evaluation and design processes: (1) Hydrologic Risk Assessment for hydrologic adequacy of existing dams and (2) Inflow Design Flood studies for design spillways and hydrologic appurtenances. Flowcharts for both processes are shown inside the front cover; the REPS Rainfall Estimation step is highlighted in red on each flowchart. The following related Colorado Dam Safety guidelines cover other steps of our hydrologic evaluation & design processes and must be used in combination with these REPS guidelines:

- Guidelines for Hydrologic Hazard Analysis
- Guidelines for Hydrological Modeling and Flood Analysis
- Guidelines for Comprehensive Dam Safety Evaluation (CDSE) Risk Assessments & Risk Informed Decision Making (RIDM)

Section 2. REPS Rainfall Estimation Tools

The REPS study in 2018 developed two computer applications for estimation of extreme precipitation; one for PMP and another for PF. On-going maintenance and improvements of the tools has continued (see *REPS Updates & Improvements* below); current versions of the tools are as follows:

2.1 **REPS PMP Web Tool:** This web-service application calculates inter-durational REPS PMP estimates and design storm temporal patterns for Local Storm, General Storm and Tropical Storm probable maximum precipitation for user-entered basin shapefiles. The current version runs as a web-application on the ESRI GIS Enterprise platform. PMP outputs are tabulated on-screen and can be exported in csv format. REPS PMP is warm-season and is developed based on liquid rainfall events only.

2.2 **REPS MetPortal PF Tool:** This web-service application calculates point and watershed precipitation frequency estimates, confidence bounds, and design storm temporal patterns for user-defined basins. Extreme annual exceedance probabilities (AEP) from 10^{-1} to 10^{-7}, needed for dam safety risk assessments, are provided. REPS PF statistics were developed from weather station precipitation regardless of phase (i.e. liquid or solid).

Section 3. <u>REPS Updates & Improvements</u>

3.1 **Each REPS tool includes an update log that describes version updates**. Following is a summary of significant changes to REPS PMP and REPS PF that have occurred since the end of the original REPS study.

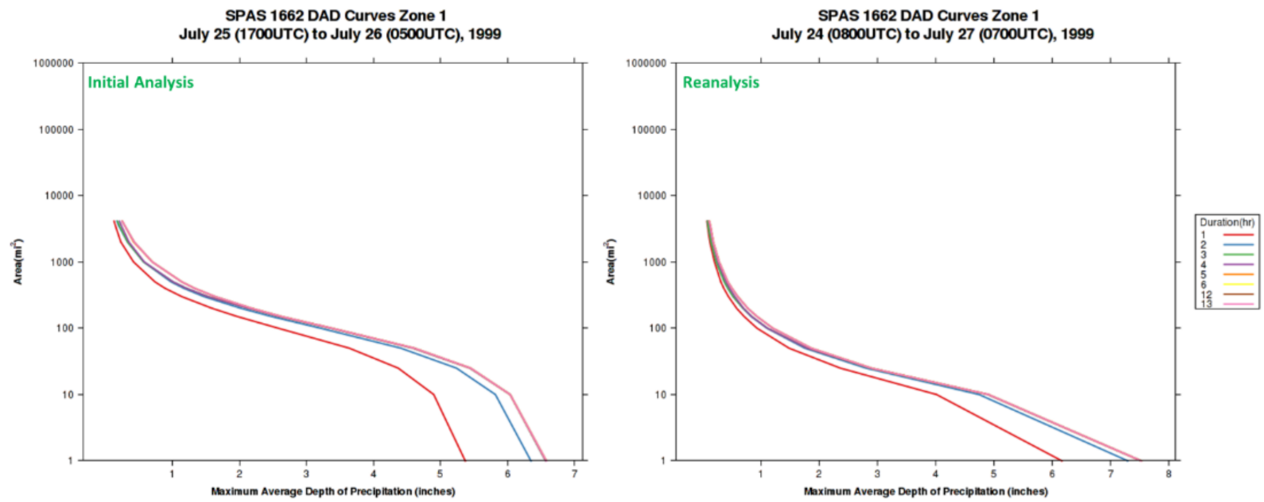
3.2 **New REPS PMP Web Tool:** In 2024 the REPS PMP tool was changed from a desktop GIS ArcTool to an on-line web-application by Applied Weather Associates, under contract with Colorado Dam Safety and other state dam safety agencies. The REPS PMP Web Tool interpolates basin-specific PMP from statewide REPS PMP grids at various area sizes and storm types, previously generated by AWA. The REPS PMP Web Tool provides the following process improvements:

- Colorado Dam Safety can now make & document updates to REPS PMP seamlessly through the web-service.
- Does not require users to have ESRI ArcMap to run & generate REPS PMP
- Runs significantly faster (generally <2 minutes) compared to REPS PMP desktop ArcTool, which took as long as 20-30 minutes depending on user's computer and the size of basin.
- Consolidates output into a small number of csv files, which are easier to export and manipulate for use in HEC-HMS than previous GIS outputs
- Automatically generates all applicable REPS PMP storms (e.g. 24hr Local Storm & Tropic Storm) based on basin location
- Improved handling of Tropical Storm PMP for basins that cross 38.5°N latitude, north of which REPS TS PMP is not applicable. Now TS PMP is not calculated when a basin centroid lies north of 38.5°, rather than previously providing 'NULL' or 0.0" rainfall as REPS PMP desktop ArcTool did and which led to erroneously low basin-average TS PMP estimates in some cases.

3.3 **Reanalysis of SPAS 1662 Saguache July 1999 storm:** The REPS PMP Web Tool incorporates our 2023 reanalysis of the Saguache July 1999 storm (SPAS 1662), the result of which is a significantly reduced areal footprint of the storm center, as shown in the image below comparing *Initial Analysis* (from previous REPS desktop ArcTool) and *Reanalysis* depth-area-duration curves. For example, by the *Initial Analysis*, 10-square mile, 1-hour rainfall was estimated at about 4.9 inches, compared to the *Reanalysis* amount of around 4.0 inches (~18% reduction). Note that the reanalysis does show increased rainfall at area sizes less than about 2 square miles, due to finer spatial resolution of the reanalysis. Overall the reanalysis has the potential to significantly lower REPS PMP estimates in basins between about 2 and 100 square miles in area, located in REPS storm transposition zones 5, 6 and 17 (mountains >7500-ft elevation, east of the Continental Divide); while it may increase REPS PMP for very small (< 2 sqmi) basins in those zones.

The Saguache storm reanalysis resulted from Colorado Dam Safety's Mountain Hydrology Research Study with Colorado State University. The reanalysis was a collaboration between Colorado Dam Safety, CSU, and Applied Weather Associates, and included stream gage analysis work, channel survey and HEC-RAS model, bucket survey interviews with local ranchers, hydrologic rainfall-runoff modeling, and reanalysis of the NEXRAD weather radar. The standard of practice in PMP studies uses best-available hydrometeorological data to reconstruct historical extreme storms. Any time more and better data becomes available, it may be possible to improve storm reconstructions. Our Saguache storm reanalysis study is documented in the 2023 ASDSO conference proceedings, *Reanalysis of Record-Breaking Storm in Colorado Rockies-Combining Meteorology with Hydrology to Find the Answer*, by Kappel and others, and is available at the following link:

https://drive.google.com/file/d/1ip_2PFKpgmNwK6BGdGXGVwRBIOzf71Kc/view?usp=drive_link



Saguache July 1999 extreme local thunderstorm depth-area-duration curves: Initial analysis from 2018 REPS study (left) and 2023 reanalysis (right) from Colorado Dam Safety and Colorado State University's Mountain Hydrology Research Study. Source: *Reanalysis of Record-Breaking Storm in Colorado Rockies-Combining Meteorology with Hydrology to Find the Answer*, Kappel and others, Association of State Dam Safety Officials, conference proceedings, Palm Springs, CA, 2023.

3.4 **REPS MetPortal changes:** While mostly unseen to end-users, hosting of the REPS MetPortal precipitation frequency web-service changed to RTI International in January 2024. RTI now maintains, supports, and continues to develop the REPS MetPortal PF web-application under contract with Colorado Dam Safety, New Mexico Dam Safety, and BC Hydro. The following improvements have been made to the application since its original release:

- Basin shapefiles can be in any defined coordinate projection (formerly required WGS84)
- For frequency table output, added option to download all storm types at once (Local Storms, Mesoscale with Embedded Convection storms, and Mid-Latitude Cyclones)
- For temporal distributions, added option to download all AEPs by storm type at once. This option helps facilitate hydrologic risk analysis where user is running all 21 probabilistic storms (10^{-1} through 10^{-7} AEPs for LS, MEC & MLC storm types).

3.5 **Previous REPS tool versions are superseded:** Please note that all previous versions of REPS tools, including the REPS PMP desktop GIS ArcTool are superseded by current versions and future updates. Future updates will be made through the REP PMP Web Tool and REPS MetPortal PF web applications and documented in their respective version logs. Previous desktop versions of the tools will not be updated. **Storm and non-storm data contained in the REPS PMP desktop geodatabase may continue to be valuable to users.**

Section 4. Instructions for Use of REPS Tools

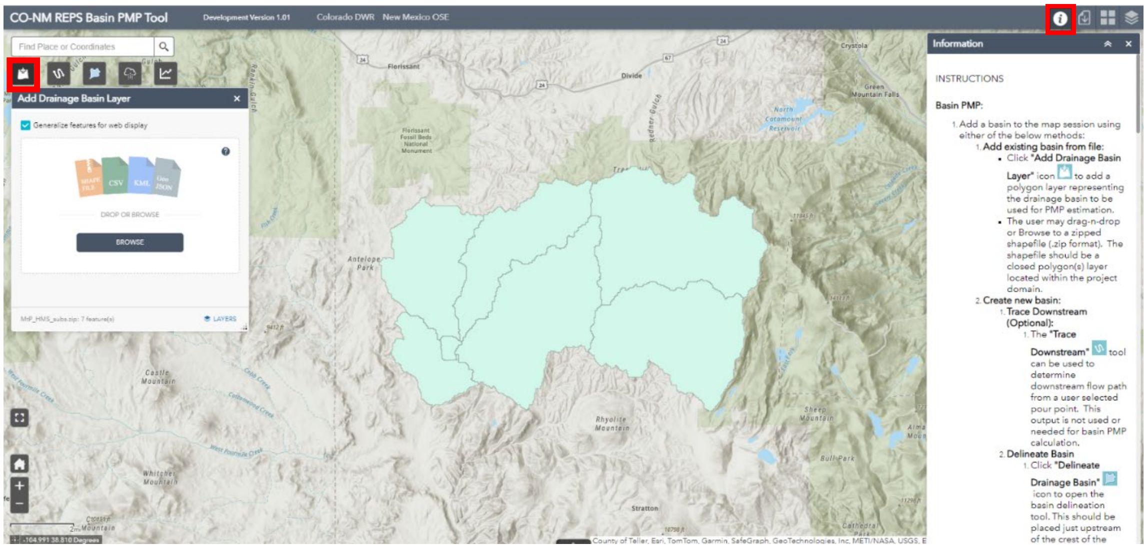
4.1 **REPS PMP Web Tool:** Launch the tool from the following link:

https://gis.appliedweatherassociates.com/portal/apps/webappviewer/index.html?id=91da07833953420ba692898062aa3c6b

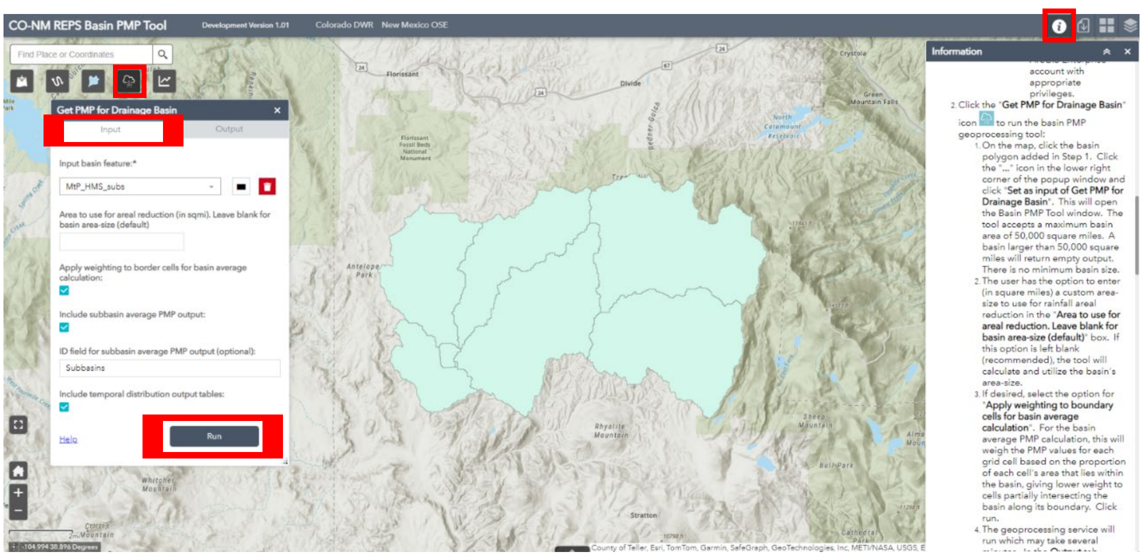
The following instructions for use are offered by Applied Weather Associates (REPS PMP Web Tool developer) and are also provided at the Information icon in the tool):

- **Add existing basin from file:** Click **"Add Drainage Basin Layer"** icon to add a polygon layer representing the drainage basin to be used for PMP estimation (see image below). The user may drag-n-drop or Browse to a zipped shapefile (.zip format). The shapefile should be a closed polygon(s) layer located within the REPS study domain.

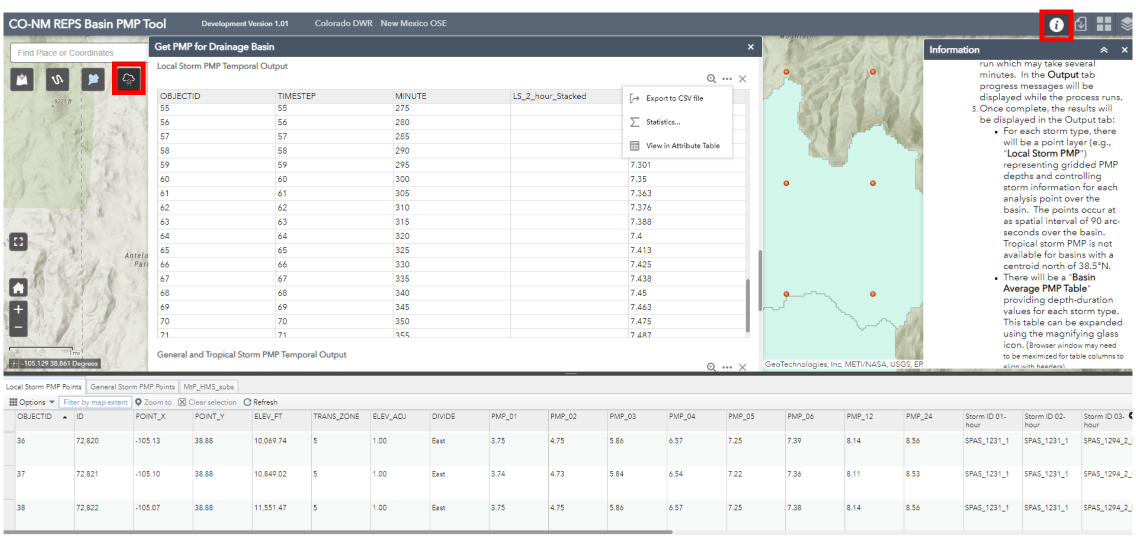
[*recommended method by Colorado Dam Safety*]. **Alternatively, create new basin** [at user's risk; basin delineation accuracy must be verified by user]**:** more information is provided in the REPS PMP Web Tool)



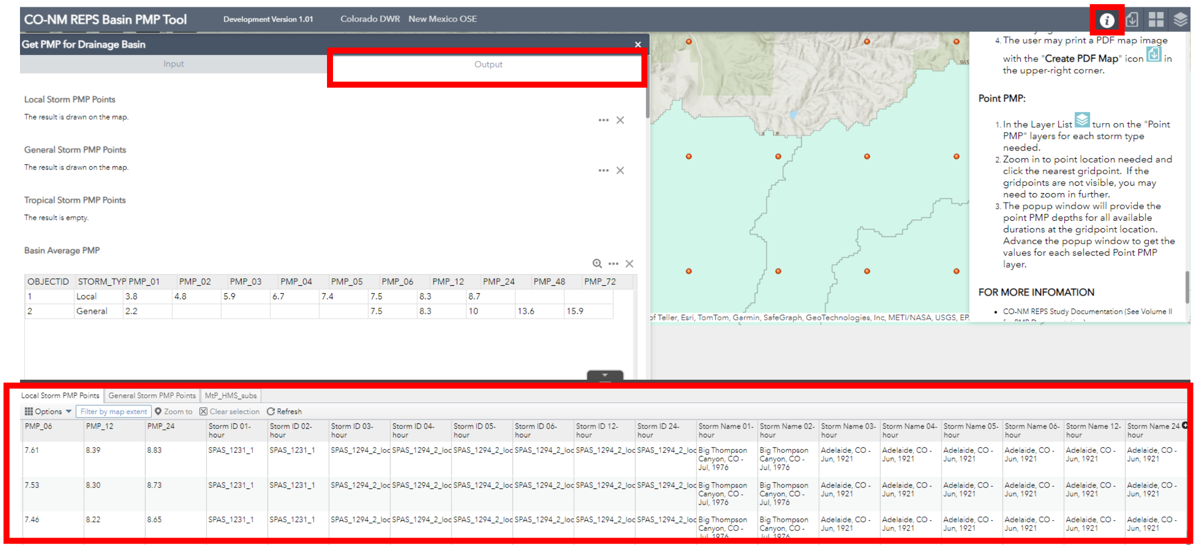
- **Generate PMP for basin-of-interest:**
  - Select the "**Get PMP for Drainage Basin**" icon  to run the basin PMP geoprocessing tool (see image below):
  - Select the shapefile for the basin-of-interest. The tool accepts a maximum basin area of 50,000 square miles; there is no minimum size. User has the option to enter (in square miles) a custom area-size to use for rainfall areal reduction in the "**Area to use for areal reduction. Leave blank for basin area-size (default)**" box. If left blank (recommended), PMP is calculated based on the entire basin area size.
  - Option for "**Apply weighting to boundary cells for basin average calculation**" (recommended): for the basin average PMP calculation this option will weigh PMP values for each grid cell based on the proportion of each cell's area that lies within the basin.
  - **Click run.** The geoprocessing service will run which may take several minutes. In the **Output** tab, progress messages will be displayed while the process runs.



- **Output: Once PMP estimates are complete, results are displayed in the Output tab:**
    - For each PMP storm type (e.g. Local Storm) there will be a point layer output representing gridded PMP depths and controlling storm information for each analysis point over the basin. The points are spaced at 90 arc-seconds (~2100 m).
    - "**Basin Average PMP Table**" output provides basin-average PMP values at applicable inter-durations for each PMP storm type. *Note tables can be expanded using the magnifying glass icon and the browser window may need to be resized to table extents for table columns to align correctly with headers.*
    - If the user selected the option to include subbasin average PMP output, a "**Subbasins Average PMP"** summary table will be created for each storm type. The subbasins averages will be calculated with the areal reduction of the entire drainage area. The border cells of each subbasin will be area-weighted if the user selected that option. The subbasins will be labeled according to the OBJECTID field or the user can specify another unique field identifier from the input shapefile.
    - **"Local Storm PMP Temporal Output"** and **"General/Tropical Storm PMP Temporal Output"** tables (see image below) are provided if the user selected the "Include temporal distributions" option. Applicable Local Storm 2-hr Stacked, 6-hr Synthetic, 24-hr Hybrid, 72-hr General Synthetic, and 72-hr Tropical Synthetic distributions are provided based on the basin location. 24-hr Hybrid storms are only applicable to REPS transposition zones 1 & 3; 72-hr Tropical storms are only applicable where the basin centroid lies south of 38.5º latitude.
    - **For each output layer/table, the user may click the "..." ellipse icon to access additional operations (see image below) including:** zoom to layer, export to .csv, feature collection, or geoJSON, and view the attribute table.
    - The user can view a PMP "Depth-Duration Chart", comparing basin average depths by storm type. The user has the option to copy/save the chart as an image by right-clicking on chart.
    - Lastly, the user may print a PDF map image with the "**Create PDF Map**" icon in the upper-right corner.



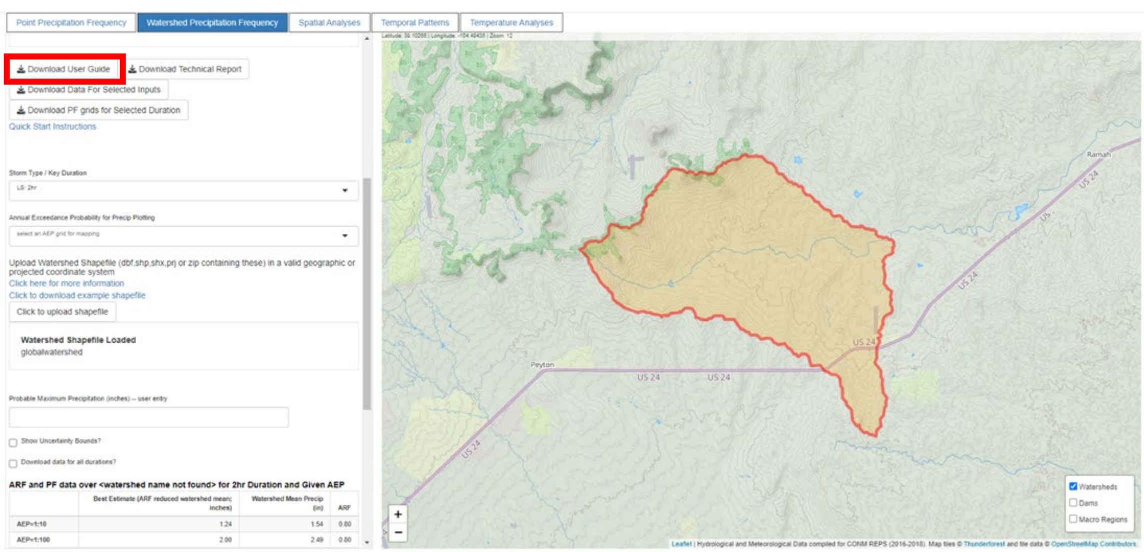
- **Gridded PMP Output:** The REPS PMP Web Tool works by interpolating REPS PMP at 90 arc second (~2100 m) grid spacing over the basin and then aggregating results for basin or sub-basin average REPS PMP estimates. To view the interpolated point PMP estimates, in the Layer List turn on the "Point PMP" layers for each storm type. Then zoom in to a point location and click any grid point. A popup window will provide the point PMP depths and controlling storm information for all available durations (see image below). Advance the popup window to get the values for each selected Point PMP layer.



4.2 **REPS MetPortal PF Tool:** Point and watershed precipitation frequency (PF) tables and design storm temporal distributions are estimated for three storm types. Lauch the REPS MetPortal PF Tool using the following link:

https://rti-metportal.shinyapps.io/conm_region/

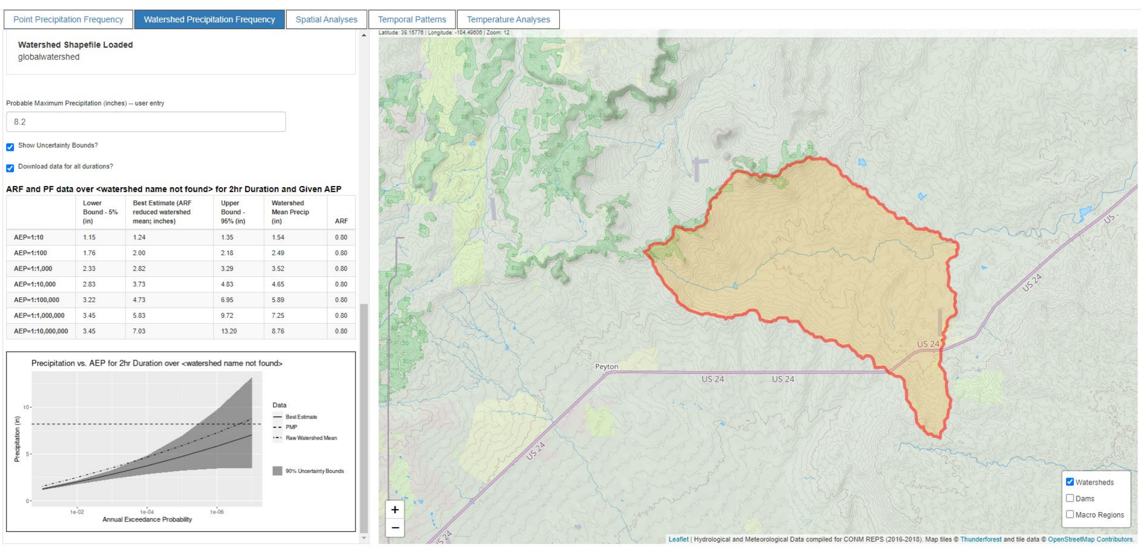
The image below shows the user interface. Note there are five tabs across the top banner: Point Precipitation Frequency, Watershed Precipitation Frequency, Spatial Analysis, Temporal Patterns, and Temperature Analysis.



<u>Instructions for use are provided below. More details are provided in the User Guide, which can be downloaded within the tool (action button highlighted in red in the previous image).</u>

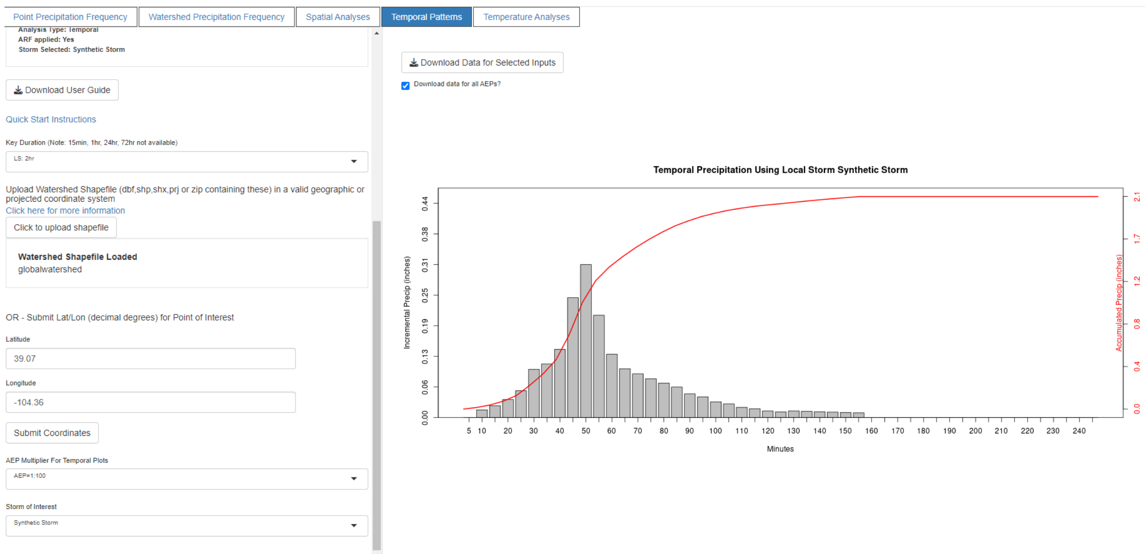
- **Select Water Precipitation Frequency tab.**

- **Select “Click to Upload shapefile” action button. Watershed shapefiles can be uploaded for basin-average PF analysis. Upload all constituent files of the shapefile (e.g., dbf, shp, shx and prj).** Shapefile must have a defined coordinate system.
- **Select storm type from the Storm Type/Key Duration drop down: LS: 2hr, MEC: 6hr or MLC/TSR: 48hr.** NOTE: 15-min, 1-hour, 24-hr & 72-hr precipitation frequency statistics are provided for information only, but should not be used for Colorado Dam Safety purposes (they were scaled from the primary 2-hr, 6-hr and 48-hr statistics).
- The user can manually enter basin PMP for visual comparison of notional AEP of PMP (i.e. where PMP lies in terms of AEP estimates).
- Select “Show Uncertainty Bounds”: 5% and 95% confidence bounds on the watershed PF curve.
- Select “Download data for all durations”
- REPS MetPortal will display basin precipitation frequency curve for the selected storm type, tabular precipitation frequency estimates for 10^{-1} through 10^{-7} AEP, upper & lower 90% confidence bounds, and plot a horizontal PMP line if PMP was entered (see image below). The table provides “Watershed Mean Precip (in)”, which is simply the areal average of REPS point precipitation frequency estimates over the basin-of-interest, for each AEP. “ARF” (areal reduction factor) is in the next (last) column, and “Best Estimate (ARF reduced watershed mean; inches)” gives the Watershed mean multiplied by the ARF for basin-average PF. The 5% and 95% confidence bounds apply to the Best Estimate.



- **Temporal Patterns Tab:** From the Watershed Precipitation Frequency tab, the user should be able to move to the Temporal Patterns tab; however, sometimes the tool crashes and the user will see a “reload” screen, in which case, reload, and move directly to the Temporal Patterns tab. Select “Click to upload shapefile” action button and again select all constituent shapefiles for the basin of interest. There is not a display map on the Temporal Patterns page, but the user can confirm that the Lat/Long for Point of Interest, populated by the tool, corresponds to the correct basin centroid.
  - **Select key duration from the dropdown list (see image below).** Here the only options are LS: 2hr, MEC: 6hr, and MLC/TSR: 48hr. These are the three independent precipitation frequency storms types from the REPS study. Select “AEP multiplier” and “Storm of Interest” from the respective dropdown lists (Section 7 below provides guidelines on Storms of Interest, i.e. temporal patterns to use for Colorado

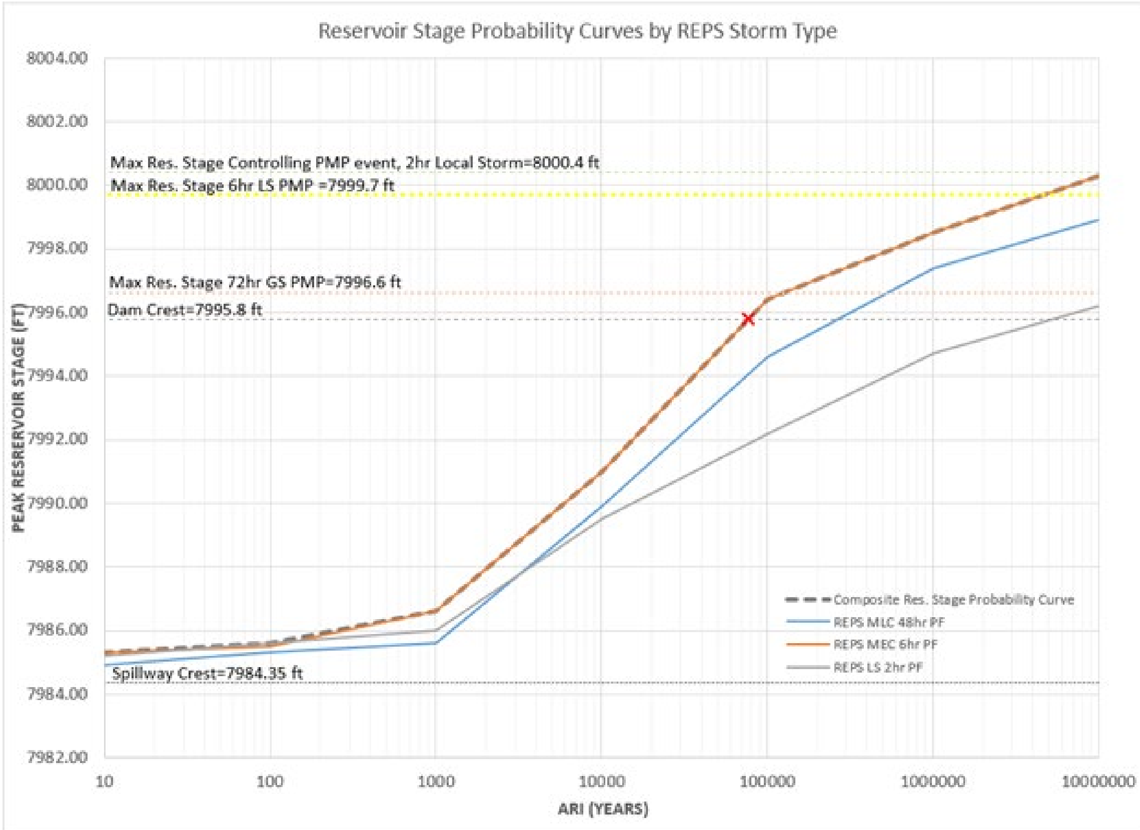
Dam Safety hydrology purposes). The user can select the “Download data for all AEPs?” option at the top of the page and then select the “Download Data for Selected Inputs” action button. Opting to download data for all AEPs provides a csv file with the selected temporal pattern scaled to each AEP PF estimate (10^{-1} through 10^{-7} AEP), for the selected storm type (2hr LS, 6hr MEC or 48hr MLC). The user must repeat the process for each storm type. Downloading all AEPs is convenient for hydrologic risk assessment studies, where the user will model all AEPs for all storm types (21 PF storms total) to generate hydrologic loading curves (see Section 5 below). **The scaled temporal pattens for each storm type and AEP can be copied into HEC-HMS for rainfall-runoff simulation of probabilistic floods.**



Section 5. <u>REPS for Hydrologic Risk Assessments (see Flowchart 1 inside front cover)</u>

5.1 State Dam Safety Rule 5.2.2 allows for evaluation of existing dams by potential failure model analysis (PFMA) and risk assessment. Colorado Dam Safety’s *Guidelines for Use of Comprehensive Dam Safety Evaluation (CDSE) Risk Assessments & Risk Informed Decision Making (RIDM)* expands on our methods to evaluate existing dams in a context of failure modes, failure likelihood, and failure consequences, to determine risk.

5.2 REPS PF estimates can be used to develop hydrologic loading curves for risk assessments. Typically a reservoir stage probability curve is developed to determine likelihood of dam overtopping. Other hydrologic loading curves may be warranted for specific failure modes, for example, spillway shear stress likelihood curves or tailwater flood depths. All REPS PF AEP estimates (10^{-1} through 10^{-7} AEP) for all storm types (LS, MEC & MLC) can be modeled in HEC-HMS, then relevant model outputs can be plotted as a function of AEP to generate hydrologic loading curves. A separate loading curve should be plotted for each storm type, and the critical loading curve represents the worst-case composite, where controlling storm type may vary with AEP. An example reservoir stage probability curve is shown in the following figure.



5.3 State Dam Safety Rule 7.2, Inflow Design Floods and Hydrologic Hazard Category, does not apply to hydrologic risk analysis. Rule 7.2.4, atmospheric moisture factor (7% increase for future climate change) generally should not be applied to REPS PF estimates for hydrologic risk analysis, because the purpose is to determine present risk.

5.4 Although hydrologic risk studies mainly use REPS PF estimates to model probabilistic floods and generate hydrologic loading curves, it may be helpful to estimate REPS PMP and model PMF. REPS PMP and PMF can provide valuable calibration points for rainfall-runoff models against regional peak flow envelopes and can provide independent cross-checks of PF estimates, particularly at extremely low likelihoods. For example, see the maximum PMF reservoir stages plotted on the reservoir stage probability curve above.

5.5 More information on hydrologic risk analysis can be found in Colorado Dam Safety's *Guidelines for Hydrologic Hazard Analysis* and *Guidelines for Hydrological Modeling and Flood Analysis*.

Section 6. REPS for Inflow Design Floods (IDF) for Design Projects (see Flowchart 2 inside front cover)

6.1 State Dam Safety Rule 7.2 provides IDF Critical Rainfall requirements based on Hydrologic Hazard Category, as shown in the table below (from Table 7.1, 2020 State Dam Safety Rules):

Prescriptive IDF Requirements

Hydrologic Hazard	Critical[1] Rainfall
Extreme	Probable Maximum Precipitation (PMP)
High	0.01% AEP
Significant	0.1% AEP
Low	1% AEP

[1] Critical refers to the controlling storm duration, spatial pattern, temporal distribution and other storm variables that result in the highest maximum reservoir water surface elevation during reservoir routing.

where the following definitions apply (from State Dam Safety Rule 4.15):

> ***Hydrologic Hazard***: Potential consequences downstream of a dam caused by floodwaters released by overtopping failure of the dam [or other hydrologic failure mode]. Hydrologic hazard [category] establishes design criteria for spillway size [and other hydrologic appurtenances].

And Hydrologic Hazard Categories (Rule 4.15 and Table 7.1) are defined as follows:

Extreme: Life loss potential of 1 or more.
High: Life loss potential of less than 1.
Significant: No life loss potential but significant damage is expected to occur.
Low: No life loss potential or significant damage is expected to occur.

6.2 The REPS PMP Web Tool should be used to estimate PMP for IDF purposes, and it supersedes NOAA HMR PMP for Colorado Dam Safety purposes.

6.3 The REPS MetPortal PF Tool should be used for frequency-based IDFs and supersedes NOAA Atlas 14 for Colorado Dam Safety purposes.

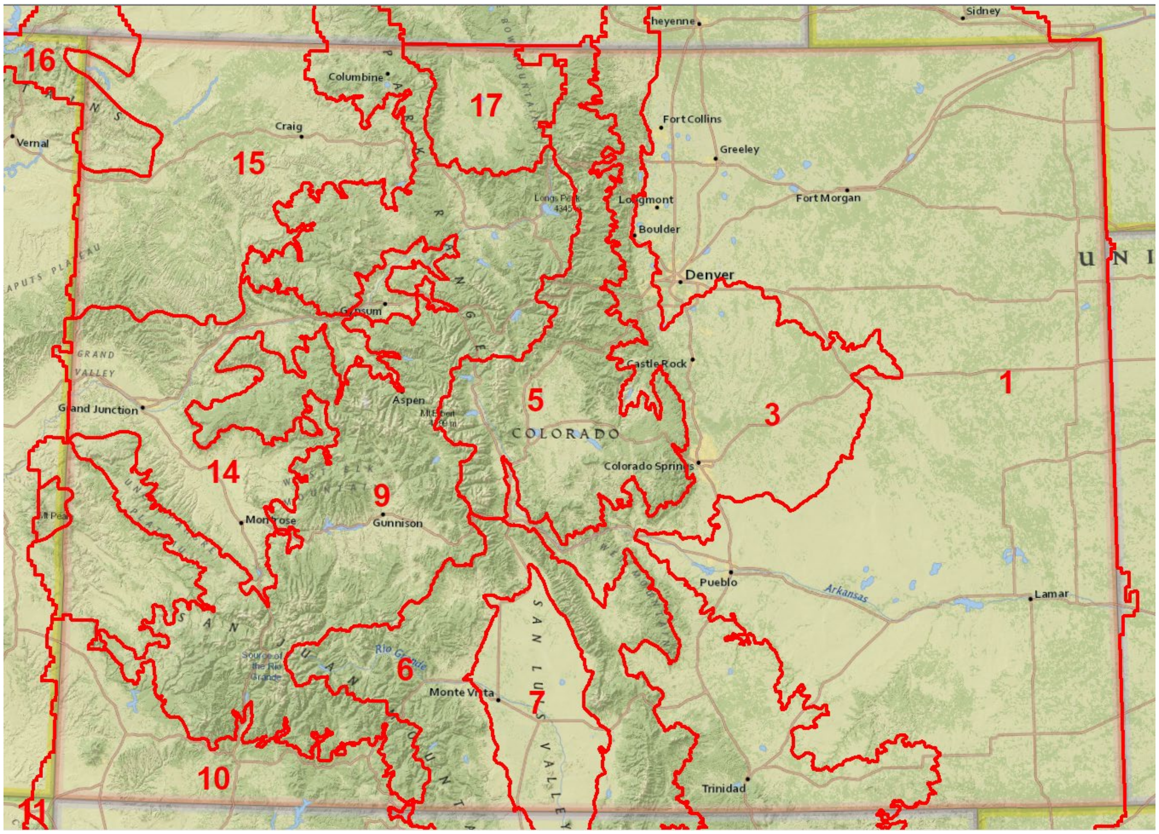
6.4 Site-specific PMP and PF studies are allowed pursuant to State Dam Safety Rule 7.2.3.3. Site-specific studies may provide an opportunity to refine extreme precipitation estimates for a specific basin in terms of storm transposition limit assumptions, data interpolation and smoothing, etc., that necessarily occur in a regional study like REPS. However, in general REPS methods define the standard-of-practice and should be followed for site-specific studies (reference REPS report documentation). Dam Safety Rules Table 7.1 IDF criteria apply for site-specific studies.

6.5 State Dam Safety Rule 7.2.4 requires that a 7% atmospheric moisture factor be applied to all design rainfall estimates to account for expected increases in atmospheric temperature and precipitable water at saturation over the next 50 years (assumed project design life), based on a recommendation by NOAA as part of the REPS study. The 7% increase is applicable to all REPS PMP and PF estimates for IDF purposes. The 7% factor can easily be applied to design storms in HEC-HMS as a precipitation ratio for each Simulation Run.

Section 7. REPS Temporal Distributions

7.1 REPS PMP Web Tool Temporal Distributions

7.1.1 REPS PMP is calculated by comparing rainfall from historical storms that are transpositionable to a basin-of-interest. REPS PMP Transposition Zones are shown in the image below. Historical storm data is extracted from depth-area-duration tables in a REPS PMP geodatabase at the basin area size and relevant durations, then scaled by an in-place maximization factor, geographic transposition factor, and moisture transposition factor. The controlling storm (i.e. worst case PMP) may vary spatially by grid cell and by duration, such that REPS basin-average PMP is an envelopment of controlling storms. See REPS report Volume II for details on PMP development. As explained previously, the REPS PMP Web Tool runs faster and outside of ArcMap by simply interpolating previously generated REPS PMP gridded data, computed for various area sizes and storm types.



REPS PMP Storm Transposition Zones

7.1.2 The REPS PMP Web Tool provides basin and subbasin-average PMP estimates for Local, General and Tropical (south of 38.5d N latitude only) storm types. Example basin-average PMP at 1, 2, 3, 4, 5, 6, 12, 24, 48 & 72-hour inter-durations is shown below. ***PMP_0X* (column heading) refers to the X-hour inter-durational estimate of PMP in inches.**

Get PMP for Drainage Basin

Basin Average PMP

OBJECTID	STORM_TYI	PMP_01	PMP_02	PMP_03	PMP_04	PMP_05	PMP_06	PMP_12	PMP_24	PMP_48	PMP_72
1	Local	3.8	4.8	5.9	6.7	7.4	7.5	8.3	8.7		
2	General	2.2					7.5	8.3	10	13.6	15.9

7.1.3 **Temporal distributions are the primary REPS rainfall output for use in hydrologic modeling. The REPS PMP Web Tool automatically generates applicable temporal distributions for the basin location as required by Colorado Dam Safety for hydrologic risk assessments and IDF hydrology studies, as follows:**

- **2-hr Local Storm Stacked Distribution, 5-minute timestep**
- **6-hr Local Storm Synthetic Distribution, 5-minute timestep**

- **24-hr Local Storm Hybrid Distribution (Transposition Zones 1 and 3 only), 5-minute timestep**
- **72-hr General Storm Synthetic Distribution, 15-minute timestep**
- **72-hr Tropical Storm Synthetic Distribution (centroid lies south of 38.5° latitude only), 15-minute timestep**

7.1.4 More details about REPS PMP temporal patterns are provided below (see REPS report Volume II for full documentation):

7.1.4.1 **2-hr Local Storm Stacked:** This temporal pattern was created by analysis of sub-hourly NEXRAD data for short (1-2 hr) extreme storms in the PMP storm list. The REPS study found these 1-2 hr storms typically have a small areal footprint, are independent of longer duration Local Storms, and often significantly exceed 1-2 hr rainfall amounts associated with longer Local Storms. Analysis did not find significant differences in this pattern with location, therefore, a single 2-hr pattern is used for the entire state.

7.1.4.2 **6-hr Local Storm Synthetic (East, West):** The REPS study found these longer duration Local Storms are typically independent of the shorter duration simple convective storms, therefore, 1-hr to 3-hr REPS inter-durational PMP estimates are not embedded in this 6-hr Local Storm pattern. This is consistent with REPS Task 2 (precipitation frequency analysis) finding of separate 2-hr LS and 6-hr MEC storm types. The REPS PMP 6-hr Synthetic distribution was created as an approximate average behavior of historical 6-hr (+/-) extreme storms on the REPS PMP storm list. Behavior was observed to differ east and west of the Continental Divide; therefore, REPS uses separate East and West 6-hr Local Storm Synthetic patterns, which are automatically assigned by the REPS PMP Web Tool based on the location of the basin-of-interest.

7.1.4.3 **24-hr Local Storm Synthetic Hybrid:** The REPS PMP Web Tool only generates this pattern for basins that lie east of the 7500-ft (+/-) contour along the Front Range foothills and Eastern Plains (transposition zones 1 & 3). This pattern was developed because REPS classified the longer duration complex convective storms that occur in the Front Range Foothills and Eastern Plains as Local Storms, whereas HMR 55A classified them as General Storms. The most significant example is the Elbert-Cherry Creek May 1935 storm. The strong convective characteristics of this and similar storms are consistent with Local Storms, and so it was judged to be unreasonable to embed them in General Storm PMP (as HMR 55A did); however, the storm duration of Cherry Creek 1935 and similar storms exceeds the traditional 6-hr duration for Local Storms, and their 18-hr and 24-hr rainfall often exceeds that from General Storms. The REPS PMP 24-hr Synthetic Hybrid temporal pattern was created as an approximate average behavior of historical 18 to 24-hr duration Local and Hybrid extreme storms on the REPS PMP storm list.

7.1.4.4 **72-hr General & Tropical Storm Synthetic (East, West):** This distribution is used for the traditional 72-hr General Storm PMP *and* Tropical Storm PMP. The 72-hr distribution was created as an approximate average behavior of historical General and Tropical storms on the REPS PMP storm list, specifically looking at the average behavior of the core 24 hours of these storms. The REPS study initially looked at General and Tropical storms separately but found no significant differences in their average temporal behavior. However, differences *were* observed east and west of the

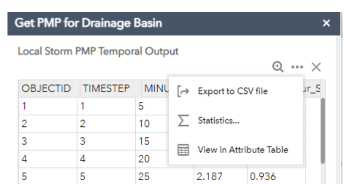
Continental Divide; therefore, REPS assigns East and West 72-hour Synthetic patterns based on basin location.

7.1.5 **The REPS PMP Web Tool generates a *Local Storm PMP Temporal Output Table* and a *General and Tropical Storm PMP Temporal Output Table* (see image below). The tables give accumulated PMP in inches by time (time increment varies by storm type, as listed above).**

General and Tropical Storm PMP Temporal Output

OBJECTID	TIMESTEP	MINUTE	GS_72_hour_Synthetic_East
1	1	15	0.037
2	2	30	0.075
3	3	45	0.112
4	4	60	0.15
5	5	75	0.188
6	6	90	0.225
7	7	105	0.263
8	8	120	0.3
9	9	135	0.337
10	10	150	0.375
11	11	165	0.412
12	12	180	0.45
13	13	195	0.487
14	14	210	0.525
15	15	225	0.562
16	16	240	0.6
17	17	255	0.637
18	18	270	0.675
19	19	285	0.712
20	20	300	0.75
21	21	315	0.787
22	22	330	0.825
23	23	345	0.862
24	24	360	0.9
25	25	375	0.937
26	26	390	0.975
27	27	405	1.012
28	28	420	1.05

Temporal Output tables can be exported by selecting the three-dot/ellipse button and then "Export to CSV file" (see images below). CSV file distributions can be copied into HEC-HMS as time series precipitation gage data and linked to a specified hyetograph meteorological model.



7.2 REPS MetPortal PF Tool Temporal Distributions

7.2.1 REPS PF storm types Local Storm (LS), Mesoscale with Embedded Convection (MEC), and Mid-Latitude Cyclone (MLC) are independent and must all be modeled for a basin-of-interest to determine critical hydrologic loading, e.g., the case that results in the highest routed reservoir stage.

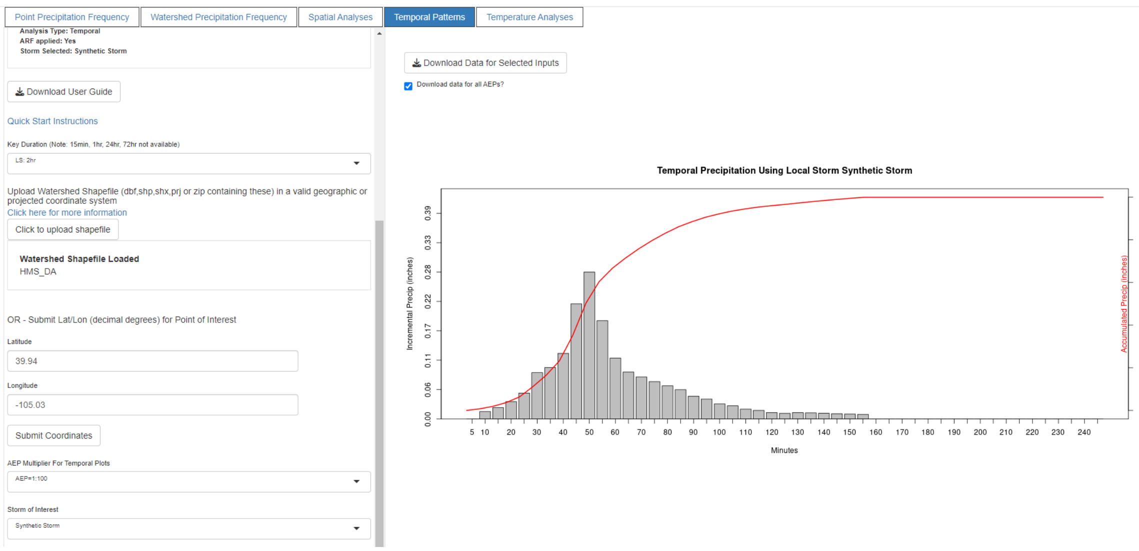
7.2.2 **Temporal distributions are the primary REPS rainfall output for use in hydrologic modeling and can be generated for PF storms using the REPS MetPortal PF Tool, *Temporal Patterns tab*. The user should select the following temporal patterns from the *Storm of Interest* dropdown list; *East, West and Rio Grande* refer to REPS PF Macro Regions, which can be selected and shown on the MetPortal map display:**

- **2-hr LS Synthetic Storm (East, West, Rio Grande), 5-minute timestep**
- **6-hr MEC:**
    - **Front-Loaded Synthetic Storm (East), 5-minute timestep**
    - **Synthetic Storm (West, Rio Grande), 5-minute timestep**
- **48-hr MLC:**
    - **Center-Loaded Synthetic Storm (East, Rio Grande), 1-hour timestep**

○ **Synthetic Storm (West), 1-hour timestep**

7.2.3 REPS MetPortal PF synthetic temporal patterns use temporal statistics from historical storms, including seasonality, overall storm shape, precipitation-depth-duration relationships, time to the highest intensity rainfall, and position of next highest intensity rainfall relative to the peak (see REPS report Volume III for more details).

7.2.4 The following image shows the REPS MetPortal PF Tool, Temporal Patterns tab for an example basin: 2-hr LS storm type (“Key Duration”), located in the East Macro Region (automatically assigned), AEP Multiplier is AEP=1:100, and “Storm of Interest” is the Synthetic Storm.



7.2.5 The user can download a CSV file of temporal distributions using the “Download Data for Selected Inputs” action button (see image above). Select the “Download data for all AEPs?” option to include scaled temporal distributions for all AEPs (10^{-1} through 10^{-7}) for the selected storm type (LS, MEC or MLC). The CSV file gives incremental and cumulative rainfall distributions. The process must be repeated for each storm type. For hydrological modeling, the appropriate distribution can be copied from the CSV file and input to HEC-HMS as time series precipitation gage data linked to a specified hyetograph meteorological model.

7.2.6 The CSV file also provides *unscaled* incremental and cumulative temporal patterns. The unscaled patterns can be useful for hydrologic risk analysis, where there are 21 probabilistic storms to model (10^{-1} through 10^{-7} AEP for LS, MEC & MLC). One way to handle this large number of probabilistic storms in HEC-HMS is to create a Meteorological Model for each unscaled temporal pattern (LS, MEC & MLC), then create a simulation for each AEP, and scale the patterns by PF estimates using the Precipitation Ratio tab.

Section 8. <u>REPS Area Size Limits & Spatial Patterns</u>

8.1 REPS PMP Web Tool Area Size Limits & Spatial Patterns

8.1.1 REPS PMP is calculated from historical storm depth-area-duration data at the basin-of-interest size, therefore, no areal reduction factors are used.

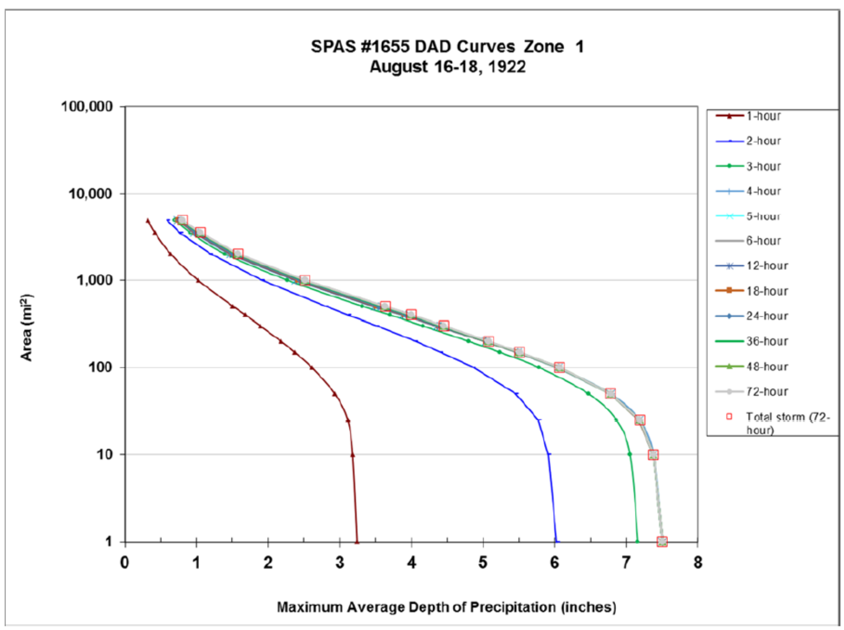
8.1.2 By default REPS PMP and design storm temporal distributions are provided as spatially uniform, basin-average rainfall; this is considered to be appropriate for small and hydrometeorologically uniform basins.

8.1.3 The REPS PMP Web Tool has the option to estimate PMP by subbasin (see Section 9 below for details). Subbasin analysis should be used where climatological or hydrological characteristics vary significantly over a basin.

8.1.4 REPS PMP raster grid data are provided as output from the REPS PMP Web Tool. The grid patterns reflect underlying precipitation climatology (based on NOAA Atlas 14), topography, and moisture availability at approximately ~2100-meter grid resolution. These patterns can be used in a fully distributed hydrological model, if desired. Note that basin and sub-basin average REPS PMP are aggregated from the gridded data, so the choice of rainfall aggregation size is up to the user.

8.1.5 The REPS study recommended that basin size should be 100 square miles or smaller for Local Storm PMP analysis. This is a recommendation, not hard coded into the REPS PMP Web Tool. It is based on average size of historical Local Storms. The following additional area size guidance is provided:

> 8.1.5.1 Controlling historical storms for the basin-of-interest are shown in the PMP points layers (described in Section 4 above).
>
> 8.1.5.2 In [REPS report Volume II, Appendix F](), depth-area-duration curves can be reviewed for controlling historical storms (see image below) to determine the areal footprint.



> 8.1.5.3 Partial area analysis should be performed for basins significantly larger in size than their controlling storms. For example, if a 120 square mile mountain basin is controlled by a historical Local Storm that had a 20 square mile footprint, then consideration should be given to creating subbasins and doing partial area analysis.

8.1.5.4 Controlling storms in the REPS PMP Web Tool vary by location, storm type, and duration. Area size for a 2-hr Local Storm PMP controlling storm is expected to be smaller than that for a 6-hr Local Storm PMP controlling storm. Similarly historical controlling Local Storms on Colorado's Eastern Plains are typically larger in area size than those in high elevation mountain terrain.

8.1.5.5 See Colorado Dam Safety's *Guidelines for Hydrological Modeling and Flood Analysis* for more details on REPS design storm area sizes and partial area analysis for hydrology modeling.

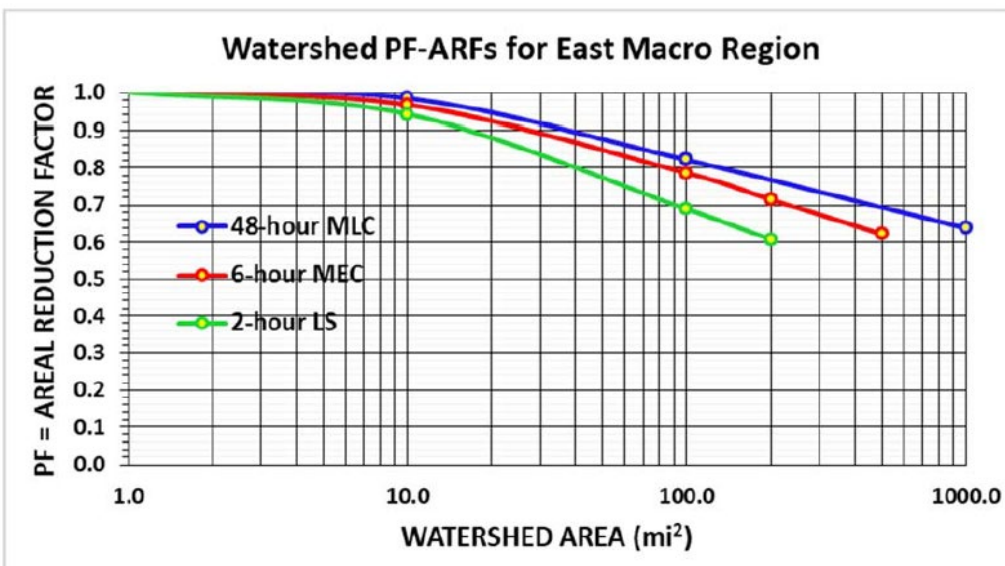
8.2 REPS MetPortal PF Tool Area Size Limits & Spatial Patterns

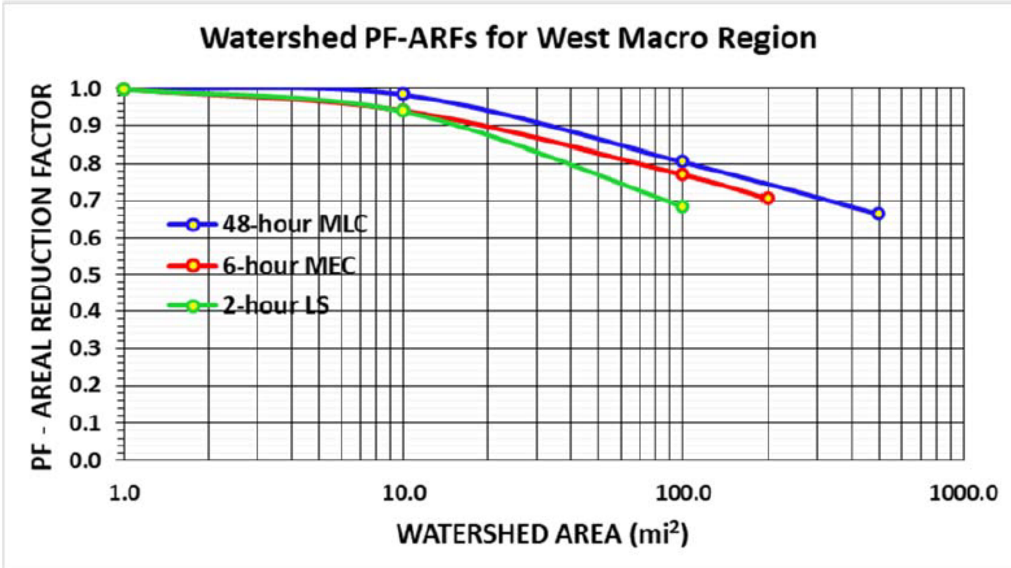
8.2.1 The REPS MetPortal PF Tool provides both point and watershed-average PF estimates. Watershed average PF estimates use stochastically-generated areal reduction factors (ARF), derived from historical storm spatial patterns.

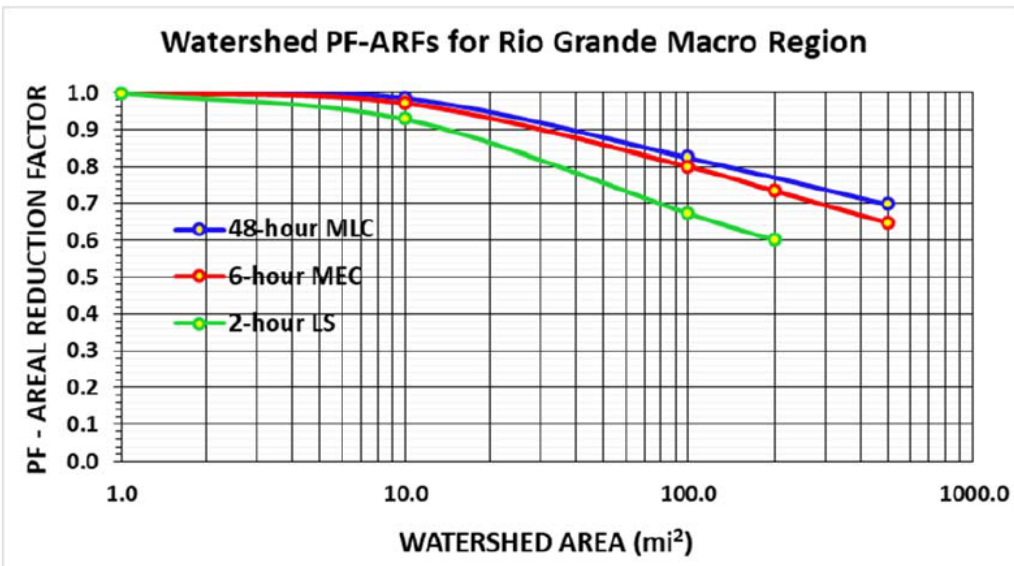
8.2.2 Recommended watershed area size limits, based on ARFs, are shown below by storm type and macro region, from REPS Volume III, Table 36:

MACRO REGION	LS (2-HOUR)	MEC (6-HOUR)	MLC (48-HOUR)
East	Up to 200 mi^2	Up to 500 mi^2	Up to 1,000 mi^2
Rio Grande	Up to 200 mi^2	Up to 500 mi^2	Up to 500 mi^2
West	Up to 100 mi^2	Up to 200 mi^2	Up to 500 mi^2

Areal reduction curves from REPS Volume III, Section 5.2 are shown below, by storm type and macro region:







ARF curve equations, from REPS Volume III, Section 5. 2, Table 37 are shown below. The MetPortal PF Tool computes ARFs automatically for the basin-of-interest, and it will extrapolate beyond the recommended area size limits shown above, in order to facilitate engineering analysis and design, where extrapolated estimates may be the best available information, but should be used with caution.

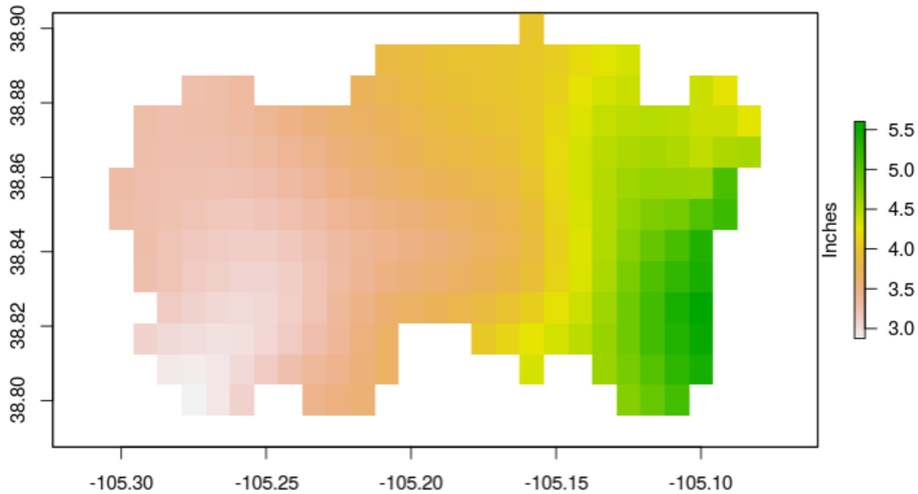
Macro Region	Storm type	Watershed size (mi^2)	Equation used where y=ARF; x=Log10(watershed area, sq mi)
East	MLC	1 - 1000	$y = -0.013257x^5 + 0.108832x^4 - 0.300585x^3 + 0.265403x^2 - 0.076466x + 1.000694$
East	MEC	1 - 500	$y = -0.009114x^5 + 0.078659x^4 - 0.228760x^3 + 0.198464x^2 - 0.072290x + 1.000464$
East	LS	1 - 200	$y = -0.019265x^5 + 0.146755x^4 - 0.371625x^3 + 0.278722x^2 - 0.092194x + 1.000226$
West	MLC	1 - 500	$y = -0.014771x^5 + 0.121212x^4 - 0.334808x^3 + 0.296515x^2 - 0.085609x + 1.000792$
West	MEC	1 - 200	$y = 0.010574x^3 - 0.088460x^2 + 0.020526x + 0.998281$
West	LS	1 - 100	$y = 0.013351x^4 - 0.058832x^3 - 0.013985x^2 - 0.000290x + 0.997799$
Rio	MLC	1 - 500	$y = -0.012973x^5 + 0.106852x^4 - 0.295968x^3 + 0.261726x^2 - 0.075402x + 1.000672$
Rio	MEC	1 - 500	$y = -0.008558x^5 + 0.071635x^4 - 0.200460x^3 + 0.156794x^2 - 0.047929x + 1.000196$
Rio	LS	1 - 200	$y = -0.018704x^5 + 0.129375x^4 - 0.282599x^3 + 0.131023x^2 - 0.030251x + 0.998530$

Lastly, from REPS Volume III, Section 5.2:

Watershed area sizes beyond the end-points of the curves for each storm type in each region have greater uncertainty and the curves should not be extrapolated. The area size limits are based on the size of test watersheds that were used for calculating the PF-ARFs and not a representation of storm footprint size. For watersheds larger than 1,000 mi2, a detailed site-specific watershed precipitation frequency analysis is [considered to be best practice].

8.2.3 The MetPortal PF Tool does not support subbasin analysis (see Section 9 below for more details).

8.2.4 The *Spatial Analysis* tab of the REPS MetPortal PF Tool will generate basin-specific spatial patterns, which are based on PRISM monthly average precipitation, where the user selects a month of interest. The patterns can be scaled to storm type and AEP and downloaded in raster format (see image below), then aggregated in ArcGIS as needed for subbasin or distributed analysis. WGS84 geographic coordinate system projection must be assigned in ArcMap to MetPortal spatial patterns.

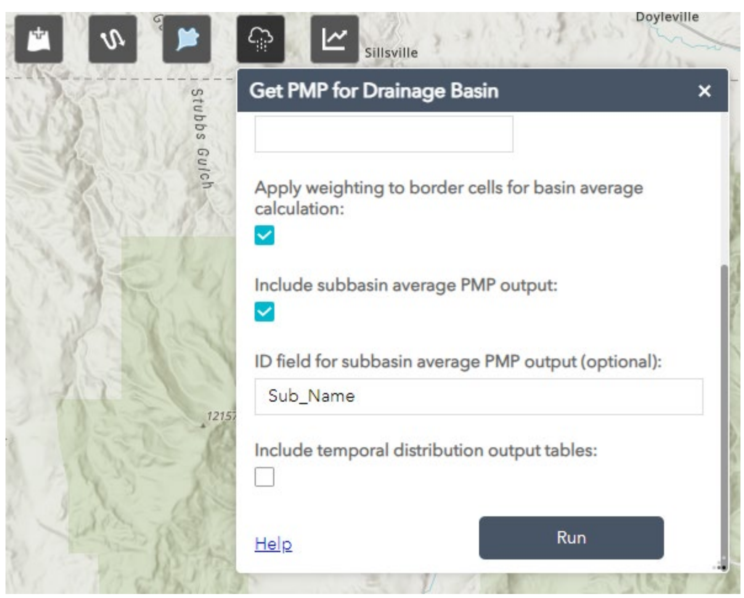


Section 9. Subbasin Analysis and other Advanced Applications

9.1 Subbasin Analysis:

9.1.1 REPS PMP Web Tool:

9.1.1.1 The REPS PMP Web Tool will provide subbasin PMP estimates when the “Include subbasin average PMP output” option is checked near the bottom of the Input dialogue box. The basin shapefile must contain subbasins. The OBJECTID field is used by default or the user can manually enter another subbasin field name (see below).



9.1.1.2 If the subbasin option is selected, the REPS PMP Web Tool creates a Subbasin Average PMP output table, which can be downloaded as a CSV file.

9.1.1.3 The tool does not automatically generate subbasin temporal distributions. There are two options for generating these:

- If the basin is topographically and climatologically uniform, then the basin temporal distribution can be normalized by the user (i.e. divided by the maximum rainfall amount) and then rescaled by subbasin PMP.

- If the basin differs climatologically and topographically (e.g. a basin that extends from the Eastern Plains up to the Continental Divide), then subbasin temporal pattern shape may vary, because REPS temporal patterns are generated by combining various inter-duration PMP estimates. In this case, then subbasin temporal distributions can be generated <u>individually</u> in the REPS PMP Web Tool, selecting a subbasin element and running PMP, entering the overall basin area size in the "Area to use for aerial reduction" Input field, to obtain individual subbasin temporal distributions.

9.1.2 **REPS MetPortal PF Tool:** Currently the REPS MetPortal PF Tool does not do sub-basin analysis. It can be run for individual subbasins; however, PF results will be scaled to the subbasin size by stochastically generated areal reduction factors. It is possible to obtain ARFs by region from REPS report Volume III, then manually rescale subbasin Watershed Mean PF by the overall basin ARF. Alternatively, REPS MetPortal spatial patterns can be used to represent climatological variation across subbasins as discussed above.

9.2 **Design storm temporal patterns for REPS PMP gridded data using the REPS PMP Web Tool.** The REPS PMP Web Tool provides gridded PMP data at selected inter-durations. However, it does not provide 5-minute or 15-minute grids or dimensionless temporal patterns. If desired, the user can normalize the basin-average temporal distribution and then rescale gridded data for the appropriate storm type and duration.

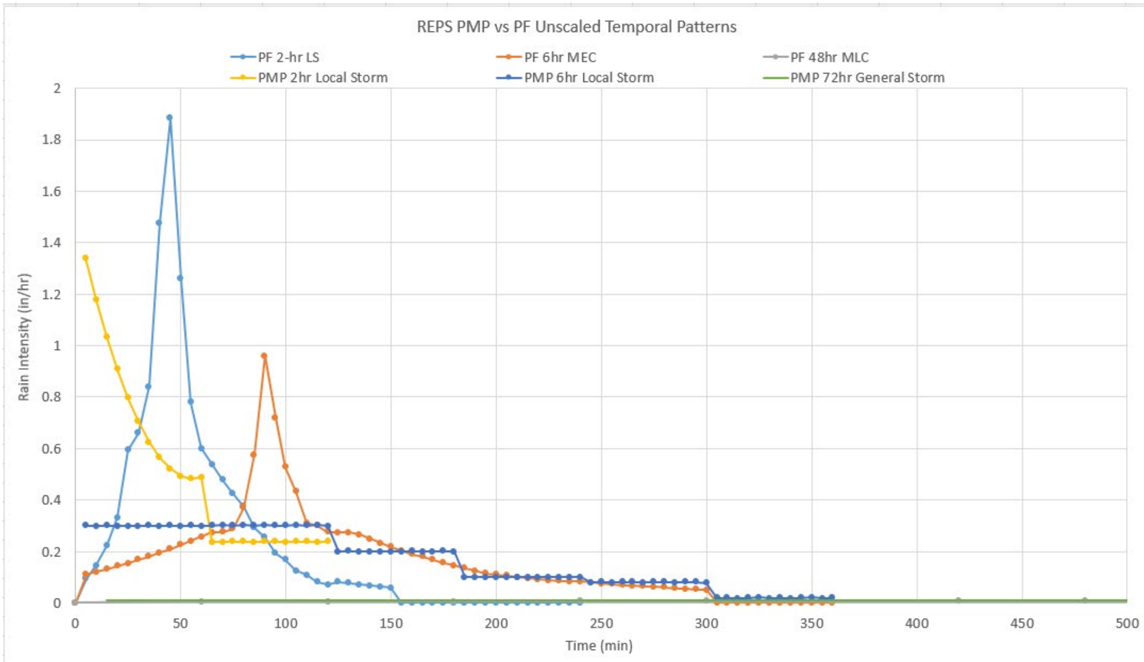
9.3 **REPS MetPortal Temperature and Freezing Level Data.** REPS MetPortal PF statistics are based on total precipitation of all phases (i.e. snow, rain, hail) as measured at weather stations. To facilitate hydrological modeling, the MetPortal PF Tool provides Freezing Level and 1000mb Temperature time series. These data series can be used in HEC-HMS in the meteorological model, snowmelt method, to differentiate between liquid and solid phase precipitation. Studies using this approach should be coordinated with Colorado Dam Safety in advance.

Section 10. <u>Precipitation volumes and rates</u>

10.1 The REPS PMP Web Tool generates temporal distributions in accumulated volume per unit area (i.e. depth) in inches. The REPS timesteps are 5 minutes for Local/Hybrid Storms and 15 minutes for General/Tropical storms. Sometimes it is desirable to look at precipitation intensity in inches/hour. To do so, incremental rainfall depths can be computed as the difference in accumulated volumes and then multiplied by the factor [60 minutes/timestep in minutes]. For example, 5-minute incremental depths would be multiplied by 12 to get precipitation intensity in units of inches/hour.

10.2 The REPS MetPortal PF Tool provides temporal distributions in both accumulated volume per unit area (inches) and incremental volume (inches/timestep). LS and MEC temporal distributions use a 5-minute timestep; MLC distributions use a 1-hour timestep. Again, incremental depth units can be converted to inches/hour, if desired for comparisons or reporting.

10.3 The graph below shows -- for an example Colorado Front Range basin -- precipitation intensity in inches/hour for the various REPS PMP and REPS MetPortal PF synthetic temporal distributions, each normalized to 1 inch of total rainfall. Exact patterns vary throughout the state, but the graph gives a useful indication of the relative rainfall intensities of the various REPS synthetic temporal distrubions.



Section 11. <u>Reporting Requirements</u>

See Colorado Dam Safety's *Guidelines for Hydrological Modeling and Flood Analysis* for REPS PMP & PF reporting requirements, as part of a larger hydrology study report.

Section 12. <u>REPS Verification Checks</u>

Because PMP involves subjective judgments, transparency is important and was a goal of the REPS study. REPS Volume II, its appendices, and the REPS PMP Web Tool contain a large amount of background data that supports development of REPS PMP estimates. The following is a list of key supporting information which the user can use to check REPS PMP estimates:

12.1 REPS PMP point layers and tables list controlling historical storms by grid cell, inter-duration, and storm type.

12.2 REPS report Volume II Appendix F contains storm data for all historical storms on the REPS PMP storm list. Applicable controlling storms can be reviewed in terms of depth-area-duration data, storm meteorological conditions, location, maximum rainfall rates, etc.

12.3 The in-place maximization factor (IPMF) applied to each storm can be found in REPS report Volume II, Table 2, *Short Storm List*.

12.4 Moisture transposition factor (MTF) maps for each storm are included in REPS report Volume II, Appendix B. The MTF value for a given controlling storm can be estimated for the basin-of-interest.

12.5 Geographic transposition factor (GTF) maps for each storm are included in REPS report Volume II Appendix C. The GTF value for a given controlling storm can be estimated for the basin-of-interest.

12.6 Transposition limits for each historical storm are shown on MTF and GTF maps and can be checked against the location of the basin-of-interest.

12.7 A rough check of REPS PMP can be calculated as:

PMP=controlling storm rainfall (from D-A-D table at duration & area size) x IPMF x MTF x GTF

Section 13. Summary of Key Updates

<table>
<tr><th>Guidelines publication date</th><th>Guidelines Section</th><th>Summary of key updates</th></tr>
<tr><td>1/21/2020</td><td></td><td>Original publication</td></tr>
<tr><td rowspan="6">8/22/2024</td><td>Inside front cover</td><td>Added SEO hydrology flowcharts for 2 hydrologic study processes and where these REPS guidelines fit. Added references for related guidelines for hydrologic risk & hydrological modeling</td></tr>
<tr><td>Section 2</td><td>Replaces REPS PMP GIS tool with REPS PMP Web Tool</td></tr>
<tr><td>Section 3</td><td>Added to explain updates to the REPS tools:
New REPS PMP Web Tool and updated PMP based on Saguache 1999 storm re-analysis
REPS Metportal changed to RTI hosting</td></tr>
<tr><td>Section 4</td><td>New instructions for use of the REPS PMP Web Tool & new hyperlink; removed old installation instructions for GIS tool.
New MetPortal hyperlink and updated instructions for use based on changes Metstat, DTN & RTI made since 2018 launch.</td></tr>
<tr><td>Section 5</td><td>Added new section for REPS use in hydrologic risk assessments (Flowchart process 1)</td></tr>
<tr><td>Section 6</td><td>Minor updates to this previous section which discussed use of REPS for Inflow Design Floods, making distinction that this is Flowchart 2 (design projects).
Removed previous discussion of 2007 SEO Rules & HMR rainfall, as the comparison is no longer considered relevant</td></tr>
</table>

Section 14. References

14.1 *Reanalysis of Record-Breaking Storm in Colorado Rockies-Combining Meteorology with Hydrology to Find the Answer*, Kappel and others, Association of State Dam Safety Officials, conference proceedings, Palm Springs, CA, 2023

14.2 *Guidelines for Hydrological Modeling and Flood Analysis*, Colorado Dam Safety, Sept 2022, or most recent version.

14.3 *Guidelines for Comprehensive Dam Safety Evaluation (CDSE) Risk Assessments & Risk Informed Decision Making (RIDM)*, March 2021, or most recent version.

14.4 *Guidelines for Hydrologic Hazard Analysis*, Colorado Dam Safety, January 2020, or most recent version.

14.5 *Rules and Regulations for Dam Safety and Dam Construction* (2-CCR 402-1), January 2020, or most recent version.

14.6 *Colorado-New Mexico Regional Extreme Precipitation Analysis, Summary Report Volume II*, *Deterministic Regional Probable Maximum Precipitation Estimation.* Colorado Department of Natural Resources and New Mexico Office of the State Engineer, November 30, 2018.

14.7 *Colorado-New Mexico Regional Extreme Precipitation Analysis, Summary Report Volume III, Regional Precipitation-Frequency Estimation*. Colorado Department of Natural Resources and New Mexico Office of the State Engineer, November 30, 2018.