Advances in Flood Hydrology for Modeling High Elevation Mountain Basins in Colorado with Applications to the Gross Dam Enlargement Study

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Abstract-- In Colorado's mountain terrain, traditional Probable Maximum Precipitation and flood hydrology approaches often result in spillway design floods that are perceived to be unreasonably large, ranging up to two orders of magnitude larger than floods of record. In this region traditional flood hydrology methods tend to over-estimate infiltration-excess runoff due to use of low infiltration rates and low surface retention losses. During Denver Water's 2017 site-specific hydrology study for their proposed Gross Dam enlargement, Colorado Dam Safety developed a model to account for interflow and saturation excess runoff mechanisms, which literature suggests are dominant processes for mountain basins. The model successfully simulated irregularities in hydrographs from the historic September 2013 floods. When applied to the Probable Maximum Flood, it simulated lower peak flows and volumes compared to a traditional flood hydrology model. Results suggest the new model better reproduces the dominant physical processes that occur in Colorado's mountain basins.

I. Introduction

Characterizing extreme floods is an essential but difficult part of dam safety engineering. Estimating extreme floods in the Rocky Mountain region has proved particularly challenging. The U.S. Bureau of Reclamation's (USBR) *Flood Hydrology Manual* (Cudworth, 1989) says of the Rocky Mountain region: [hydrology] "data representing basins located at higher elevations of these 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".

Relying on the paleoflood record, Dr. Robert Jarrett (ASCE Engineering Hydrology, 1993) questioned new HMR Probable Maximum Precipitation (PMP) and flood hydrology methods that resulted in substantially larger probable maximum flood (PMF) estimates for the Rocky Mountain region. Jarrett and Costa (1988) reported the revised PMF for the USBR's Olympus Dam, located in Estes Park, Colorado, at 7,481 feet elevation was around 98,000 cfs, but the dam's spillway had been designed to convey only 22,500 cfs. They estimated a paleoflood peak for the Big Thompson River above Olympus Dam over the past 8,000-10,000 years to be in the range of 3,000 to 5,000 cfs (the Big Thompson River accounts for approximately 88 percent of the dam's drainage area).

Part of the problem is making reasonable extreme precipitation estimates in the Rocky Mountains. One of many difficulties is characterizing the sharp gradient in extreme precipitation that exists from the plains-mountains interface west into the high elevation mountain terrain. Catastrophic extreme storms have occurred along the plains-mountain interface (ex. Big Thompson 1976, Penrose 1921) but not in the high mountains. Where do such storms stop and why? HMR 55A PMP estimates for the mountains were regarded as unrealistically high by some. Dr. Jarrett (1989) proposed a limit around 7,500 feet to 8,500 feet, above which the regional paleoflood record did not show evidence of rain-driven flooding. Colorado Dam Safety has pursued this extreme precipitation problem for nearly 30 years. During this time questions have remained about how to reasonably enforce spillway regulations. Currently Colorado and New Mexico are conducting the Colorado-New Mexico Regional Extreme Precipitation Study. Numerous consultants and federal agencies are participating to bring the best available science to bear.

But the other part of the problem is developing accurate flood hydrology for mountain basins, which seemingly has received less scrutiny than extreme precipitation. Traditional dam safety flood hydrology methods like those in *Flood Hydrology Manual* (Cudworth, 1989) used relatively low infiltration rates, saturated antecedent moisture conditions, and ignored interflow. Cudworth acknowledged field infiltration rates are almost always higher than his recommended values, but said field infiltration rates do not match overall basin flood response. Uniquely to the western U.S., he concluded there were two distinct runoff responses for the Rocky Mountain region: a slow response for low-intensity general storms and a fast response for high-intensity thunderstorms. Research by Larsen et al (2009) and Lin (2008) suggests infiltration rates and surface retention may be quite high for forested mountain basins, and that saturation-excess runoff and subsurface flow may be important runoff processes. But are these processes relevant to PMF flood hydrology? And if so could they help explain Cudworth's two distinct runoff responses?

This paper presents a new physically-based hydrology method developed by Colorado Dam Safety for mountain basins. Colorado Dam Safety applied the method to the Gross Dam basin during a recent site specific hydrology study by Denver Water. Results are summarized and are shown to out-perform traditional dam safety flood hydrology methods on calibration and verification events. The new method is applied to the PMF. Remaining work and future research are discussed.

II. Gross Dam basin Characteristics

Gross Dam is located on South Boulder Creek in Colorado's Front Range mountains at elevation 7,290 feet. The dam height and volume are currently 345 feet and 41,811 acre-feet. Denver Water, the dam owner, is currently designing an enlargement to 471 feet and 119,000 acre-feet. As part of this effort they completed a Site Specific PMP and PMF hydrology study, performed by Applied Weather Associates and MWH Global and completed in April 2017.

Gross Dam's drainage area is 93 square miles and extends upward to elevation 13,400 feet, with 55% above 9,000 feet; 76% of the basin is forested (MWH, 2017). Geology consists primarily of granitic and metamorphic rock (Tweto, 1979). Soil surveys and site investigations revealed the presence of thin soils over shallow bedrock. The Gross Dam basin has similar characteristics as the neighboring Olympus Dam basin, of which Jarrett and Costa (1988) wrote. Similar to Olympus Dam, Gross Dam's previous PMF, based on a preliminary version of HMR 55A PMP and traditional flood hydrology methods, had a peak flow of around 90,000 cfs (Goodson and Associates 1987).

III. Regional Historic floods

To put the 90,000 cfs PMF into perspective, this section provides selected regional peak flows. USGS StreamStats gives a 100-YR peak flow estimate of 1,370 cfs at Gross Dam (https://streamstatsags.cr.usgs.gov/), making the previous PMF about 66 times the 100-YR peak flow. The USGS's South Boulder Creek at Eldorado Springs gage is located about 7 miles downstream of Gross Dam at elevation 6,080 feet and has a drainage area of 111 square miles. The record peak there is 7,390 cfs (September 1938); flood frequency estimates there are 3,240 cfs (100-YR), 8,710 cfs (1000-YR), and 20,600 cfs (10,000-YR), (MWH, 2017). The period of record is 103 years, but includes both unregulated and regulated flows (Gross Dam was completed in 1955).

The USBR Olympus Dam Hydrologic Hazard assessment (2009) provides a regional peak flow envelope curve based on stream gage data. For basins from 80 to 140 square miles the highest recorded peak flow is 8,710 cfs, which occurred at the North Fork Big Thompson at Drake gage (85.1 sq mi drainage area), located immediately upstream of the confluence with the Big Thompson River, during the catastrophic July 1976 Big Thompson flood. The USGS (1979) reported this observed peak was 1.4 times the 100-YR peak flow estimate. The USGS also made indirect peak flow estimates for the 1976 flood at ungaged locations:

1) Big Thompson River above Drake: 28,200 cfs, 34 sq mi contributing drainage area, unit discharge of 829 cfs/sq mi, and ratio to the 100-YR peak of 3.8.
2) Big Thompson River below Drake: 30,100 cfs, 121 sq mi contributing drainage area, unit discharge of 249 cfs/sq mi, and ratio to the 100-YR peak of 2.9.

While the 1976 Big Thompson storm was centered approximately 30 miles from Gross Dam, it occurred downslope within the aforementioned sharp extreme precipitation gradient from the plains to the high mountains and below the 7,500 foot boundary for rain-driven flooding proposed by Dr. Jarrett.

Perhaps more representative for Gross Dam is the peak inflow observed at Olympus Dam during the region's historic September 2013 flood: 5,327 cfs (Jacobs, 2014), 155 sq mi drainage area, unit discharge of 34 cfs/sq mi, and ratio to the 100-YR peak flow estimate of 1.9. The 2013 peak inflow is also within the range of paleoflood non-exceedance threshold estimates for the Big Thompson River above Olympus Dam given by Jarrett and Costa (1988).

Finally a paleoflood non-exceedance threshold of 7,300-9,950 cfs over the last 6,500-6,700 years was estimated by the USBR below Buttonrock Dam following the September 2013 flood (USBR, 2015). The paleoflood site had comparable drainage area (101 sq mi) to Gross Dam, but was lower in elevation and closer to the plains-foothills interface, which presumably would result in larger floods.

IV. Hydrological Methods

A. *Traditional flood hydrology model*

Denver Water's consultant for the site specific PMF study developed what will be referred to herein as a *traditional flood hydrology* model for the Gross Dam basin. *Traditional* in the sense that the model minimized initial losses, ignored subsurface flow, used low infiltration rates, and produced runoff solely by infiltration-excess (i.e. Horton runoff). Infiltration rates were based on SCS hydrologic soil groups and the following ultimate infiltration rates, consistent with Cudworth (1989): Group A (0.3-0.5 in/hr), Group B (0.15-0.30 in/hr), Group C (0.05-0.15 in/hr), and Group D (0-0.05 in/hr). The *traditional* model used the Modified Clark transform method, applied on a gridded basis in HEC-HMS, and a calibrated $R/(T_c+R)$ ratio of 0.6.

B. *Mountain flood hydrology model*

Colorado Dam Safety developed an independent model for the Gross Dam basin to check the consultant's model and to test our hydrological methods. Research literature suggests saturation-excess runoff and subsurface flow are important runoff mechanisms for forested and mountain basins. However application and relevance to flood hydrology is not clear from traditional dam safety hydrology references. Based on research and experience Colorado Dam Safety has developed the following elements to model what are believed to be key physical, hydrologic processes for mountain basin flood hydrology in Colorado's Rocky Mountains:

1) Reasonable antecedent moisture conditions (AMC) considering the climate, time of year, and soil hydraulic properties
2) Initial abstractions considering vegetation cover, slope, and surface litter
3) Green & Ampt infiltration model with infiltration rates based on the limiting soil texture in the soil profile and increased infiltration rates for vegetative cover
4) Simulated infiltration volume checked against soil profile water storage capacity for thin, coarse-grained soils with shallow bedrock
5) Evaluation of whether saturation-excess runoff is expected to be a dominant runoff process; if so then simulated infiltration volume limited to the soil profile storage capacity, and infiltration losses taken as initial losses that must be satisfied prior to generating runoff
6) Dimensionless unit hydrographs for the Rocky Mountain Thunderstorm and Rocky Mountain General Storm based on guidance by Cudworth (1989) and Sabol (2008).
7) Baseflow recession model to represent interflow-generated runoff.

Reasonable judgment of AMC is allowed in Colorado Dam Safety's *Hydrologic Basin Response Parameter Estimation Guidelines* (HBRPEG) (Sabol, 2008). Experience shows a very large rain event is needed to produce saturated conditions in the coarse-grained soils of mountain basins. It may be helpful to recall the World Meteorological Organization definition of PMF, which states that the conditions could plausibly occur in a locality at a particular time of year (WMO, 2009).

HBRPEG (Sabol 2008) provides values for initial abstractions from 0.1 to 1.0 inch, depending on basin slope and vegetative cover. It also allows that initial abstractions may be increased based on factors such as extensive duff cover in forested basins.

Bare ground saturated hydraulic conductivity (Ksat) is initially assigned to the limiting soil texture in each basin soil series profile using values in HBRPEG (Sabol, 2008), which are based on work by the Agricultural Research Service (Rawls and Brakensiek, 1983), e.g. 1.2 in/hr for sand and loamy sand and 0.4 in/hr for loam. Then bare ground Ksat values are increased as much as two times using a linear function of percent vegetative cover (Sabol, 2008), based on research by Rawls et al (1989).

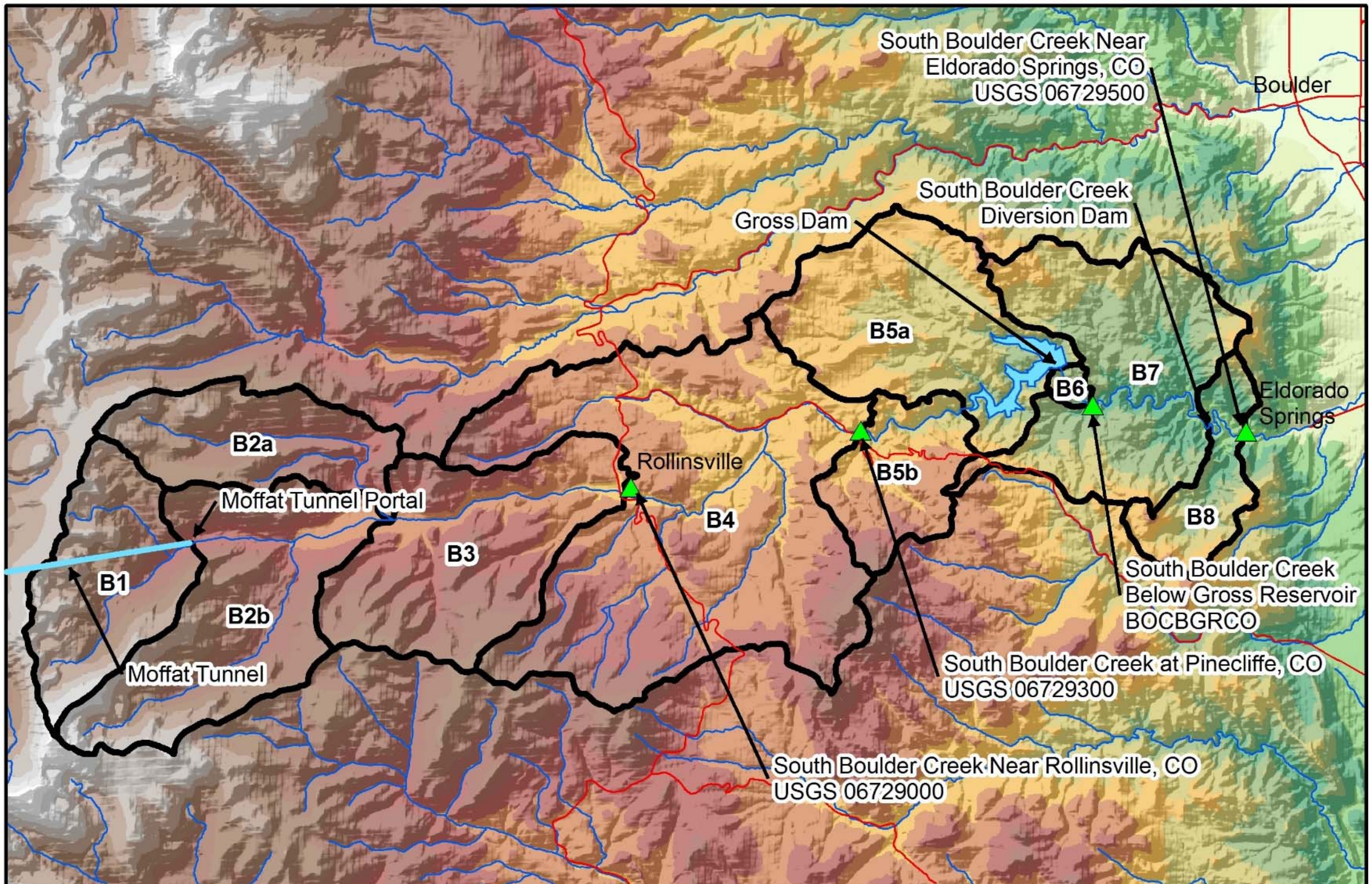
Initially infiltration is modeled using the Green & Ampt method with the understanding that it assumes an infinite soil depth and may overestimate losses (and thereby underestimate runoff) in thin, coarse-grained mountain soils with shallow bedrock. Therefore, a procedure from U.S. Army Corps of Engineers EM-1110-2-1417 (1994) is used to check simulated infiltration volume for a particular rain event and soil series against soil profile storage capacity. If the infiltration volume exceeds soil profile storage capacity, then Ksat is reduced until the two volumes are equal at the end of the event. The reduced Ksat is used for this soil series towards computing a sub-basin weighted-average Ksat. This check is referred to as soil profile storage analysis (SPSA). SPSA is necessary to correctly model infiltration volume in thin, coarse-grained soils where profile saturation is expected to occur; however, reducing Ksat rates could adversely affect the simulated timing of runoff. Therefore, for sub-basins where saturation-excess runoff is expected to be a dominant runoff process, the loss volume by SPSA is taken upfront as an initial loss that must be satisfied prior to generating runoff. Green & Ampt losses are then minimized, with only a small infiltration rate maintained to feed interflow.

Observed flood hydrographs in mountain basins typically show a long, slow recession, which suggests a subsurface response. Interflow is modeled so as to conserve mass with infiltration losses, e.g. the linear reservoir baseflow method in HEC-HMS. Colorado Dam Safety has not yet developed guidance for baseflow parameters for ungaged basins, so at this time application is limited to basins which can be calibrated to observed flood events.

V. Application to the Gross Dam Basin and Calibration Results

The traditional flood hydrology method (Section IV.A) was applied to the Gross Dam basin using a distributed HEC-HMS model, and the mountain flood hydrology method (Section IV.B) used a lumped parameter model in HEC-HMS. Both models used seven sub-basins above the dam and three below (see **Figure 1**). Three historic floods were simulated (September 1938, May 1969, and September 2013) for calibration and verification. September 1938 was a short, intense rain event that produced the record peak flow at the South Boulder Creek Eldorado Springs stream gage; May 1969 was an early-season, long duration, high volume storm with some precipitation falling as snowfall; and September 2013 was a late-season, long duration, high volume storm in which precipitation fell in liquid form up to the Continental Divide. **Table 1** shows rainfall data for each storm as reconstructed by Applied Weather Associates (AWA, 2017). Simulated flood hydrographs were compared to stream gage data at the USGS South Boulder Creek at Pinecliffe gage (upper basin, below subbasin B4), at Gross Reservoir, and at the USGS Eldorado Springs gage (below subbasin B8). Most dams in Colorado are located in ungaged basins; quality rainfall and stream gage data provided an unusual opportunity to test Colorado Dam Safety's mountain hydrology method.

First the traditional flood hydrology model was rigorously calibrated. But calibration and verification to observed flows proved difficult within accepted parameter ranges. The traditional model tended to produce flashy hydrographs with shorter



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Miles

COLORADO
Division of Water Resources
Department of Natural Resources

FIGURE 1 - GROSS DAM DRAINAGE AREA MAP
WITH MODEL SUB-BASINS (AFTER MWH, 2017)
GROSS DAM PMF STUDY

DAM SAFETY

SEP 2017

Table 1: Gross Dam rainfall data for historic storms and PMP (data by Applied Weather Associates)

Subbasin	Historic rainfall (inches) used for calibration & verification			Probable Maximum Precipitation (PMP) (inches)				
	September 1938	May 1969	September 2013	Site Specific PMP Local Storm (6-HR)	Site Specific PMP General Storm (72-HR)	Site Specific PMP using 1964 Gibson Dam Storm	HMR 55A Local Storm PMP² (6-HR)	HMR 55A General Storm PMP² (72-HR)
B1	1.87	6.73	1.79	4.91	15.93	23.28		
B2a	2.05	7.31	5.92	5.01	16.53	24.07		
B2b	2.03	7.23	4.93	4.78	16.16	23.60		
B3	2.29	8.45	6.37	4.90	17.07	24.44		
B4	2.58	9.49	7.06	5.28	17.88	25.57		
B5a	3.59	10.12	10.40	6.15	19.34	27.62		
B5b	3.34	10.11	9.79	6.05	19.76	28.30		
B6	4.70	10.50	n/a¹	n/a¹	n/a¹	n/a¹		
B7	4.87	11.13	12.47	n/a¹	n/a¹	n/a¹		
B8	5.48	10.75	14.63	n/a¹	n/a¹	n/a¹		
Basin Average	**2.94**	**9.08**	**7.70**	**5.26**	**17.53**	**25.22**	**6.80**	**30.00**

1. Subbasin not used to model this storm.
2. Only basin average was calculated for HMR 55A PMP.

Table 2: Comparison of saturated hydraulic conductivities by subbasin for the traditional and mountain hydrology flood models.

Subbasin	Traditional Model constant loss rate (in/hr)¹	Mountain hydrology model, Green & Ampt Ksat (in/hr) by storm event					
		September 1938	May 1969	September 2013	PMP Local Storm	PMP General Storm	Original Ksat (prior to SPSA)
B1	0.185	0.51	0.44	0.51	0.51	0.44	0.51
B2a	0.158	0.39	0.25	0.34	0.39	0.25	0.39
B2b	0.159	0.44	0.27	0.41	0.43	0.26	0.44
B3	0.114	0.5	0.21	0.31	0.48	0.22	0.5
B4	0.127	0.55	0.23	0.26	0.46	0.24	0.56
B5a	0.084	0.59	0.18	0.19	0.38	0.18	0.59
B5b	0.062	0.69	0.26	0.3	0.54	0.27	0.69
B6	0.050	0.30	0.015	n/a²	n/a²	n/a²	0.8
B7	0.237	0.44	0.12	0.14	n/a²	n/a²	0.7
B8	0.069	0.49	0.12	0.15	n/a²	n/a²	0.93

1. Used to model all storm events with the traditional flood hydrology model
2. Subbasin not used to model this storm event

recession limbs compared to observed flood hydrographs. These results suggested that something else was going on in terms of runoff mechanisms.

Table 2 shows saturated hydraulic conductivities developed for the two models: (1) Constant loss rates based on SCS hydrologic soil groups (used in the traditional model) and (2) Green & Ampt Ksat values based on soil texture and vegetative cover (Sabol, 2008) and reduced as needed based on SPSA (mountain hydrology model). Original Ksat values based solely on soil texture and vegetative cover, prior to SPSA are shown for comparison. The "original" Ksat values (Sabol, 2008) are significantly higher than traditional loss rates; in the mountain hydrology method the original Ksat values are then dialed back using SPSA on a storm-by-storm basis. Ksat values determined by SPSA change for each storm, but this does not imply unique calibration to each storm. Instead SPSA uses the original Ksat values, soil profile depth, and the pore volume available at the beginning of each storm (Green & Ampt parameter $\Delta\theta$) in a spreadsheet to perform simple soil moisture accounting outside of HEC-HMS; the reduced Ksat values are calculated such that simulated infiltration volume for each storm is equal to the soil profile storage capacity.

Summary results are presented for the September 2013 calibration event at the Pinecliffe and Eldorado Springs gage locations in order to illustrate key points. **Figure 2** shows the observed flood hydrograph at Pinecliffe along with simulated hydrographs from the mountain hydrology and traditional flood hydrology models. **Table 3** summarizes peak flows, volumes and percent errors for each model. **Figure 3** and **Table 4** show results at the Eldorado Springs gage.

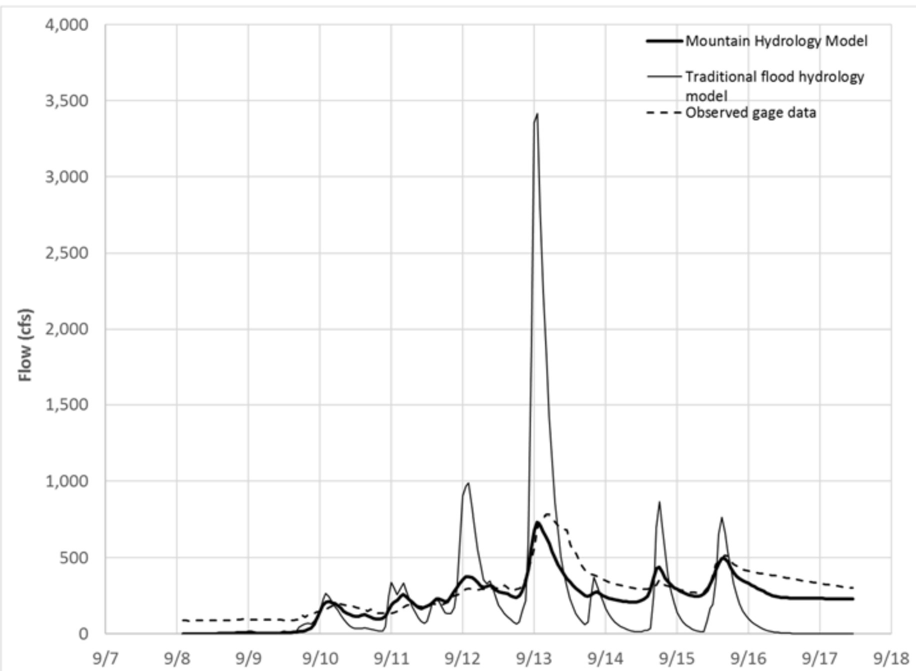

Figure 2: Hourly flow hydrographs at South Boulder Creek Pinecliffe gage. NOTE: Moffat tunnel flows are included in the observed gage hydrograph, but not in the model simulation hydrographs.

Table 3: Peak discharge and runoff volume for the September 2013 calibration flood at the South Boulder Creek Pinecliffe gage.

	Observed	Mountain flood hydrology model	Traditional flood hydrology model
Peak Discharge, cfs (% error)	780	731 (-6%)	3,415 (338%)
Runoff Volume, ac-ft (% error)	4,429 (a)	4,425 (0%)	4,195 (-5%)

a) Moffat Tunnel flow volume removed

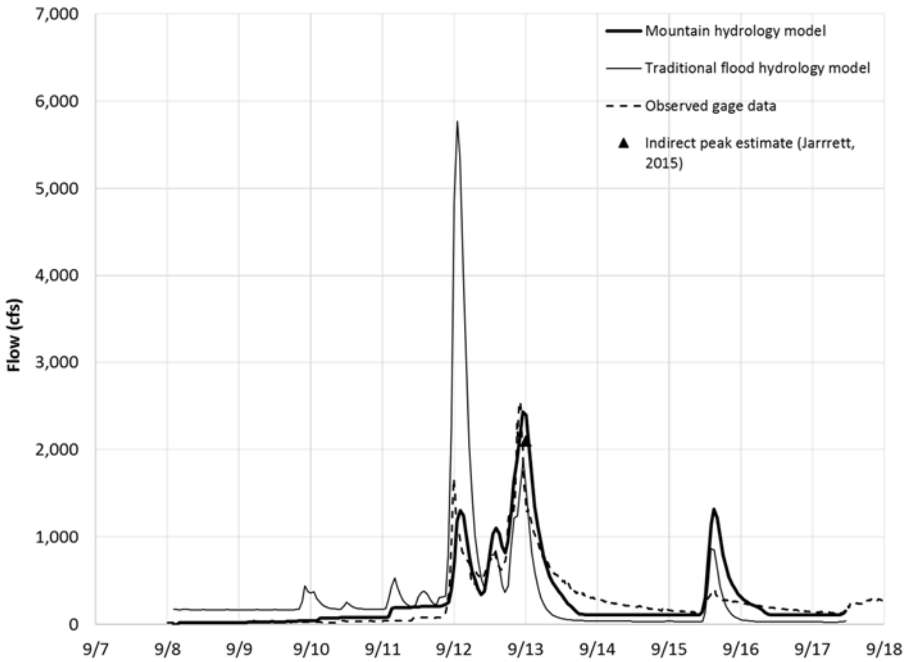

Figure 3: Hourly flow hydrographs at South Boulder Creek Eldorado Springs gage.

Table 4: Peak discharge and runoff volume for the September 2013 calibration flood at the South Boulder Creek Eldorado Springs gage.

	Observed	**Mountain flood hydrology model**	**Traditional flood hydrology model**
Peak Discharge, cfs (% error)	2,552	2,436 (-5%)	5,768 (126%)
Runoff Volume, ac-ft (% error)	5,221	5,705 (9%)	7,442 (30%)

VI. Discussion of Calibration Results

September 2013 rainfall generally decreased with increasing elevation. Above Pinecliffe rainfall did not significantly exceed the soil profile storage capacity, therefore reduced Ksat values from SPSA are similar to the original Ksat values based solely on soil texture. This resulted in high infiltration losses in the mountain hydrology method. High infiltration losses along with interflow (as linear reservoir baseflow recession) more accurately represent the observed flood response than does the traditional flood hydrology model. The traditional model, which only produces Horton runoff, significantly over-estimates peak flows. Despite extensive efforts the traditional flood hydrology model proved difficult to calibrate to match both peak flow and runoff volume.

In contrast, September 2013 rainfall below Gross Dam greatly exceeded soil profile storage capacities, as indicated by significant reductions in Ksat values for subbasins B7 and B8 by SPSA. Therefore, infiltration loss volumes determined by SPSA were taken upfront as initial losses in an attempt to better simulate peak flows and timing associated with saturation-excess runoff. The mountain hydrology method correctly reproduces the timing and peak runoff with respect to the observed hydrograph, whereas the traditional flood hydrology method overestimates the peak flow and shows it occurring about a day too early. In order to understand why, compare HEC-HMS results for subbasin B7 with infiltration modeled solely by the Green & Ampt method (**Figure 4**) versus an equivalent loss volume taken upfront as initial losses (**Figure 5**). In **Figure 4** the peak flow occurs at the time of peak rainfall intensity (the early hours of September 12th), which is consistent with Horton runoff and the traditional flood hydrology model. In **Figure 5** peak runoff does not occur until the initial losses "bucket" is full, which occurs nearly 24 hours after the peak rain intensity (early hours of September 13th). The timing of the peak in **Figure 5** is consistent with that at Fish Creek, near Estes Park, Colorado, based on a post-flood study by Colorado Dam Safety (2015). At Fish Creek the peak runoff occurred near midnight on September 13th and coincided with massive debris flows, indicative of widespread basin saturation (Colorado Dam Safety, 2015).

Another point is the mountain hydrology model overestimates runoff at Eldorado Springs on September 15th, several days after the flood (see **Figure 3**). This can be explained because the initial losses "bucket" in the model is not able to drain;

whereas the observed hydrograph indicates the soil profile had drained, likely by interflow, and was again infiltrating at a high rate by the 15th.

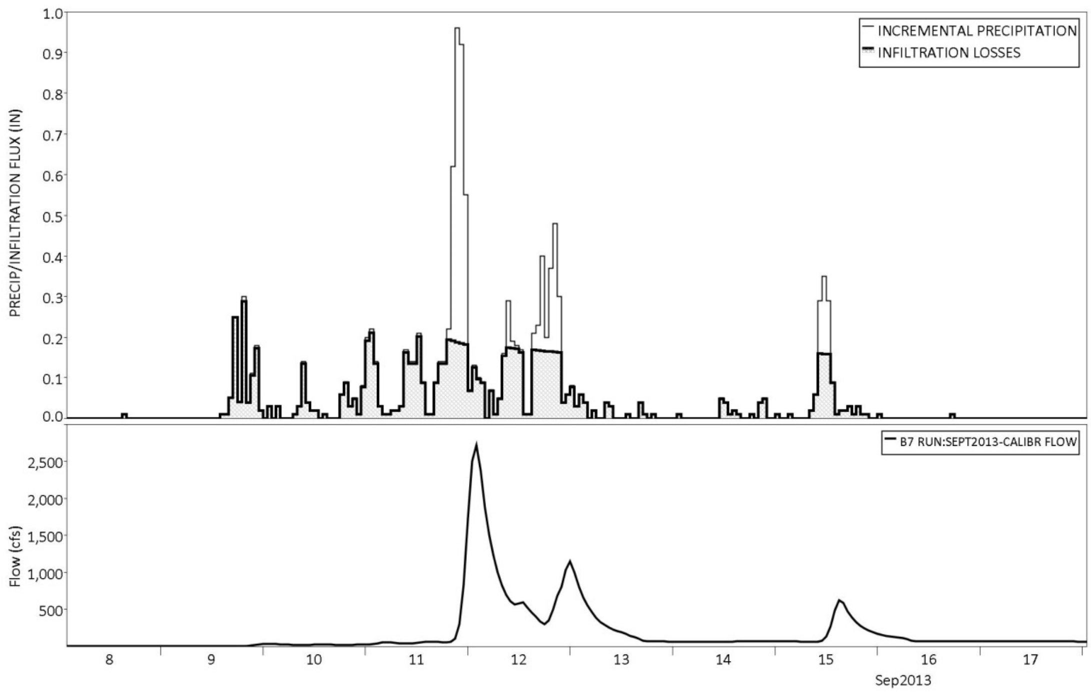

Figure 4: HEC-HMS precipitation hyetograph, rainfall losses (top) and runoff hydrograph (bottom) for subbasin B7 with infiltration modeled using Green & Ampt method.

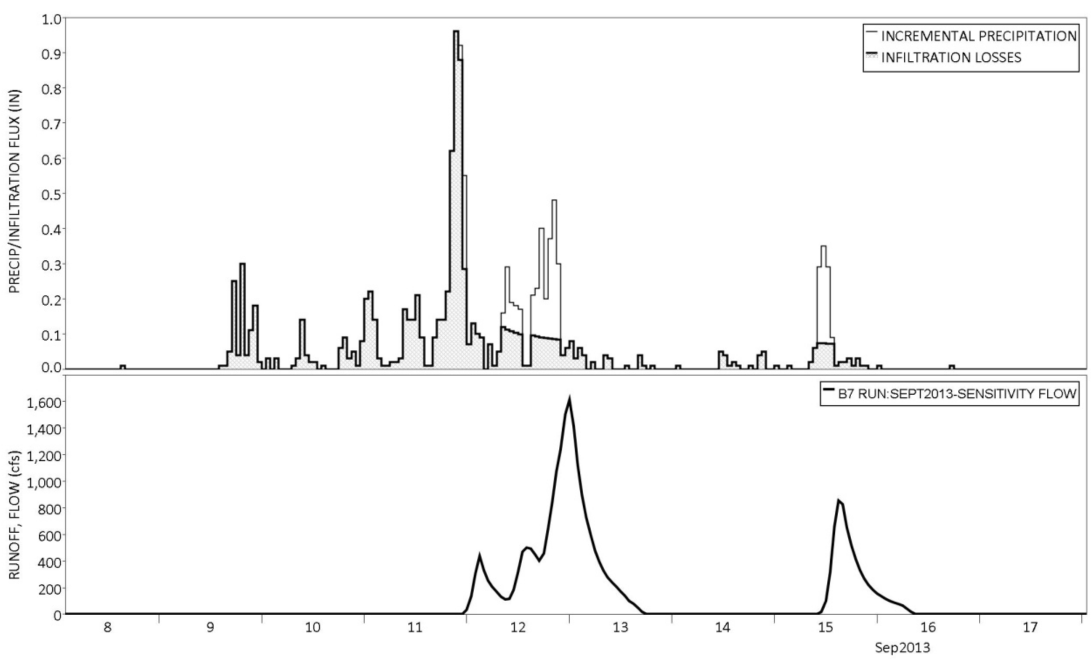

Figure 5: HEC-HMS precipitation hyetograph, rainfall losses (top) and runoff hydrograph (bottom) for subbasin B7 with infiltration losses taken upfront as an initial loss "bucket".

Finally, a separate validation of the mountain flood hydrology method was found in another study of the September 2013 flood, sponsored by the Colorado Department of Transportation (Jacobs Inc., 2014). Jacobs (2014) calibrated a rainfall-runoff model to 10-day September 2013 flows in the upper Big Thompson River basin, located north of Gross Dam. Automated calibration yielded high initial loss parameters and low infiltration rates, resulting in almost no runoff until 5 days into the 10-day event, followed by a rapid switch to high runoff. Although the CDOT report did not attempt a physical explanation, these results are consistent with saturation-excess runoff. A physical explanation, as proposed herein, may allow better flood prediction at other basins.

VII. PMF RESULTS

The calibrated traditional flood hydrology and mountain hydrology models were enlisted to generate PMFs using Site Specific PMP hyetographs provided by Applied Weather Associates (2017). Gross Dam Site Specific PMP estimates are shown above in **Table 1**. In the mountain hydrology model field capacity was used for AMC, and SPSA was performed to determine loss volumes based on soil profile capacity. SPSA indicated soil profile saturation is expected throughout the basin during the controlling PMP event (General Storm); therefore, losses were taken upfront as an initial loss "bucket" to represent saturation-excess runoff. Only minimal Green & Ampt infiltration was maintained in the model to feed interflow. Again interflow was modeled using the linear reservoir baseflow recession method in HEC-HMS.

Table 5 compares PMF results from the traditional flood hydrology and mountain hydrology models in terms of peak flows, volume, and peak reservoir stage at Gross Dam. The mountain hydrology model clearly depicts a different PMF response than the traditional flood hydrology model does. This should not be surprising based on the differences in calibration results shown above.

Table 5: PMF General Storm Results

	Peak Inflow (cfs)	Peak Outflow (cfs)	Inflow Volume (ac-ft)	Peak Reservoir Stage (ft)
Mountain Hydrology model	16,026	15,106	28,141	7411.3
Traditional Flood Hydrology Model	40,115	36,409	59,772	7415.6

VIII. PUT UNCERTAINTY WHERE IT BELONGS

Although the mountain basin hydrology model was considered a proof-of-concept effort for the Gross Dam study (i.e. results will not be used for design purposes), it may seem to have put Colorado Dam Safety in an unusual position of arguing for a lower PMF. In fact, Colorado Dam Safety has an interest in accurate hydrologic modeling. That will allow uncertainties to be assigned in their correct place.

For example, early in the Gross Dam Site Specific PMP study there was considerable discussion between Applied Weather Associates, Colorado Dam Safety, and the Federal Energy Regulatory Commission Board of Consultants regarding whether the historic 1964 Gibson Dam storm from Montana should be transposed to the Gross Dam basin to develop PMP. The final meteorological recommendation by AWA was the Gibson storm should not be used at Gross. AWA's reasoning included: (1) the two locations are separated by more than 6 degrees latitude resulting in a significant difference in Coriolis parameters and storm vorticity (see HMR 57 Section 7.4, page 69 for further discussion), (2) the synoptic meteorological features of the Gibson storm were not judged to be possible with the same intensity so late in the season (mid-June) over the Gross basin, and (3) moisture inflow to Gross would encounter significant differences in upwind topography. All study participants including Colorado Dam Safety concurred with AWA's recommendation as the best available science. Still, Colorado Dam Safety wanted to investigate the sensitivity of this meteorological judgment. Using the conservative traditional flood hydrology model there may have been resistance to adding conservative meteorology on top of conservative hydrology. However, the mountain hydrology model provided a better basis for this sensitivity analysis without adding unreasonable conservatism. The mountain hydrology model found PMP using the Gibson Dam storm produced a PMF that was not significantly larger than the PMF without the Gibson Dam storm by the traditional flood hydrology model. This finding was a valuable contribution towards addressing the Site Specific PMP sensitivity.

Colorado Dam Safety has historically ignored snowmelt, rain-on-snow, and burn-scar runoff processes for spillway design because traditional PMF hydrology methods have produced such conservative results for high mountain basins. In reality these processes are significant causes of flooding in the high mountains. By modeling mountain hydrology more accurately uncertainties and sensitivities surrounding snowmelt and burn-scar runoff will need to be confronted.

IX. Summary

The mountain hydrology method presented herein is based on research and experience regarding hydrologic processes that are important in controlling runoff from mountain basins in Colorado's Rocky Mountains. The method was demonstrated at Gross Dam as part of a rigorous site specific PMP and PMF hydrology study, and was shown to out-perform a traditional dam safety flood hydrology model in numerous calibration and verification cases. Subsequently it yielded a much smaller PMF. However, the mountain hydrology model was considered proof-of-concept at Gross Dam, and its PMF will not be used for design of the proposed dam enlargement.

The magnitude of the reduction in the mountain hydrology PMF relative to the traditional hydrology PMF may be viewed suspiciously by some; the reduction compared to the previous Gross Dam PMF, which used HMR 55A rainfall and traditional flood hydrology, may be downright alarming. But let us return to the historic flood flows in Section III to provide perspective. The mountain hydrology PMF peak flow (16,026 cfs) is 12 times the estimated 100-YR peak flow at Gross Dam. It is 1.6-2.2 times the estimated paleoflood non-exceedance threshold from a site that was closer to the plains-mountains interface and higher along the extreme precipitation gradient that exists there (again, the Gross Dam basin is west of the first upslopes and therefore within the region of much smaller observed floods). Even in the 1976 Big Thompson flood, regarded as the most extreme storm to hit Colorado in recorded history, peak flows above and below Drake, while very high magnitude, were only 3.8 and 2.9 times the 100-YR peak flow at each respective location. The plains-to-mountains extreme precipitation gradient is clearly reflected in flood frequency estimates, and our Gross Dam PMF is shown to be much larger in terms of its ratio to the 100-YR peak flow than was the 1976 Big Thompson flood.

Future research is needed to develop a more accurate yet simple model of the mountain hydrological processes identified herein. Colorado Dam Safety is working with Colorado State University in a study to develop such a model that would allow production of both infiltration-excess (i.e. Horton) and saturation-excess runoff, soil moisture accounting, and interflow runoff. If a better model can be developed it will be tested on other basins across Colorado's Rocky Mountains.

The majority of regulated dams in Colorado are in ungaged drainage basins, meaning hydrologic model calibration is very limited. Therefore, model processes and parameters must be physically based to the extent possible. Improved physically-based parameter guidelines are needed to allow better modeling of the subsurface interflow contribution to flood runoff.

More realistic PMP estimates for the Rocky Mountains are expected from the Colorado-New Mexico Regional Extreme Precipitation Study (scheduled for completion in mid-2018). As hydrology and rainfall are improved it will become necessary to investigate sources of PMF uncertainty. Better snowmelt, rain-on-snow, and burn scar hydrological processes need to be developed to determine if they contribute to PMF for safe spillway design. More accurate hydrological modeling of mountain basins is clearly needed. We feel that refining the mountain hydrology approach demonstrated herein will be a key step towards achieving the goal of more accurately predicting PMFs for dams in the Rocky Mountains.

X. Acknowledgment

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XI. References

Applied Weather Associates (2017), Site-specific probable maximum precipitation study for Gross Reservoir, Colorado Dam ID: 060211, prepared for Denver Water.

Colorado Dam Safety (2015), Carriage Hills No. 2 Dam (DAMID 040110) September 2013 Dam Failure Forensic Investigation Report.

Cudworth, Arthur G., Jr. (1989), Flood Hydrology Manual, U.S. Bureau of Reclamation, Denver, Colorado.

Goodson & Associates, Inc (1987). Safety Inspection Report for Gross Dam, Reservoir and Appurtenant Structures, prepared for Denver Water Department.

Hansen, E.M, Schwarz, F.K., and J.T. Riedel (1994): Probable Maximum Precipitation- Pacific Northwest States, Columbia River (Including portion of Canada), Snake River, and Pacific Drainages. *Hydrometeorological Report No. 57*, National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Silver Spring, MD.

Jacobs Inc. (2014), Hydrologic Evaluation of the Big Thompson Watershed, prepared for Colorado Department of Transportation.

Jarret, Robert D. and John E. Costa (1988), Evaluation of the flood hydrology in the Colorado Front Range using precipitation, streamflow, and paleoflood data for the Big Thompson River Basin, U.S. Geological Survey, Water Resources Investigation Report 87-4117, Denver, Colorado.

Jarrett, Robert D. (1989), Hydrology and paleohydrology used to improve the understanding of flood hydrometeorlogy in Colorado. In Maurice L. Albertson and Rahim A. Kia (Eds.), Design of Hydraulic Structures, Balkema, Rotterdam.
Jarrett, Robert D. (1993), Flood elevation limits in the Rocky Mountains. In Engineering Hydrology Symposium, Hydraulics Division/ASCE, San Francisco, California.
Larsen, Isaac J., Lee H. MacDonald, Ethan Brown, Daniella Rough, Matthew J. Welsh, Joseph H. Pietraszek, Zamir Libohova, Juan de Dios Benavides-Solorio, and Keelin Schaffrath (2009) Causes of post-fire runoff and erosion: water repellency, cover, or soil sealing? Soil Science Society of America Journal, Vol. 73, Number 4.
Lin, Henry, Erin Brooks, Paul McDaniel, and Jan Boll (2008), Hydropedology and surface/subsurface runoff processes, Encyclopedia of Hydrologic Sciences, 10.
MWH now part of Stantec (2017), Gross Reservoir Hydroelectric Project Probable Maximum Flood Study, prepared for Denver Water.
Rawls, W.J. and Brakensiek, D.L. (1983), A procedure to predict Green and Ampt infiltration parameters, Proceedings of the American Society of Agricultural Engineers Conference on Advances in Infiltration, Chicago, Illinois, pp. 102-112.
Rawls, W.J., D.L. Brakensiek, and M.R. Savabi (1989), Infiltration parameters for rangeland soils, Journal of Range Management, Vol. 42, No. 2.
Sabol, George V., (2008), Hydrologic Basin Response Parameter Estimation Guidelines. State of Colorado Dam Safety Branch.
Tweto, Ogden (1979), Geologic Map of Colorado, U.S. Geological Survey.
U.S. Army Corps of Engineers (1994), Flood-Runoff Analysis, EM 1110-2-1417, Washington, D.C.
U.S. Bureau of Reclamation (2009), Olympus Dam Comprehensive Facility Review Hydrologic Hazard.
U.S. Bureau of Reclamation (2015), Olympus Dam Comprehensive Review Hydrologic Hazard.
U.S. Geological Survey and National Oceanic and Atmospheric Administration (1979), Storm and Flood of July 31-August 1, 1976, in Big Thompson River and Cache la Poudre River Basins, Larimer and Weld Counties, Colorado, Geologic Survey Professional Paper 1115. United States Government Printing Office, Washington.
World Meteorological Organization (2009), Manual on estimation of probable maximum precipitation (PMP), WMO-No. 1045, Geneva, Switzerland.

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