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

GUIDELINES
FOR
HYDROLOGICAL MODELING AND FLOOD ANALYSIS

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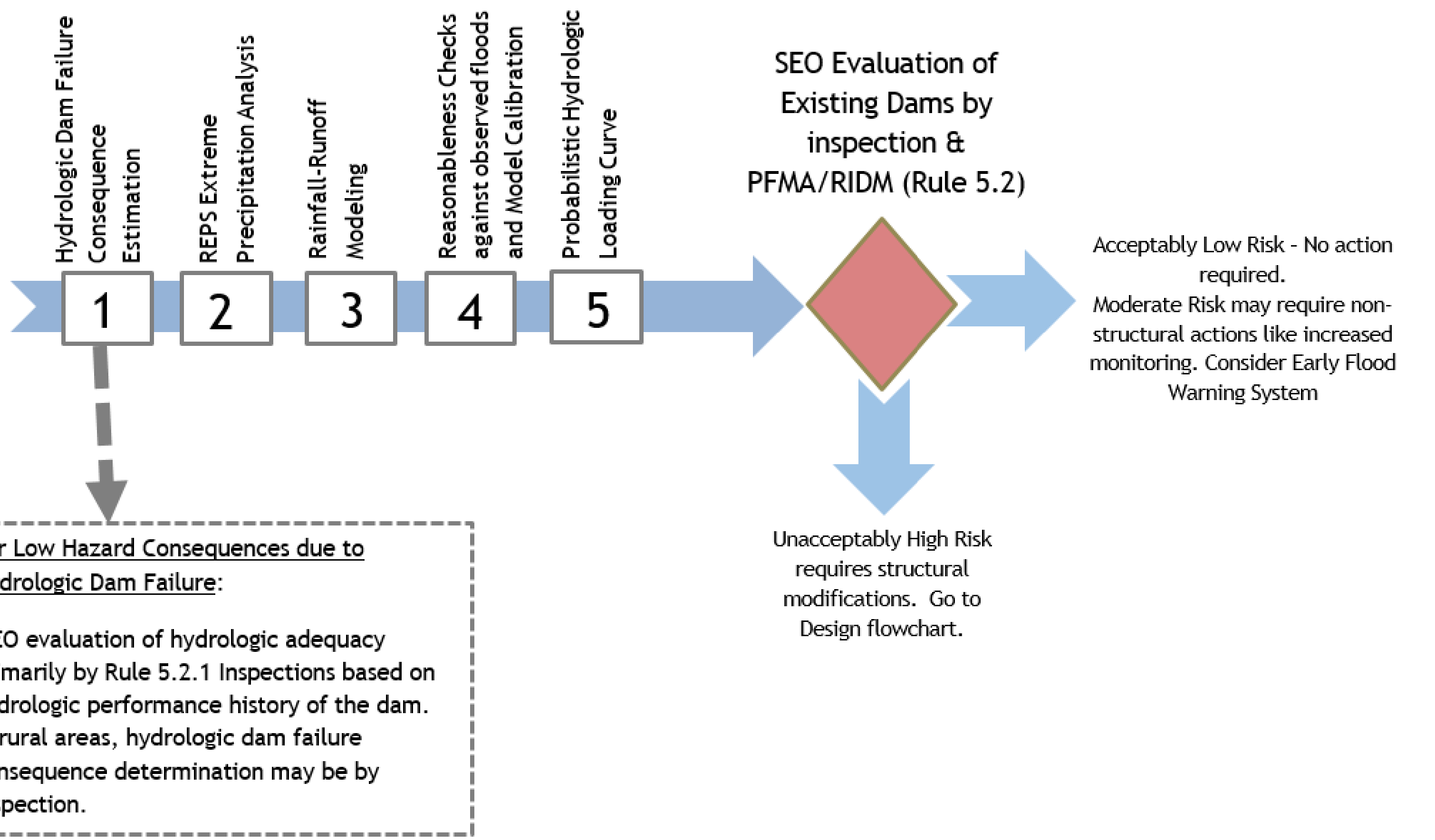
1313 Sherman Street, Room 818 Centennial Building
Denver, Colorado
303-866-3581

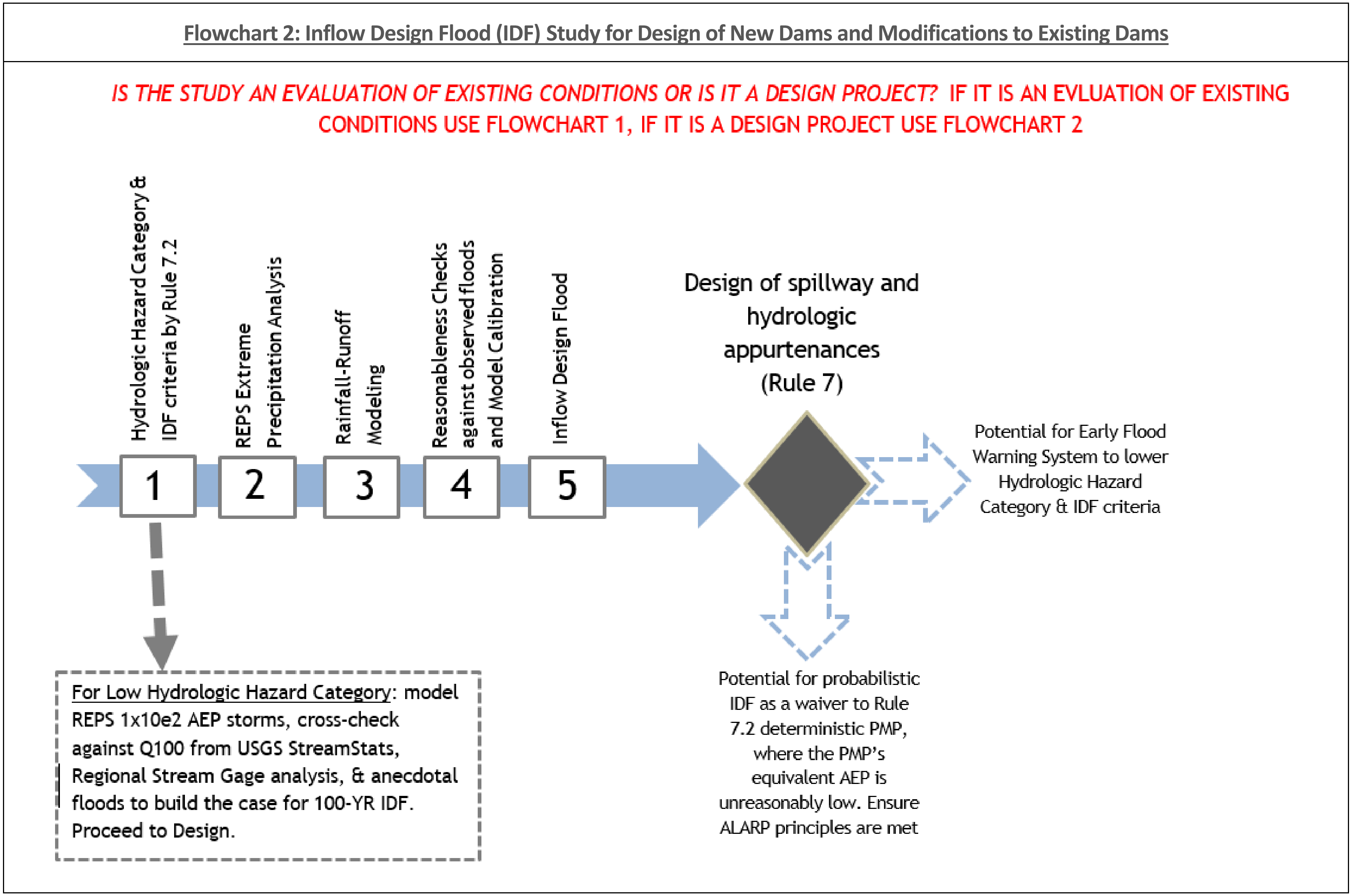
https://dwr.colorado.gov/services/dam-safety

Flowchart 1: Risk-informed Hydrologic Evaluation and Consequence Analysis for Existing Dams

IS THE STUDY AN EVALUATION OF EXISTING CONDITIONS OR IS IT A DESIGN PROJECT? IF IT IS AN EVLUATION OF EXISTING CONDITIONS USE FLOWCHART 1, IF IT IS A DESIGN PROJECT USE FLOWCHART 2



Reference *Overview of Hydrologic Evaluation and Design Process*, State of Colorado Dam Safety, March 2021.



Reference *Overview of Hydrologic Evaluation and Design Process*, State of Colorado Dam Safety, March 2021.

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Hydrology study reporting requirements are provided throughout Sections 5 through 10 below and are marked with a scroll icon and section heading in red text. Reporting will facilitate subsequent steps in the hydrology modeling & checking process. **Please see [Example reports in Appendix A] and [Reporting checklists in Appendix C] before you begin.**

YouTube

YouTube tutorial videos demonstrating application of these guidelines, with examples, are provided on the Colorado DWR YouTube channel:
https://www.youtube.com/playlist?list=PLfxQZOzykdUvqEWL3c4HtbAV2LeKCY9Tm

Section 1. **Introduction**

This document provides Colorado Dam Safety guidelines for hydrological modeling and flood analysis for design and risk analysis of hydrologic features of dams. Guidelines represent the agency's current thinking and are recommended for use on projects that require agency approval. We have spent many years updating our approach to hydrological analysis. From about 2016-2018, Colorado and New Mexico performed a multi-year Regional Extreme Precipitation Study (REPS), which developed new probable maximum precipitation (PMP) estimates and extreme precipitation frequency estimates for the region. The REPS study was overseen by a project review board of federal and state subject matter experts. Using probabilistic rainfall estimates from REPS, Colorado developed a new hydrologic risk analysis framework, in which hydrologic event likelihood and consequences of hydrologic dam failure are used for risk-informed evaluation of existing dams and to develop risk-based Inflow Design Flood (IDF) criteria for dam design. During 2018 – 2021, Colorado Dam Safety collaborated with Colorado State University (CSU) to develop improved hydrological rainfall-runoff modeling methods to more accurately represent extreme flooding in Colorado, particularly in the mountains and Colorado's western slope, where historically dam safety modeling methods have grossly over-estimated the magnitude of floods, relative to the observed flood record. Finally, Colorado Dam Safety recognized the need to incorporate information about observed floods, both site-specific and regional, into dam safety flood analysis. Significant efforts to document and understand extreme/extraordinary floods and paleo-floods in Colorado have been made over the past 30 years by U.S Geological Survey (USGS) researchers Robert Jarrett and Michael Kohn, U.S. Army Corps of Engineers hydrologist John England, and others. Valuable regional data sets like USGS StreamStats and the USGS Colorado Flood Database can help estimate floods for dams on ungaged basins.

These guidelines describe a new and different hydrological modeling process that incorporates site-specific and regional observed flood information. We still greatly rely on rainfall estimates and rainfall-runoff modeling to simulate flood timing, durations, volumes, and to extrapolate to unobserved floods. Yet while REPS rainfall estimates and the CSU rainfall-runoff modeling are considered to be best available science, they involve many simplifying assumptions, e.g., assumed storm transpositions limits, idealized temporal distributions, use of large-scale soil surveys to estimate soil hydraulic properties, etc. Uncalibrated rainfall-runoff model results are viewed here as an initial starting point, and *reasonableness* or accuracy of such results should not be assumed. Checking and calibrating model results against the historical flood record is considered to be an integral step, involving stream gage flood frequency analysis, regional flood frequency relationships, historical flooding, history and frequency of spillway activation, record pools, regional peak flow envelopes, and more, all to make a case for model results. Only after these checks are done do we consider the model to provide a best-estimate of flooding. At the same time, *confidence* is built through the reasonableness checks process. Some dams and basins may have a large amount of historical flood information, which makes a case for *strong confidence* in model results. Other basins may have very little flood information and may rely on regional data sets. Regardless, we have found that the process yields more defensible hydrology results than odeling alone.

<u>Caveats:</u>

1. Before starting a new hydrology study, please see our *Overview of Hydrologic Evaluation and Design Processes* document for a high-level roadmap of our two distinct hydrology processes: (1) risk-informed hydrologic evaluation for existing dams and (2) inflow design flood (IDF) analysis for new dams/modifications. Hydrologic risk analysis involves probabilistic analysis and consequence analysis of hydrologic dam failure, and is the basis for Colorado Dam Safety's risk-informed hydrologic evaluation of existing dams (see Flowchart 1, inside front cover herein). In contrast, IDF studies are used to develop a design flood to be used in design of new or modified dams and appurtenances (see Flowchart 2).

2. Please also see the following related Colorado Dam Safety guidelines:
   - For extreme rainfall estimation using Colorado's Regional Extreme Precipitation Study (REPS) tools, please see *Guidelines for the Use of Regional Extreme Precipitation Study (REPS) Rainfall Estimation Tools*
   - For analysis and estimation of consequences from hydrologic dam failure (used for hydrologic risk analysis and to determine risk-based Inflow Design Flood criteria), please see *Guidelines for Hydrologic Hazard Analysis*.

3. Previous *Colorado Dam Safety Hydrologic Basin Response and Parameter Estimation Guidelines* (2008) are superseded by these current hydrological modeling guidelines.

Section 2. **Background**

Previous Colorado Dam Safety hydrology guidelines (2008) recommended the Green & Ampt method to model infiltration losses. Because Green & Ampt is an infinite sink (i.e., losses are unlimited), maximum infiltration rates (Ksat) were artificially capped at 1.2 in/hr to prevent overestimation of losses. In practice, we found this approach could both underestimate losses for high-intensity thunderstorms (because the infiltration rate was artificially capped) and overestimate losses for low intensity general storms (because Green & Ampt is an infinite sink). This is particularly true for forested, mountain basins that have coarse grained, thin soil profiles. Our previous guidelines also recommended using U.S. Bureau of Reclamation *Flood Hydrology Manual* (Cudworth, 1989) unit hydrographs. The Rocky Mountain Thunderstorm UH in particular produced flashy design flood hydrographs, with implausibly high peak flows for Colorado's high-mountain basins.

Flood Hydrology Manual (Cudworth, 1989) hydrology methods have been popular for dam safety purposes for many years. But at the time of its publication Cudworth acknowledged "data representing basins located at higher elevations of these [Rocky Mountains] mountain ranges are generally lacking", and "the infrequency of severe rainstorms in these areas…precludes acquisition of a good data base representing severe event phenomena". Like our previous guidelines, Cudworth also recommended artificially low infiltration rates for modeling in order to explain observed floods. Then, unique to his treatment of the western U.S., he concluded there were two distinct rainfall-runoff UH transformations for the Rocky Mountain region: a slow transformation response for low-intensity general storms and a fast transformation for high-intensity thunderstorms. The new method presented herein is better at reproducing observed floods in the Rocky Mountains.

In 2017, as part of a site-specific hydrology study for a dam enlargement project, Colorado Dam Safety developed a proof-of-concept hydrology model ("Mountain Hydrology Model") that used higher infiltration rates (i.e., without artificial caps) and an approximate method of soil moisture accounting. At the same time, the project's design engineers used a traditional flood hydrology model using lower infiltration rates from Cudworth (1989). In general, the Colorado Dam Safety method outperformed the traditional model in reconstructing September 2013 flood hydrographs on a Front Range drainage, extending from high mountains down to the lower foothills (Perry et al, 2017). Figures 1 and 2 below compare simulated hydrographs at Pinecliffe (Figure 1), a high mountain location where infiltration losses were high and little surface runoff was observed, and at Eldorado Springs (Figure 2), along the first upslopes, where runoff was large but could only be explained by delayed saturation-excess runoff. Table 1 compares simulated September 2013 flood peak discharges and Probable Maximum Flood peaks calculated by the Mountain Hydrology Model and the traditional flood hydrology model for the study basin, and shows regional flood frequency and paleoflood peak flow estimates for comparison.

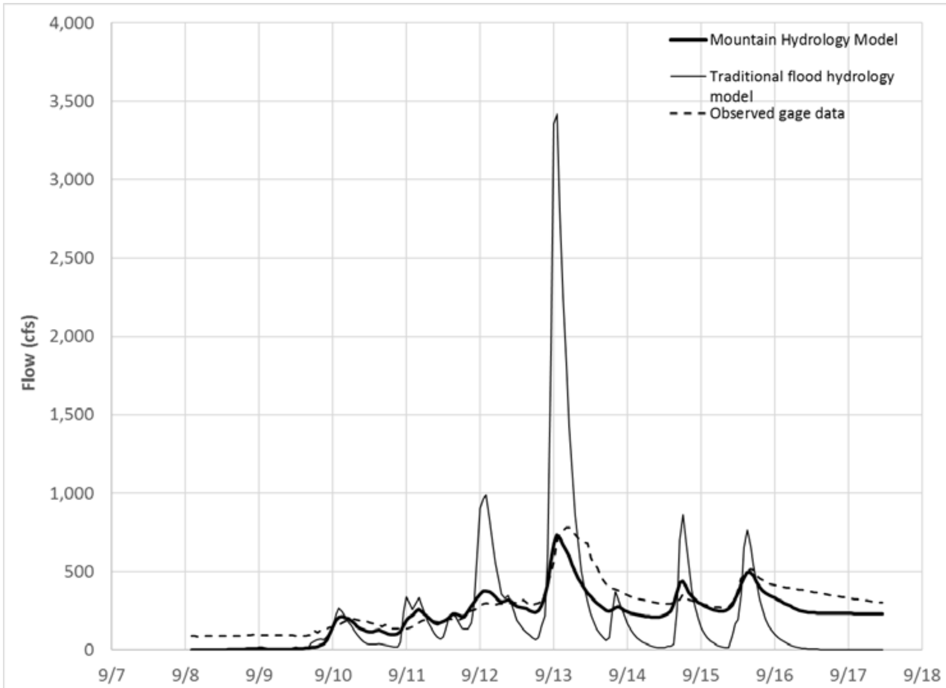

Figure 1: Colorado Dam Safety Mountain Hydrology model Sept 2013 hydrograph on South Boulder Creek at Pinecliffe (near 7930 ft elevation) versus the observed flood and a traditional flood hydrology model simulation. High infiltration losses occurred in the mountains above Pinecliffe and the traditional model significantly overestimated runoff (Perry et al, 2017).

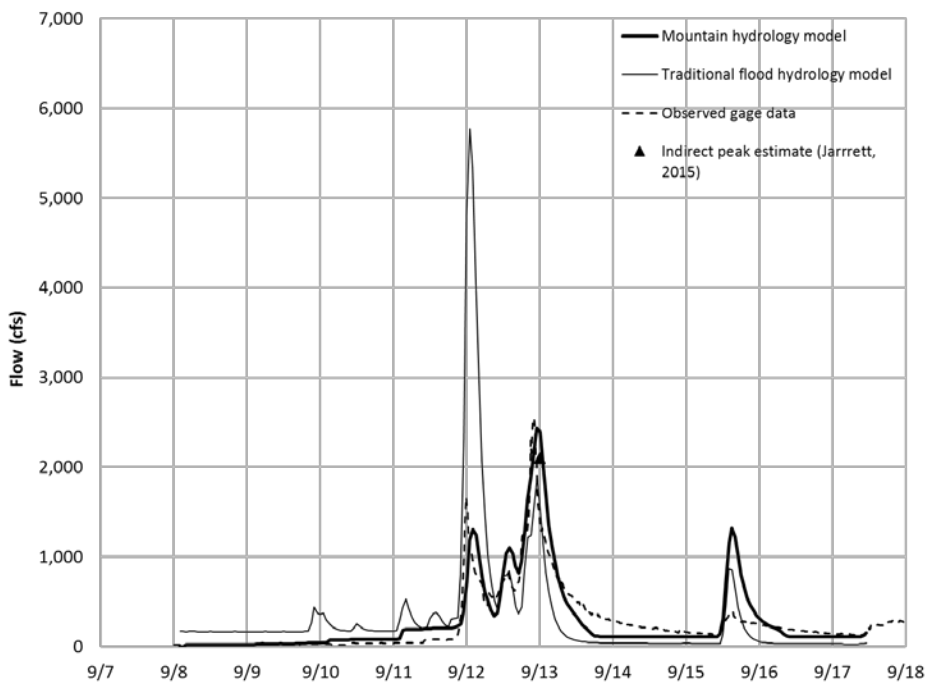

Figure 2: Colorado Dam Safety Mountain Hydrology model Sept 2013 hydrograph on South Boulder Creek at El Dorado Springs (near 6080 ft elevation) versus the observed flood and a traditional flood hydrology model simulation. Large runoff occurred here, but could only be explained by saturation-excess runoff and associated delayed runoff peak, which the traditional infiltration-excess model could not do (Perry et al, 2017).

Table 1: Comparison of peak flows and runoff volumes from Colorado Dam Safety's Mountain Hydrology Model versus traditional dam safety flood hydrology model for a Front Range basin. Regional flood frequency and paleoflood peak flow estimates are provided for comparison (Perry et al, 2017).

	Observed	Colorado Dam Safety Mountain Hydrology Model	Traditional Dam Safety Flood Hydrology Model
Peak Q at Pinecliffe, cfs (% error)	780	731 (-6%)	3415 (+338%)
Runoff Volume at Pinecliffe, ac-ft (% error)	4429	4425 (0%)	4195 (-5%)
Peak Q at Eldorado Springs, cfs (% error)	2552	2436 (-5%)	5768 (+126%)
Runoff Volume at Eldorado Springs, ac-ft (% error)	5221	5705 (+9%)	7442 (+30%)
Probable Maximum Flood Peak Q (cfs) at Gross Dam [upstream of Eldorado Springs] (DA=93 sqmi)	n/a	16,026 cfs[(1)]	40,115 cfs[(1)]
Regional Flood Frequency and Paleoflood Estimates For Comparison			
Bulletin 17C 500-YR (0.2%) Peak Flow Estimate at Eldorado Springs (DA=111 sqmi)	4,970 cfs		
Paleoflood Q Olympus Dam, Estes Park, CO (DA=138 sqmi)	3000-5000 cfs (P=3,000-5000 years), (Jarrett, 1989)		
Paleoflood Q at Buttonrock Dam (DA=101 sqmi)	7,300-9,950 cfs (P=6,500-6,700 years), (USBR, 2015)		

Note (1) PMF here was calculated using Site Specific PMP, estimated in a similar manner as the CO-NM REPS study. The historical PMF using HMR 55A rainfall had a peak discharge of around 90,000 cfs.

Following the 2017 proof-of-concept study, Colorado Dam Safety began a multi-year Mountain Hydrology Research Study with Colorado State University to develop new hydrology methods that accurately reproduce extreme flood production mechanisms in Colorado. In Phase I, CSU researchers used the soil moisture accounting (SMA) loss method in HEC-HMS to simulate historical extreme floods from 1976, 1997 and 2013 in five Colorado Front Range basins. They showed that HEC-HMS with SMA can produce three runoff mechanisms: infiltration excess runoff, saturation excess runoff (assumed to occur where saturation fraction of soil storage exceeds 85%), and subsurface lateral flow. Further they showed that these mechanisms are necessary and sufficient to accurately simulate observed flood hydrographs (Woolridge, 2019 and Woolridge et al, 2020).

During the course of the CSU Phase I study, Colorado Dam Safety completed the Regional Extreme Precipitation Study (REPS), which provides updated extreme precipitation frequency and probable maximum precipitation estimates for Colorado. REPS found that there are three distinct storm types that produce extreme precipitation here: local convective storms (small scale, short-duration, extreme rainfall intensity), meso-scale with embedded convection storms (medium spatial scale and duration, with embedded high rainfall intensity), and mid-latitude cyclones (large spatial coverage, long duration, and low rainfall intensity). In the Mountain Hydrology Study, CSU modeled REPS design storms by storm type for the five Front Range study-basins and showed that the controlling runoff mechanisms vary by storm type, storm magnitude, and by drainage basin (see Table 2). Traditional dam safety hydrology assumes that only infiltration excess runoff is relevant to extreme floods for dam safety design, but the CSU study showed that soil saturation runoff and subsurface flow can be relevant as well. Therefore, a hydrological model that produces these three runoff mechanisms is necessary.

Table 2. Controlling storm duration and dominant runoff mechanism for probable maximum precipitation (PMP) and annual exceedance probability (AEP) design storms

Basin	Storm type	Controlling storm duration (h)	Peak rainfall intensity (mm/h)	Total storm depth (mm)	Runoff mechanism
Bear Creek	PMP	6	47.5	158	S-E
	10^{-7} AEP	6	45.6	143	S-E
	10^{-6} AEP	6	38.5	120	S-E
	10^{-5} AEP	2	133.4	73	Both
	10^{-4} AEP	6	25.7	80	S-E
	10^{-3} AEP	48	12.6	139	S-E
Big Thompson River	PMP	72	22.3	339	S-E
	10^{-7} AEP	48	26.9	297	S-E
	10^{-6} AEP	48	22.7	2,501	S-E
	10^{-5} AEP	48	18.7	207	S-E
	10^{-4} AEP	2	87.8	48	I-E
	10^{-3} AEP	2	68.0	37	I-E
Cheyenne Creek	PMP	2	327.4	249	I-E
	10^{-7} AEP	48	41.4	458	S-E
	10^{-6} AEP	48	34.3	379	S-E
	10^{-5} AEP	48	27.8	308	S-E
	10^{-4} AEP	2	151.1	83	I-E
	10^{-3} AEP	2	119.0	65	I-E
North Fork Big Thompson River	PMP	2	222.8	169	I-E
	10^{-7} AEP	2	191.6	105	I-E
	10^{-6} AEP	2	160.6	88	I-E
	10^{-5} AEP	2	132.0	76	I-E
	10^{-4} AEP	2	105.5	58	I-E
	10^{-3} AEP	48	12.4	137	None
South Boulder Creek	PMP	72	30.5	422	S-E
	10^{-7} AEP	48	30.2	334	S-E
	10^{-6} AEP	2	160.8	88	I-E
	10^{-5} AEP	2	133.2	80	I-E
	10^{-4} AEP	2	107.6	59	I-E
	10^{-3} AEP	48	12.6	132.2	Both

Note: S-E = saturation-excess runoff; and I-E = infiltration-excess runoff.

In Phase II of the Mountain Hydrology Research Study, CSU developed parameter estimation methods for HEC-HMS SMA and then verified these methods for three basins and six historical floods in the San Juan Mountains (Irvin et al, 2021). CSU's research forms the basis of the CSU-SMA modeling method presented herein.

Finally, a large amount of historical extreme and extraordinary flood information exists for Colorado and forms the basis of reasonableness checks and model calibration discussed later in Sections 9 and 10 of these guidelines. In brief, two simple figures will suffice here to show key regional characteristics of historical floods in Colorado: Figure 3, taken from Jarrett and Tomlinson (2000), shows two curves of maximum observed unit discharges versus elevation. The following conclusions can be made: (1) flood yields are typically much higher in Eastern Colorado (east of the Continental Divide) than on the Western Slope below about 2,300 meters (approximately 7,500 feet) elevation and (2) flooding decreases dramatically with increasing elevation along the Front Range, with relatively low unit discharges observed above about 7,500 feet elevation. And Figure 4, taken from Smith et al (2018), shows that some of the country's most extreme floods (red dots), in terms of the ratio of observed peak flows to 10-YR flood frequency estimates, can occur in Colorado, but are concentrated along the highly-dynamic weather region of the Front Range foothills.

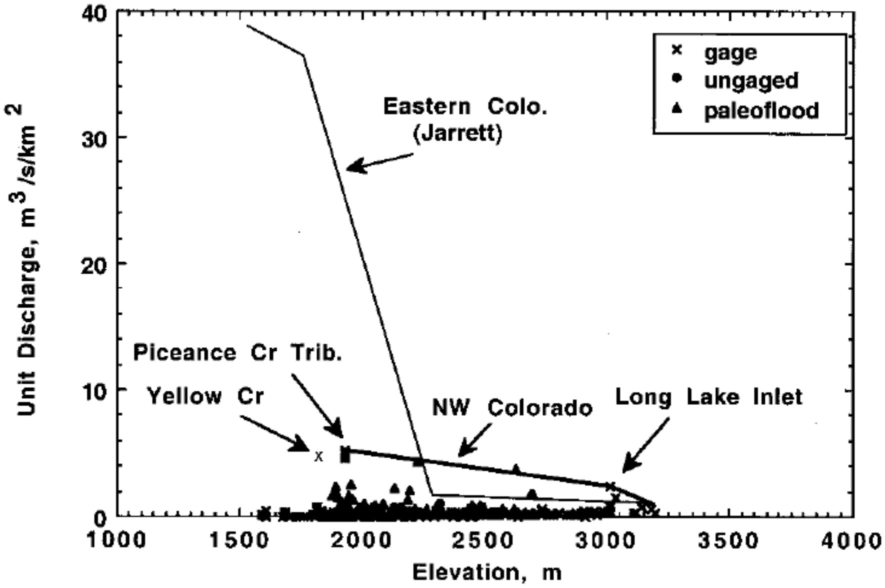

Figure 3: Regional relationships between maximum observed flood yields and elevation in Eastern Colorado and Northwest Colorado (from Jarrett and Tomlinson, 2000)

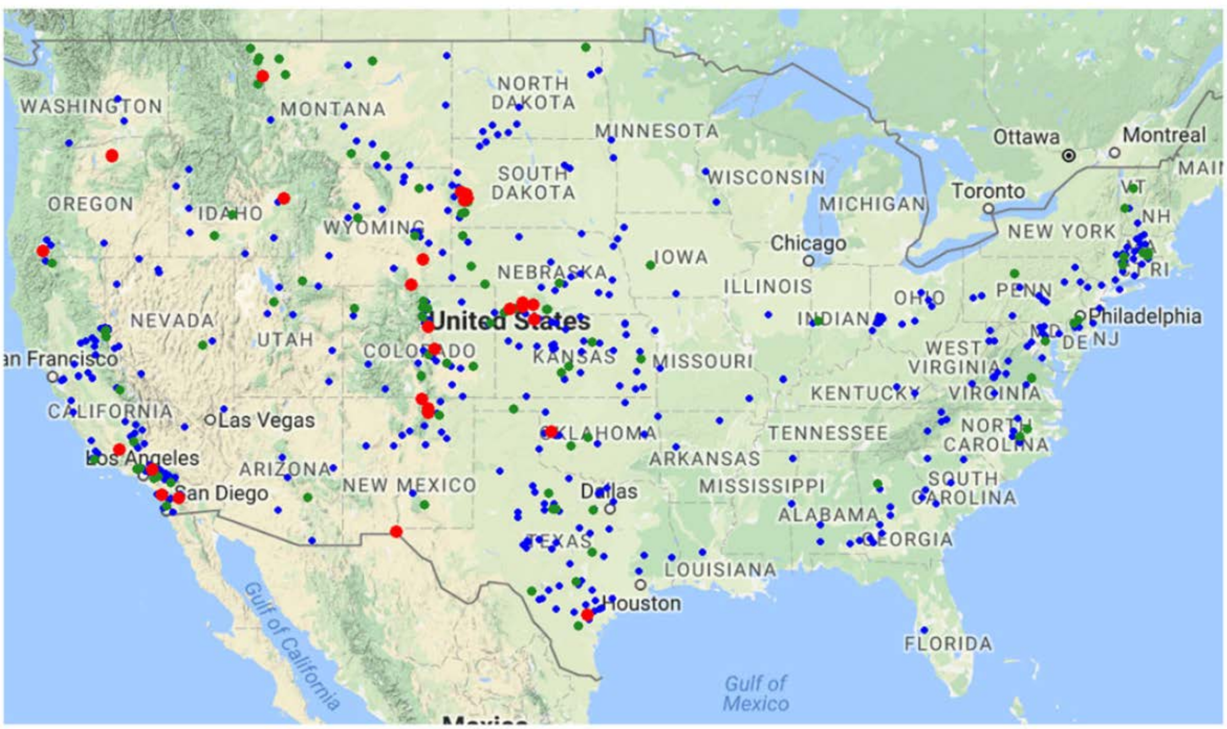

Figure 4: USGS stream gage locations where the ratio of maximum observed flood peak to the 10-YR flood frequency estimate is greater than 20 (red dots), 10-20 (green) and 5-10 (blue) (from Smith et al, 2018)

Section 3. **Overview of CSU-SMA Hydrology Modeling Method**

3.1 The previous section explained limitations of traditional dam safety flood hydrology modeling approaches and introduced the new Colorado State University-Soil Moisture Accounting (CSU-SMA) approach that can simulate infiltration-excess, saturation-excess, and subsurface runoff. Equally important is the use of the Clark Unit Hydrograph method, which allows more flexibility in modeling runoff transformation to shallow subsurface flow versus quickflow. Woodridge et al (2020) showed these flood production mechanisms are necessary and sufficient to reproduce historical extreme flood hydrographs in Colorado's Front Range Mountains and that they are necessary to capture variations in controlling design floods by REPS storm type for dam safety purposes.

3.2 This section provides an overview of the CSU-SMA model. It was developed using HEC-HMS 4.7; however, because computer programs change frequently, the discussion here is intended to allow adaptation to future versions of HEC-HMS or other hydrology modeling software. Figure 5 provides a schematic of the elements in the CSU-SMA method. Precipitation is the first element and is input using REPS design storm temporal patterns. Canopy storage represents interception that must be filled before throughfall occurs to the ground surface. In the CSU-SMA model water can leave canopy storage through evaporation. Throughfall will infiltrate the soil profile at a rate up to the soil infiltration capacity, after which infiltration-excess runoff occurs (surface runoff). Infiltration capacity is defined by a linearly-decreasing function of soil [water] storage in the profile (Figure 6). Infiltration losses are tracked and go towards filling the specified soil [water] storage volume.

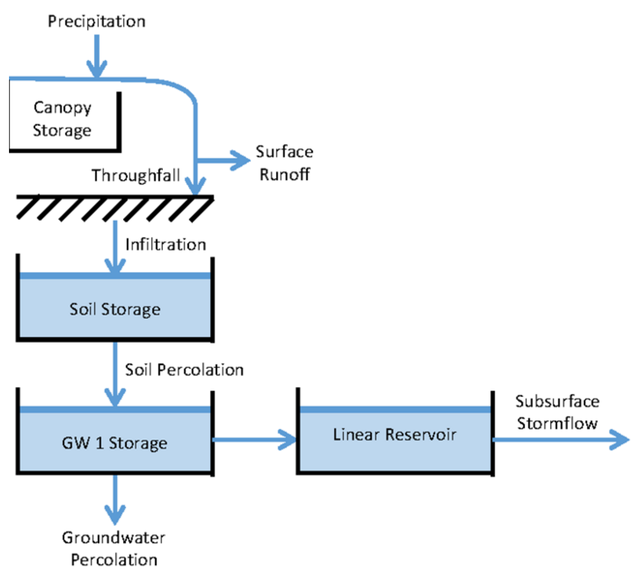

Figure 5: Schematic of CSU-SMA method (Woolridge, 2019)

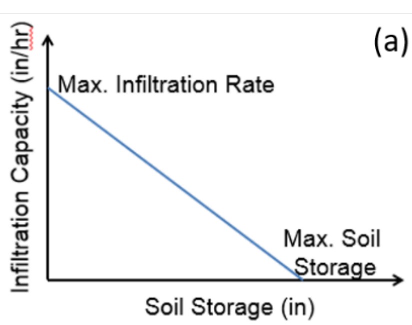

Figure 6: HEC-HMS SMA relationship between infiltration Capacity rate and Soil [water] Storage (Woolridge, 2019).

As soil water storage increases towards saturation, infiltration capacity decreases from its maximum, at zero soil storage, to zero infiltration, at soil saturation. This is a key difference from previous Green & Ampt and Initial and Constant Loss methods, which allowed infiltration to continue indefinitely. In the CSU-SMA model, as soil storage fills and infiltration approaches zero, then throughfall is forced to run off as saturation-excess runoff. At the same time, as the soil storage fills, soil water is allowed to percolate to a lower groundwater layer, which then can flow laterally back to streamflow or can percolate out of the system.

3.3 Other models, both existing and future, may be able to adequately represent the necessary flood production mechanisms. These may include GSSHA, MIKE SHE, SEFM and others. A layered Green & Ampt approach with soil moisture accounting may accurately model both infiltration-excess and saturation-excess runoff. Engineers may use adequate modeling methods other than the one described below, however, the reasonableness checks and calibration procedures described later in this document should be performed. NOTE: the SCS Curve Number method models a conceptually similar finite infiltration capacity (*S*); however, *CN*, from which *S* is calculated, is not physically based, and the SCS CN method does not produce subsurface flow.

3.4 The CSU-SMA model uses the Clark UH method in HEC-HMS for rainfall-runoff transformation. The Clark UH is well documented in hydrology literature and is widely used in practice. Our experience (and CSU research) suggests that the unit hydrograph approach is adequate for modeling floods in most undeveloped basins in Colorado, especially when model results are considered along with the reasonableness checks and calibration described in these guidelines. That said, other transform methods, including distributed models like HEC-RAS, may be justified on a basin-specific basis, for example, where basin shape, terrain or development do not lend themselves to a simple unit hydrograph approach.

3.5 The CSU-SMA model uses the Linear Reservoir baseflow method.

3.6 The CSU-SMA loss method in combination with the Clark UH is a conceptual approach that can produce a wide range of streamflow responses seen in the diverse terrain across Colorado. Later in these guidelines we suggest that flashy unit hydrograph surface runoff response is typical of floods in the Front Range foothills, Eastern Plains, and western canyons, indicating *quickflow* or *Horton runoff*; whereas, slower unit hydrograph response is typical of mountain basins, indicating *interflow* or shallow-subsurface flow. Mountain watersheds often have coarse-grained soils, fractured surficial bedrock, and large colluvial deposits, which may act to minimize quickflow and increase interflow and groundwater flow. Conceptually the CSU-SMA model represents both quickflow and interflow as "surface runoff", but Clark UH parameters can be varied to differentiate between them. Using checks and calibration against the observed flood record (Sections 9 & 10 herein), the CSU-SMA model can reproduce these varied conditions.

3.7 Snowmelt and rain-on-snow runoff are not explicitly addressed in the CSU-SMA modeling method. Clearly snowmelt is an important runoff production mechanism for mountain basins in Colorado. Typically, annual peak flows for basins above about 7,500 feet elevation are caused by snowmelt. However, Colorado Dam Safety's experience is that snowmelt floods do not control flooding at rare probabilities of interest for design of High and Significant Hazard dams. (For Low Hazard dams, flood frequency analysis or regional peak flow relationships, e.g. USGS StreamStats, both of which would reflect the influence of snowmelt runoff, should be used to determine more frequent inflow design floods -- see inset on Flowchart 2 above). Likewise rain-on-snow flooding has the potential to cause large floods, but seems to be rare in Colorado at this time, subject to future climate change. Rain-on-snow modeling is not specifically addressed in the CSU-SMA modeling method, but it can be identified by checks against the observed flood record described herein. Rain-on-snow modeling may be warranted on a basin-specific basis, where the observed flood record indicates it is relevant to extreme flood production.

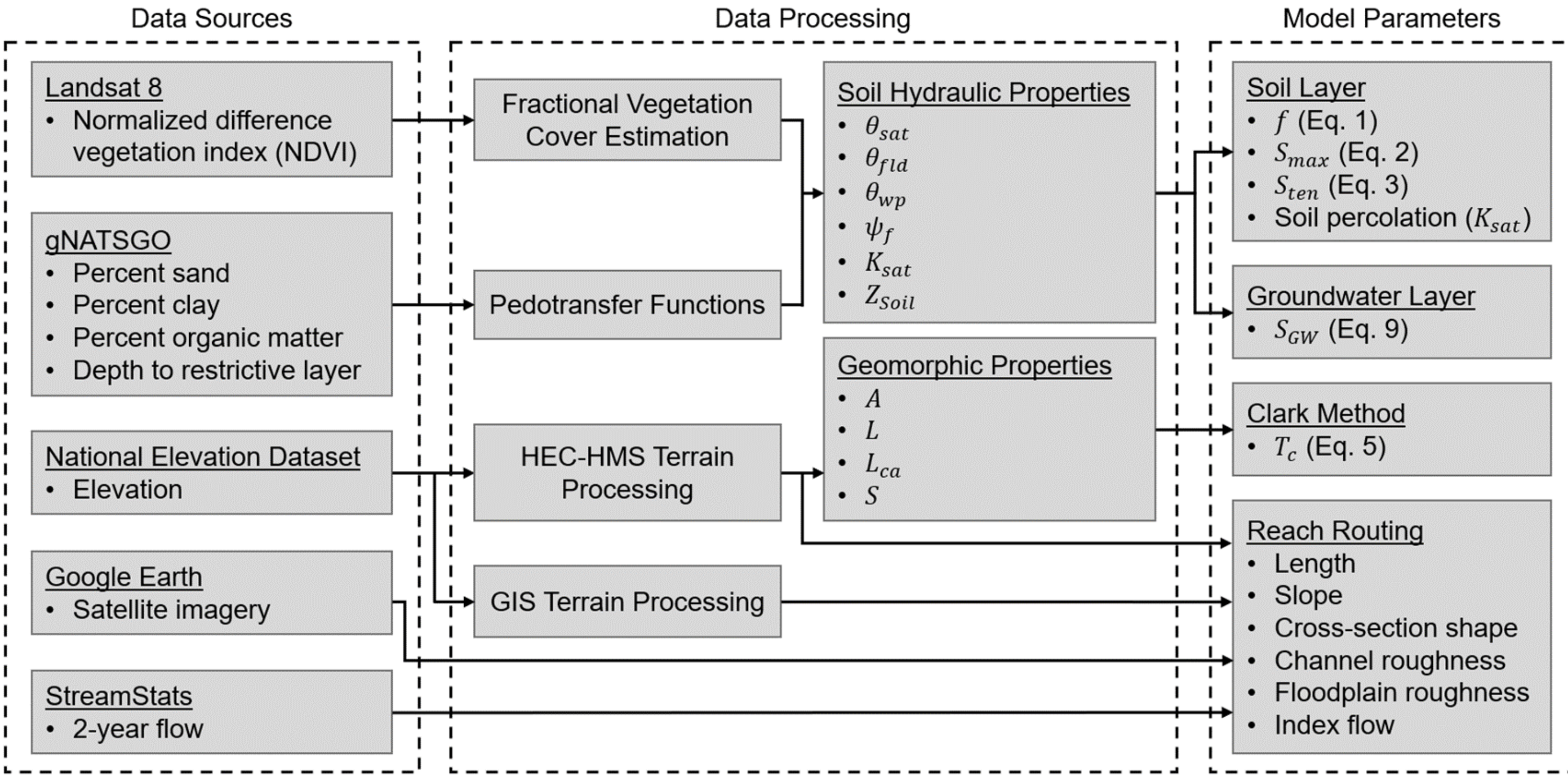

Figure 7: Overview of data sources, processing, and model parameters for the CSU-SMA modeling method (from Irvin et al, 2021, with permission).

Figure 7 gives an overview of the data, processing, and model parameters that are needed for the CSU-SMA modeling method. The following Sections 4, 5, and 6 provide details on each step.

3.8 Limitations: **The CSU-SMA modeling method described below requires user expertise and judgment. Sections 4-8 provide prescriptive steps, which should be considered as a starting point. Sections 9 and 10 describe checks, confidence, and calibration, which require hydrology and engineering expertise to ensure that model results are reasonable. Ultimately it is up to the engineer/user to make the case for their hydrology analysis and results; multiple lines of evidence (e.g. rainfall-runoff modeling, flood frequency analysis, review of historical floods) will increase confidence.**

Key references used in these guidelines are available at the following DWR ftp link for easy access and transparency so that the user is fully informed of the methods described herein (also see *References* section at the end of these guidelines):

https://drive.google.com/drive/folders/1bJBtYHy96ejo1YdS5xosaJi2TsVKto20?usp=sharing

The CSU-SMA method has been tested over a variety of basins across Colorado; however, situations requiring engineering judgment are sure to arise, at the responsibility of the user. Likewise, the computer tools provided herein are provided in good faith to advance the safety of dams in Colorado, and should be used at the user's risk. The methods and tools were developed using HEC-HMS 4.7 and ArcMap 10.4.1 with Spatial Analyst Extension. Colorado Dam Safety will attempt to update these guidelines following major software changes; however, some amount of interpretation for software changes and data sources should be expected by the user.

Lastly, these guidelines do not address burn scar hydrology associated with wildfires or their increasing occurrence in Colorado. Further research is needed on the effects of burn scar hydrology on extreme floods in Colorado and on joint probabilities associated with wildfire occurrence, burn scar duration, and extreme precipitation events in order to facilitate hydrologic risk analysis. We hope to address these issues in the future. Until then, risks associated with burn scar flooding should be addressed on an as-needed basis in consultation with Colorado Dam Safety.

Section 4. **CSU-SMA Method Input Data**

4.1 This section describes input data sets needed for the CSU-SMA method using HEC-HMS 4.7 and ArcMap 10.4.1 with Spatial Analyst Extension. Data sources may change and are the responsibility of the user. *Tip: the CSU-SMA method involves a large amount of input and output data. We recommend creating a folder structure that roughly follows the organization of these guidelines (e.g. Input data->DEM, Landsat, REPS). We recommend that all data be saved to the user's hard drive/local drive to facilitate analysis is ArcMap.*

4.2 Drainage basin boundary and point of concentration GIS shapefiles: These can easily be generated for the basin-of-interest using USGS StreamStats at https://streamstats.usgs.gov/ss/

4.3 DEM Terrain data: DEM data is needed for input to HEC-HMS for delineation of sub-basins and for determining certain basin properties used for unit hydrograph transformation and reach routing. DEM data can be downloaded from the USGS, currently at the following website: https://apps.nationalmap.gov/downloader/#/

In general, 10 meter (1/3 arc second) DEM grid resolution is considered to be adequate for hydrologic analysis; however, higher resolution DEM data, where available, may be useful for small or complex basins*. DEM data must be in GeoTiff format. The following instructions are suggested for the current version of the USGS National Map website: (1) zoom to area of interest on the map, (2) Select the following: Data sets tab -> Area of Interest=Map Extent; Data -> Elevation Products (3DEP) -> 1/3 are-second DEM -> File Format: GeoTiff, (3) Search Products (button at upper left), (4) Product tab -> add to cart, and (5) Cart tab -> download TIF. Note that multiple DEM tiles may be needed to cover the basin-of-interest.

* LiDAR DEM data for most of Colorado is available from the CWCB Colorado Hazard Mapping & Risk MAP Portal at the following weblink: https://coloradohazardmapping.com/lidarDownload

4.4 Landsat red and infrared band images[1]: These data sets are needed to calculate fractional vegetative cover (Fg) for the basin. Landsat images can be downloaded from the following website: https://earthexplorer.usgs.gov/

The following instructions are suggested for the current version of the Earth Explorer website: (1) create a login (user must be logged-in to download data), (2) Set Search Criteria -> Use map and zoom to area of interest, (3) Select Data Sets -> Landsat-> Landsat Collection 2 -> Landsat 4-5 TM C2 Level-1 or Level-2, (4) Additional Criteria: Land Cloud Cover <10%, Satellite=Landsat5, (5) Select the "footprint" icon and choose a flight path(s) that covers the entire basin-of-interest, if possible (if multiple tif images are required, guidance on combining them for analysis is provided in Section 5 below). The recommendation is to use imagery from September or October in order to conservatively estimate vegetative cover for the basin. Another approach would be to base the Landsat imagery date/season on the seasonality of REPS design storms (discussed more in Section 9 below). Finally, (6) download the Landsat red (B3 band) and infrared (B4) GeoTiff file(s) using the download icon, then select the *Product Options* drop down from the *Download Options* window, and download the *tif* files ending in *B3* and *B4* (e.g., *LT05_L1TP_034034_20111115_20200820_02_T1_B3.TIF* .

4.5 Soil property raster data sets: Raster data sets of percent sand, percent clay, percent organic matter, and of depth to restrictive layer were obtained from the NRCS Gridded National Soil Survey Geographic Database (gNATSGO). These raster data sets have been tiled and clipped to cover the tributary area of Colorado and can be downloaded from the following DWR ftp link.

[1] NOTE: This Landsat-based method is provided as an automated, consistent way to estimate fractional vegetative cover (Fg), which is used in the CSU-SMA method to adjust infiltration rates. Other methods to determine Fg, adequately justified, may be used, if desired.

NOTE: (1) total file size is about 850 MB and (2) raster data units are % for soil texture rasters and centimeters for depth to restrictive layer:
https://dnrftp.state.co.us/#/DWR/DamSafety/Colorado_Soils/

Alternatively, gNATSCGO data can be downloaded directly from the NRCS website:
https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcseprd1464625

4.6 Design Storms, Temporal Data: Colorado Regional Extreme Precipitation Study (REPS) PMP and precipitation frequency tools should be used for design storm inputs. See Colorado Dam Safety's *Guidelines for the Use of Regional Extreme Precipitation Study (REPS) Rainfall Estimation Tools* at the following Google Drive link:
https://dnrweblink.state.co.us/dwr/ElectronicFile.aspx?docid=3566813&dbid=0

Where a drainage basin size exceeds storm area size limits in REPS, then partial area analysis should be performed. REPS area size limits by storm type are shown below in Table 3.

Table 3: REPS PMP Tool and MetPortal Precipitation Frequency tool storm area size limits by storm type

Region	**REPS PMP, Storm Area Size Limits**		
	2-hr & 6-hr Local Storm PMP	24-hr Local Storm PMP	72-hr General & Tropical Storms PMP
All	100 sq mi	Refer to area size of controlling historical storm(s), see REPS Summary Report Vol. II, App. F	No limit
	REPS MetPortal Precip. Frequency, Storm Area Size Limits		
	2-hr Local Storm PF	6-hr MEC Storm PF	48-hr MLC storm PF
East Macro Region*	200 sq mi	500 sq mi	1000 sq mi
Rio Grande Macro Region*	200 sq mi	500 sq mi	500 sq mi
West Macro Region*	100 sq mi	200 sq mi	500 sq mi

* REPS Metportal macro region for basin-of-interest is reported on the Watershed PF tab of MetPortal; also, the Macro Region layer can be turned on in the MetPortal map display.

In general, partial area analysis should use the maximum storm area size allowed by REPS, with the storm area positioned closest to the dam or basin outlet. Individual cases may vary in terms of determining controlling runoff.

Tip: In practice, HEC-HMS modeling will be easier if sub-basins are delineated first (see Section 5 below), and then REPS partial areas, if needed, are selected to consist of discrete HEC-HMS sub-basins, as close in size to the REPS storm area size limits as possible without exceeding them. Partial area shapefile(s) can be uploaded to REPS MetPortal and REPS PMP Tool (NOTE: For MetPortal make sure to first remove/dissolve any sub-basins boundaries in ArcMap). Finally, REPS partial area design storms can be input into HEC-HMS as precipitation gages and then assigned to the applicable sub-basins that comprise the partial area.

Where the basin-of-interest is smaller than REPS storm area size limits, then simply run the REPS PMP and MetPortal precipitation frequency tools for the entire basin area. We recommend using spatially uniform REPS design storms for most basins. Optionally, the REPS PMP Tool will return partially distributed PMP estimates for sub-basin elements within a larger basin shapefile, if desired. Our guidance is to use the sub-basins option when the REPS gridded PMP values vary significantly across the basin, for example, if the basin crosses major REPS climate regions like the 7,500-ft boundary along the Front Range foothills.

Section 5. **Generating CSU-SMA Model Sub-basin Properties**

5.1 Some minor pre-processing of the input data is necessary in order to generate sub-basin properties in ArcMap and in HEC-HMS, which are in turn used to generate CSU-SMA model parameters.

5.1.1 Calculate a fractional vegetative cover (Fg) raster from Landsat images (directions are based on ArcMap 10.4.1)[2]:

- Load USGS Landsat 5 B3.tif (red) and B4.tif (near-infrared) images into ArcMap
- If multiple Landsat tif images are needed to cover the basin-of-interest, then mosaic them in ArcMap:
    - use Data Management Tools -> Raster -> Raster Data set ->Mosaic
    - Input Rasters: select all B3 (or B4) tifs that cover entire basin
    - Target Raster: select one of the existing B3 (or B4) tifs
    - Mosaic operator: select Maximum
    - Ignore background value: 0
    - Mosaic Tolerance: 0
- Calculate normalized difference vegetation index (*NDVI*) using ArcMap's Map Algebra Raster Calculator in the Spatial Analyst Toolbox: *Tip: Spatial Analyst license is required and the extension must be turned on.*
    - In Raster Calculator, select output folder and name output raster *NDVI*
    - Enter the following *NDVI* equation in Raster Calculator:

      Float(B4 – B3)/Float(B4+B3)

      where B3 and B4 are Landsat 5 band rasters for red and NIR, respectively. *Tip: Raster Calculator requires use of its functions, i.e., select functions, do not type them (e.g. "float" function is in the right hand menu box).*
    - General notes about *NDVI*:
        - *NDVI* will range from 1 (if B3=0) to -1 (if B4 = 0)
        - Negative *NDVI* corresponds mostly to open water and snow; rock outcrop may also appear as negative
- Next, calculate *Fg* from *NDVI* raster:
    - In Raster Calculator, select output folder and name output raster *Fg*
    - Enter the following *Fg* equation in Raster Calculator:

$$(Float("NDVI_i") - NDVI_0)*(Float("NDVI_i") - NDVI_0) \;/\; ((NDVI_{inf} - NDVI_0)*(NDVI_{inf} - NDVI_0))$$

      where "$NDVI_i$" is the *NDVI* raster calculated above, $NDVI_{inf}$ and $NDVI_0$ are numerical estimates for forested/lush vegetation and for bare soil locations, respectively. *Tip: The intent of $NDVI_{inf}$ and $NDVI_0$ is to bracket the range of NDVI values for the basin-of-interest.*
    - Montandon & Small (2007) suggest determining regional values for $NDVI_{inf}$ and $NDVI_0$ Tip: *turn on aerial photo in ArcMap and use Identify tool to find $NDVI_i$ raster values at heavily forested and at barren soil locations near the basin-of-interest. ALTERNATIVELY, find min, max NDVI in ArcMap raster properties OR from the NDVI raster histogram (e.g. Spatial Analyst->Reclassify->Classify will generate a raster histogram)*
    - Timilsina et al (2021) found $NDVI_0$ =0.04, $NDVI_{inf}$=0.7 for Colorado's Front Range mountains. Colorado Dam Safety has generally found similar values.

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[2] During beta testing, this Fg raster calculation resulted in some difficulty. Some testers asked if Colorado Dam Safety could calculate an Fg raster for the entire state? Unfortunately, that is not practical because Landsat images should be selected based on low cloud cover, season-of-interest, etc. for each basin. For perspective on your Fg effort, our recommendation is simply to use the Fg raster as a starting point, understanding that it affects SMA infiltration rate (see Section 6), which can be calibrated later by the procedures in Sections 9 & 10 below.

5.1.2 Next in terms of pre-processing input data to determine sub-basin properties: first *mosaic* DEMs if multiple DEMs are needed to cover basin-of-interest, (see ArcMap *mosaic* instructions in Section 5.1.1), then *clip* the DEM in ArcMap to the general basin area, in order to minimize drainage network processing time in HEC-HMS. We recommend clipping the DEM to the USGS StreamStats basin boundary shapefile with a buffer to allow for differences between USGS StreamStats and HEC-HMS DEM-based delineations:

- To buffer basin shapefile: Use ArcToolbox Analysis Tools->Proximity->Buffer
- To clip the DEM tif:
    - o Data management Tools -> Raster ->Raster Processing->Clip (keep output in tif format for use in HEC-HMS)
    - o Check the box: Use input features for clipping geometry
    - o Specify ".tif" extension in output raster filename

5.2 For determining sub-basin properties, delineate sub-basins in HEC-HMS using the clipped DEM, then calculate sub-basin characteristics and reach characteristics in HEC-HMS[3]:

- Open HEC-HMS, create a new project and save. Select U.S. Customary units. NOTE: DEM units (typically meters) are specified when the terrain model is imported (see below).
- Create a basin model: Components >> Basin Model Manager
- Create a terrain model: Components >> Terrain Model Manager
- Name new Terrain
- Navigate to your clipped DEM tif file (see above). Specify elevation units (typically meters)
- **For Sub-basin Delineation:** In the watershed explorer, select the basin model and link Terrain Data to the new Terrain model, then follow the prompts:
    - o Select UTM predefined coordinates (Zone 13N for most of CO, except Zone 12N for the far west) (GIS drop down menu, select coordinate system – predefined). *Tip: At this point user may need to link the basin model to the terrain model again for the DEM to appear in the HEC-HMS desktop display.*
    - o Next, GIS menu -> select "Process Sinks" – HMS will then identify and fill in any drainage pits in the DEM (NOTE: engineer should use judgement to determine whether this step is appropriate for the basin-of-interest)
    - o GIS menu -> select "Process Drainage" – this step combines the creation of flow direction and flow accumulation grids.
    - o GIS menu -> select "Identify Streams" – this will create a stream network based on a user-specified **area threshold***

***Guidance on Area Threshold:** Area threshold in HEC-HMS defines the minimum contributing area where streams start. Area threshold is related to, but not equal to sub-basin area size. Under "Delineate Elements" (see below) HEC-HMS will create sub-basins at stream junctions -- smaller area thresholds will result in a denser stream network, which will result in more and smaller sub-basins (see *Guidance on Sub-basin Area Size* below). CSU's Mountain Hydrology Research Study used an area threshold of 15 km^2 (5.77 sqmi) based on spatial variation in observed (historical) storm rainfall. On one hand, for our purposes, REPS design storms do not have the same spatial variation (we generally use spatially uniform REPS rainfall); on the other hand, during Phase II verification, CSU found their model parameter estimation methods are dependent on area threshold size. When larger areas were used (i.e. fewer sub-basins), CSU found that modeled peak flows were lower. Therefore, we recommend using an area threshold of 10 sqmi or less. However, a mitigating factor here is our additional steps of reasonableness checks and model calibration against the observed flood record (Sections 9 & 10 below), which may provide an opportunity to "correct" a model that uses larger sub-basin areas.

    - o Next, right click anywhere in the basin model window and select "Map Layers" -> Add -> USGS StreamStats point of concentration shapefile (i.e. *globalwatershedpoint.shp*) to define the basin outlet

[3] The HEC-HMS method is described here for the user's benefit. Other industry standard methods for sub-basin delineation and calculating basin properties are acceptable.

- Turn off all map layers except the USGS StreamStats POC and the *Identified Streams* layer
- Zoom in to the POC
- Use Break Point Creation Tool (cross with red dot) -> select point on stream closest to USGS StreamStats POC to define the basin outlet (*Tip: break point must be directly on an identified stream*)
- Repeat Break Point Creation Tool to create break points at specific **sub-basin locations*, if desired; otherwise, HEC-HMS will automatically delineate sub-basins based on junctions in its identified stream network**.

***Guidance on Sub-basins** (cross-reference *Guidance on Area Threshold*, above).
The following factors should be considered in determining sub-basin area sizes and locations:

1) REPS Climate Regions: Sub-basins should be used where REPS PMP estimates vary significantly across climate regions, for example, if the basin spans across REPS climate (storm transposition) zone 3 (foothills) and zone 5 (mountains). In this case, the sub-basins option should be used in the REPS PMP Tool to get semi-distributed sub-basin PMP estimates and then assign them as separate precipitation gages in HEC-HMS.
2) REPS Storm Area Size Limits (see Section 4.6 above): If the basin-of-interest exceeds REPS storm area size limits, then partial area sub-basins should be used for REPS analysis of relevant storm types.
3) CSU Contributing Area Threshold (see *Guidelines on Area Threshold* above): HEC-HMS *area threshold* per the above guidance will determine the density of HEC-HMS's stream network and sub-basins at junctions, by default. However, if breakpoints are entered manually they will override the area threshold for sub-basin delineation.
4) Physiographic differences: Sub-basins should used to separate significant differences in basin soils, vegetative cover, slope, etc., which would result in different unit hydrograph responses and infiltration losses.
5) Key locations for model reasonableness checks and model calibration: e.g. stream gage locations, locations of paleoflood estimates, indirect flood peaks, etc.

- Next, use GIS menu and select "Delineate Elements"
- Set subbasin prefix to "Sub-", set reach prefix to "Reach-", "Yes" for insert junctions, set junction prefix to "Junction-", and "Yes" for convert breakpoints
- Click OK and HMS will delineate the watershed of interest and create sub-basins and stream reach structure
- Export the sub-basin structure as a shapefile: GIS menu -> "Export Georeferenced Elements"
- In ArcMap create a raster version of the sub-basin shapefile using ArcToolbox->Conversion Tools->To Raster->Polygon to raster. Both the polygon and the raster versions will be needed to estimate parameters in Section 6 below.
- The user needs to check the HMS basin delineation for accuracy. *Tip: If necessary, the user can manually edit the subbasins shapefile in ArcMap. Then re-open HEC-HMS and delete only the edited sub-basin elements and re-import the edited sub-basin shapefile into HEC-HMS using GIS->Import Georeferenced Elements. Basin and Reach characteristics must be recomputed for edited elements using the Parameters menu.*

- **For Clark Unit Hydrograph:**
  - HEC-HMS Parameters menu -> Subbasin Area. Lists area size of each subbasin.
  - HEC-HMS Parameters menu -> Characteristics -> Sub-basin. HMS will calculate sub-basin properties to be used in unit hydrograph parameter calculations (Clark UH parameter calculations are described in Section 6 below).
  - The following relevant sub-basin properties are calculated by HEC-HMS: area, longest flow path length, longest flowpath slope, and centroidal flowpath length.

- **For Muskingum-Cunge Reach Routing:**
  - HEC-HMS Parameters menu -> Characteristics -> Reach. HEC-HMS will calculate

reach properties to be used in routing parameter calculations. Unit conversions will need to be done by the user.
  - The following relevant reach properties are calculated by HEC-HMS: length & slope.
  - Stream reach cross-section geometry must be determined by the user. *Tip: transects can be cut from DEM to help estimate channel shape.*

5.3 The final step in *Generating Sub-basin Properties* is to calculate sub-basin average soil and vegetation properties: %sand, %clay, %organic matter, depth to restrictive layer, and fractional vegetation cover. These sub-basin properties can be calculated using the CSU-SMA python ArcToolbox, which is provided as a courtesy at the user's risk and is described in detail in Section 6, *Parameter Estimation*. Before the script calculates the CSU-SMA model parameters, it first calculates sub-basin properties using the gNATSCO soils and Fg vegetation raster data. The *CSU-SMApython* script generates the following sub-basin property GIS attribute table output:

- *Sbprop_sand_table*: sub-basin average sand fraction, use Mean column [unitless]
- *Sbprop_clay_table*: sub-basin average clay fraction, use Mean column [unitless]
- *Sbprop_om_table*: sub-basin average organic matter fraction, use Mean column [unitless]
- *Sbprop_dtrl_table*, sub-basin average depth-to-restrictive-layer, use Mean column [inches]
- *Sbprop_fg_table*, sub-basin average fractional vegetation cover (described above), use Mean column [unitless]

As described in the following section the *CSU-SMApython* script will use these soil and vegetative cover properties to calculate HEC-HMS SMA soil loss parameters with pedotransfer functions by Saxton & Rawls (2006).

NOTE: The gNATSCO data set has a small fraction of missing data over Colorado, but is considered best available information. The CSU-SMApython script simply ignores missing data when calculating sub-basin average properties and model parameters. We recommend that the user view missing data in ArcMap for your basin-of-interest and factor it into your model confidence evaluation and calibration. In some cases it may be possible to use other sources of soil data to help estimate sub-basin properties, e.g. US Forest Service soil surveys.

5.4 **Sub-basin Properties Reporting Requirements:** Engineers should provide the following reporting and quality control checks for sub-basin properties (**NOTE: see hyperlinks below to supporting spreadsheet tools, provided as a courtesy and at the user's risk. See Example Reporting in Appendix A and Reporting Checklists in Appendix C**): *Tip: Our recommendation is to perform this reporting step before proceeding to Parameter Estimation, such that reporting and checking are completed linearly; reporting facilitates subsequent steps in the process.*

5.4.1 REPS PMP Tool Output Reporting (see examples in Appendix A):

- Print GIS map of cumulative rainfall for each PMP storm type applicable to the basin of interest (e.g. 2hr LS PMP, 6hr LS PMP, 24hr LS PMP (Zones 1 and 3 only), 72hr GS PMP, and 72hr TS PMP (south of 38.5º lat. only))
- Print basin average PMP GIS attribute table output for each storm type.
- Print temporal distribution data and graph the cumulative rainfall hyetographs for each storm type (link to spreadsheet tool). For each storm type, only include the temporal distribution(s) used in the analysis (e.g. LS 6hr Synthetic West; see REPS guidelines for recommended distributions).
- For each storm type, print *PMP_points* GIS attribute table output (e.g. Local_PMP_Points_basinname_XXsqmi), which shows controlling historical storms by duration and location at each grid cell in the basin-of-interest.

5.4.2 REPS MetPortal Precipitation Frequency Output:

- Print screen image of Frequency Curve with confidence bounds and REPS PMP for the same duration, along with the map image of the basin shapefile, for each storm type.
- Print temporal distribution hyetograph image from MetPortal and print the temporal distribution data for each storm type (scaled to 10e-2 for reporting purposes).

5.4.3 If Partial Area Analysis is performed based on REPS storm area size limits (see Section 4.6 above), include a summary table that shows which sub-basins are included and area size for each partial area by REPS storm type (*link to sample spreadsheet tool*)

5.4.4 Document and report the selected $NDVI_o$ and $NDVI_{inf}$ values for basin-of interest that were used to calculate fractional vegetative cover (Fg).

5.4.5 Print the five *CSU-SMApython* sub-basin property output tables listed above in Section 5.3 (*Sbprop_sand_table, Sbprop_clay_table, Sbprop_om_table, Sbprop_dtrl_table, and Sbprop_fg_table*).

5.4.6 Create a sub-basin properties summary table for reporting and review purposes to include the following properties by sub-basin: average %sand, average %clay, average %OM, average Depth to Restrictive Layer in inches, and average % fractional vegetative cover (obtained from CSU python script output), and from HEC-HMS: sub-basin area, L (longest flow path), Lca (length of centroid flow path), and slope (longest flowpath slope) *(link to sample spreadsheet tool).*

5.4.7 Create a stream reach properties table for reporting and review purposes to include the following: reach length in feet, reach slope in ft/ft, and stream cross-section geometry description *(Link to sample spreadsheet tool).*

5.4.8 Print GIS maps of the following sub-basin properties (*see examples in Appendix A*):

- Sub-basin delineation & labels with stream reach structure and labels -- *INCLUDE PARTIAL AREAS by REPS storm type, if applicable (see Section 4.6 above)*
- Aerial imagery
- Topographic map
- Sand fraction
- Clay fraction
- Organic matter fraction
- Depth to restrictive layer
- Fractional vegetative cover

5.4.9 For QC checking, sub-basin maps and sub-basin property averages should be reviewed to determine whether they make physical sense for the basin and region of interest.

Section 6. **CSU-SMA Model Parameter Estimates**

6.1 The CSU-SMA method uses the following elements & methods in HEC-HMS, for which parameter estimates are necessary (cross-reference Figure 5 above):

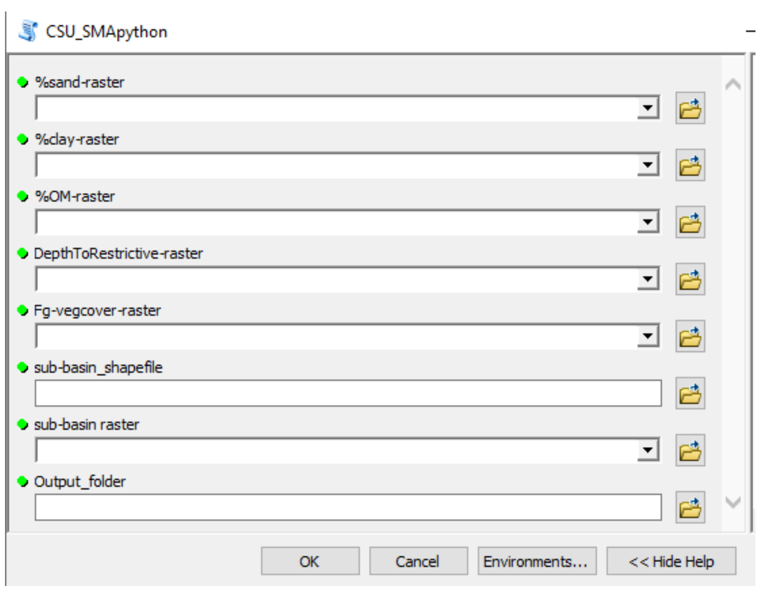
- Meteorological Model: Precipitation Specified Hyetograph, Annual Evapotranspiration
- Basin Model: Simple Canopy, Soil Moisture Acccounting (SMA) loss, Clark Unit Hydrograph transform, Linear Reservoir baseflow
- Reach Routing: Muskinghum-Cunge

6.2 **HEC-HMS SMA model loss method parameters** can be estimated based on the CSU Mountain Hydrology Research Study Phase II (Irvin, 2021). Irvin (2021) developed soil hydraulic properties after Rawls et al (1983), Saxton and Rawls (2006), and Sabol (2008). CSU and Colorado Dam Safety developed a python script named *pedotransfer_fn.py* and an ArcToolbox named *CSU_SMApython2,* in order to automate HEC-HMS SMA parameter estimation per Irvin (2021). The script is provided as a courtesy, at the user's risk, and can be downloaded from the following DWR Google Drive link:
https://drive.google.com/drive/folders/1nuF3Oj8UTfgLm7YRZQS4lvKVAJbf69UV?usp=sharing

Please note the following points about the CSU-SMApython2 ArcTool and python script:

- The CSU_SMApython2.tbx file, *Loss* folder, and all files in the folder must be downloaded
- We recommend saving the files/folder to a local hard drive to run in ArcMap
- The full script is shown in Appendix B, for transparency. The downloaded script can be edited as-needed using IDLE, with the understanding that Colorado Dam Safety will review projects based on our version and significant changes should be documented by the user.
- Irvin (2021), Rawls et al (1983), Saxton and Rawls (2006), and Sabol (2008) papers are provided at the following Google Drive link, for easy reference and transparency: https://drive.google.com/drive/folders/1bJBtYHy96ejo1YdS5xosaJi2TsVKto20?usp=sharing

To run the CSU_SMApython2 tool in ArcMap, select "Add Toolbox" in the ArcToolbox window and navigate to the downloaded *CSU_SMApython2.tbx* file. In the new toolbox, right click on *CSU_SMApython*, select properties, and navigate to the location of the downloaded *pedotransfer_fn.py* script. Next, double-click on *CSU_SMApython* to run the ArcTool and the following user interface should appear:



Using the dropdowns, select the %sand, %clay, % organic matter (OM), depth to restrictive layer input data (all from Section 4.5 above), and Fg fractional vegetative cover raster (from Section 5.1 above). Navigate to the HEC-HMS Sub-basin shapefile and then to the Sub-basin raster (both from Section 5.2 above). Navigate to the desired output folder, where the *CSU-SMApython* script will save sub-basin property and parameter output tables (we recommend saving files to the user's local hard drive). Click *OK* to run the script.

First the *CSU_SMApython* script calculates the following soil hydraulic properties using pedotransfer functions from Rawls et al (1983), Saxton and Rawls (2006), and Sabol (2008):

- Soil water fraction at saturation (*theta_s*)
- Soil water fraction at field capacity (*theta_33*)
- Soil water fraction at wilting point (*theta_1500*)
- Wetting front suction head (*psif*)
- Saturated hydraulic conductivity for bare ground in mm/hr (*Ksatbare*)
- Saturated hydraulic conductivity adjusted for vegetative cover in mm/hr (*Ksat*)
- Max infiltration rate over 3-inch depth using Green & Ampt equation (*f*)
- Maximum soil water storage, inches, (*S_max*)
- Field capacity water storage, inches, (*Si_fld*)
- Wilting point water storage, inches, (*Si_wp*)

Next the *CSU_SMApython* script uses the above soil hydraulic properties to estimate the following HEC-HMS SMA loss method parameters. Equations for parameters are shown in Table 4.

- Max infiltration, in/hr (*HMS_maxinfil*)
- Soil percolation, in/hr (*HMS_soilperc*)
- Soil storage, inches (*HMS_ss*)
- GW1 storage, inches (*HMS_GWst*)
- Tension storage, inches (*HMS_tens*)
- Initial soil moisture, Soil, % (*HMS_InSM*)

Table 4: CSU-SMA parameter equations

Parameter	Pedotransfer Equation
Max Infiltration Rate	½*Ksat(1+psif/d_{wf}), d_{wf}=75mm, (Woolridge et al, 2020), where, Ksat=Ksatbare*(1 + (Fg*100 – 10)/90)
Soil Percolation	¼*Ksat
Soil Storage	(1-pctgGW)(Smax – Si_wp), pctgGW=0.10, (Koren et al 2000)
GW1 Storage	pctgGW(Smax – Si_wp), (Koren et al, 2000)
Tension Storage	Si_fld – Si_wp, (Koren et al 2000)
Initial Soil Moisture	(S_fld – Si_wp)/(Smax – Si_wp)

The *CSU_SMApython* script creates output tables for sub-basin average soil properties (listed in Section 5.3 above), and it creates the following output tables for HEC-HMS SMA loss method parameter estimates:

- *hms_maxinfil_table* [units=in/hr] == HEC-HMS Max Infiltration (in/hr)
- *hms_soilperc_table* [units=in/hr] == HEC-HMS Soil Percolation (in/hr)
- *hms_soilstorage_table* [units=inches] == HEC-HMS Soil Storage (in)
- *hms_gw1storage_table* [units=inches] == HEC-HMS parameter GW1 Storage (in)
- *hms_tensionstore_table* [units=inches] == HEC-HMS Tension Storage (in)
- *hms_initialsm_table* [units=%] == HEC-HMS Soil (%)

Navigate to the user-specified *CSU_SMApython* output folder and load the soil property and SMA parameter output tables into ArcMap as attribute tables, then export the tables as text files for use in report documentation and to facilitate input to HEC-HMS.

6.3 **Clark Unit Hydrograph parameters** can be estimated using the Dam Safety Branch's *Clark UH parameters.xlsx* spreadsheet, provided at the following DWR Google Drive link: https://docs.google.com/spreadsheets/d/1acY4BqPT50dB_HgfI3rJ3b3ISwHTEjN4/edit?usp=sharing&ouid=115042170524029578776&rtpof=true&sd=true

The CSU-SMA model method calculates Clark UH time of concentration, T_c, per Sabol (2008) for generally undeveloped basins in the Rocky Mountains, Great Plains, and Colorado Plateau, as:

$$T_c = 2.4A^{0.1}L^{0.25}L_{ca}^{0.25}S^{-0.2}$$

where A is total sub-basin area, sq mi
L is longest flowpath length, miles
S is longest flowpath slope, ft/mile
L_{ca} is centroidal flowpath length, miles

Sabol (2008) also provides T_c equations for agricultural and urban basins, which may be appropriate for developed basins and sub-basins.

CSU's mountain hydrology research estimated the Clark UH storage coefficient parameter (R) assuming that the ratio $R/(T_c+R)$ is regionally uniform (Wang and Dawdy, 2012) and within the range of 0.6 to 0.8 (i.e., R=1.5T_c to 4T_c) for Colorado's mountain basins (Dunn et al, 2001; MWH Global, 2017). Wang and Dawdy (2012) suggest that lower ratio values should be used for urbanized basins and basins with less hillslope storage (e.g., prairie or canyon lands). For Front Range foothills and canyons, Colorado Plateau canyons, and Eastern Plains, Colorado Dam Safety has found that $R/(T_c+R)$ values between 0.2 and 0.3 (i.e. R=0.25T_c to 0.43T_c) may be appropriate. It is interesting to note that the Clark UH with R of 0.25-0.43T_c and T_c per the Sabol, 2008 (equation shown above), agrees well with the USBR Rocky Mountain Thunderstorm unit hydrograph (Cudworth, 1989), Kn between 0.5 and 0.8, as recommended previously by Sabol (2008). This seems appropriate because Cudworth developed the USBR RMTS UH from Front Range Foothills floods, before the 7,500-ft limit on rain-driven extreme flooding in Colorado's Rocky Mountains was well understood. The often-reported over-conservatism of the USBR RMTS UH appears to have resulted from Cudworth's extrapolation of its application to high elevation mountain terrain in the Rocky Mountains. The CSU-SMA method and Clark UH parameters recommended herein attempt to correct this long-standing problem by using a slower basin response for the high mountains above about 7,500 feet elevation and faster response for the foothills and canyons below 7,500 feet.

Users should be aware that hillslope storage (represented by R) may not depend on sub-basin size as implied by the uniform $R/(T_c+R)$ ratio approach. CSU tested different sub-basin sizes and found that the uniform $R/(T_c+R)$ ratio method did not work well for larger sub-basins, because hillslope length does not necessarily increase. Larger values for R led to lower predictions of peak flow and more attenuated hydrographs. For mountain sub-basins larger than about 10 sqmi, CSU found that a constant value of 7 hours for R (based on an average of their mountain test basins) worked well (Irvin, 2021), representing average hillslope storage for Colorado mountain basins. No similar analysis was done for the foothills, canyons and plains regions; our recommendation is to determine T_c and R by Sabol (2008) as a starting point. However, we have found that HEC-HMS's Clark UH *Variable* method for estimating Tc and R may help in model calibration per Section 10 below, particularly for Front Range foothills and Eastern Plains basins (more details in Section 10). This suggests a non-linear runoff transformation response, with increasing speed at increasing rainfall intensity. As of the issuance of these guidelines, CSU has a research study on non-linear unit hydrograph response in Colorado basins.

Table 5 provides a summary of the above Clark UH T_c and R parameter estimation guidelines. These estimates should be used as a starting place; T_c and R should be checked and calibrated as needed based on reasonableness checks against peak flow envelopes and flood frequency estimates, as discussed in Sections 9 & 10 below.

Table 5: Summary of guidance for Clark UH T_c and R parameter estimation by region(1)

Region	Tc, time of concentration (hrs)	R, storage coefficient (hrs)
Mountains > 7,500 ft	$T_c = 2.4A^{0.1}L^{0.25}L_{ca}^{0.25}S^{-0.2}$ (Sabol, 2008)	Sub-basin<10sqmi: $R/(T_c+R)$=0.6-0.8 Sub-basin>10sqmi: 7 hours
Front Range foothills, Eastern Plains, and West Slope Canyons(2)	$T_c = 2.4A^{0.1}L^{0.25}L_{ca}^{0.25}S^{-0.2}$ (Sabol, 2008)	$R/(T_c+R)$ = 0.2-0.3 **<u>or</u>** $R=0.37T_c^{1.11}L^{0.8}A^{-0.57}$ (Sabol, 2008)
Agricultural	$T_c=7.2A^{0.1}L^{0.25}L_{ca}^{0.25}S^{-0.2}$ (Sabol, 2008)	$R=0.37T_c^{1.11}L^{0.8}A^{-0.57}$ (Sabol, 2008)
Urban/developed	$T_c=3.2A^{0.1}L^{0.25}L_{ca}^{0.25}S^{-0.14}RTIMP^{-0.36}$ (Sabol, 2008)	$R=0.37T_c^{1.11}L^{0.8}A^{-0.57}$ (Sabol, 2008)

(1) These estimates should be used as a starting place; T_c and R should be checked and calibrated as needed based on reasonableness checks against peak flow envelopes and flood frequency estimates, as discussed in Sections 9 & 10 below.

(2) HEC-HMS's Clark UH Variable method for estimating T_c and R may help in model calibration per Section 10 below

Finally, because of some engineers' interest in using HEC-RAS 2D for rainfall-runoff transformation, several caveats are offered here: No specific RAS 2D parameter guidelines are provided here because it was not used in CSU's mountain hydrology flood calibration studies. The CSU research showed that the unit hydrograph approach is generally adequate for modeling historical extreme floods in mountain basins. However, use of RAS 2D runoff transform may be desired for basins with unique topography *and* may be helpful for modeling non-linear runoff response from extreme high-intensity rainfall, similar to HMS's Variable Clark UH method. Such non-linear response has been indicated by extreme floods along Colorado's Front Range foothills and Eastern Plains. Users should be aware that 2D diffusion wave runoff may not be a physically accurate representation of runoff production in mountain basins, which are notable for their lack of surface flow (Larsen et al, 2009; Lin et al, 2008); therefore, RAS 2D model parameters should be calibrated to observed floods. Also, RAS 2D does not currently perform rainfall loss calculations; excess precipitation would be calculated in another program, e.g. HEC-HMS. And sub-surface flow, considered to be an important component of mountain basin runoff production, would need to be added to RAS 2D generated surface runoff hydrographs.

6.4 **Linear Reservoir Baseflow method parameters** are as follows: Reservoirs = 1, Initial Type = Discharge, GW1 Initial (cfs)=0, GW1 Fraction = blank, GW 1 Step is 1, and GW Coefficient = 3**R*, where *R* is the Clark UH storage coefficient described above.

6.5 **For Muskinghum-Cunge Reach Routing parameters**, use reach properties calculated per Section 5.2 above using HEC-HMS Parameters->Characteristics -> Reach. Simple unit conversion may be needed. The user must determine reach cross-section geometry. Transects can be cut from the DEM to help estimate channel shape.

6.6 **Table 6 below summarizes all CSU-SMA method HEC-HMS parameters, estimation methods, and recommended values, where applicable:**

Table 6: CSU-SMA method HEC-HMS parameter list, estimation methods, & values

HMS Method	Parameter (units)	Parameter estimation method	Recommended Parameter value
Meteorological Model			
Precipitation Specified Hyetograph	Specified Hyetograph (NOTE: include subbasins=yes)	See REPS Guidance document for creating REPS design storms and entering as HEC-HMS Time Series -> Precipitation gages	
Annual Evapotranspiration	Rate (in/day) (NOTE: include subbasins=yes)	Use uniform 2-2.5 mm/day (0.079 - 0.098 in/day), per CSU research (Timilsina, 2021)	0.098 in/day
Basin Model			
Simple Canopy	Initial Storage (%)	parsimony	0
	Max Storage (in)	Use uniform 4.3 mm (0.169 inch), average of north-facing & south-facing slopes from Cache La Poudre site (Woolridge,2019)	0.169 in
	Uptake Method		Simple
Soil Moisture Accounting (SMA) Loss	Soil (%)	For design storms, base antecedent moisture condition (AMC) on seasonality of storm type. In general for extreme storms in CO, use field capacity (i.e. limit of gravity drainage)	Obtain from CSU-SMApython output ***hms_initialsm_table*** (use *mean* field) NOTE: CSU Python script assumes field capacity. *User can edit code for AMC other than field capacity.*
	GW1 (%)	Parsimony	0
	GW2 (%)	Parsimony	0
	Max Infiltration (in/hr)	Green & Ampt infiltration rate using ½ Ksat and delta = 75mm (~3 in) (Woolridge, 2019)	Obtain from CSU-SMApython output ***hms_maxinfil_table*** (use *mean* field)
	Impervious (%)	Uniform 5%, based on CSU calibrations/verifications, for undeveloped mountain basins.	5% as recommended starting place for mountain undeveloped basins. Use other methods where appropriate (ex. developed basins) **and calibrate %impervious as needed per Sections 9 & 10 below**
	Soil Storage (in)	Allocate 85-95% of total soil water storage to soil storage, per CSU recommendation	Obtain from CSU-SMApyhton output ***hms_soilstorage_table*** (use *mean* field). CSU-SMA script is coded for 90% of available storage (10% to GW), user can adjust as needed
	Tension Storage(in)	Soil water storage between field capacity and wilting point	Obtain from CSU-SMApython ***hms_tensionstore_table*** (use *mean* field)
	Soil Percolation (in/hr)	Use ¼* Ksat, calculated by Saxton & Rawls pedotransfer functions. CSU used ½*Ksat (Irvin, 2021). Colorado Dam Safety reduced to ¼*Ksat based on beta testing to reduce subsurface flow	Obtain from CSU-SMApython ***hms_soilperc_table*** (use *mean* field)

HMS Method	Parameter (units)	Parameter estimation method	Recommended Parameter value
	GW 1 Storage (in)	Allocate 5-15% of total soil storage to GW1 layer, per CSU recommendation	Obtain from CSU-SMApython ***hms_gw1storage_table*** (use *mean* field). CSU-SMA script is coded for 10% of avail. Storage; user can adjust as needed
	GW1 Percolation (in/hr)	Uniform try 2.5mm/hr (0.1 in/hr), based on CSU calibrations/verifications for Front Range basins; CSU used 0.5mm/hr for San Juan basins.	0.02 to 0.1 in/hr **Calibrate as needed per Sections 9 & 10 below, affects losses from system**
	GW1 Coefficient (hr)	Use 3 x Clark UH storage coefficient (i.e., 3x*R*)	3 x *R* (from Clark UH*) *Calculate in Clark UH parameters.xlsx spreadsheet. Calibrate as needed per Sections 9 & 10 below
	GW2 Storage (in)	Parsimony	0
	GW2 Percolation (in/hr)	Parsimony	0
	GW2 Coefficient (hr)	parsimony	0
Clark Unit Hydrograph Transform	Method	see Section 6.3 and Section 10	Standard or Variable
	Time of Concentration, *Tc* (hr)	Use Tc from Sabol (2008) for Rocky Mountain, Great Plains & Colorado Plateau or for Urban and Agricultural basins Ref: Sabol (1987) and Sabol (1993).	**See Table 5 above** Calculate in Clark UH parameters.xlsx spreadsheet, using sub-basin characteristics from HEC-HMS (parameters->characteristics->sub-basin)
	Storage Coefficient, *R* (hr)	Use *R/(Tc+R)* ratio method or *R* from Sabol (2008) – **see Table 5 above**	**See Table 5 above** Calculate in Clark UH parameters.xlsx spreadsheet, using sub-basin characteristics from HEC-HMS (parameters->characteristics->sub-basin)
	Time-area Method	Use default	HEC-HMS default
Linear Reservoir Baseflow	Reservoirs (#)		1
	Initial Type		Discharge
	GW1 Initial (cfs)		0
	GW1 Fraction		Blank
	GW Coefficient	Use 3 x Clark UH storage coefficient (i.e., 3x*R*)	3 x *R* (from Clark UH*) *Calculate in Clark UH parameters.xlsx spreadsheet. Calibrate as needed per Sections 9 & 10 below
	GW1 Steps		1
Muskingum-Cunge Reach Routing	Length (ft), Slope (ft/ft)		from HEC-HMS Parameters menu->Characteristics->Reach
	Initial Type		Discharge = Inflow

HMS Method	Parameter (units)	Parameter estimation method	Recommended Parameter value
	Mannings n	Use literature values	Generally 0.03 – 0.07 for mountain streams
	Index Method		Flow
	Index Flow (cfs)	Use Q-2yr (50% AEP) estimate from USGS StreamStats or other bankfull flow estimate	
	Shape	Trapezoid or 8-point, etc., depending on channel and available data. Transects from DEM may help determine channel/floodplain shape	

6.7 **Parameter Estimation Reporting Requirements:** Engineers should provide the following documentation (See example reporting in Appendix A):

- Summary table of all parameter estimates listed in Table 6 above, by sub-basin (*link to sample spreadsheet*)
- Print *CSU_SMApython* output tables for review in order to cross-check against HEC-HMS model input: *hms_initialsm_table*, *hms_maxinfil_table*, *hms_soilstorage_table*, *hms_tensionstore_table*, *hms_soilperc_table* *hms_gw1storage_table*.
- Print the completed *Clark UH parameters.xlsx* spreadsheet

6.8 Parameter estimates should be reviewed for reasonableness based on sub-basin properties (from Section 5) and comparison to USGS StreamStats basin properties, NRCS Web Soil Survey, published parameter values, and on basin characteristics and region of study. Table 7 below provides a summary of Green & Ampt parameters -- porosity, wetting front suction head, and saturated hydraulic conductivity -- by soil texture (Chow, 1988) for cursory checks of *CSU_SMApython* output. For example, a back of envelope check can be made where soil storage should be roughly equal to porosity for predominate soil texture in each sub-basin multiplied by its average depth to restrictive layer. Clark UH and reach routing parameters can be checked against USGS StreamStats basin characteristics.

Table 7: Green & Ampt infiltration parameters by soil classification (Chow, 1988) – provided ONLY for rough check of *CSU_SMApython* output

Soil classification	Porosity, n	Wetting front suction head, psif (inch)	Hydraulic conductivity, K (inches/hour)
sand	0.437	1.9	4.64
loamy sand	0.437	2.4	1.18
sandy loam	0.453	4.3	0.43
loamy sand	0.463	3.5	0.13
silt loam	0.501	6.6	0.26
sandy clay loam	0.398	8.6	0.06
clay loam	0.464	8.2	0.04
silt clay loam	0.471	10.7	0.04
sandy clay	0.43	9.4	0.02
silty clay	0.479	11.5	0.02
clay loam	0.475	12.5	0.01

Section 7. **HEC-HMS Model Setup**

7.1 In HEC-HMS a new project with a basin model and terrain data should be created (described in Section 5.2 above for purposes of sub-basin delineation and determining sub-basin and reach properties). See Figure 8 below.

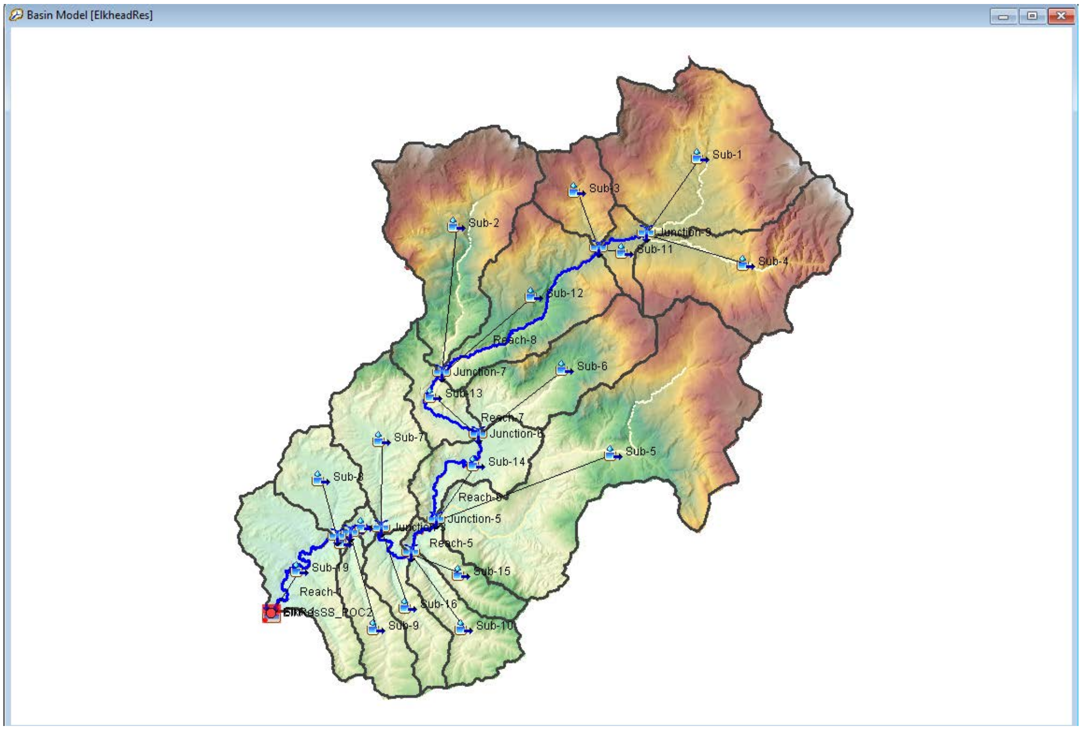


Figure 8: Example basin model and terrain setup in HEC-HMS

7.2 At this point all necessary model parameters have been generated and can be entered into the HEC-HMS model. REPS temporal patterns for input to HMS were discussed in Sections 4 and 5 above. SMA loss method, Clark UH, Linear Reservoir Baseflow, and Reach Routing parameters have been estimated per Section 6. The user's parameter estimation summary table (see Section 6.6 and Table 6 above) can serve as an easy reference for HEC-HMS model parameter input. If partial area analysis is being done, then the partial area analysis summary table generated in Section 5.4.3 above will be useful for model setup.

7.3 Precipitation Gage Time Series:

7.3.1 For REPS design storms, the recommendation is to create a Precipitation Gage Time Series for each REPS storm (a zero-rain precipitation gage can be created to facilitate partial area analysis). Time series should be input in cumulative inches. Table 8 shows the time interval for each REPS design storm temporal distribution.

Table 8: REPS design storm time intervals

Design Storm	Temporal Distribution Time Interval
REPS PMP 2-hr, 6-hr and 24-hr Local Storms	5 minutes
REPS PMP 72-hr GS and TS	15 minutes
REPS PF LS	5 minutes
REPS PF MEC	5 minutes
REPS PF MLC	1 hour

7.3.2 Storm Durations: The recommendation for the CSU-SMA model method is to run all 2-hr through 24-hr design storms for minimum 2-day simulation duration and run all 48-hr & 72-hr duration design storms for minimum of 10-day simulation duration to ensure the full recession limb volume of the hydrograph is modeled, including subsurface flow. At the end of the simulation, discharge should be equal or less than 5% of the peak flow. Cumulative precipitation gage time series data must be extended to these same durations. Table 9 shows recommended simulation durations (and thereby precipitation time-series durations) by REPS storm type.

Table 9: Recommended HEC-HMS simulation & precip time-series duration by REPS storm type

Design Storm	Recommended Simulation/ Time-series Duration
REPS PMP 2-hr, 6-hr and 24-hr Local Storms	2 days (2880 minutes)
REPS PMP 72-hr GS and TS	10 days (240 hours or 14,400 minutes)
REPS PF LS	2 days
REPS PF MEC	2 days
REPS PF MLC	10 days

NOTE: At the end of the simulation, discharge should be equal or less than 5% of the peak flow

7.3.3 REPS temporal distribution time series can be copied and pasted from REPS temporal distribution output text files into the HEC-HMS precipitation gage time series. *<u>Tip</u>: REPS MetPortal v2.2.0 allows the user to download precip frequency storm temporal patterns scaled to all AEPs at once, by storm type. The user must manually check the "Download data for all AEPs?" box at the top center of the Temporal Patterns page.*

A REPS temporal pattern spreadsheet tool to extend all PF and PMP distributions to the recommend time-series durations per Table 9 above can be downloaded from the following Google Drive link:
https://docs.google.com/spreadsheets/d/1HCPFrPRnbK3lt7TuO61BkPR6NaPb8DGR/edit?usp=sharing&ouid=115042170524029578776&rtpof=true&sd=true

<u>Tip:</u> For efficiency, in HEC-HMS a single precipitation gage can be created for each time increment/duration combination per Tables 8 and 9 above (e.g. 5-minute time interval, 2 day duration), then this "template" can be copied in HEC-HMS for each applicable REPS design storm (e.g. REPS 10e-1 thru 10e-7 AEP LS and MEC and REPS 2hr, 6hr, and 24hr LS PMP); then each REPS temporal distribution from the temporal pattern spreadsheet can be copied and pasted into HEC-HMS.

Figures 9 and 10 below show example precipitation gage setup in HEC-HMS.

7.4 Meteorological Model Setup: A meteorological model should be created for each REPS design storm.

<u>Tip:</u> For efficiency, the recommendation here, based on HEC-HMS 4.7, is to create the first meteorological model and setup annual evaporation. This Met Model can then be copied for other storm types. Also, if partial area analysis is being done, then it may be helpful to setup each partial area Met Model "template" that can then be copied and edited for other design storms that use the same partial area.

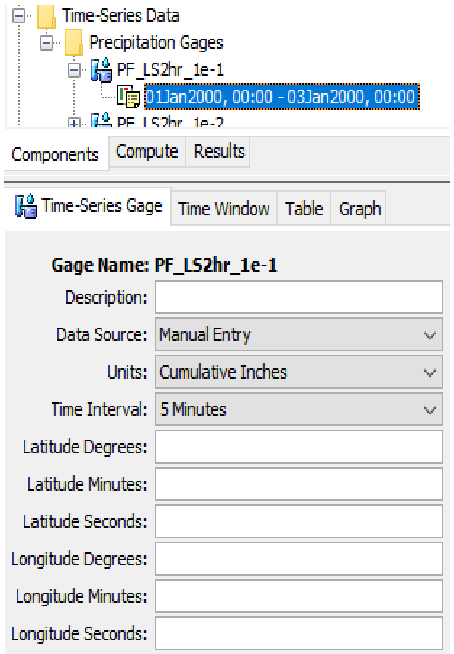
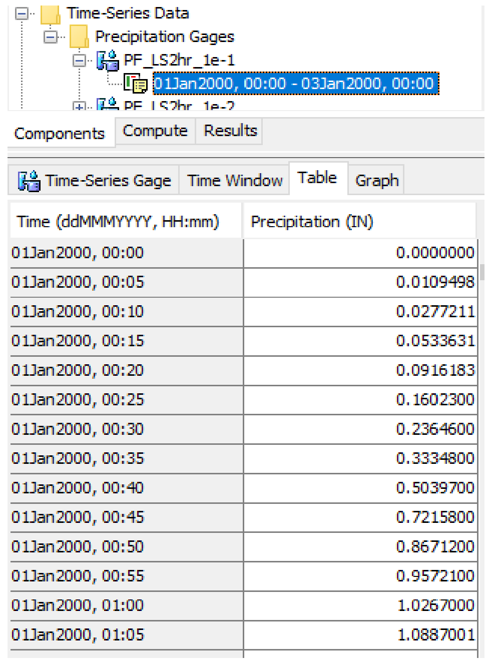


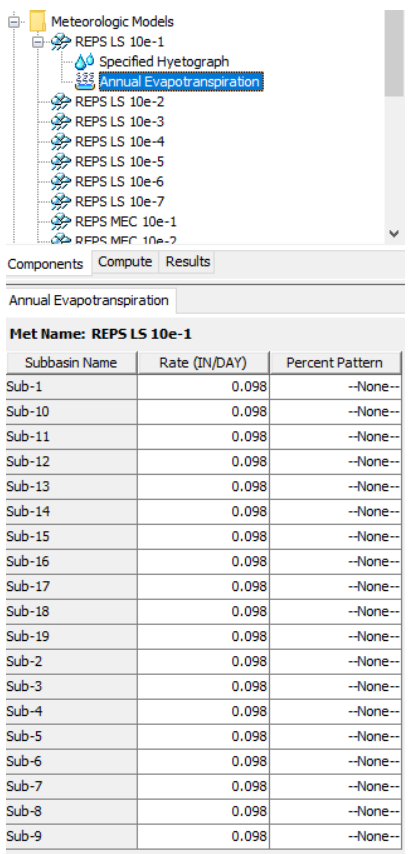
Figure 9: Precip Gage setup



Time (ddMMMYYYY, HH:mm)	Precipitation (IN)
01Jan2000, 00:00	0.0000000
01Jan2000, 00:05	0.0109498
01Jan2000, 00:10	0.0277211
01Jan2000, 00:15	0.0533631
01Jan2000, 00:20	0.0916183
01Jan2000, 00:25	0.1602300
01Jan2000, 00:30	0.2364600
01Jan2000, 00:35	0.3334800
01Jan2000, 00:40	0.5039700
01Jan2000, 00:45	0.7215800
01Jan2000, 00:50	0.8671200
01Jan2000, 00:55	0.9572100
01Jan2000, 01:00	1.0267000
01Jan2000, 01:05	1.0887001

Figure 10: Precip gage time series table

7.4.1 Evaporation: Enter annual evaporation rate (0.098 in/hr, see Table 6 above) for all sub-basins. Figure 11 shows an example evaporation element setup.



Subbasin Name	Rate (IN/DAY)	Percent Pattern
Sub-1	0.098	--None--
Sub-10	0.098	--None--
Sub-11	0.098	--None--
Sub-12	0.098	--None--
Sub-13	0.098	--None--
Sub-14	0.098	--None--
Sub-15	0.098	--None--
Sub-16	0.098	--None--
Sub-17	0.098	--None--
Sub-18	0.098	--None--
Sub-19	0.098	--None--
Sub-2	0.098	--None--
Sub-3	0.098	--None--
Sub-4	0.098	--None--
Sub-5	0.098	--None--
Sub-6	0.098	--None--
Sub-7	0.098	--None--
Sub-8	0.098	--None--
Sub-9	0.098	--None--

Figure 11: Evaporation->Annual Evapotranspiration setup

7.4.2 Specified Hyetographs: Next create a Specified Hyetograph for each REPS design storm Met Model, which may be for up to 26 storms, depending on the basin location (2hr LS PMP, 6hr LS PMP, 24hr LS PMP, 72hr GS PMP, 72hr TS PMP, and 10e-1 through 10e-7 AEP for LS, MEC and MLC PF storm types). Figure 12 shows an example of the recommended Met Model setup for all REPS design storms. Figure 13 shows an example Met Model Specified Hyetograph setup for partial area analysis (note the use of a zero precipitation rain gage for sub-basins outside of a partial area analysis).

NOTE: Alternatively, instead of creating a unique Precipitation Gage Time Series and Met Model for each of the 21 REPS Precipitation Frequency storms, a single Met Model could be created <u>for each storm type</u> using its REPS MetPortal <u>unscaled</u> temporal pattern. Then it can be scaled by the PF best estimate per AEP in each HEC-HMS simulation run. This "simulation scaling" approach may save time during model setup, but tends to be more difficult in terms of model analysis and documentation.

Lastly, using the recommended approach of creating a Met Model for each REPS storm, then the HEC-HMS simulation precip scaling can be used for the required 1.07 atmospheric moisture factor from State Dam Safety Rule 7.2 (see Section 10.2 below for more discussion on how to use the AMF).

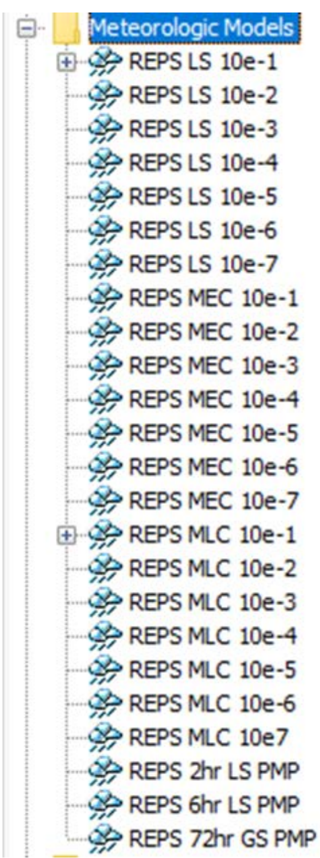


Figure 12: Example REPS design storm meteorological models

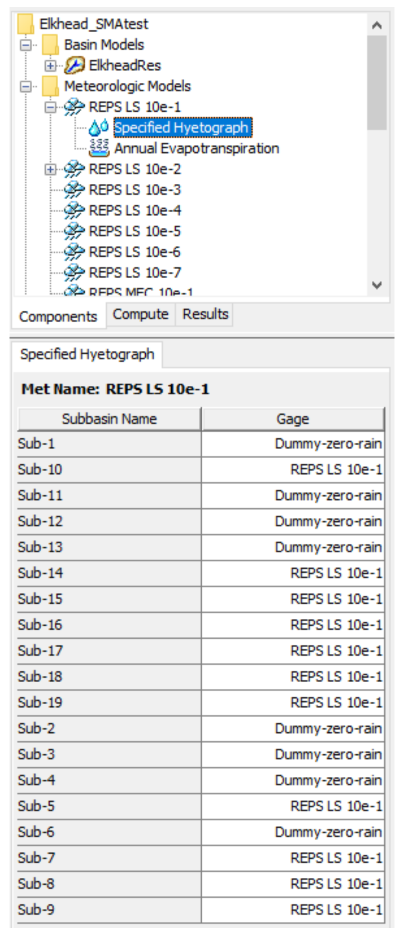


Figure 13: Example Met Model Specified Hyetograph setup for partial area analysis

7.5 Basin Model Setup:

7.5.1 Sub-basin elements. Each sub-basin element in the HEC-HMS model should be set to the following methods: Canopy method = Simple Canopy, Loss Method = Soil Moisture Accounting, Transform method=Clark Unit Hydrograph, and Baseflow Method=Linear Reservoir (see Figure 14 below) *Tip: These can be set as defaults in HEC-HMS under Tools->Program Settings-> Defaults*. The user's parameter estimation table (see Section 6.6 and Table 6 above) will facilitate easy parameter input. Figures 15-18 below show example parameter inputs for each method.

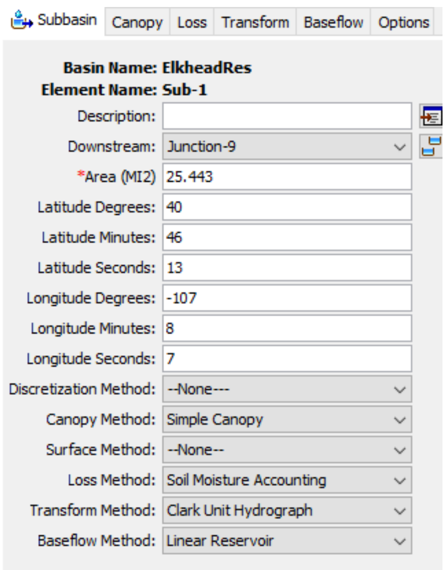


Figure 14: Sub-basin element settings

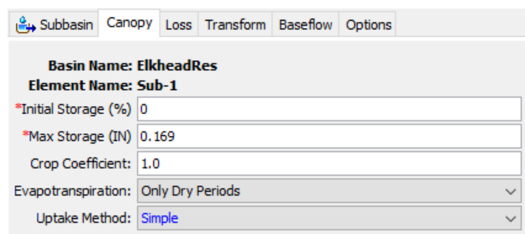


Figure 15: Simple Canopy Method, example parameters

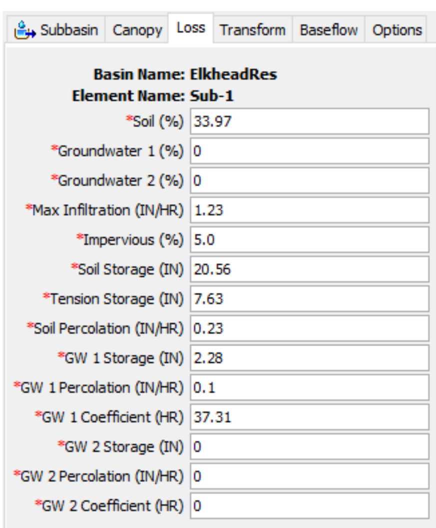


Figure 16: SMA Method, example parameters

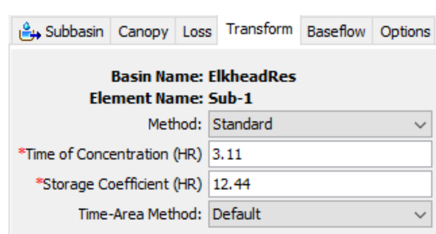


Figure 17: Clark UH transform Method, example parameters

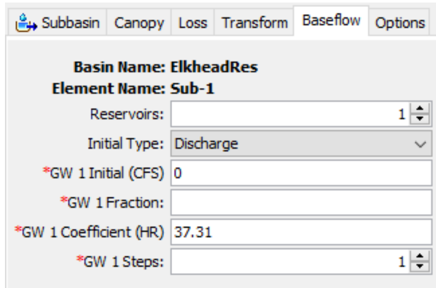


Figure 18: Linear Reservoir Baseflow Method, example parameters

7.6 HEC-HMS Control Specs: Table 9 above showed recommended simulation durations in order to ensure hydrograph recession limb and volumes are simulated completely, including subsurface flow from the SMA method. In general, two control specifications should be sufficient: General Storms (10-day duration) and Local Storms (2-day duration). The recommended simulation time interval is 5 minutes for General Storms and 1 minute for Local Storms.

7.7 **Quality Control Check:** There is a large amount of HEC-HMS model input data between the CSU-SMA method and REPS design storms. The model should be thoroughly QC checked by the user. Sub-basin property summary tables (Section 5 above) and parameter summary tables (Section 6) will facilitate QC checking. HEC-HMS Standard Reports can also be helpful for efficiently checking all model elements. As the REPS rainfall inputs require numerous steps and manipulations, please check precipitation amounts, time intervals, applied sub-basins (for partial area analysis), etc. in HEC-HMS Precip Gages and Met Models.

Section 8. **HEC-HMS Output and Report Documentation**

8.1 In HEC-HMS a simulation run for each REPS design storm should be executed (in the Compute tab) using the correct basin model, meteorological model, control specifications, and precipitation ratio (if applicable). *Tip: HEC-HMS allows multiple simulation runs simultaneously (under Compute->Multiple Compute), which can be helpful with up to 26 REPS design storms.*

8.2 **HEC-HMS output for hydrology reporting should be provided to Colorado Dam Safety, for review, as part of a comprehensive report, documenting the modeling effort, reasonableness checks (Section 9) and model calibration (Section 10). HMS output reporting should be based on the final model results, following calibration. The following HMS output should be included (See example reporting in Appendix A):**

8.2.1 **In HEC-HMS, print a summary report under Tools->Reports->Standard Reports.** Due to the large number of REPS storms and large size of the Standard Reports, the recommendation is to print only the Standard Report for the inflow design flood (IDF) for design flood studies, or in the case of a hydrologic risk study (where there is no design flood), print the dam overtopping (or other relevant hydrologic failure mode) REPS precipitation frequency event. The following output options should be selected for the Standard Report (see Figure 19 below): Global Parameter Summary Tables -- Subbasin, Reach; Element Parameter Summary Tables -- Subbasin, Sink; Element Time Series Graphs -- Baseflow, Cumulative Precipitation, Cumulative Precipitation Loss, Direct Runoff, Precipitation Loss, Saturation Fraction, Soil Infiltration, and Soil Storage.

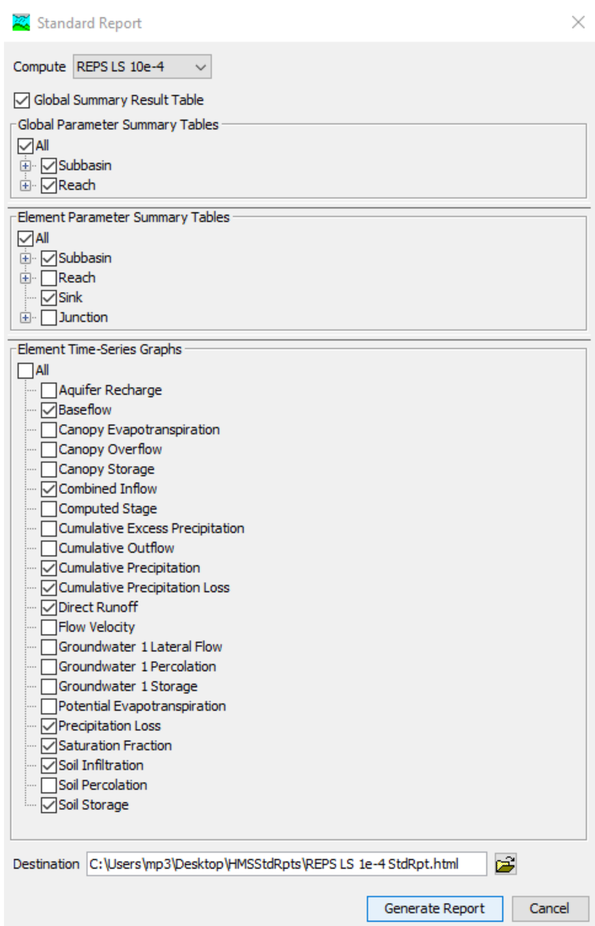


Figure 19: Recommended output options for HEC-HMS Standard Report

8.2.2 **Using HEC-DSSVue or other graphing software, the following reservoir inflow hydrographs should be generated and included in the hydrology report:**

- All AEPs and PMP reservoir inflow hydrographs overlaid on a single graph for each REPS storm type
- 10e-4 AEP reservoir inflow hydrographs for all storm types (LS, MEC, MLC)
- PMF inflow hydrographs for all applicable storm types (2hr LS, 6hr LS, 24hr LS, 72hr GS and 72hr TS)

8.2.3 **Modeled peak flow frequency curves (reservoir inflows) should be plotted** for all REPS precipitation frequency storms, along with flood frequency curves from USGS StreamStats estimates and applicable site-specific and/or regional stream gage flood frequency analyses (see Sections 9 & 10 for more details). Modeled REPS PMF peak flows should be overlaid as horizontal lines. An example plot is shown in Figure 20. A sample spreadsheet for presentation of peak flow frequency curves can be downloaded for use from the following Colorado Dam Safety Google Drive link: https://docs.google.com/spreadsheets/d/1e53m0RrJTF-NSYzNlOhxhbfnMDzaaLGo/edit?usp=sharing&ouid=115042170524029578776&rtpof=true&sd=true

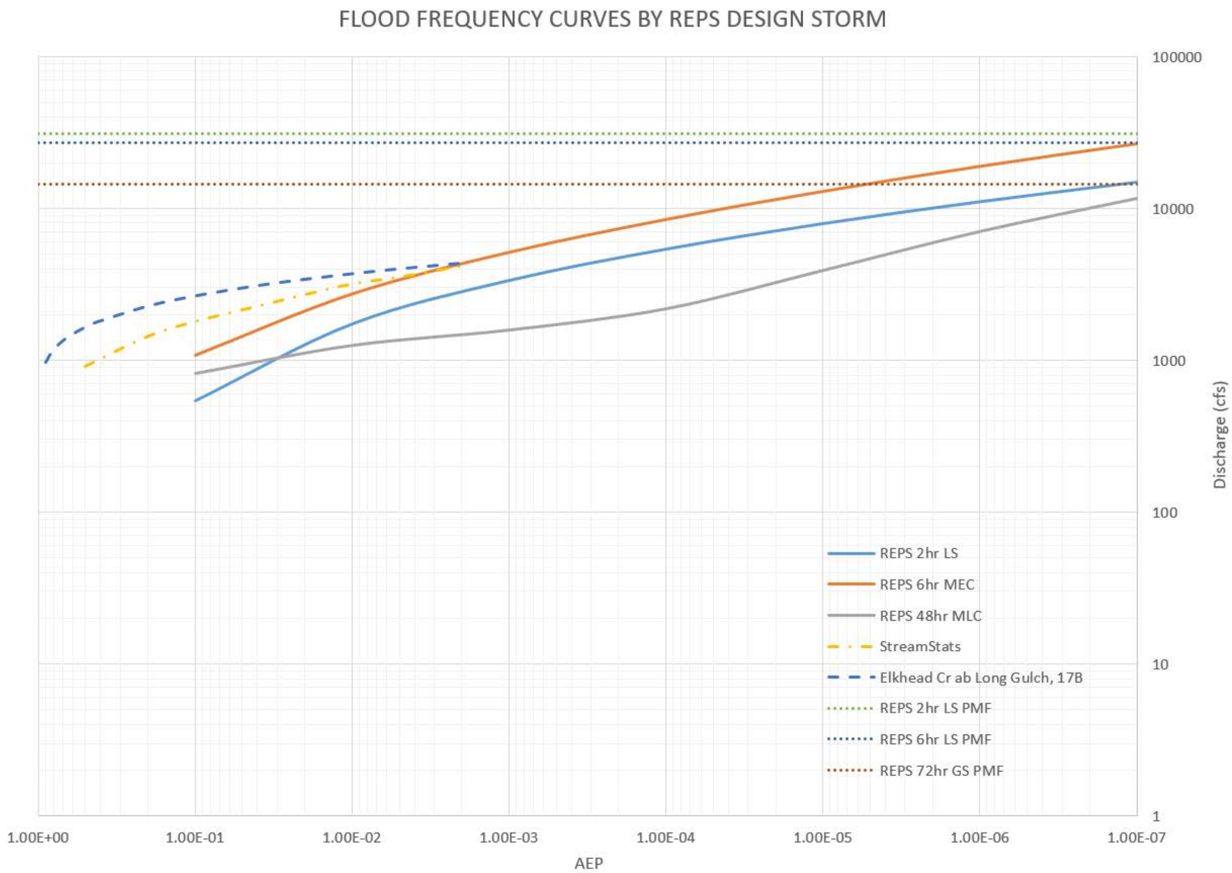


Figure 20: Example flood frequency curves plot comparing modeled REPS AEP and PMF peak flows to USGS StreamStats and stream gage flood frequency curves.

8.2.4 **Reservoir inflow, reservoir stage, and reservoir outflow hydrographs from HEC-HMS should be plotted for 10e-4 AEP floods (all storm types) and for PMF floods (all storm types).**

8.2.5 **For hydrologic risk analysis of existing dams (see Flowchart 1 at the beginning of these guidelines), reservoir stage probability curves (a.k.a., hydrologic hazard curves) should be plotted for all REPS precipitation frequency storms.** REPS PMF peak reservoir stages should be overlaid (as horizontal lines) along with pertinent dam features (e.g. spillway crest, dam crest). The sample flood frequency curve spreadsheet (see Section 8.2.3 above) includes a worksheet for graphing reservoir stage probability curves. An example plot is shown in Figure 21 below. Other probability curves may be warranted depending on credible potential failure modes (e.g. spillway unit discharge probability curves for a spillway erosion PFM).

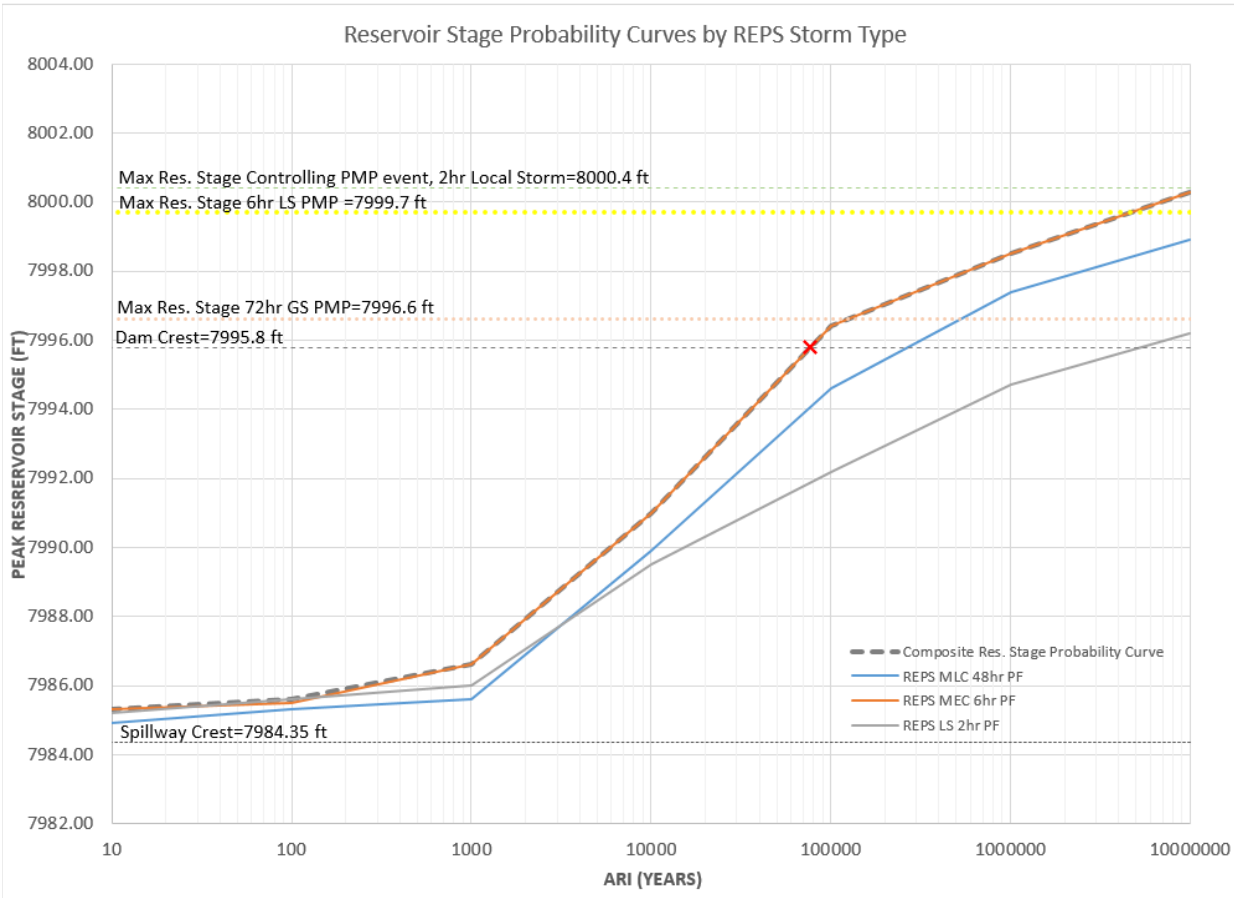


Figure 21: Example reservoir stage probability curves plot comparing modeled REPS AEP and PMF storms and relevant dam features.

8.3 HEC-HMS results should be reviewed by the engineer for the following:

- Calculate and tabulate the runoff coefficient for each design storm, which can be calculated as runoff volume divided by rainfall volume. CSU (Irvin et al, under review) found runoff coefficients averaged around 30% in their mountain hydrology research,for the studied historical extreme storms, which were around 1/100 AEP magnitude events (note: two large volume general storms produced runoff coefficients around 60-70% and one very localized, extreme thunderstorm, 15%). Runoff coefficient values generally increase with high rainfall intensities (relative to basin soil infiltration capacities), higher initial soil moistures, and with larger precipitation volumes (Niemann and Eltahir, 2004).

For example, Colorado Dam Safety has found that runoff coefficients may be as high as 80-90% for Local Storm PMF, modeled by the methods herein.

- Compare baseflow and direct runoff hydrographs to determine which is dominant. Also compare timing of baseflow and direct runoff peaks and the total hydrograph. They should generally combine to form a steady rising limb, single peak, and then steady recession limb, based on CSU's review of observed flood hydrographs in Colorado mountain basins.
- Review saturation fraction for larger volume design storm events. Saturation fraction of 85% and above is assumed to cause saturation excess runoff (Woolridge, 2019). Saturation-excess runoff may be indicated when the direct runoff hydrograph peak aligns with the soil saturation fraction peak (as shown in HEC-HMS Standard Reports). Below 85%, surface runoff is considered to be infiltration-excess, in which case the direct runoff peak is expected to align closely with maximum rainfall intensity. Saturation-excess verses infiltration-excess runoff mechanisms should be reviewed for reasonableness based on basin properties, storm type, storm AEP/magnitude, etc. In general, short-duration intense thunderstorms are expected to result in lower saturated fractions and infiltration-excess runoff. Longer duration, larger magnitude storms may result in saturation fractions above 85% and saturation-excess runoff, depending on soil properties and soil water storage volume. Saturation-excess runoff may result where soil storage volume is low and infiltration rates are high (i.e. thin, coarse-grained soils) or conversely for fine-grained soils where infiltration rates may be low but tension storage and initial soil moisture are relatively high.

Section 9. **Reasonableness Checks & Confidence**

9.1 Extreme flood estimates for dam safety evaluation and design in Colorado traditionally have been determined by extrapolation of uncalibrated rainfall-runoff models, often yielding, in the mountains and Western Slope, flood estimates several orders of magnitude larger than the largest observed floods. However, Robert Jarrett (USGS) and others have cited a lack of paleoflood and historical evidence for such extreme floods in Colorado's Rocky Mountains.

In order to address this problem, we introduce the concept of *reasonableness* here, as referring to the situation where watershed model flood-frequency outputs of flood peaks and volumes for a range of AEPs are consistent with site-specific or regional flood-frequency statistics for hydrologically similar watersheds, and watershed model parameter values are consistent with parameter values obtained for hydrologically similar watersheds in the region where good calibration was obtained between watershed model outputs and observed streamflows. More generally, watershed model flood outputs and watershed model parameters are consistent with historical data in the region.

The intent of the *reasonableness checks* step here is to ground rainfall-runoff model estimates in the reality of the historical flood record. As stated in Bulletin 17C, *Guidelines for Determining Flood Flow Frequency* (England et al, 2019):

> *Over the past several decades, historical data and information have been shown to be extremely valuable in flood frequency analysis (Leese, 1973; Condie and Lee, 1982; Stedinger and Cohn, 1986, 1987; Cohn and others, 1997; England and others, 2003a). Dalrymple (1960) notes the following: "Historical floods provide probably the most effective data available on which to base flood frequency determinations, and where the data are reliable, this information should be given the greatest weight in constructing the flood frequency graph." Historical flood information should be obtained and documented whenever possible. Use of historical data assures that estimates fit community experience and improves the frequency determinations. This information is valuable in flood frequency analysis because it directly contributes extreme flood data on low annual-exceedance probability floods.*

Further, Waltemeyer (2008), talking about regional envelopes of observed flood peaks, said they can "serve as a guide to the reasonableness of flood frequency estimates for large recurrence intervals."

As stated in Section 1 above: uncalibrated rainfall-runoff model results, per Sections 4 through 8 above, are viewed here only as a starting point, and *reasonableness* of such results should not be assumed. Checking and calibrating model results against the historical flood record is considered to be an integral step in these guidelines. Only after these checks are done do we consider the model to provide a best-estimate of flooding. At the same time, *confidence* is built through the reasonableness checks process. Some dams and basins may have a large amount of site-specific historical flood information, which makes a case for strong confidence in calibrated model results. Other basins may have very little flood information and may rely on regional data sets. Regardless, we have found that the process of gathering available historical flood information yields more defensible hydrology results.

Engineers should use multiple lines of evidence to make the case for reasonable design floods -- using gaged floods, indirect flood measurements, anecdotal flood records, and paleoflood studies. Regional flood frequency methods, like USGS StreamStats, can be used as well as stream gage flood frequency analyses by Bulletin 17C (England et al, 2019). Historical floods can be researched using SEO Dam Safety files, newspaper archives, Colorado State University's *Extreme Storm Precipitation Data Study, #97-1* (McKee and Doesken, 1997), the USGS Colorado Flood

Database, etc. These data can be plotted on regional peak flow envelope curves, along with plotting modeled REPS probabilistic and REPS PMF peak flows, and on flood frequency curve plots comparing simulated REPS flood frequency curves with USGS StreamStats and Bulletin 17C stream gage flood frequency curves. The reasonableness checks discussed in this section tend to emphasize discharge, not runoff volume. Peak flow is generally considered to be more difficult to model correctly (and it typically controls spillway design in Colorado). Volume is thought to follow from simulating the correct controlling REPS storm type(s), which is addressed by several of the reasonableness checks below.

The following sub-sections provide guidance on specific reasonableness checks.   Also see Appendix A for Example Reasonableness Checks summary reports and Appendix C for a Reasonableness Checks template.

9.2 Stream Gage Flood Frequency Analysis: Many stream gages are or have been operated in Colorado, by the USGS, DWR, Mile High Flood District, and others. If the basin of interest is gaged with a minimum of 10 years of non-zero annual peak flows, then flood frequency analysis should be performed and plotted as a check of modeled REPS design storm flood frequency curves, assuming AEP neutrality, i.e., the simplifying, but useful, assumption that a given AEP rainfall event produces the same AEP flood peak. 1/10, 1/100, 1/1000, etc. AEP flood frequency estimates can be estimated using USGS Bulletin 17C (England et al, 2019) methods and then compared to modeled REPS probabilistic design storms. Longer periods of record will result in stronger confidence. Flood frequency estimates beyond 1/1000 AEP may be possible if paleo-flood estimates are available. The USGS PeakFQ and USACE HEC-SSP computer programs are helpful for flood frequency analysis. (NOTE: Caution and additional research is needed for stream gages with missing peak flows, which may indicate that a large flood peak exceeded a gage discharge rating or that the gage was damaged by a large flood). Bulletin 17C analysis by programs such as PeakFQ provide 90% confidence bounds on flood frequency estimates. For purposes of these guidelines, REPS modeled peak flows that are closer to Bulletin 17C flood frequency best estimates are considered to be more defensible, but may vary within 90% confidence bounds on flood frequency estimates, if corroborated by additional lines of evidence.

If the basin or site of interest is ungaged, then flood frequency analysis can be performed for stream gages at hydrologically similar locations in close proximity, if possible. Then the resulting flood frequency estimates can be transpositioned to the site of interest using the drainage area ratio (DAR) method or more generally, a ratio of regional peak flow predictor equations like those by Capesius and Stephens (2009) or Kohn et al (2016). Asquith and Kohn (2022) suggest that the following DAR equation and area ratio exponents may be reasonable over area ratios of 0.25 to 2.0, with increasing caution beyond area ratios of 0.5 to 1.5:

$$Q_{T(u)} = Q_{T(g)}\ (A_u/A_g)^x$$

where, $Q_{T(u)}$ is the unknown but desired flood frequency discharge (cfs) at an ungaged site for T-year average recurrence interval (ARI)
$Q_{T(g)}$ is the Bulletin 17C flood frequency discharge at a gaged site for T-year ARI
A_u is the drainage area in square miles at ungaged site
A_g is the drainage area in square miles at stream gage
x is the average exponent for drainage area, by region Front Range Foothills~=0.6 and Eastern Plains~=0.33 (Kohn et al, 2016)*.

* Kohn, et al (2016) provides specific area exponents by flood AEP. Note that fractional exponents are an indication of partial area contribution during flood events (Asquith and Kohn, 2022).

Furthermore, Kohn and Asquith (2022) suggest that a more generalized ratio of regional peak flow predictor regression equations like those by Capesius and Stephens (2009) or Kohn et al (2016) is another reasonable method to transposition or rescale Bulletin 17C stream gage flood frequency estimates, after the following example using area, precipitation, and slope as predictors:

$$Q_{T(u)} = Q_{T(g)}\ (A_u/A_g)^x(P_u/P_d)^y(S_u/S_d)^z$$

where, $Q_{T(u)}$ is the unknown but desired flood frequency discharge at an ungaged site for T-year ARI
$Q_{T(g)}$ is the Bulletin 17C flood frequency estimate at a gaged site for T-year ARI.
A, P and *S* are example predictor variables (area, mean annual precipitation, and main channel slope) at *u*, the ungaged site, and *g*, the gaged site.
x, y and *z* are exponents on the predictor variables from a regional peak flow regression equation* of the form $Q_T=A^x P^y S^z$

*Specific regional peak flow regression equations for Colorado by flood AEP and by region, along with valid ranges of predictor variables can be found in Capesius and Stephens (2009) and Kohn et al (2016). Use of the regression equations outside of the listed ranges will increase uncertainty. Note that the USGS plans to publish a new report in 2023 that will supersede Capesius and Stepens (2009) for the region west of the Front Range and will result in small improvements to peak flow equations.

Lastly, regional stream gages for multiple basin sizes can be used to define a regional flood frequency curve for a given AEP (e.g. 1/100) on a peak flow vs. drainage area graph, which then can be compared to REPS AEP model results for the basin-of-interest.

In terms of uncertainty for transpositioned or rescaled flood frequency estimates and for regional flood frequency curves, errors may generally be on the order of 1/4 to 1/3 log10 cycle, consistent with historical peak flow regression studies in Colorado (Asquith and Kohn, 2022). Again, for purposes of these guidelines, REPS modeled peak flows that are closer to flood frequency best estimates are considered to be more defensible, but may vary within 90% confidence bounds on the flood frequency estimates, if corroborated by additional lines of evidence.

9.3 Regional Regression Flood Frequency Methods: In conjunction with stream gage data, USGS StreamStats peak flow estimates should be determined for the basin-of-interest: https://streamstats.usgs.gov/ss/

USGS StreamStats provides regional regression equation flood frequency estimates, for 1/2 (i.e., 50%) through 1/500 (i.e., 0.2%) AEP. Generally, USGS StreamStats flood frequency curves can be extrapolated to 1/1000 AEP for our purposes and then compared to modeled peak flows from REPS probabilistic design storms. As discussed in the previous section, use of USGS StreamStats for basins outside of the range of predictor variables found in Capesius and Stephens (2009) and Kohn et al (2016) will decrease *confidence*. And again, a new USGS report is expected in 2023 that will result in small improvements to regional regression equations and minor changes to peak flow estimates. In terms of uncertainty, USGS StreamStats provides average standard error of prediction in percent (ASEp) for their regional regression equations after Capesius and Stephens (2009) and Kohn et al (2016). USGS StreamStats ASEp may best be considered qualitatively in terms of *confidence* (personal communication with Mike Kohn, USGS) (see Section 9.11 herein for more on *confidence*), in that some regions have larger ASEp than others and ASEp generally, but not always, increases for rarer AEPs. If desired, USGS StreamStats ASEp can be converted to native log10 space, in which regional peak flow regressions are done, using Table 10 below, and then used to calculate approximate 90% confidence bounds (Asquith and Kohn, 2022 and personal communication with Mike Kohn, USGS). For example, USGS StreamStats gives a 0.2-percent AEP flood best estimate of 14,100 cfs for an example basin in the Plains Region and ASEp of 170%, which equates to about 0.51 log cycle, using Table 10. Therefore, approximate 90% confidence bounds on the USGS StreamStats best estimate would be 4,360 cfs and 45,630 cfs (10^(log10(14,100)±0.51). Confidence bounds on regional estimates may be quite large,

Table 10 Relation of standard error (ASEp,%) to Log10 cycle (from Tasker, 1978)

Log10 cycles	ASEp (%)	Log10 cycles	ASEp (%)	Log10 cycles	ASEp (%)	Log10 cycles	ASEp (%)	Log10 cycles	ASEp (%)	Log10 cycles	ASEp (%)
0.01	2.3	0.11	25.7	0.21	51.3	0.31	81.5	0.41	120	0.51	172
0.02	4.6	0.12	28.2	0.22	54.1	0.32	84.9	0.42	124	0.52	179
0.03	6.9	0.13	30.6	0.23	56.9	0.33	88.4	0.43	129	0.53	185
0.04	9.2	0.14	33.1	0.24	59.8	0.34	92	0.44	134	0.54	192
0.05	11.6	0.15	35.6	0.25	62.7	0.35	95.6	0.45	139	0.55	199
0.06	13.9	0.16	38.1	0.26	65.7	0.36	99.4	0.46	144	0.56	207
0.07	16.2	0.17	40.7	0.27	68.7	0.37	103	0.47	149	0.57	214
0.08	18.6	0.18	43.3	0.28	71.8	0.38	107	0.48	155	0.58	223
0.09	20.9	0.19	45.9	0.29	75.0	0.39	111	0.49	160	0.59	231
0.1	23.3	0.2	48.6	0.3	78.2	0.4	116	0.5	166	0.6	240

but as stated in the previous section, for purposes of these guidelines, modeled peak flows that are closer to flood frequency best estimates are considered more defensible. Modeled peak flows should in all cases lie within 90% confidence bounds; significant differences from flood frequency best estimates should be supported by additional lines of evidence.

If a basin is gaged with a minimum of 10 years of non-zero peaks, then Bulletin 17C flood frequency estimates (Section 9.2) will generally have smaller uncertainty and should be given more importance than USGS StreamStats for checking against modeled peak flows.

9.4 Review of Historical and Paleo-Floods: Much can be learned by investigating historical floods in the basin or region of interest. Newspaper archives and local historical societies are good sources. Colorado Dam Safety files often have records of noteworthy floods at existing dams. Many dams in Colorado are 100-years old or older, providing a good record of historical flooding. Colorado State University's *Extreme Storm Precipitation Data Study, Report #97-1* (McKee and Doesken, 1997), the USGS Colorado Flood Database, and REPS Summary Report Volume II provide good inventories of historical floods (DWR Google drive link to historical flood documents). These documents do not include all Colorado flood information; the user is encouraged to do further research as needed to build a record of historical flooding for the basin/region of interest.

Paleo-flood studies, as a sub-set of historical floods, are particularly useful in providing upper limits of the largest floods that have occurred over hundreds to thousands of years (Jarrett and Tomlinson, 2000). Paleo-flood studies use physical evidence to provide valuable information about historical or ancient flooding at a site. The information can be non-exceedance thresholds or maximum flood stages. Paleo-flood indicators can include gravel bars, terraces, high water marks, flood scarring, etc. Dating methods include dendrochronology, radio-carbon, or relative dating techniques. Site-specific paleo-flood studies will only be feasible for the most advanced hydrology studies for large, complex projects. Fortunately, many existing regional paleo-flood studies are available in Colorado by the USGS, USBR, USACE and others, in scientific literature. The USGS Colorado Flood Database (discussed in detail below) contains paleo-flood estimates and links to studies by USGS.

Modeled reservoir stage probability curves (see Section 8.2.5 above) should be checked for consistency with the historical record at existing dams, in terms of controlling storm/flood types, record stage, frequency of spillway activation, past dam overtopping incidents, etc. Modeled REPS floods should be checked against historical flood peak flows, durations, storm types, and time of year, for consistency with observed flooding.

9.5 Event Calibration: For more advanced studies, flood reconstruction modeling of historical storms/floods can be performed. For historical storms used in the REPS PMP study (see REPS Summary Report Vol. II, Table 2, for a list of storms) Colorado Dam Safety may have access to hourly rainfall raster data for event calibration. Other historical storms (i.e. not used in REPS) that occurred in a basin-of-interest can often be reconstructed by consulting meteorologists. The sources listed in Section 9.4 above may be useful for identifying historical storms/floods in a basin-of-interest for event calibration. USGS, DWR, and other stream gage data sets can be reviewed to determine whether historical flood hydrograph data are available.

9.6 Controlling Storm Type: Modeled controlling REPS storm type(s) should be compared to the storm/flood type(s) of historical flooding for the basin or region of interest. Information on storm types of observed, historical floods can be discerned from flood reports, date/season of occurrence, flood duration, and stream gage hydrographs. Users are reminded that REPS PMP storm types are Local Storm (2hr, 6hr and 24hr hybrid, with the latter applicable only to the Eastern Plains and Front Range foothills), General Storm (72hr) and Tropical Storm (72hr, applicable only south of 38.5º latitude); and REPS MetPortal precipitation frequency storm types are LS(2hr), MEC (6hr) and MLC(48hr). Flood frequency curve and reservoir stage probability curve plots (see Sections 8.2.3 and 8.2.5 above) depict controlling REPS storms type(s) over the range of AEP and PMP magnitudes.

Controlling storm type can vary due to non-linearities in basin hydrology and due to attenuation of inflow floods by reservoir routing. Table 11 is offered as initial guidance in identifying likely controlling storm type by region and basin area size.

Table 11 - Likely Controlling Storm Type by Region and Watershed Size for Extreme Storms

Likely Controlling Storm Types by Region & Watershed Size for Extreme Storms			
Flood Region	**Nominal Watershed Size (sq mi)**	**Likely Controlling Storm Type**	**Comments**
Western Colorado & Mountains above 7500 Ft	watershed < 50	LS	Areal coverage of LS and MEC storms is much smaller than in Eastern Plains and Front Range foothills <7,500 ft
	50 < watershed < 200	MEC	
	Watershed > 500	MLC	
Eastern Plains and Front Range Foothills below 7500 Ft	watershed < 100	LS	MEC storms may be the controlling storm type even when that storm has partial areal coverage over the watershed. This is due to very high unit discharges produced by very intense convective precipitation
	100 < watershed < 1000	MEC	
	2500 < watershed	MLC	

Convective storms (LS and MEC storm types) will typically be controlling for small and intermediate sized watersheds in cases where reservoirs have a relatively small volume for flood storage. Convective storms will generate higher unit discharges for these watershed sizes than stratiform and orographic precipitation produced by the MLC storm type. In these cases, flood peak magnitude will be the most important flood characteristic for determining spillway size. The MLC storm type becomes the controlling storm type for larger watersheds and watersheds where the reservoir has large floodwater storage capacity. In these cases, flood volume and the shape of the flood hydrograph in addition to flood peak become important factors for spillway sizing. Note that transition in watershed sizes from the LS to MEC controlling storm type and from MEC to MLC controlling storm type likely varies widely, dependent upon watershed-specific characteristics and rainfall-runoff modeling parameters.

9.7 Seasonality of Controlling Storms/Floods: In Colorado there are strong seasonal aspects to rainfall, storm types, and flooding, and these vary by region. Historical flood and stream gage peak flow records provide information about the seasonality of flooding in a basin or region of interest. CO-NM REPS analyzed seasonality of the largest 50 historical storms of each storm type (LS, MEC & MLC) in each of the regions shown below in Figure 22 (northwest, northeast, southwest, and Rio Grande); Figures 23, 24, and 25 below show histograms of the resulting seasonal distributions of the largest LS, MEC, and MLC storms, respectively, by region (from REPS Summary Report, Vol. III, 2018). Further, REPS Vol. II (PMP), Appendix F, provides the time of year for historical extreme storms used for REPS PMP.

As a reasonableness check of rainfall-runoff model results, the seasonality of the controlling REPS storm type(s) (i.e. using model results and Figures 23, 24 & 25) should be checked against the seasonality of historical flooding for the basin/region of interest. This seasonality check may help to verify that the model is producing the correct controlling REPS storm type, where the actual storm type of historic floods may not be known to the engineer, but the time of year is known. For example, suppose your model for a basin in the Rio Grande region shows the controlling REPS storm type is the MLC, which is most likely to occur in September by the last histogram in Figure 25. Looking at regional stream gages, you find that historical peak flows for the region typically occur in August or September, consistent with model results.

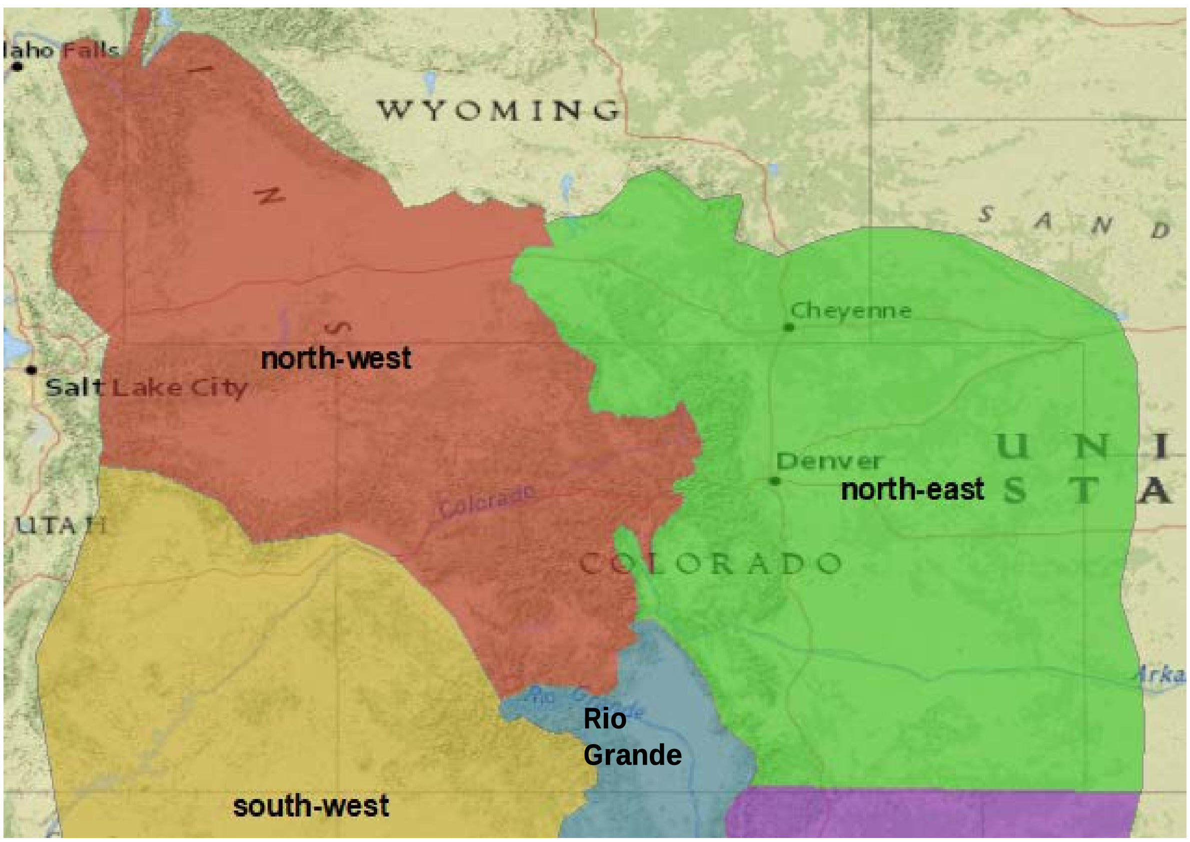
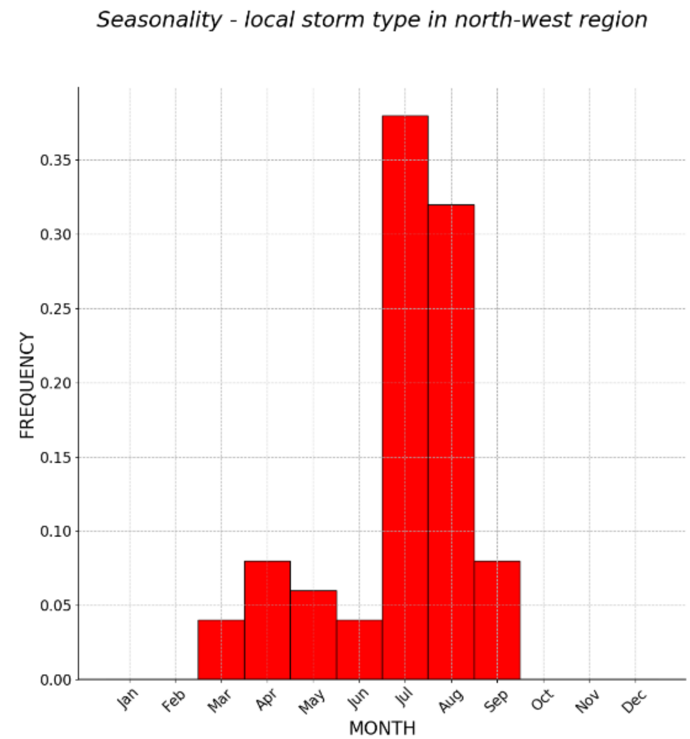


Figure 22: Regions for CO-NM REPS storm seasonality analysis.



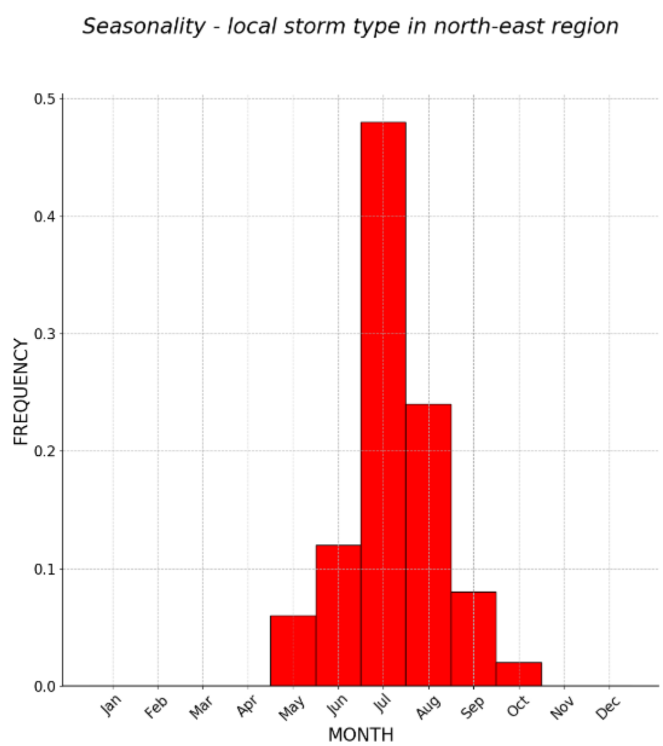
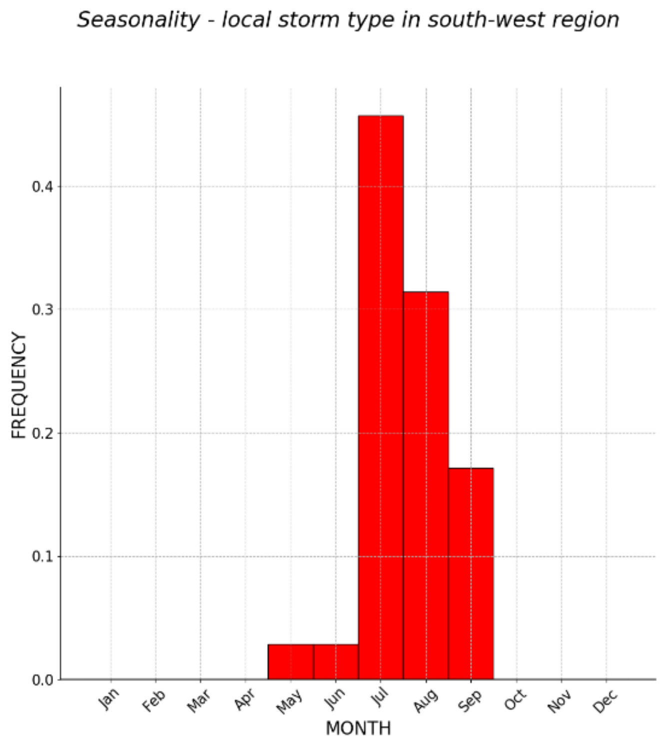


Figure 23 (cont'd on next page): Seasonal distribution of largest 50 **Local Storms** in each region. Top histogram is for north-west region, bottom is for north-east region (cf: Figure 22). (REPS Vol. III, 2018)



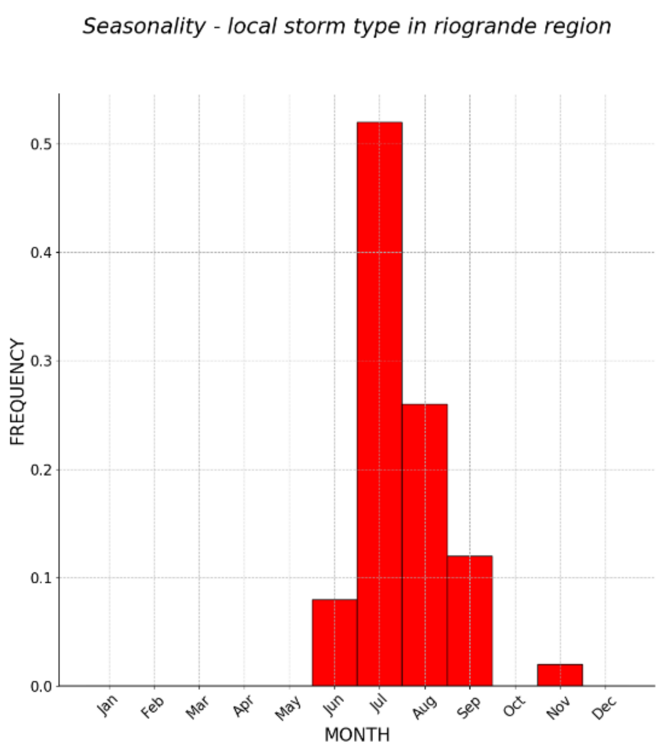
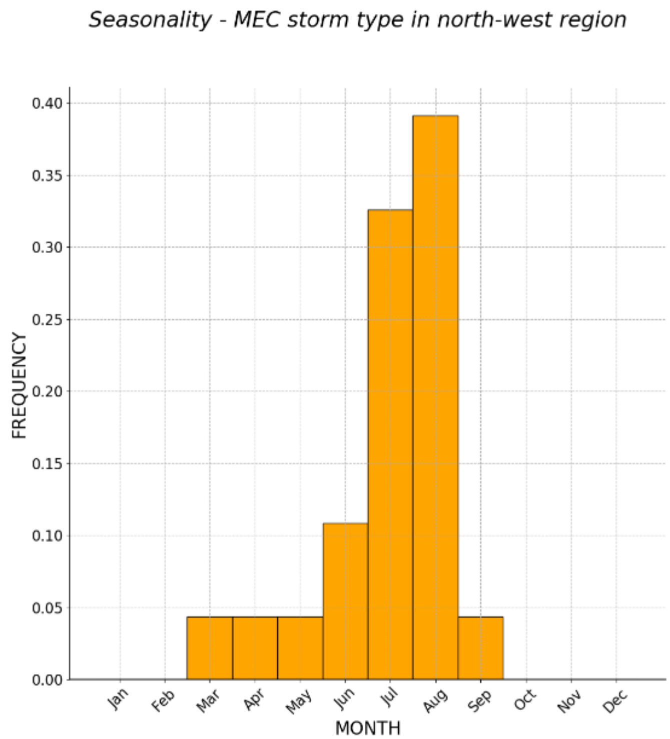


Figure 23 (cont'd from previous page): Seasonal distribution of largest 50 **Local Storms** in each region. Top histogram is for south-west region, bottom is for Rio Grande region (cf: Figure 22) (REPS Vol. III, 2018)



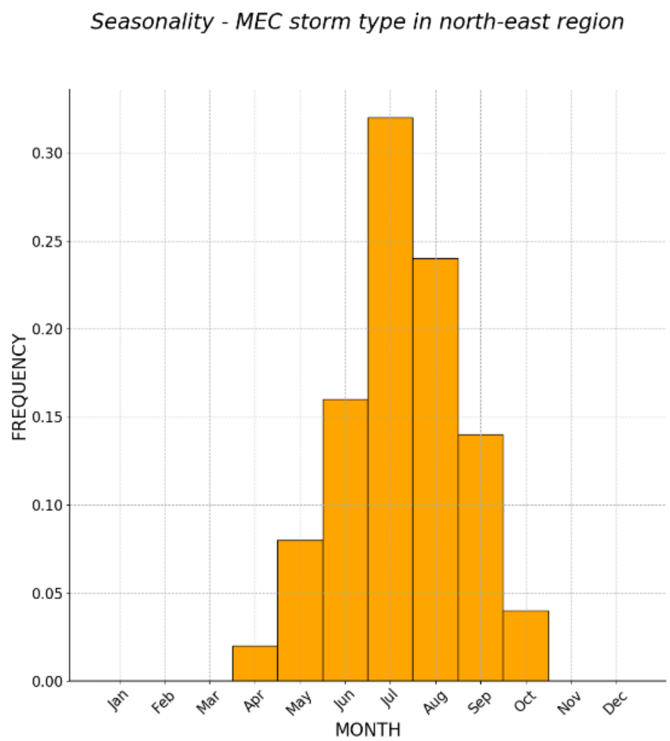
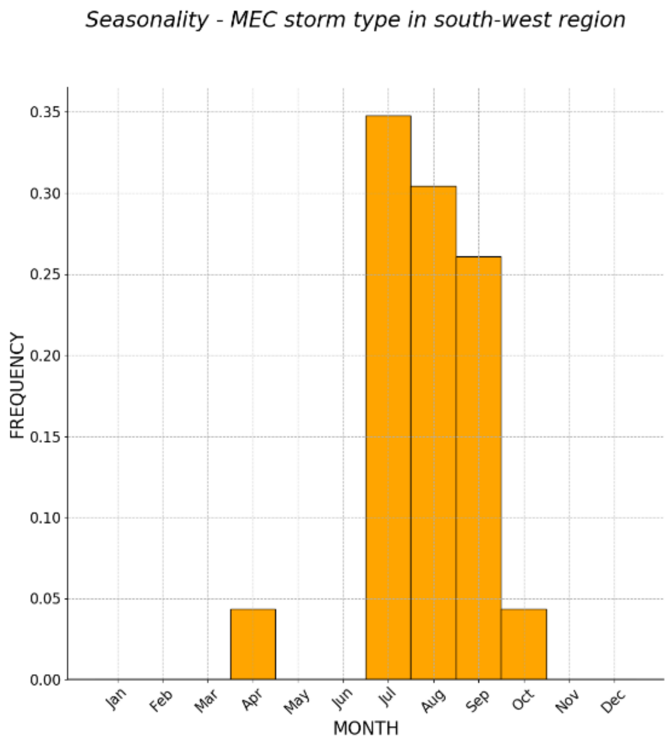


Figure 24 (cont'd on next page): Seasonal distribution of largest 50 **Meso-scale with Embeded Convection (MEC)** storms in each region. Top histogram is for north-west region, bottom is for north-east region (cf: Figure 22) (REPS Vol. III, 2018)



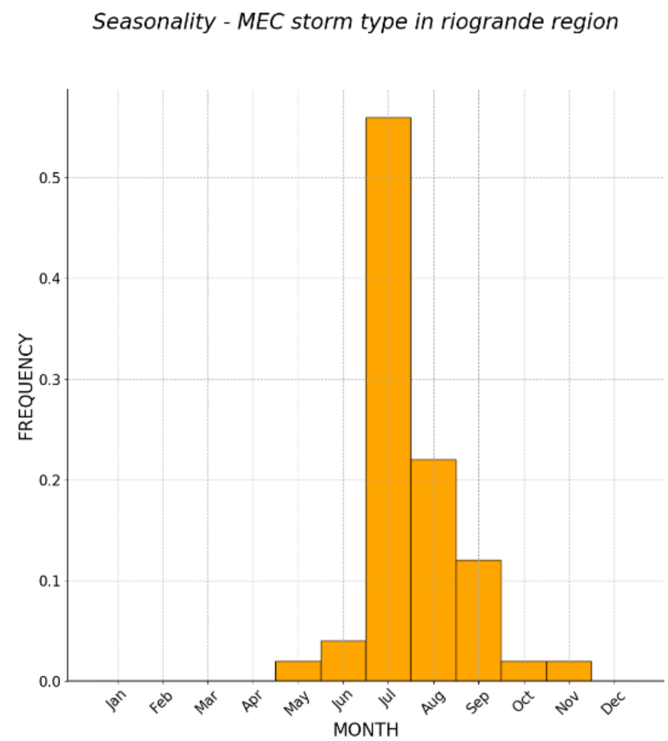
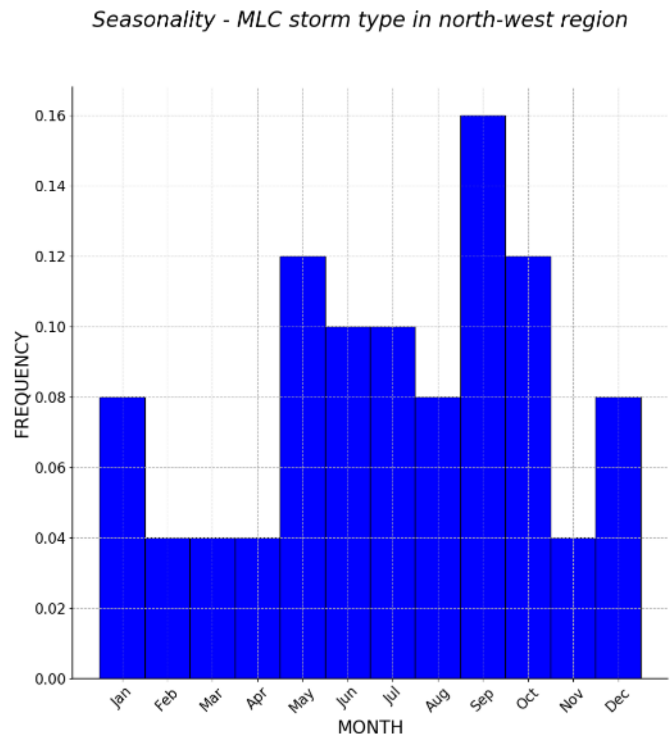


Figure 24 (cont'd from previous page): Seasonal distribution of largest 50 **Meso-scale with Embedded Convection (MEC)** storms in each region. Top histogram is for south-west region, bottom is for Rio Grande region (cf: Figure 22) (REPS Vol. III, 2018)



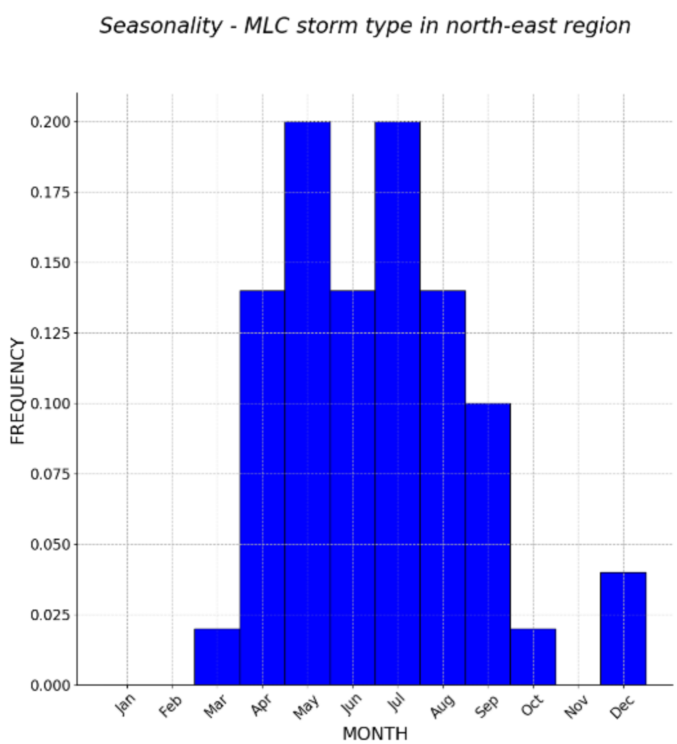
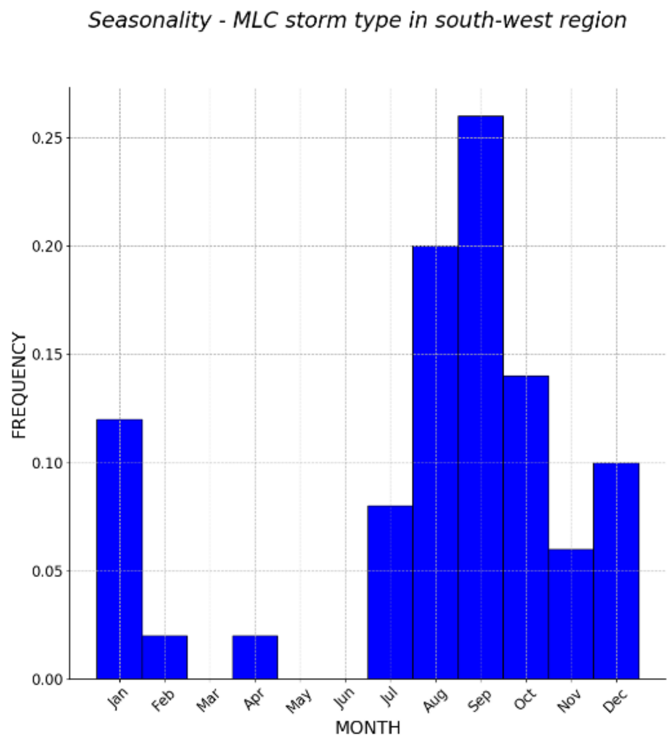


Figure 25 (cont'd on next page): Seasonal distribution of largest 50 **Mid-Latitude Cyclone (MLC) storms** in each region. Top histogram is for north-west region, bottom is for north-east region (cf: Figure 22) (REPS Vol. III, 2018)



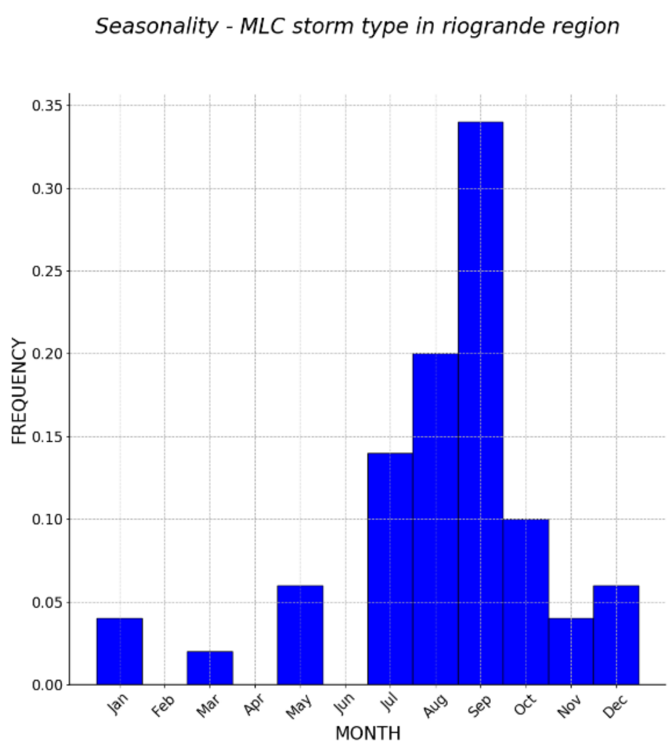


Figure 25 (cont'd from previous page): Seasonal distribution of largest 50 **Mid-Latitude Cyclone storms** in each region. Top histogram is for south-west region, bottom is for Rio Grande region (cf: Figure 22) (REPS Vol. III, 2018)

9.8 Regional Peak Flow Envelope Curves & USGS Colorado Flood Database:

9.8.1 Modeled peak flows can be plotted on regional peak flow envelopes as a reasonableness check against maximum observed flood discharges. Peak flow envelopes typically plot observed maximum floods -- gaged, indirect (i.e., surveyed after-the-fact), and paleo-flood estimates -- as a function of drainage area; the plots are typically shown in log-log space due to large non-linearities. Peak flow envelopes have been widely used in hydrology literature to examine possible upper limits of flooding and regional variations in flood production (Crippen and Bue, 1977; Wolman and Costa, 1982; Costa, 1987; and O'Connor and Costa, 2004). Crippen and Bue (1977) divided the continental U.S. into 17 regions based on variations in physiography and rainfall intensity; Regions 12-14 cover Colorado. Crippen and Bue (1977) then plotted peak flow measurements from gaged and indirect discharge measurements from 883 locations and defined regional peak flow envelope curves. O'Connor and Costa (2004) used a data set comprised of the top 10% of annual peak discharges from USGS stream gage stations, resulting in 35,663 annual peak flows at 14,815 U.S. gages, and then plotted peak flow envelopes for 90th percentile and 99th percentile peak flows. They then mapped the 90th and 99th percentile flow locations to show regions that are prone to extreme flooding. They concluded such regions have access to atmospheric moisture and have topographic relief, causing orographic forcing of rainfall and rapid concentration of streamflow. Peak flows that fall into the U.S. 90th percentile have occurred along Colorado's Front Range Foothills and along the Colorado-New Mexico border south of the Raton Mesa and in the Republican River basin on Colorado's Eastern Plains.

Envelope curves have often been used to guide engineering design (Wolman and Costa, 1982). Wolman and Costa (1982) state that envelope curves provide a useful check on peak flow estimates, but should not be relied on solely for engineering design because of basin-specific variations. While the curves capture large regional differences based on climate and terrain, they do not address basin-scale variations like micro-climates, soil variations, basin slope, etc. Wolman and Costa (1982) also showed that new peak flows are increasing the U.S. peak flow envelope more slowly as time goes by and the data set of peak flows increases. They suggested at that time (1982) that the envelope may be approaching a physical limit. Although Crippen and Bue (1977) stated there is no statistical return interval associated with peak flow envelopes, an upper physical limit is suggestive of the probable maximum flood. Vogel et al (2007) demonstrated possible statistical methods to estimate exceedance probability of a flood of record (FOR) envelope using 226 USGS stream gages in the continental U.S. and for an envelope of associated PMF estimates (by Nuclear Regulatory Commission) at those same locations. For their data set, they estimated annual exceedance probabilities between 10e-4 and 10e-6 for the FOR envelope and about 10e-6 to 10e-8 for the PMF envelope.

The U.S. Bureau of Reclamation uses regional peak flow envelope curves as part of hydrologic risk analysis. Regional envelope curves capture important regional differences in flood production across Colorado. The USBR's regional peak flow envelope used for Colorado's Front Range (USBR, 2009) is significantly higher than that used for the Rocky Mountain inter-mountain region (USBR, 2008). For example, at 100 sq mi drainage area size, the USBR's Front Range envelope peak flow is about 40,000 cfs versus about 6,000 cfs for the inter-mountain region envelope (NOTE: these particularly 2008 and 2009 envelopes are based only on gaged peak flows, not indirect or paleo-floods). Alberta, Canada's Ministry of Transportation (undated) plotted gaged and estimated peak flows for six basins on the eastern slopes of the Canadian Rocky Mountains, and evaluated several methods of enveloping them. They concluded that Creager envelopes (Creager et al, 1950) did not perform well over the full range of area sizes (10 sqkm [3.86 sq mi] to about 100,000 sqkm [38,610 sq mi]), but visually drawn envelopes provided a better fit of the data over the range of area sizes. They caution that envelope curves provide context for an upper range of flows, but that basin runoff is a function of many properties besides drainage area.

9.8.2 Colorado Dam Safety has used the USGS Colorado Flood Database (created in cooperation with Colorado Department of Transportation) to develop regional peak flow envelopes for Colorado, for the purpose of reasonableness checks of extreme flood rainfall-runoff models for dam safety purposes. **Note that in keeping with Crippen and Bue (1977), Alberta Ministry of Transportation (undated), and others, Colorado Dam Safety's envelope curves are visually fit to the observed flood data.**

The USGS describes the importance of using historical and systematically collected flood data. The purpose of the USGS Colorado Flood Database is to make low probability events in the systematic flood records available to water resources engineers to improve flood estimates (Kohn et al, 2013). The USGS Colorado Flood Database includes gaged peak flows and indirect-measured peak flows from 1867 – 2015. **The database includes flood peaks from many of the same extreme storms that were used to develop REPS PMP, e.g., June 1921 on the Arkansas River, May 1935 Cherry Creek, June 1965 Jimmy Camp Creek, etc.** The USGS Colorado Flood Database is comprised of the 5 largest gaged peaks that have occurred at each USGS stream gage in the NWIS database; indirect measurements that were collected from floods at sites with no stream gage, at gaged sites outside of the gaged period of record, or at gaged sites during the period of record for stage-discharge rating extension or modification. The database also includes peak flow estimates from paleo-flood studies compiled from several peer-reviewed papers. The database currently (2022) includes 6,886 flood events at 1,624 sites in Colorado (see Figure 26). The USGS Colorado Flood Database web address is:

https://co.water.usgs.gov/projects/COFloodDB/html/COFloodMap.html

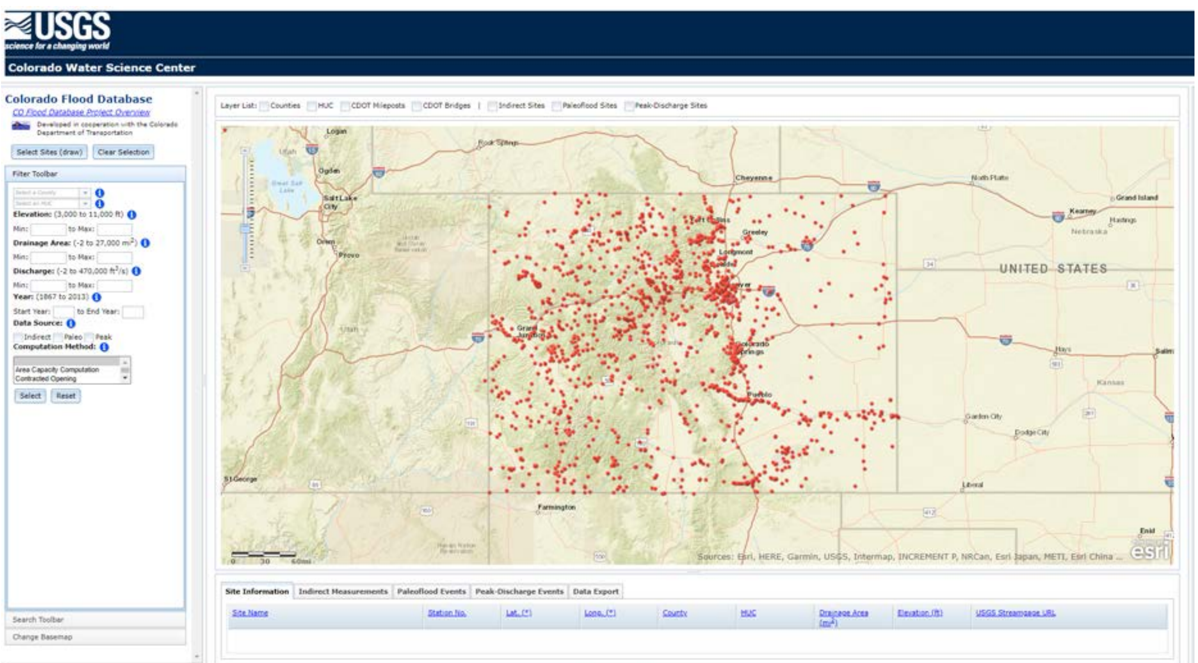


Figure 26: General distribution of the 1,624 flood sites included in the USGS Colorado Flood Database: https://co.water.usgs.gov/projects/COFloodDB/html/COFloodMap.html

9.8.3 Colorado Dam Safety mapped the USGS Colorado Flood Database data set and experimented with regional groupings that showed similar peak flow limits in terms of maximum observed peak flows versus drainage area size. Three peak flow envelope regions were determined using REPS storm transposition zones (Figures 27 & 28): (1) Eastern Plains/Front Range Foothills < 7,500 feet elevation (REPS transposition zones 1 and 3), (2) Mountains >7,500 feet elevation (REPS transposition zones 5, 6 and 9), and (3) Western Colorado < 7,500 feet elevation (REPS transposition zones 10, 14, 15, and 16). Note that REPS transposition zones 7 (San Luis Valley) and 17 (North Park) were not originally analyzed due to the small number of dams (none in zone 7), but peak flows there have been checked and found to be consistent with the Mountains Region < 7,500 ft peak flow envelope region. **The following sub-sections provide a discussion of each regional curve.**

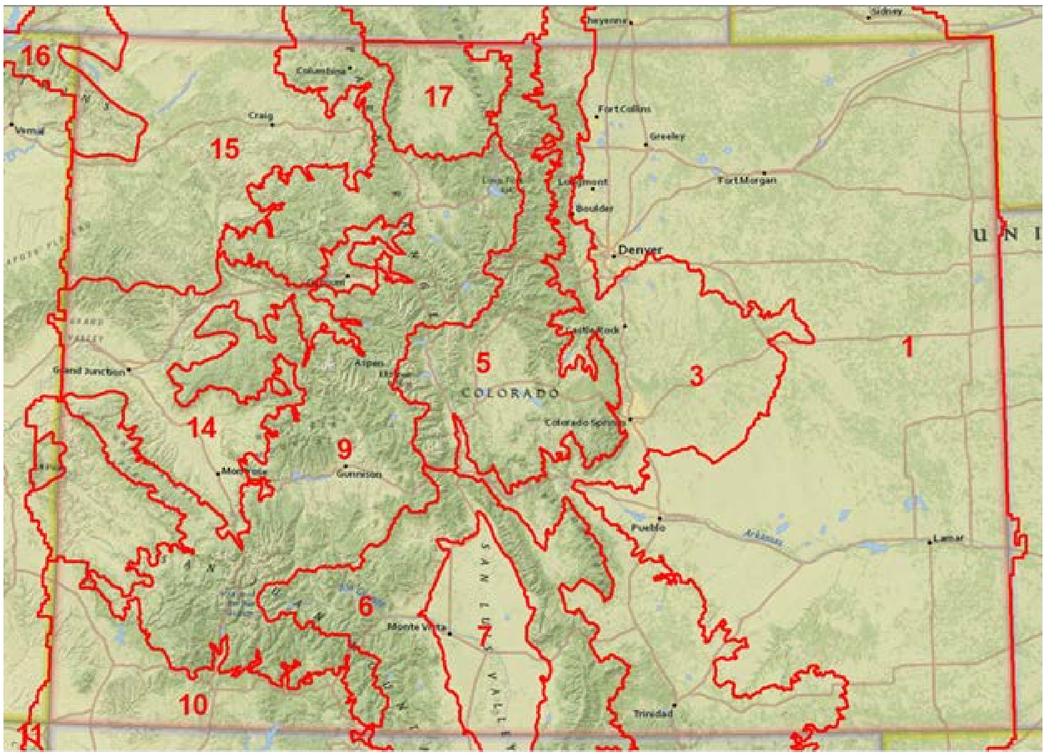


Figure 27: REPS PMP storm transposition zones (red) overlaid on terrain.

<u>9.8.3.1 Eastern Plains/Front Range Foothills < 7,500 feet elevation Peak Flow Envelope (Figure 29):</u> This peak flow envelope is by far the most extreme of the three Colorado curves. It covers the highly dynamic weather region that can see high moisture influx from the Gulf of Mexico and has steep orographic terrain along the Front Range foothills, creating orographic lift and rapid runoff response. This envelope curve is controlled by several of the worst floods in Colorado's recorded history: June 1965 on Kiowa Creek, Plum Creek and Jimmy Camp Creek (one of the highest peak flows for its drainage area size in the U.S.); April 1935 on Kiowa Creek; and July 1976 on the Big Thompson River. In terms of controlling Storm Types versus area size, the July 1976 Big Thompson storm, which generally controls the envelope at area sizes less than five square miles, is classified by REPS as a Local thunderstorm (REPS Summary Report, Vol. II, App. F). The July 1965 and May 1935 storms control the envelope above 50 sq mi. REPS PMP classifies both of these storms as Local/Hybrid storms (i.e., Meso-scale with Embedded Convection);

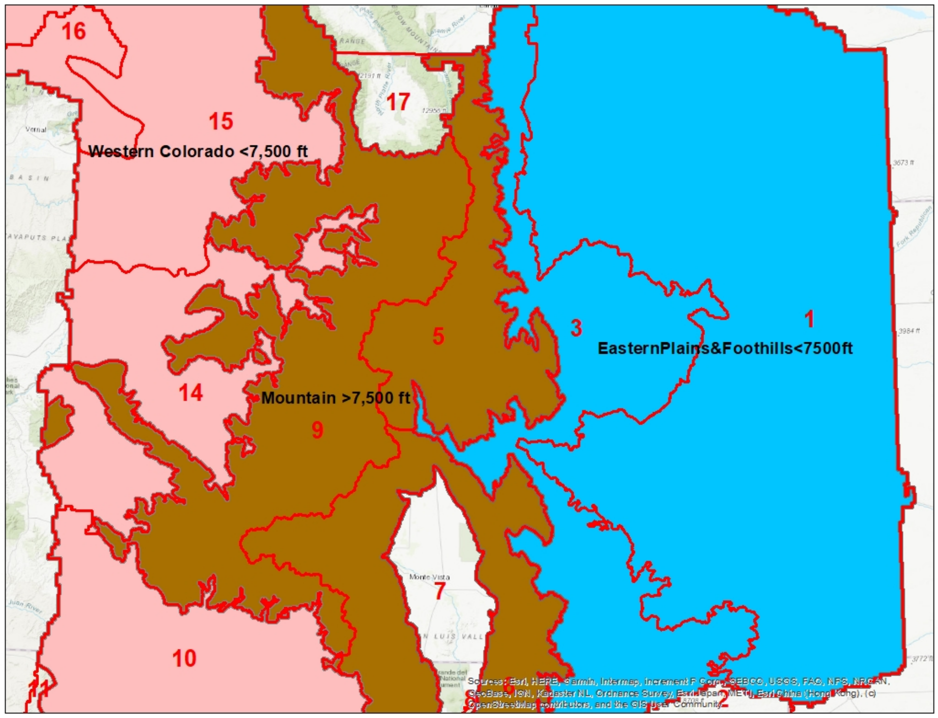


Figure 28: Colorado Dam Safety peak flow envelope regions: (1) Eastern plains and Front Range foothills < 7,500 feet elevation (blue), (2) Mountains > 7,500 feet elevation (brown), and (3) Western Colorado < 7,500 feet (pink) with REPS PMP storm transposition regions outlined and numbered in red. Note that REPS transposition zones 7 (San Luis Valley) and 17 (North Park) were not originally analyzed due to the small number of dams (none in zone 7), but peak flows there have been checked and found to be consistent with the Mountains Region > 7,500 ft peak flow envelope region.

both were large area events, but included smaller cells of embedded convection and high intensity rainfall. It is worth noting that historical long-duration, low intensity PMP General Storms along the Front Range foothills (e.g. Sept. 2013 and 1969 Big Elk Meadows) do not control the flood envelope.

USGS paleoflood estimates are included in the USGS Colorado Flood Database, but do not control the Eastern Plains/Front Range Foothills envelope. Several dam failure peak flows in the database were ignored for purposes of drawing our peak flow envelope; the dam breach peak flows stand out as outliers relative to natural floods. Crippen and Bue's (1977) eastern region (their Region 12) envelope (green dashed curve on Figure 29) follows Colorado Dam Safety's Eastern Plains/Foothills envelope well. This is encouraging, meaning the envelope has not changed significantly since 1977. As noted above, Colorado Dam Safety's envelope (red line in Figure 29) is visually fit to the data. Finally, observed peak flow data have been sub-divided by REPS transposition zone and plotted in different colors to allow the user to further compare them to the basin-of-interest.

<u>9.8.3.2 Mountains > 7,500 feet Elevation Peak Flow Envelope (Figure 30):</u> This envelope covers the orographically-sheltered region of the interior and high elevation Rocky Mountains of Colorado, including North Park and the San Luis Valley. This envelope curve is significantly less extreme than that of the neighboring Eastern Plains/foothills. For example, at 100 sq mi drainage area size, the Mountain envelope flow is about 10,500 cfs versus about 180,000 cfs for the Eastern Plains/foothills envelope. Jarrett (1989) proposed the elevation limit of around 7,500 feet in Colorado's Rocky Mountains for extreme rainfall-runoff driven

flooding, above which, he and others found no paleo-flood or historical evidence of extreme rainfall-runoff floods in the past 10,000 years. The 7,500-foot elevation limit has been studied and generally corroborated over the ensuring 30 years. USGS StreamStats makes use of it, and the REPS study used it. The September 2013 storm and rainfall-driven flooding occurred at high elevations up to the Continental Divide, yet the magnitude of the flooding above 7,500 feet was simply nowhere near as extreme as record floods at lower elevations along the Front Range foothills. In fact, September 2013 peak flows do not control the peak flow envelope for either the Mountains or Plains/foothills regions.

Colorado Dam Safety's Mountain Region envelope curve (red line in Figure 30) is controlled by the 1976 Big Thompson flood and the 1945 Quartz Creek near Ohio City flood at small area sizes (<10 sq mi). At 13.5 sq mi, the envelope is controlled by a USGS paleo-flood estimate on Cement Creek near Silverton with a reliability of 83-1000 years. At larger area sizes (>50 sq mi) the envelope is controlled by floods on the Huerfano River in the Sangre de Cristo range and by the Rio Grande River and Vallecito Creek in the San Juan range. In terms of controlling Storm Types, the 1976 Big Thompson storm was classified by REPS as a Local Storm. The September 1970 flood on Vallecito Creek in the San Juans was a classified by REPS as a General Storm (REPS Summary Report, Vol. II, 2018).

Peak flows from the July 1999 Saguache Creek flood, provide by Dr. Jarrett via email, are shown on the Mountain Region envelope plot as grey X's in order to demonstrate the possibility that larger flows at small area sizes may have in fact been debris flows (Costa and Jarrett, 1981). Dr. Jarrett thoroughly investigated the Saguache Creek flood after-the-fact and concluded that several sites experienced debris flows (email dated March 19, 2021). He also investigated the Quartz Creek near Ohio City flood indicators as part of his doctoral research at Colorado State University and concluded that these floods were likely debris flows (Jarrett, 1987). We included the Quartz Creek peak flows in our Mountain Region envelope because the USGS Colorado Flood Database recognizes them; however, Dr. Jarrett advised that the lower end of our Mountain Region envelope (<1 sq mi+/-) may be high and should be used with judgement (verbal communication). It is instructive to note that the Crippen and Bue (1977) envelope for their mountain region (Region 13) (green dash on Figure 30) is significantly higher than ours (approaching an order of magnitude higher), because Crippen and Bue (1977) included peak flow locations below 7,500 feet elevation in their mountain region -- their Region 13 envelope is defined by floods in Colorado, Idaho, Montana and Wyoming at elevations between about 2,150 ft and 5,310 ft. At the time they did their work (1977), Jarrett's (1989) 7,500-foot limit on extreme rain-driven flooding was not generally recognized.

9.8.3.3 <u>Western Colorado < 7,500 feet elevation Peak Flow Envelope (Figure 31):</u> Figure 31 applies to Colorado's Western Slope below about 7,500 feet elevation, including the flanks of the San Juan Mountains, mesas and canyons of the Colorado Plateau region, and the Yampa and Green River basins in Northwest Colorado. In comparison to the other two regions, the Western Colorado envelope lies below the Mountain Region envelope at small area sizes (<2 sq mi +/-) -- see above discussion about debris flows -- then slightly above it at larger area sizes. The entire Western envelope lies far below the Eastern Plain/Foothills envelope. The Western envelope is notably controlled by late-season floods -- August, September and October -- in contrast to the other regions. The seasonality histograms in Figures 23-25, above, generally show more likely occurrence of late season extreme storms in the northwest and southwest regions for all storms types. At small drainage areas (<20 sq mi) the Western Colorado envelope is controlled by August and September floods on Piceance Creek near Rio Blanco, Badger Wash near Fruita and

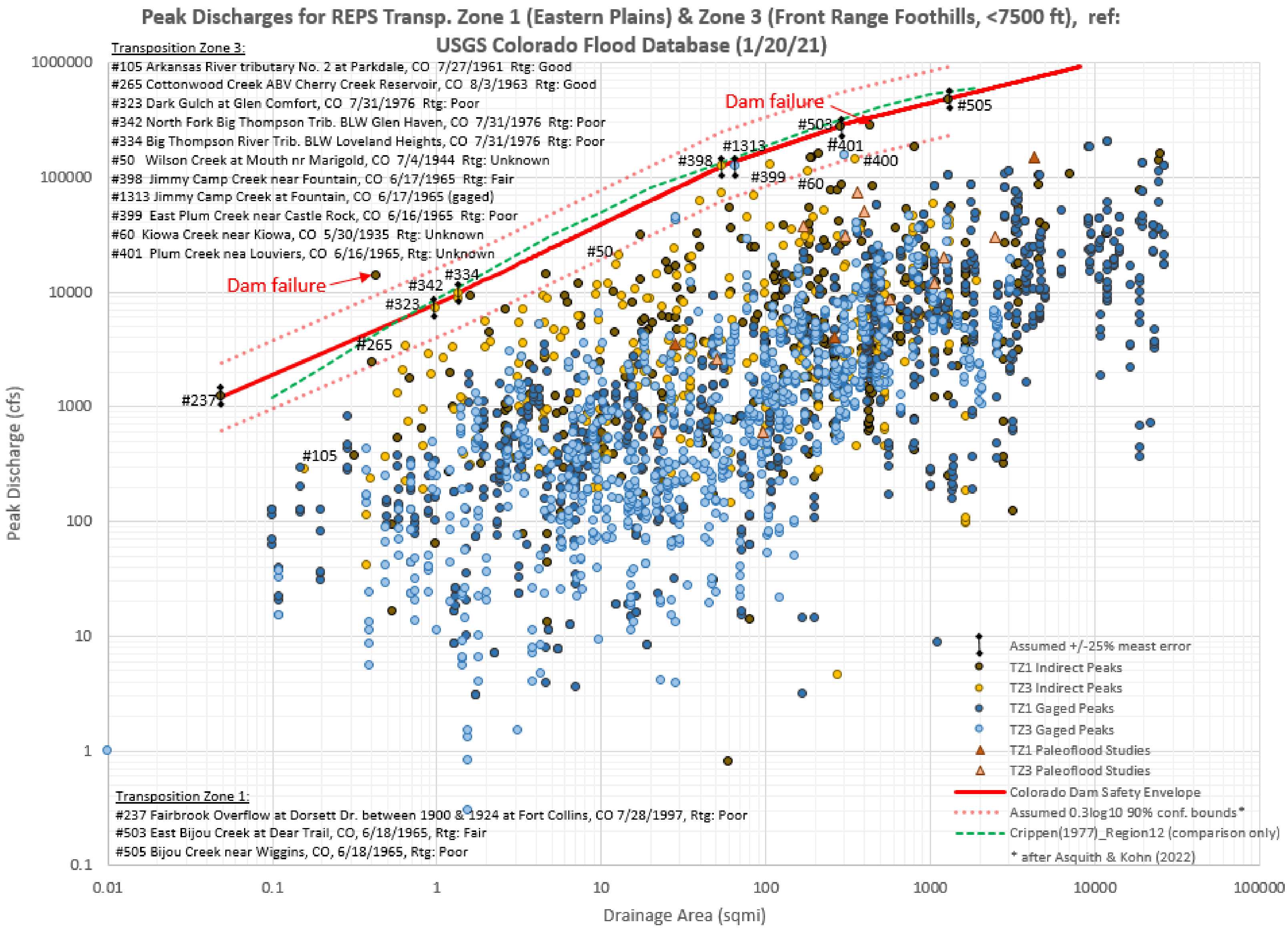


Figure 29: Observed peak flows and peak flow envelope for Colorado's Eastern Plains and Front Range foothills <7,500 feet elevation. Red line is Colorado Dam Safety's visually estimated envelope; red dotted lines are conceptual 90% confidence bounds (±0.3log10 cycle).

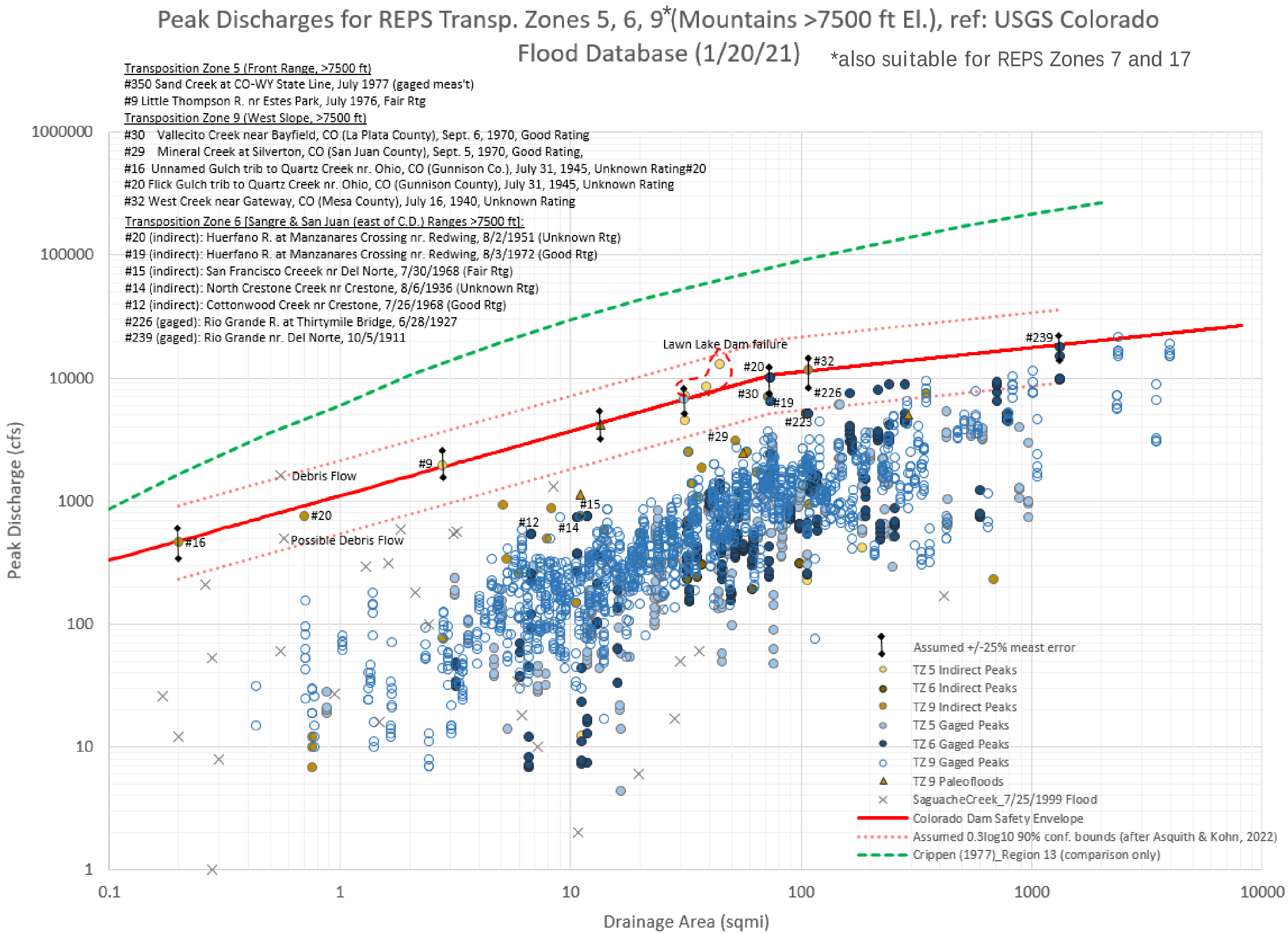


Figure 30: Observed peak flows and peak flow envelope for Colorado's Mountains >7,500 feet elevation. Red line is Colorado Dam Safety's visually estimated envelope; red dotted lines are conceptual 90% confidence bounds (±0.3log10 cycle).

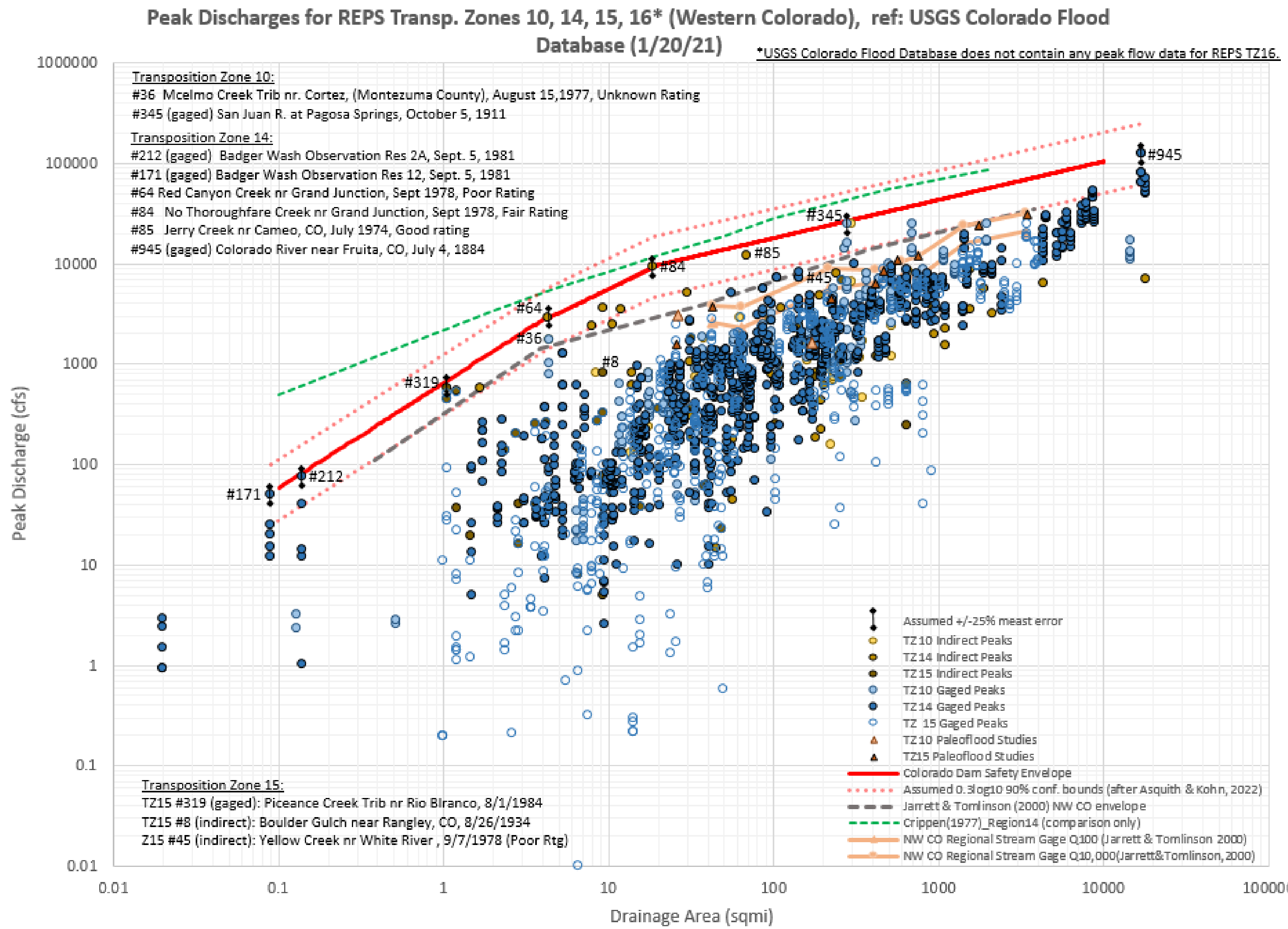


Figure 31: Observed peak flows and peak flow envelope for Colorado's Western Slope <7,500 feet elevation. Red line is Colorado Dam Safety's visually estimated envelope; red dotted lines are conceptual 90% confidence bounds (±0.3log10 cycle).

Red Canyon and No Thoroughfare Creeks near Grand Junction. The related storms were not used for the REPS PMP study, but at such small area sizes it can be assumed they were intense, convective storms. At larger area sizes (>100 sq mi), the envelope is controlled by the October 1911 flood on the San Juan River at Pagosa Springs. This storm was a General Storm/Remnant Tropic Storm.

Crippen and Bue's (1977) western region (Region 14) envelope is close to our Western Colorado envelope, except that the Crippen and Bue curve is higher at small drainage area sizes, where theirs is controlled by floods in Arizona, New Mexico, and Utah, not Colorado. It should also be noted that their western region (Region 14) includes the Colorado Plateau and western San Juan range, but not northwest Colorado, the latter of which they included in their mountain region (Region 13). This may in fact be more appropriate; however, in practice our Mountain and Western Colorado envelope curves are reasonably similar.

9.8.4 Using the peak flow envelope curves for reasonableness checks: Microsoft Excel files of Colorado Dam Safety's Peak Flow Envelope plots can be downloaded from the following link to facilitate plotting and comparison of rainfall-runoff model discharges:

https://drive.google.com/drive/folders/1Q_Y6arM0Vd4NomgBB-U4NxTBOZ0zNz-c?usp=sharing

The recommended use of Figures 29-31 is to plot all modeled REPS PMP and probabilistic peak flows for comparison, along with other reasonableness checks data, discussed above, for the basin of interest -- historical flood peak flows, flood frequency estimates, etc. *Regional* 1/100 and 1/1000 AEP flood frequency estimates should be plotted as well. Figure 32 below shows an example peak flow envelope plot with HEC-HMS REPS model results and data from reasonableness checks.

Our envelope curves are intended to provide a reasonableness check of extreme storm rainfall-runoff model results. In the past, unchecked extrapolation of rainfall-runoff models to extreme events appears to have led to design storms that were orders of magnitude beyond any observed floods, present or from paleo records. It is desirable to avoid those sorts of gross over-estimates in order to more accurately identify and quantify dam safety risks. That said, the peak flow envelopes shown in red on Figures 29, 30 and 31 are simply visual fits of the maximum data; they are not intended to imply any theoretical function of flood production with respect to drainage area. Further, observed peak flow measurements contain uncertainty; the USGS Colorado Flood Database rates its measurements on a qualitative scale of *poor*, *fair*, or *good*. Many extreme flood indirect (after-the-fact) flood discharge estimates are understandably rated *poor* with uncertainties of 25% or more. We have plotted +/-25% error bounds on individual peak flow measurements using "whiskers" to represent an approximate level of discharge measurement error for use in comparing modeled peak flows to individual historical floods. In terms of uncertainty on the envelopes themselves, the envelopes are a form of graphical regionalization of a predictive regression model, where inter-basin variation is a source of model error or uncertainty. Historically regional predictive models for Colorado flood hydrology have uncertainties of 1/4 to 1/3log10 cycle (Asquith and Kohn, 2022). On Figures 29-31 we have plotted 1/3 log10 cycle offsets to the envelopes as conceptual 90% confidence bounds for use in comparing modeled peak flows to the peak flow envelopes in light of the full scope of regional variation. Maximum flood production for a particular basin depends on many factors, not just drainage area, so the envelopes are not expected to provide an exact answer. The envelope curves are one tool of the many discussed in this section that can be used to

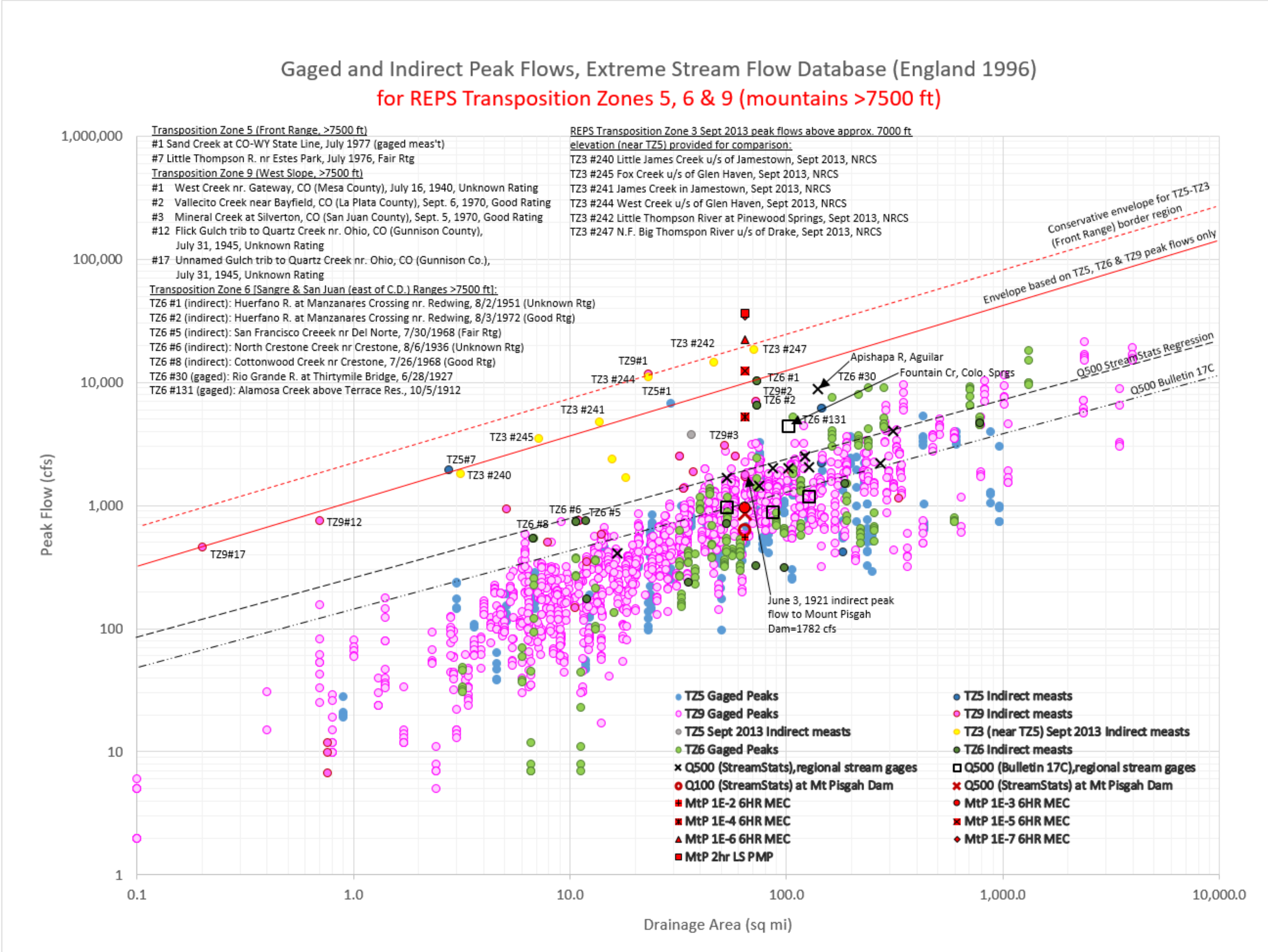


Figure 32: Example peak flow envelope with modeled REPS PF and PMF peak flows, as well as data from reasonableness checks.

make a case for defensible model results. See Section 9.11 on *confidence* and Section 10 on using *confidence* to help weight observed flood data for use in model calibration.

One of the most useful findings of the envelope plots is the regional differences in flood yields, particularly between the Eastern Plains/Front Range foothills (Figure 29) versus the rest of the state (Figures 30 and 31). This regional difference has been shown by Jarrett (1989) and others, and it is implicit in REPS rainfall estimates via storm transposition boundaries. However, historically, dam safety design flood modeling many not have reflected these regional differences. Figures 33 and 34 below compare our three regional peak flow envelope curves in log-log space (Figure 33) and linear space (Figure 34). The linear graph in particular depicts the large regional differences in flood magnitudes. The shortcoming of many past dam safety design flood studies seems to be related to erroneous extrapolation/transposition of flooding from the Front Range foothills/Eastern Plains to the rest of the state.

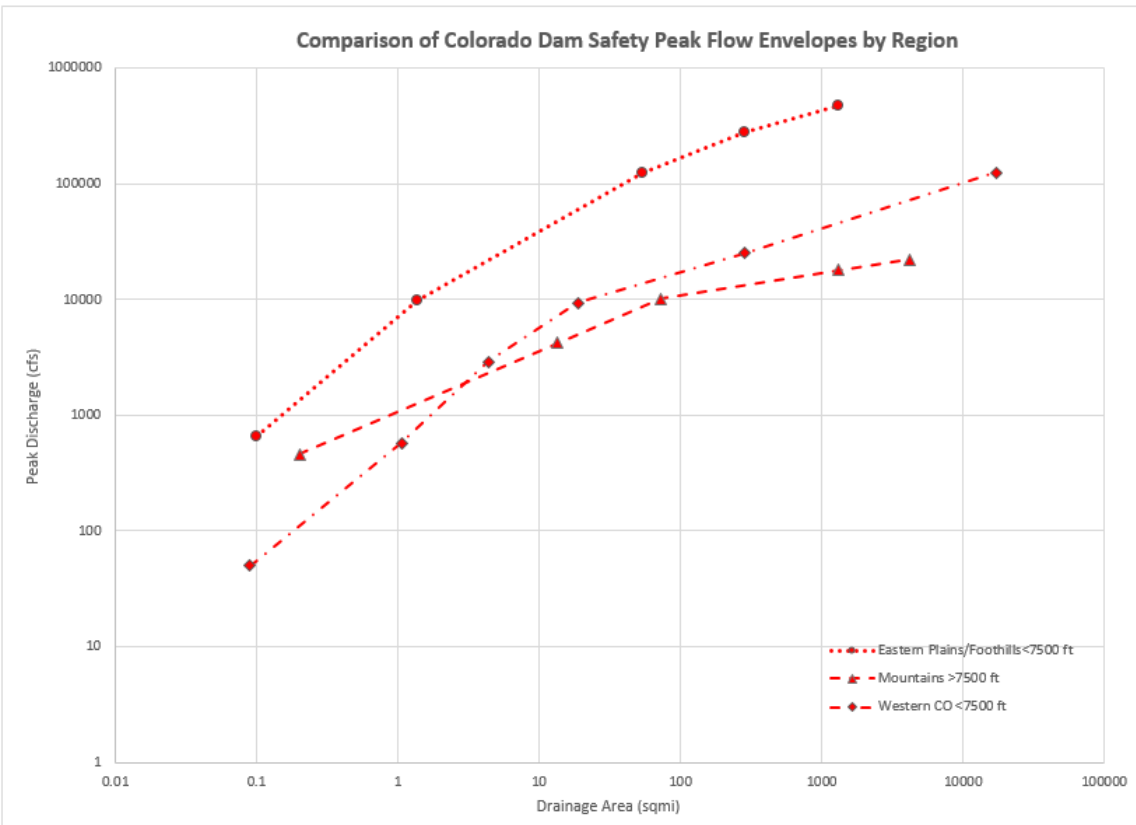


Figure 33: Comparison of Colorado Dam Safety's three regional peak flow envelope curves in log-log space.

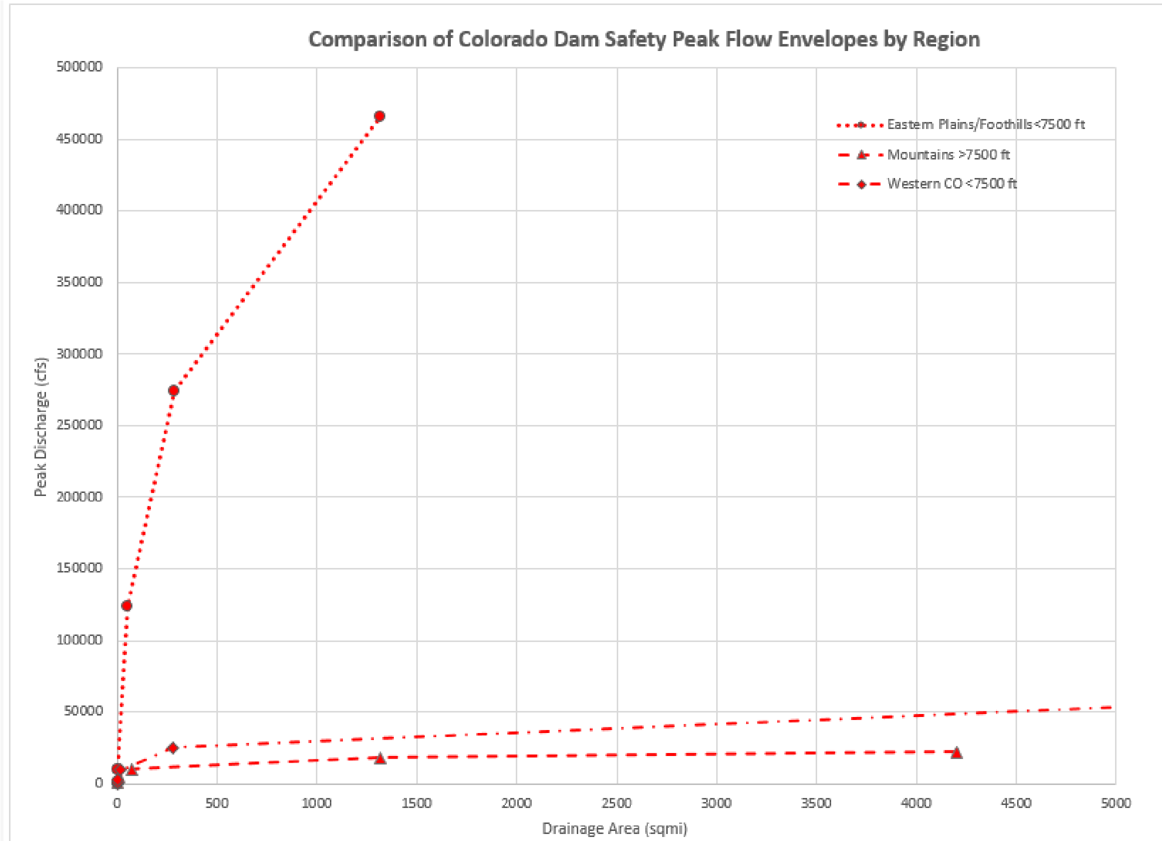


Figure 34: Comparison of Colorado Dam Safety's three regional peak flow envelope curves in linear space.

Finally, Figure 35 plots regional 1/100 AEP flood frequency estimates from USGS StreamStats and from Bulletin 17C, along with the USGS Colorado Flood Database observed peak flows, for our Mountains region >7,500 feet. There is a moderate amount of scatter in the 1/100 AEP flood estimates, indicative of basin-specific variation, but in general they make a linear trend in log-log space, consistent with a power-function relationship between flood production and drainage area. In contrast, the observed peak flows and our envelope level off at larger drainage area sizes, say above around 75 sq mi. This may be because there are fewer large basins, and so the sample size of peak flows is smaller at larger areas. The plot suggests that the peak flow envelope may not correspond to a uniform return interval and may increase in likelihood of exceedance with increasing area size. If this is the case, then the envelope curves may not represent an upper limit at larger area sizes. On the other hand, Crippen and Bue (1977) and Wolman and Costa (1982) used non-linear log-log envelopes like ours, and they do not indicate a significant or larger increase in the curves at larger area sizes since at least 1948. Research by Laurenson and Kuczera (1999) and Nathan et al (2016) on notional AEP of PMP (i.e., the likelihood corresponding to estimates of flood upper limits) calculated lower notional AEP of PMP for smaller area sizes and shorter durations, possibly consistent with what we see in Figure 35. Lastly, the shape of the observed flood data and our envelope could indicate physical limits on storm size and contributing areas of flooding on larger basins in Colorado or a change in storm type altogether controlling flooding on larger basins, e.g. from rain-driven flooding to snowmelt. This could suggest inaccuracies in flood frequency estimates as much as the peak flow envelopes. In summary, peak flow envelopes are extremely useful, but should be used with judgment.

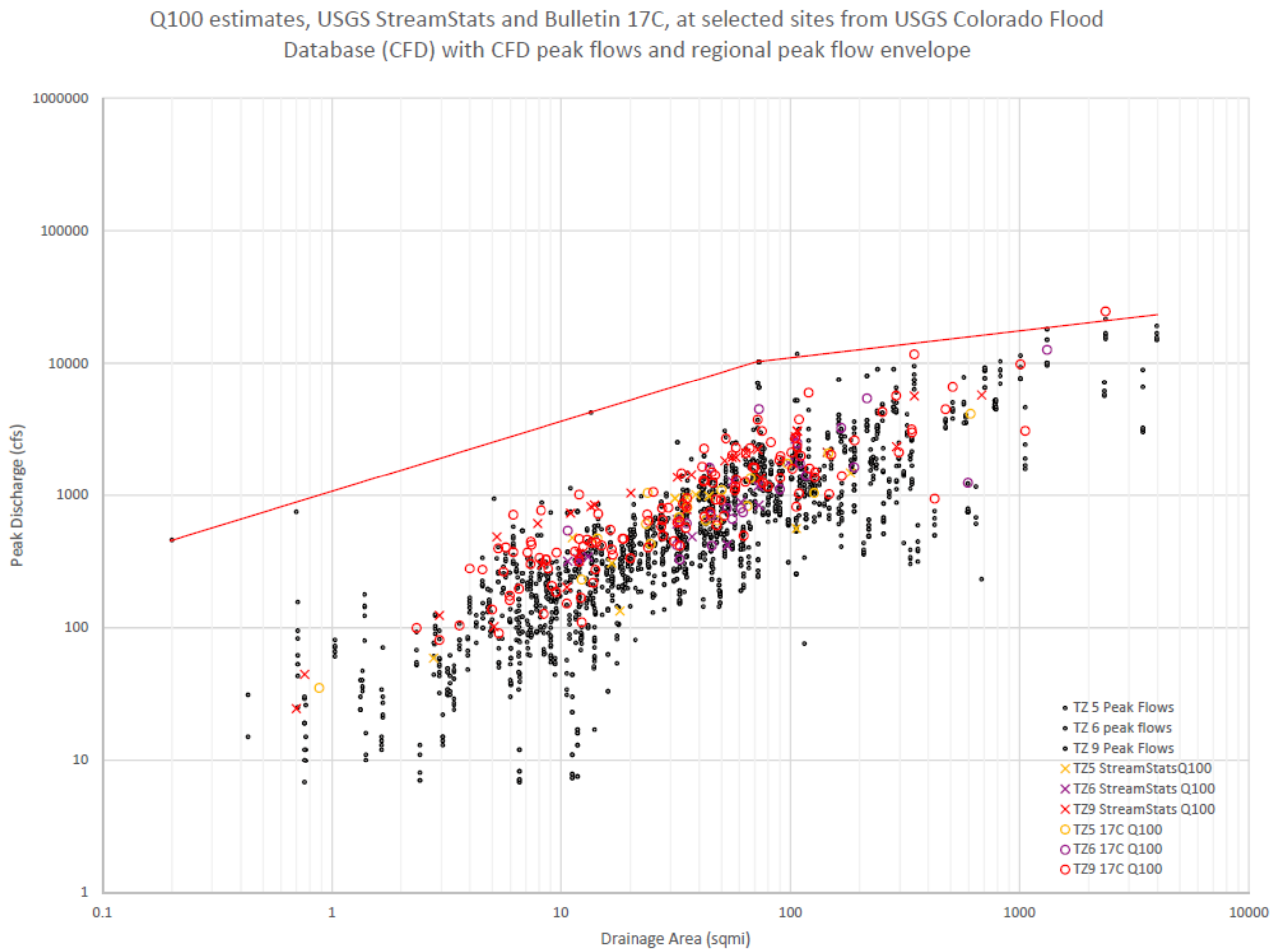


Figure 35: Regional 1/100 AEP (Q100) flood frequency estimates by USGS StreamStats (colored Xs) and by Bulletin 17C (colored circles) at selected sites in the USGS Colorado Flood Database, overlaid on observed peak flows (black dots) and the peak flow envelope for our Mountain >7,500 feet elevation region.

9.9 Upper Tail Ratios: The Upper Tail Ratio (UTR) is a statistic defined by Smith et al (2018) as the ratio of maximum observed flood to the 10-YR ARI flood frequency estimate for a basin. The UTR may serve as a good reasonableness check because it combines maximum observed flood data with a site-specific flood frequency estimate, thereby normalizing inter-basin variation in peak flows by a measure of respective site-specific flood frequency statistics. The UTR metric may prove to have less variability than peak flows alone.

Figure 35 above implies that UTR may decrease with larger area sizes. In fact, cursory analysis by Colorado Dam Safety indicate as much (see Table 12, Figures 36 and 37). Table 12 tabulates UTRs corresponding to envelope-controlling peak flows for our Mountains >7,500-ft elevation region peak flow envelope. The Table 12 UTRs are plotted against drainage area size in Figure 36 indicating decreasing UTR with area size. The calculated UTRs at small areas are high compared to those reported by Smith et al (2018); however, Smith et al (2018) generally looked at larger gaged basins in the NWIS database. Figure 36 also plots the UTR calculated for an example model design flood in comparison to the UTRs for observed floods, illustrating how UTRs may provide another reasonableness check of model results. Smith et al (2018) found strong regional differences in UTRs (refer back to Figure 4 above), which may also be useful for model evaluation. Figure 37 shows 100-YR ARI upper tail ratios (i.e. USGS Colorado Flood Database peak flow divided by 100-YR ARI flood frequency estimate) at the same selected locations as the flood frequency estimates plotted in Figure 35. Again there appears to be a drainage area dependence for the largest upper tail ratios.

Table 12: Upper tail ratios for envelope-controlling peak flows in Colorado Dam Safety's Mountain >7,500-ft elevation region

Upper Tail Ratios (ref: Smith, James et al, Water Resources Research, 2018)

Flood event location & description	DA (sqmi)	Observed Qpeak	StreamStats Q10	UTR (Qpeak/Q10)	Notes
Example Dam Inflow Design Flood	2.14	7946	59.9	133	
Observed floods by relevant REPS storm transposition zones (ref: TZ 5, 6 & 9 Peak Flow Envelope Curve)					
TZ6 (Sangre de Cristo Range & San Juan Range east of C.D. >7500 ft elev)					
TZ6 #1 (indirect): Huerfano R. at Manzanares Crossing nr. Redwing, 8/2/1951 (Unknown Rtg)	73	10200	409	25	eastern slope of Sangre de Cristo Range
TZ6 #2 (indirect): Huerfano R. at Manzanares Crossing nr. Redwing, 8/3/1972 (Good Rtg)	73	6520	409	16	eastern slope of Sangre de Cristo Range
TZ6 #5 (indirect): San Francisco Creeek nr Del Norte, 7/30/1968 (Fair Rtg)	11.8	754	154	5	
TZ6 #6 (indirect): North Crestone Creek nr Crestone, 8/6/1936 (Unknown Rtg)	10.7	735	139	5	
TZ6 #8 (indirect): Cottonwood Creek nr Crestone, 7/26/1968 (Good Rtg)	6.77	540	83.5	6	
TZ6 #30 (gaged): Rio Grande R. at Thirtymile Bridge, 6/28/1927	163	7500	2270	3	Regulated - immediately below Rio Grande Reservoir
TZ6 #131 (gaged): Alamosa Creek above Terrace Res., 10/5/1912	107	5200	1550	3	
TZ5 (Front Range >7500 ft elev, east of C.D.)					
#1 Sand Creek at CO-WY State Line, July 1977 (gaged meas't)	29.2	6710	283	24	Laramie Mountains
#7 Little Thompson R. nr Estes Park, July 1976, Fair Rtg	2.77	1940	31	63	100% basin >7500 ft elev. Mean basin elev. 8324 ft, Max elev. 9250 ft
TZ9 (West Slope >7500 ft elev.)					
#2 Vallecito Creek near Bayfield, CO (La Plata County), Sept. 6, 1970, Good Rating	72.1	7050	1080	7	
#3 Mineral Creek at Silverton, CO (San Juan County), Sept. 5, 1970, Good Rating	51.7	3070	890	3	
#12 Flick Gulch trib to Quartz Creek nr. Ohio, CO (Gunnison County), July 31, 1945, Unknown Rating	0.7	750	12.6	60	Lat/Long does gives DA =0.86 sqmi vs. Peak Streamflow Database DA=0.7 sqmi. This UTR is very high for mountains. Need to QC check this
#17 Unnamed Gulch trib to Quartz Creek nr. Ohio, CO (Gunnison Co.), July 31, 1945, Unknown Rating	0.2	460	3.97	116	Lat/Long does not plot on channel. This UTR is extremely high for mountains. Need to QC check this

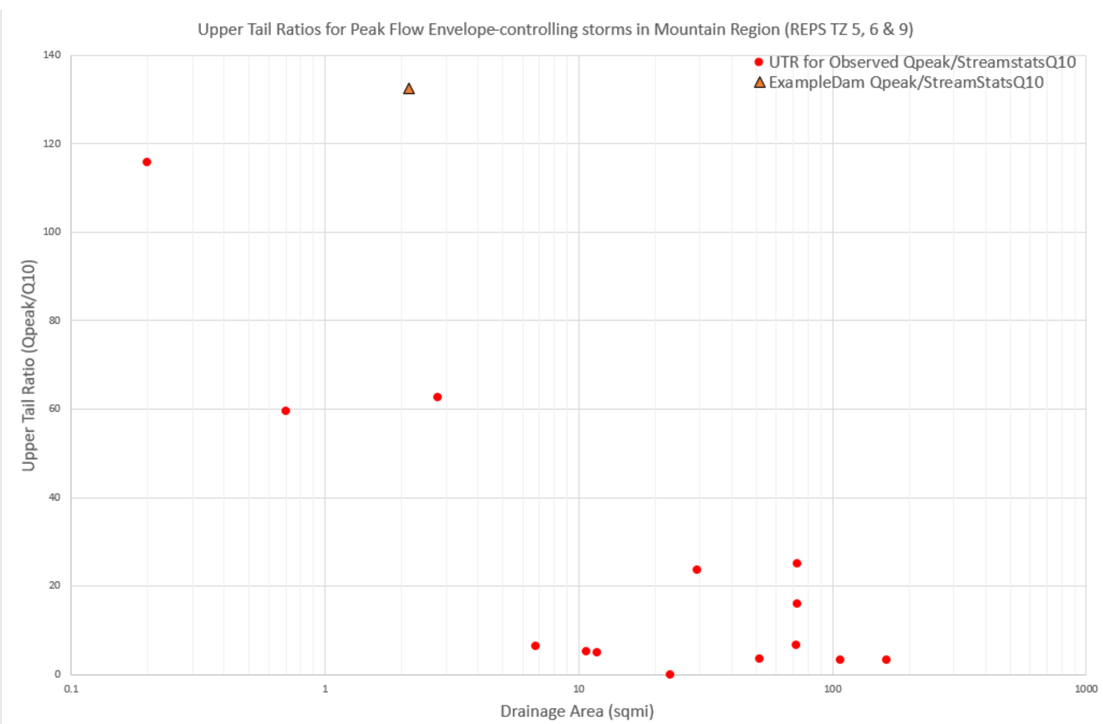


Figure 36: Upper tail ratios (UTRs) for the Mountain region envelope-controlling peak flows in Table 12, along with an example modeled design flood UTR for comparison.

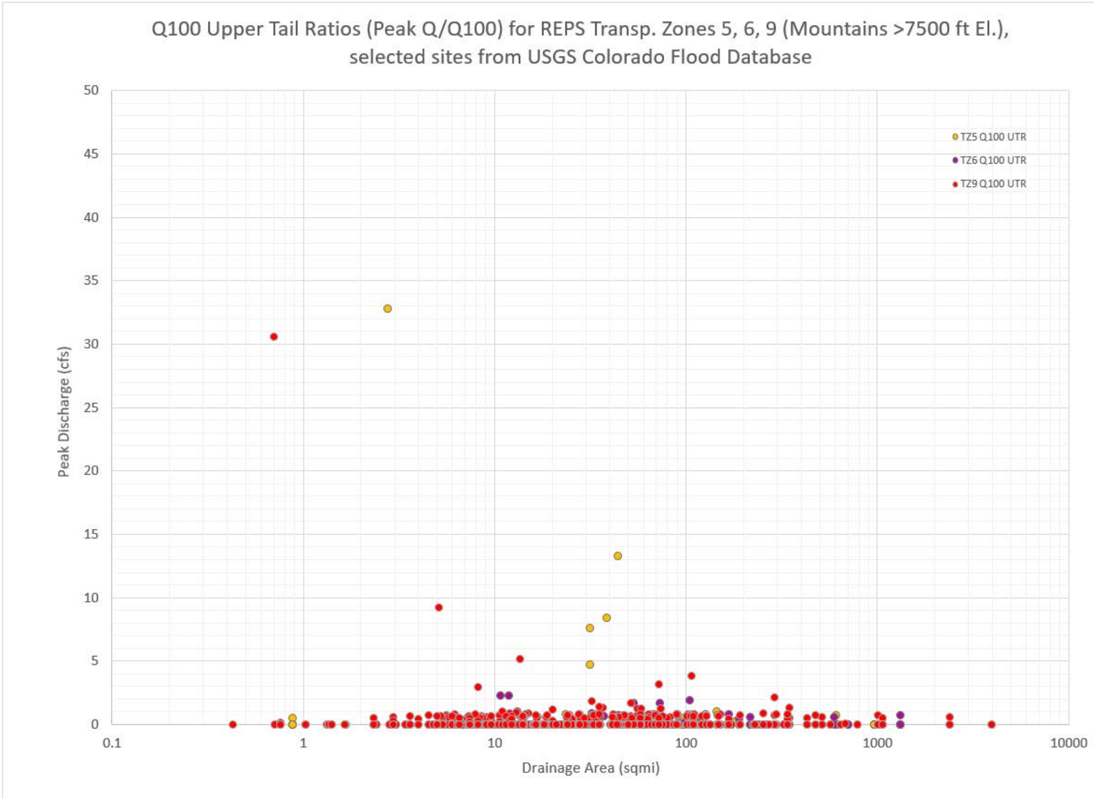


Figure 37: Ratio of observed peak flows to 100-YR flood estimates at selected sites from the USGS Colorado Flood Database in our Mountains > 7,500-ft elevation region, the same sites for which flood frequency estimates are plotted in Figure 35.

9.10 <u>Previous Hydrology Studies:</u> Lastly in terms of reasonableness checks on CSU-SMA rainfall-runoff model results, previous hydrology studies can be a good source of past hydroogical information, floods and analyses. Although their methods may be outdated, the results often provide a good point of comparison for explaining why current model results differ. Previously study results should be concisely summarized for comparison.

9.11 **<u>Confidence:</u> The reasonableness checks described above are firstly intended to evaluate rainfall-runoff model accuracy. However, they should also be used to build *confidence***. For risk-informed decision making, Colorado Dam Safety ranks confidence levels as *Strong, Medium, or Poor* (see Table 13 below). The USBR (2004) and others have defined limits of credible flood frequency curve extrapolation in terms of the quality of available flood data (see Table 14 below). Finally Nathan and Weinmann (2001) depict flood estimation procedures and uncertainties by AEP (see Figure 38).

For Colorado Dam Safety hydrology study purposes, we propose that the following *confidence levels* should be used by the engineer/user to assess their results based on (1) REPS rainfall and CSU-SMA model confidence, (2) quality and amount of historical flood data that results from the above reasonableness checks, and (3) magnitude of storms/floods of interest:

<u>Strong confidence</u>: Confidence in REPS PMP storm transpositions and REPS AEP estimates; hydrologically similar basins to those CSU-SMA research used for calibration and verification. Stream gage data for basin-of-interest or transpositionable stream gate data from hydrologically similar basin(s) with longer periods of record, paleo-flood estimate(s), long (80-100 years) records of floods and hydrologic performance at an existing dam, and/or good regional data sets.

Table 13: Example Confidence Levels from Colorado Dam Safety's *Guidelines for Comprehensive Dam Safety Evaluation (CDSE) Risk Assessments & Risk Informed Decision Making (RIDM)*, March 2021.

Confidence Level	***Description***
STRONG	The team ***is confident*** in the risk characterization, and it is ***unlikely that additional information would change the order of magnitude*** of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty would change.
MEDIUM	The team ***is relatively confident*** in the risk characterization, ***but key additional information might possibly change the order of magnitude*** of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty may change.
POOR	The team ***is not confident*** in the risk characterization, and it is ***entirely possible that additional information would change the order of magnitude*** of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty could change.

Table 14: USBR recommended credible limits on flood frequency extrapolation (Swain et al, 2004)

Type of data used for flood frequency analysis	Limit of credible extrapolation for annual exceedance probability	
	Typical	Optimal
At-site streamflow data	1 in 100	1 in 200
Regional streamflow data	1 in 500	1 in 1,000
At-site streamflow and at-site paleoflood data	1 in 4,000	1 in 10,000
Regional precipitation data	1 in 2,000	1 in 10,000
Regional streamflow and regional paleoflood data	1 in 15,000	1 in 40,000
Combinations of regional data sets and extrapolation	1 in 40,000	1 in 100,000

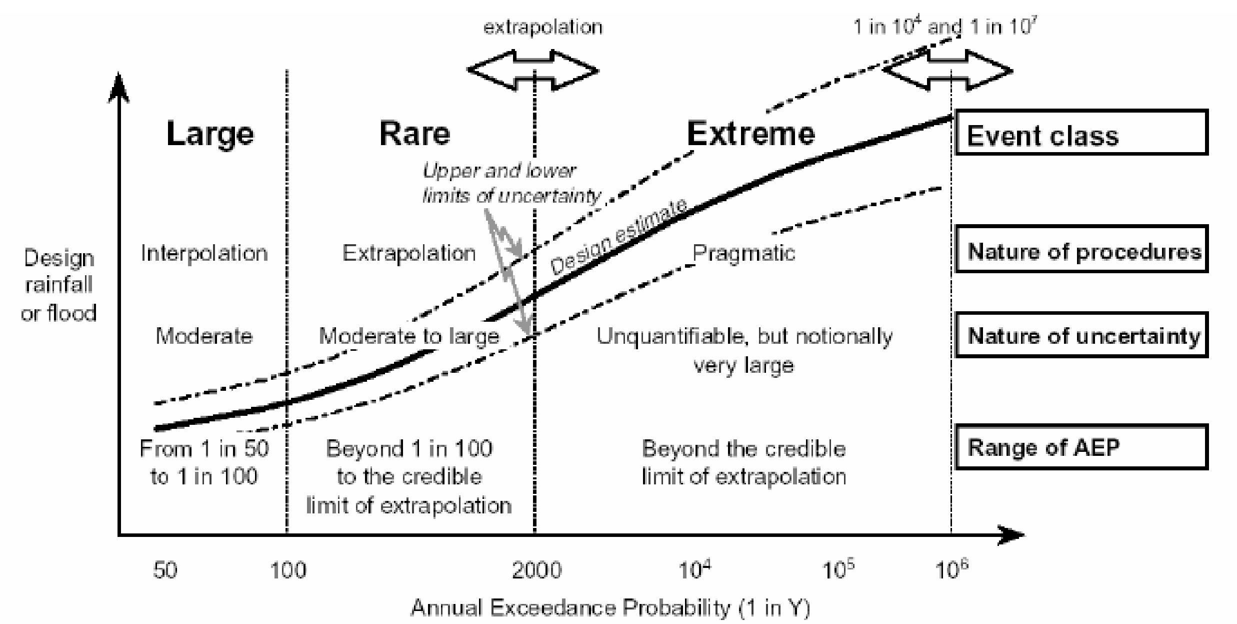


Figure 38: Depiction of flood estimation procedures and uncertainty by AEP (from Nathan and Weinmann, 2001)

Good agreement is found between CSU-SMA modeled floods and multiple lines of site-specific historical flood evidence, e.g., flood frequency estimates, flood seasonality, controlling storm types, historical floods, etc. vs. rainfall-runoff model results. Or differences between modeled floods and observed floods are within 90% confidence bounds (e.g. ASEp for USGS StreamStats, 90% confidence bounds on Bulletin 17C flood frequency estimates, and conceptual 90% confidence bounds on peak flow envelopes) and the engineer can make a strong case for such differences on the basis of basin-specific hydro-meteorological characteristics. Applies to floods of interest out to PMF for optimal data or to more frequent floods (e.g. 1/10,000 or 1/1000) with typical data.

<u>Medium confidence</u>: Confidence in REPS PMP storm transpositions and REPS AEP estimates; hydrologically similar basins to those CSU-SMA research used for calibration and verification. Good regional flood estimates are available (e.g. transpositioned/re-scaled Bulletin 17C flood frequency estimates, USGS StreamStats flood frequency estimates, and peak flow envelopes) within range of hydrologically similar data sets. Good agreement is found between CSU-SMA modeled floods and multiple lines of regional flood evidence, e.g., flood seasonality, controlling storm types, historical floods, etc. vs. rainfall-runoff model results. Differences between modeled floods and observed floods are within 90% confidence bounds on observed flood estimates; the engineer can partially, but not fully, explain such differences on the basis of basin-specific hydro-meteorological characteristics. Data quality, model agreement or justification of differences needs to be commensurate with the magnitude of design flood of interest.

<u>Poor confidence:</u> Less confidence in REPS PMP storm transpositions and wider confidence bounds on REPS AEP estimates; less confidence in CSU-SMA rainfall-runoff model parameters. Only regional flood estimates (e.g. USGS StreamStats, peak flow envelopes) are available for reasonableness checks and require extrapolation beyond range of observed floods. Minimal lines of corroborating evidence are available in the observed flood record to support CSU-SMA model results. Differences between modeled floods and observed floods (whether within 90% confidence bounds on regional flood estimates or not) cannot be explained convincingly based on basin-specific hydro-meteorological characteristics.

Section 10. **CSU-SMA Model Parameter Calibration**

10.1 Traditionally extreme floods for dam safety in Colorado were estimated by extrapolation of uncalibrated rainfall-runoff models to extreme storms, often with unreasonably conservative results -- several orders of magnitude larger than observed floods in some cases. In contrast, current agency thinking is that sufficient extreme flood data exists to allow model calibration in order to improve accuracy of model estimates. The rational extension of the reasonableness checks described in the previous section is to adjust rainfall-runoff models to produce general agreement, to the extent possible, to the various checks -- flood frequency curves, controlling storm/flood type, historical flooding at dams, regional peak flow envelopes, etc. Industry precedence exists for calibration of modeled flood-frequency estimates to observed flood-frequency curves (Novembre and Wright, 2013; Schaefer et al, 2012; and Schaefer and Barker, 2005).

10.2 Combining the CSU-SMA model approach and reasonableness checks against he observed flood record offers the opportunity for use of two independent sources of flood information to improve dam safety hydrology estimates. Each method has advantages, disadvantages, and its own sources of uncertainty, which will vary by basin. **The following CSU-SMA model calibration procedure is recommended, which considers both modeled and observed flood information, weights each according to the user's *confidence level* (from Section 9.11), and allows the engineer to use their expertise to make the case for the final hydrology results[4].** **See Appendix C for a Model Parameter Calibration Checklist/template.**

1) Determine the most likely controlling storm type for the basin based on comparison of initial CSU-SMA model results versus basin area size (see Section 9.6 and Table 10), type of historical storms/floods (Sections 9.4 and 9.8), and seasonality of historical/observed floods (Section 9.7, Figures 23-25). If there is no clear controlling storm type for a basin-of-interest, then calibrate all modeled storm types.

2) Calibrate CSU-SMA model parameters to obtain reasonable agreement between the REPS 10e-2 AEP controlling storm-type peak flow and the 1/100 AEP flood frequency estimate from the observed flood record (e.g. by Bulletin 17C, transpositioned Bulletin 17C estimate, USGS StreamStats, etc.), based on the assumption of AEP neutrality (i.e., a given AEP storm yields the same AEP flood peak). For purposes of these guidelines, closer agreement between modeled peak flow and the flood frequency estimate is better, but in all cases, model results should be within 90% confidence bounds on flood frequency estimates. Remaining differences after calibration should be explained by the engineer. Recommendations are provided below in terms of which model parameters should be adjusted based on controlling storm type and controlling flood production mechanism. NOTE: Modeled flood <u>volume</u> calibration is recommended for basins and dams where long duration storms/floods (e.g. 48hr MLC, 72hr General Storm PMF) are controlling, and therefore flood volume and hydrograph shape are important for reservoir routing and spillway sizing. In practice, flood volume calibration may only be possible for gaged basins or existing dams with good reservoir storage data, such that daily flood-volume frequency analysis can be performed.

3) Similar checks between modeled peak flows and flood frequency estimates and further calibration, if needed, should be made at 2x10e-3 and 10e-3 AEPs. Consideration should be given to calibrating to paleo-flood peak flow estimates, if available for the basin-of-interest or re-scaled from hydrologically similar basins, using the estimated paleo-age.

[4] Model calibration should be performed prior to applying Dam Safety Rule 7.2.4, Atmospheric Moisture Factor (1.07), to Inflow Design Floods. See the next page for more details.

4) Other site-specific reasonableness checks from Section 9 should be used to inform the model calibration. For example, model parameters should be adjusted to produce general agreement with reservoir record pool, record inflows or record dam overtopping over the lifetime of an existing dam, historical frequency of spillway activation, historical large floods, historical storm types and seasonality of flooding, etc.

5) Lastly, run REPS PMP (all applicable storm types) in the calibrated CSU-SMA model, and the controlling modeled PMF peak flow should be checked against Colorado Dam Safety's regional peak flow envelopes. For the purposes of these guidelines, closer agreement between modeled PMF peak flow and its respective regional envelope is better, but in all cases the modeled PMF peak flow should lie within the conceptual 0.3log10 cycle - 90% confidence bounds on the envelopes. **Model calibration should then be completed using a weighted-average of modeled and envelope peak flows per Table 15 below, according to the user's *confidence level* (see Section 9.11). This weighting can be viewed as an empirical Bayesian approach after Kuczera (1982) that gives greater weight to the CSU-SMA model (and site-specific calibration in steps 1-4 above) when *confidence* in them is strong, but greater weight to the regional flood information in the envelope curves when confidence in the basin model is poor.**

Table 15: Weights for modeled REPS PMF peak flow and regional envelope peak flow, based on *confidence level*, for final CSU-SMA model calibration to weighted average PMF.

Confidence Level (see Section 9.11)	Weight applied to CSU-SMA model controlling REPS PMF peak flow	Weight applied to regional envelope peak flow	Comments
Strong	1.0	0	CSU-SMA model (after site-specific calibration steps 1-4 above) used without further calibration to regional envelope peak flow. Model PMF peak flow must lie within envelope 90% confidence bounds, and engineer can make a strong case for such differences on the basis of basin-specific hydro-meteorological characteristics.
Medium	0.5	0.5	CSU-SMA model (after site-specific calibration steps 1-4 above) PMF peak flow weighted equally with regional envelope peak flow; Final calibration of CSU-SMA model PMF should be made to match the resulting weighted average PMF peak flow.
Poor	0	1.0	CSU-SMA model (after site-specific calibration steps 1-4) PMF peak flow is not reliable due to poor confidence in reasonableness checks and lack of site-specific information. Final calibration of CSU-SMA model PMF should be made to match the regional envelope peak flow.

The following additional considerations are offered for model calibration:

- Where a basin spans multiple peak flow envelope regions, then an area-weighted average envelope peak flow may be used or use partial area analysis in the controlling region.

- Particularly for the Front Range & Eastern Plains region, large differences in the observed flood record between regional envelope peak flows and more frequent 1/100 and 1/1000 AEP floods suggest possible non-linear runoff response to extreme rainfall. If the CSU-SMA rainfall-runoff model cannot be calibrated to work at both upper and lower ends (i.e. PMF to the peak flow envelope and 100-YR to flood frequency curve), then consideration should be given to using non-linear runoff transformation, for example, by HEC-HMS's Variable Clark UH method or using HEC-RAS 2D. In HMS's Clark Variable method, T_c and R parameters can be decreased for increasing excess precipitation to allow calibration of the 100-YR flood, PMF to the peak flow envelope, and other intermediate points (ex. 1000-YR flood, paleo-flood, etc.). These calibration points can be used to define a percentage curve table of %Tc and %R versus %excess precipitation (relative to an index value). Also for the Mountain Region (>7,500 ft elev.), non-linear runoff transformation may be indicated at small area sizes (<5 sq mi); however, the user should consider caveats regarding possible influence of debris flows as discussed in Section 9.8 above.

- Calibration to regional peak flow envelopes may not capture basin-specific differences. Our experience is that the regional differences that *are* captured by the regional envelope curves far out-weigh basin-specific differences (when compared to historical hydrology studies that ignored regional differences).

- Notional AEP of PMP and PMF can be determined by comparing REPS PMP results against REPS precipitation frequency (see Sections 4 and 8 above). This cross-check is a strength of REPS. Where notional AEP of REPS PMP/PMF is far less than 10e-7 AEP, then the modeled PMF may plot far above the regional peak flow envelopes. In such cases the State Engineer may grant a waiver to State Dam Safety Rule 7.2, allowing an acceptable risk-based probabilistic IDF criteria less than deterministic PMP.

- Climate change has the potential to increase flood yields in Colorado in the future (REPS Summary Report, Vol. VI). Based on the recommendations by NOAA and others, Colorado Dam Safety implemented Dam Safety Rule 7.2.4, Atmospheric Moisture Factor (AMF), which requires that rainfall estimates for determining inflow design floods shall be multiplied by 1.07 to account for expected increases in temperature and moisture-holding capacity of the atmosphere over the next 50 years. This factor must be applied to IDFs for new dams, enlargements, and spillway design projects to account for expected design life; it should be applied after hydrology model calibration. Generally, the AMF should not be applied for hydrologic risk studies and evaluation of the safety of existing dams, because risk-analysis reflects current conditions.

- Where observed peak flows and historical flooding are dominated by snowmelt, which is true for many basins above 7,500 feet elevation in Colorado, then rainfall flood frequency estimates are necessarily lower, at least within the period of record. However, the general assumption is that rainfall flooding will exceed snowmelt flooding at some extreme AEP (i.e. steeper flood frequency curve), although Jarrett and Tomlinson (2000) said this assumption is not supported by paleo-flood data out to 10,000 years based on their study in northwest Colorado. Nevertheless, the conservative and recommended approach here is to calibrate the controlling REPS storm type to the snowmelt-based 100-YR flood frequency estimate, per the calibration procedure described above, unless paleo-flood or other evidence suggests some other AEP. This approach is considered to be conservative, but still reasonably supported by the magnitude of historical flooding. Alternatively, a baseflow may be used in HEC-HMS to make up the difference between the modeled REPS and flood frequency 100-YR floods, assuming this difference is due to snowmelt.

- As discussed in Section 9, advanced studies may perform historical flood event calibration using reconstructed rainfall and stream gage flood hydrographs, reservoir stage records, etc. If possible, independent verification should be done on multiple historical storms/floods. This approach is only expected for large, complex projects and as warranted by dam size or hazard potential.

10.3 **This section provides information on specific CSU-SMA model parameters for calibration.** Select parameters can be adjusted based on controlling storm type and controlling runoff mechanisms in order to better match historical flooding:

- **Impervious (%):** The percentage of sub-basin area that will not infiltrate/store any precipitation. These areas will always produce surface runoff. Increasing impervious area will tend to produce larger surface runoff, particularly from high-intensity rainfall.
- **Soil % (Initial soil moisture):** The percentage of soil storage occupied by water at the beginning of the storm. Special care should be applied when setting this value. If the initial soil moisture is set higher than tension storage, the model will start in a phase of discharge from subsurface stormflow and may overestimate the rising limb of the hydrograph. High initial soil moisture may also lead to saturation-excess runoff.
- **Maximum Infiltration Rate (in/hr):** Maximum rate at which water can enter soil storage. The actual infiltration rate varies as a function of available soil storage. Higher available soil storage translates to an infiltration rate closer to the specified maximum. Increasing maximum infiltration rate will tend to produce less infiltration-excess runoff.
- **Soil Storage (inches):** This value represents the maximum amount of water that can be stored in the soil layer and directly affects infiltration rate (see above). Lower soil storage may lead to soil saturation and saturation-excess runoff.
- **Tension Storage (inches):** This value is the portion of soil storage that must be overcome before water can leave the soil layer and enter the groundwater layer via soil percolation. Higher tension storage values can restrict/delay subsurface stormflow. Mainly applicable where long-duration General Storms control the design flood; decreasing tension storage will increase sub-surface flow associated with low intensity rainfall.
- **Max Soil Percolation Rate (in/hr):** Maximum rate at which water leaves the soil layer and enters the groundwater layer. Like max infiltration, this rate is a function of soil storage. This rate only comes into play once tension storage is overcome. Constricting this value can force saturation-excess runoff to occur. If this parameter is higher, the model will produce more subsurface stormflow instead of saturation-excess runoff.
- **GW % (GW saturation):** defines the percentage of groundwater storage occupied by water at the beginning of the storm. The CSU-SMA method assumes this value is zero since flow before the rising limb of the observed hydrographs remains nearly constant. Starting a simulation with water in the GW layer is similar to when initial soil moisture is above the tension storage threshold and the soil percolation rate is high (i.e. may cause overestimation of early storm flows by subsurface stormflow).
- **GW Storage (inches):** Represents the maximum amount of water that can be stored in the GW layer. Large values for this parameter result in models that emphasize the subsurface component of the hydrograph. Reducing this value can force saturation excess runoff for long duration storms. However, using small values for this parameter means that groundwater layer is usually saturated. This creates a near-constant discharge from this layer that is not as sensitive to changes in precipitation. Woolridge (2019) showed that using small values for GW storage can accurately simulate subsurface stormflow dominant hydrographs (i.e. Bear Creek, Sept. 2013 flood).
- **GW Time Coefficient (hr):** This parameter controls the rate at which water is released from the groundwater layer. Shorter time constants lead to increased subsurface stormflow with similar timing as surface runoff. Models using shorter time constants are also more sensitive to changes in precipitation. Models using longer time constants result in more attenuated hydrographs that are not as sensitive to changes in precipitation. Where subsurface flood flows are significant, calibration of this parameter may be necessary in order to make subsurface and surface peaks coincide, i.e., to avoid a double peak hydrograph.
- **GW Percolation Rate (in/hr):** This parameter determines net loss to the system and can help with adjusting flood volume. For the CSU-SMA method it was determined through calibration to historical floods in both the Front Range and San Juans. The value in the Front Range basins (2 – 3 mm/hr) is higher than that in the San Juans (0.5 – 1 mm/hr). Changing this value can have large effects on peak flows and volume.
- **Linear Reservoir Coefficient (hr):** This parameter controls the rate at which water that has left the groundwater layer is routed to the stream. Effects of changing this parameter are similar to those listed in the "GW Time Coefficient" description.

- **Clark Unit Hydrograph Time of Concentration (hr):** T_c generally represents channel storage and travel time through the basin stream network. Decreasing T_c will produce larger peak flows and flashier surface runoff hydrographs. See discussions above about use of Clark Variable method to produce non-linear runoff response, i.e., flashier runoff response with increasing rainfall intensity and excess precipitation.
- **Clark Unit Hydrograph Storage Coefficient (hr):** *R* generally represents hillslope storage in the basin. Decreasing *R* will have a similar effect as decreasing T_c, producing larger peak flows and flashier surface runoff hydrographs.

10.4 The following additional guidance is provided on parameter calibrations for emphasizing different runoff production mechanisms:

- For Infiltration-Excess Runoff:
  - **Max infiltration rate:** Reduction of infiltration rate will force more excess precipitation leading to higher peak flows and volumes of infiltration-excess runoff by intense REPS Local Storms.
  - **Impervious Area:** Increasing the impervious area can result in higher runoff peak flows and volumes and overall quicker response runoff.

- For Saturation-Excess Runoff:
  - **Reduce soil storage, increase tension storage to a value closer to soil storage, and reduce soil percolation rate:** Less soil storage for water to fill up will cause saturation-excess runoff to occur. Increasing the tension storage capacity would allow water (both pre-event and event) to remain in the soil layer longer without draining to the groundwater layer. Reducing the rate water is transferred from the soil layer to the groundwater layer leads to the soil layer filling up earlier.
  - **Increase GW time coefficient:** This method is not as direct as the preceding ones, but creates a back-up of groundwater into soil storage. Longer time constants translate to a slower subsurface flow response. However, slowing the groundwater flow can lead to dissimilar timing with surface runoff and create an unrealistic double-peak effect in the output hydrograph.

- Subsurface Stormflow:
  - **Increase GW storage:** Since subsurface stormflow is modeled as a linear reservoir, increasing the storage will increase the magnitude of outflow. If there is a combination of high subsurface flow and surface runoff, this adjustment may cause an unrealistic double-peak effect due to the differences in timing of the two flow components. This usually takes the form of an early spike in the hydrograph from saturation-excess runoff, followed by large volumes of subsurface flow.
  - **Reduce GW time coefficient:** Reducing the time coefficient speeds up the rate water is released from the groundwater layer. If reduced enough, resulting subsurface stormflow hydrographs could look like surface runoff hydrographs.
  - **Reduce GW percolation rate:** By reducing system loss, more water is available from the storm to translate to streamflow. This parameter can change runoff mechanisms and flow volumes drastically in some cases.

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Appendix A

Examples of Reporting & Reasonableness Checks

Appendix B

CSU-SMApython Script

Appendix C

Reporting Checklists

Appendix D

Subject Matter Expert (SME) Review Documentation

Appendix E

Revisions Log: Summary of significant changes to address SME comments