When it Rains *Does* it Pour? Design Precipitation Depths for Dam Safety

Introduction

If a dam and its spillway are not sized appropriately to pass the required inflow, a precipitation event can lead to dam overtopping and failure. Selecting the design precipitation is the first step in the hydrologic analysis used to size the dam and spillway. The design precipitation is typically based on either a selected precipitation frequency (i.e. 100-year event) or Probable Maximum Precipitation (PMP) event.

This article looks at the references available for estimating the design precipitation for small dams in Colorado, Montana, Utah, and Wyoming. The recent extreme precipitation event in Colorado is also examined in relationship to frequency estimates and discussed in the context of dam safety.

Colorado's 2013 Precipitation Event

The September 9-16, 2013, precipitation event was caused by a slow-moving cold front stalled over Colorado, clashing with warm humid monsoonal air from the south. The precipitation resulted in catastrophic flooding along Colorado's Front Range from Colorado Springs, north to Fort Collins. Numerous low hazard dams that were designed to withstand a 100-year precipitation event overtopped, with nine earthen dams breaching. According to the Colorado Division of Water Resources, the high hazard dams within the affected area performed well, with many conveying spillway flows for the first time since they were built.

The Hydrometeorological Design Studies Center (HDSC) developed maps for the September event showing the annual exceedance probabilities of the worst case precipitation in relation to published frequency data presented in National Oceanic and Atmospheric Administration (NOAA) Atlas 14. **Figure 1** shows the map for the full seven day storm duration. Maps for 24-hour and 48-hour durations are also available.

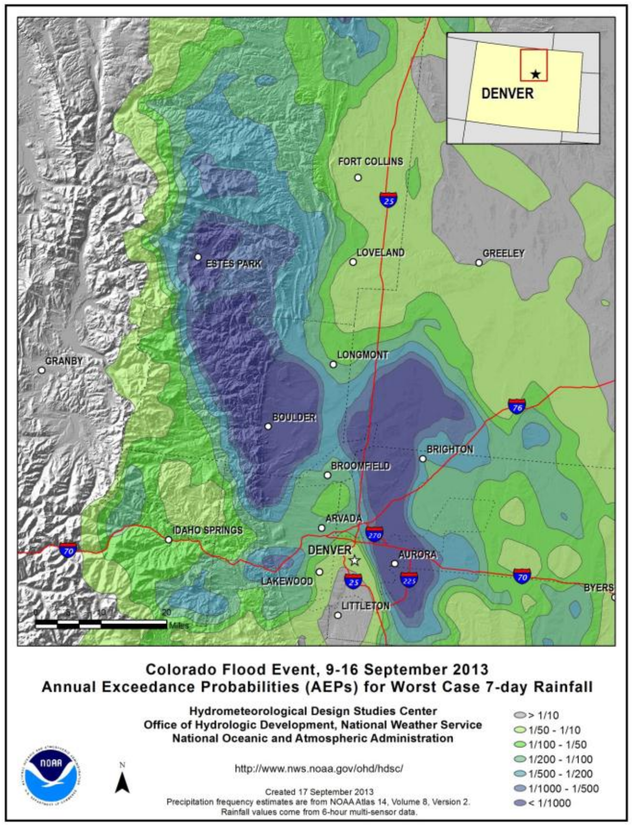


Figure 1: Worst Case 7-day Rainfall Annual Exceedance Probabilities

As shown in Figure 1, exceedance probabilities were estimated to be greater than the 0.1% (1/1000) for areas including Estes Park, Boulder, and Aurora.

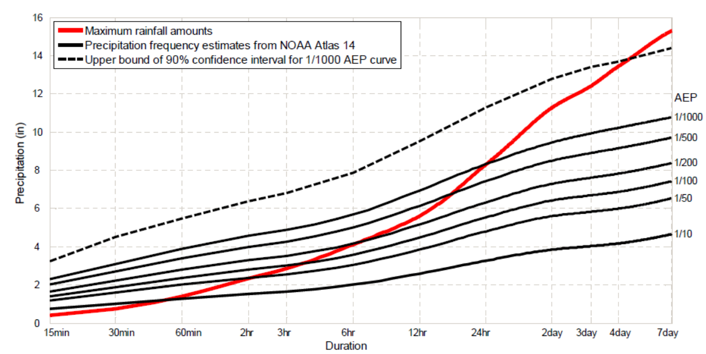


Figure 2: Maximum observed rainfall amounts in relationship to NOAA 14 estimates

Figure 2 shows the observed rainfall amounts for the Justice Center rain gauge located in Boulder, in relationship to the NOAA Atlas 14 precipitation frequency estimates. For the seven day duration, the observed precipitation was greater than the upper bound of 90% confidence interval for the 1,000-year precipitation event.

The September event is a reminder of the importance of designing a dam for the appropriate precipitation event and hazard classification. Flooding did result from the low hazard dam failures; however, there was little flooding from the state-classified high hazard dams, where failure would likely result in widespread damage and loss of human life, because these dams were designed appropriately for the PMP event.

State Criteria for Design Precipitation

The state criterion for determination of the dam design precipitation is based upon dam size and hazard classification. The hazard classification typically accounts for dam height, storage capacity, likelihood of failure (e.g. a dam located within a series of dams), and potential for loss of life and property, should a failure occur. The following discussion summarizes the hazard classification system and methods used to identify the dam design precipitation for Colorado, Utah, Montana, and Wyoming.

For Colorado, design precipitation is selected based upon dam size and hazard classification as presented in **Table 1**. Additional guidelines are available for altitude adjustments in the Colorado Rules and Regulations for Dam Safety and Dam Construction.

Table 1: Colorado Inflow Design Flood Requirements

INFLOW DESIGN FLOOD REQUIREMENTS FOR COLORADO USING HYDROMETEOROLOGICAL REPORTS (HMR)				
DAM SIZE	HAZARD CLASSIFICATION			
	High	Significant	Low	NPH
Large	0.90 PMP	0.68 PMP	100 YR	50 YR
Small	0.90 PMP	0.45 PMP	100 YR	25 YR
Minor	0.45 PMP	100 YR	50 YR	25 YR

Note: NPH = No Public Hazard Dam. This table was taken from Table 5.2 of the Office of the State Engineer Dam Safety Branch's "Rules and Regulations for Dam Safety and Dam Construction," dated January 1, 2007.

For Utah, design precipitation is selected based upon hazard classification as determined by the State Engineer. Design precipitation for all low hazard dams is the 100-year event, whereas significant and high hazard dams must use the Spillway Evaluation Flood (SEF). The SEF is defined as the most critical flood of either the 100-year event applied to a saturated watershed or one of the PMP events.

For Montana, all dams with a potential for loss of life due to failure are classified as high hazard and the minimum design precipitation considered for any impoundment greater than 50 acre-feet is the 500-year event. Design precipitation for all high hazard dams is determined following a loss of life analysis using the requirements summarized in **Table 2**.

Table 2: Montana Design Flood Requirements

Loss of Life (LOL)	Design Flood
Less than or Equal to 0.5	500 YR
0.5 to 5	LOL x 1000
5 to 1000	$P_s = P_{5,000}\ (10^{rd})$ Where: r = -0.304 + .435 log10 (lol) d = log10 (PMP) - log10 (P5,000) lol = estimated loss of life PMP = probable maximum precipitation $P_{5,000}$ = 5,000-year recurrence interval precipitation P_s = design precipitation to meet spillway standard
Greater Than 1000	Probable Maximum Precipitation (PMP)

This table was taken from Montana's Rules and Regulations, Rule 36.14.502 entitled, "Hydrologic Standard for Emergency and Principal Spillways".

For Wyoming, determination of design precipitation and dam hazard classification is at the discretion of the State Engineer. Additionally, all reservoirs with a dam height greater than 20 feet, storage capacity greater than 50 acre-feet, and/or a reservoir located in an area where extensive property damage or loss of life might result, are required to have a minimum design precipitation of the 100-year event.

State rules and regulations typically prescribe the minimum criteria and not necessarily the method for satisfying the criteria. For example, a common requirement for low hazard dams is the 100-year event. This design criterion is typically the 100-year, 24-hour rainfall with a specific temporal distribution of hourly rainfall. Hydrological guidelines are then followed to determine the Design Flood. Alternately, the 100-year flood can be derived from actual stream gauge data collected within the drainage area or a similar nearby drainage area. The reader is cautioned to work with each state's dam regulatory agency to gain an understanding which methods and guidelines are acceptable for meeting the state's minimum criteria.

Precipitation Frequency Events

Since 2004, NOAA, National Weather Service (NWS), and HDSC have been working on updating and posting online precipitation frequency estimates, such as the 100-year event, as part of NOAA Atlas 14 for various parts of the United States. Funding is the largest impediment to the updating process, and is typically pooled from a variety of Federal, State, and local agencies. **Figure 3** presents where NOAA Atlas 14 is currently available in blue.

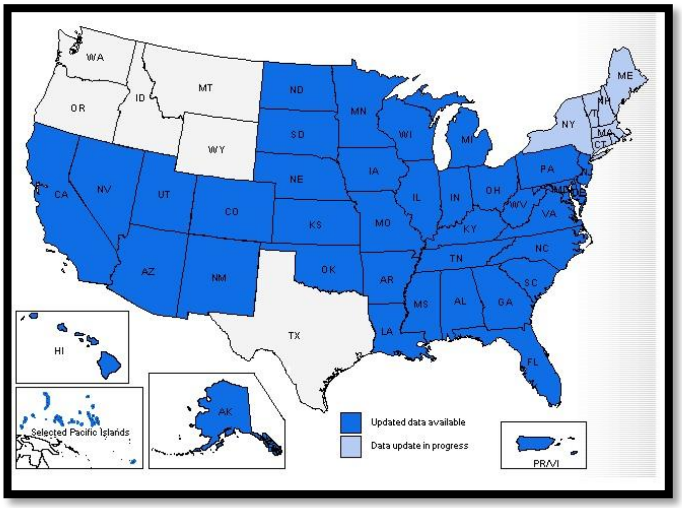


Figure 3: NOAA Atlas 14 Availability

As of 2013, Colorado and Utah have been updated to NOAA Atlas 14, while Wyoming and Montana still use NOAA Atlas 2 for storm durations of 1-hour to 24-hours. In addition to NOAA Atlas 2, Montana also uses the USGS WRI Report 97-4004 "Regional Analysis of Annual Precipitation Maxima in Montana" (Parent, 1997). This document is used to produce large recurrence intervals for 2-, 6-, and 24-hour storm durations specifically for dam design purposes. The typical duration used for dam design is the 24-hour duration.

While NOAA's goal is to update all states to NOAA 14, as of this publication, no funding has been received by NOAA and no plans are currently in place for updating Montana and Wyoming to NOAA Atlas 14.

The durations for NOAA Atlas 14 range from 5-minutes to 60 days and have an average recurrence interval ranging from 1 to 1,000 years. The updated analysis is different from NOAA Atlas 2 because it uses a longer period of record and a denser network of rain gauge stations, along with more robust and accepted statistical techniques. The precipitation magnitude-frequency relationships at individual rain gauge stations were based on regional frequency analysis approach based on L-moment statistics. The frequency analyses were carried out on annual maximum series (AMS) across a range of durations. Detailed information and discussion for deriving the estimates from rain gauge station data is provided in the NOAA Atlas 14 Document.

The Precipitation Frequency Data Server (PFDS) is an online point-and-click interface developed to deliver NOAA Atlas 14 precipitation frequency estimates and associated information. Upon clicking a state on the map or selecting a state name from the drop-down menu, an interactive map of that state will be displayed. From there, a user can identify a location from the map or enter the latitude and longitude for which precipitation frequency estimates are needed. The PFDS is shown in **Figure 4**.

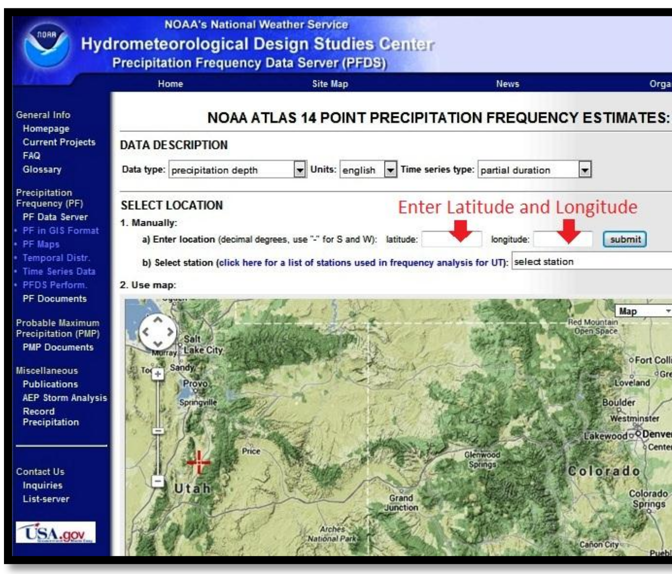
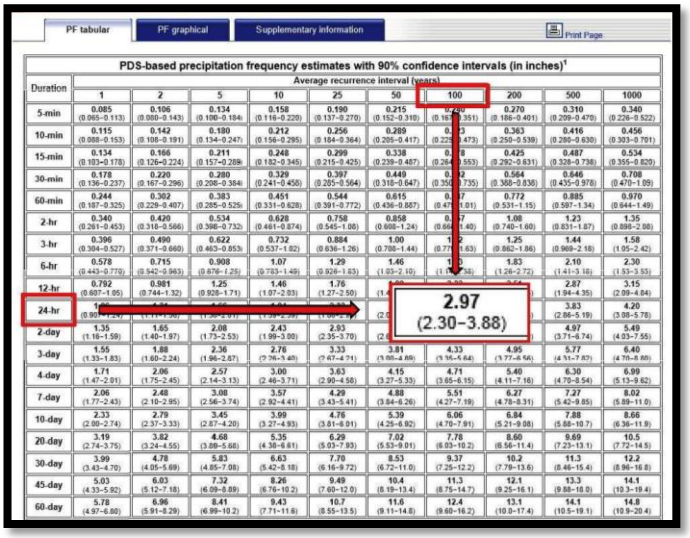


Figure 4: Precipitation Frequency Data Server

Estimates and their confidence intervals can be displayed directly as tables or graphs via separate tabs. Links to supplementary information (such as ASCII grids of estimates, associated temporal distributions of heavy rainfall, time series data at observation sites, cartographic maps, etc.) are also available. The ASCII grids of point estimates are the basis of the PFDS interface results and are available to be downloaded in a GIS compatible format. **Figure 5** presents the precipitation frequency table. The 24-hour duration, 100-year recurrence interval is highlighted in red. The numbers in parentheses are the upper and lower bound of the 90% confidence limits.



PDS-based precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	0.085 (0.065-0.113)	0.106 (0.080-0.143)	0.134 (0.100-0.184)	0.158 (0.116-0.220)	0.190 (0.137-0.270)	0.215 (0.152-0.310)	[illegible]	0.270 (0.186-0.401)	0.310 (0.209-0.470)	0.340 (0.226-0.522)
10-min	0.115 (0.088-0.153)	0.142 (0.108-0.191)	0.180 (0.134-0.247)	0.212 (0.156-0.295)	0.256 (0.184-0.364)	0.289 (0.205-0.417)	[illegible]	0.363 (0.250-0.539)	0.416 (0.280-0.630)	0.456 (0.303-0.701)
15-min	0.134 (0.103-0.178)	0.166 (0.126-0.224)	0.211 (0.157-0.289)	0.248 (0.182-0.345)	0.299 (0.215-0.425)	0.338 (0.239-0.487)	[illegible]	0.425 (0.292-0.631)	0.487 (0.328-0.738)	0.534 (0.355-0.820)
30-min	0.178 (0.136-0.237)	0.220 (0.167-0.296)	0.280 (0.208-0.384)	0.329 (0.241-0.458)	0.397 (0.285-0.564)	0.449 (0.318-0.647)	[illegible]	0.564 (0.388-0.838)	0.646 (0.435-0.978)	0.708 (0.470-1.09)
60-min	0.244 (0.187-0.325)	0.302 (0.229-0.407)	0.383 (0.285-0.525)	0.451 (0.331-0.628)	0.544 (0.391-0.772)	0.615 (0.436-0.887)	[illegible]	0.772 (0.531-1.15)	0.885 (0.597-1.34)	0.970 (0.644-1.49)
2-hr	0.340 (0.261-0.453)	0.420 (0.318-0.566)	0.534 (0.398-0.732)	0.628 (0.461-0.874)	0.758 (0.545-1.08)	0.858 (0.608-1.24)	[illegible]	1.08 (0.740-1.60)	1.23 (0.831-1.87)	1.35 (0.898-2.08)
3-hr	0.396 (0.304-0.527)	0.490 (0.371-0.660)	0.622 (0.463-0.853)	0.732 (0.537-1.02)	0.884 (0.636-1.26)	1.00 (0.708-1.44)	[illegible]	1.25 (0.862-1.86)	1.44 (0.969-2.18)	1.58 (1.05-2.42)
6-hr	0.578 (0.443-0.770)	0.715 (0.542-0.963)	0.908 (0.676-1.25)	1.07 (0.783-1.49)	1.29 (0.926-1.83)	1.46 (1.03-2.10)	[illegible]	1.83 (1.26-2.72)	2.10 (1.41-3.18)	2.30 (1.53-3.53)
12-hr	0.792 (0.607-1.05)	0.981 (0.744-1.32)	1.25 (0.928-1.71)	1.46 (1.07-2.03)	1.76 (1.27-2.50)	[illegible]	[illegible]	[illegible]	2.87 (1.94-4.35)	3.15 (2.09-4.84)
24-hr	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.97 (2.30-3.88)	[illegible]	3.83 (2.86-5.19)	4.20 (3.08-5.78)
2-day	1.35 (1.16-1.59)	1.65 (1.40-1.97)	2.08 (1.73-2.53)	2.43 (1.99-3.00)	2.93 (2.35-3.70)	[illegible]	[illegible]	[illegible]	4.97 (3.71-6.74)	5.49 (4.03-7.55)
3-day	1.55 (1.33-1.83)	1.88 (1.60-2.24)	2.36 (1.96-2.87)	2.76 (2.26-3.40)	3.33 (2.67-4.21)	3.81 (3.00-4.89)	4.33 (3.35-5.64)	4.95 (3.77-6.56)	5.77 (4.31-7.82)	6.40 (4.70-8.80)
4-day	1.71 (1.47-2.01)	2.06 (1.75-2.45)	2.57 (2.14-3.13)	3.00 (2.46-3.71)	3.63 (2.90-4.58)	4.15 (3.27-5.33)	4.71 (3.65-6.15)	5.40 (4.11-7.16)	6.30 (4.70-8.54)	6.99 (5.13-9.62)
7-day	2.06 (1.77-2.43)	2.48 (2.10-2.95)	3.08 (2.56-3.74)	3.57 (2.92-4.41)	4.29 (3.43-5.41)	4.88 (3.84-6.26)	5.51 (4.27-7.19)	6.27 (4.78-8.31)	7.27 (5.42-9.85)	8.02 (5.89-11.0)
10-day	2.33 (2.00-2.74)	2.79 (2.37-3.33)	3.45 (2.87-4.20)	3.99 (3.27-4.93)	4.76 (3.81-6.01)	5.39 (4.25-6.92)	6.06 (4.70-7.91)	6.84 (5.21-9.08)	7.88 (5.88-10.7)	8.66 (6.36-11.9)
20-day	3.19 (2.74-3.75)	3.82 (3.24-4.55)	4.68 (3.89-5.68)	5.35 (4.38-6.61)	6.29 (5.03-7.93)	7.02 (5.53-9.01)	7.78 (6.03-10.2)	8.60 (6.56-11.4)	9.69 (7.23-13.1)	10.5 (7.72-14.5)
30-day	3.99 (3.43-4.70)	4.78 (4.05-5.69)	5.83 (4.85-7.08)	6.63 (5.42-8.18)	7.70 (6.16-9.72)	8.53 (6.72-11.0)	9.37 (7.25-12.2)	10.2 (7.79-13.6)	11.3 (8.46-15.4)	12.2 (8.96-16.8)
45-day	5.03 (4.33-5.92)	6.03 (5.12-7.18)	7.32 (6.09-8.89)	8.26 (6.76-10.2)	9.49 (7.60-12.0)	10.4 (8.19-13.4)	11.3 (8.75-14.7)	12.1 (9.25-16.1)	13.3 (9.88-18.0)	14.1 (10.3-19.4)
60-day	5.78 (4.97-6.80)	6.96 (5.91-8.29)	8.41 (6.99-10.2)	9.43 (7.71-11.6)	10.7 (8.55-13.5)	11.6 (9.11-14.8)	12.4 (9.60-16.2)	13.1 (10.0-17.4)	14.1 (10.5-19.1)	14.8 (10.9-20.4)

Figure 5: Precipitation Frequency Table

The precipitation frequency data available in graphical format includes depth-duration-frequency (DDF) curves and precipitation frequency curves with 90% confidence limits. **Figure 6** presents the precipitation frequency curves.

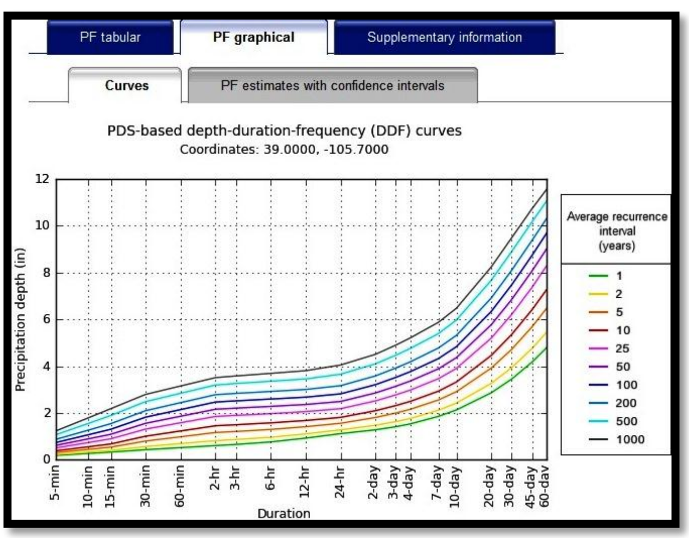


Figure 6: Graphical Precipitation Frequency Curves

Precipitation frequency estimates from NOAA Atlas 14 are point estimates, and reductions should be applied when used for areas. The conversion of a point estimate to an areal estimate is usually done by applying an areal reduction factor, obtained from a depth-area-duration curve, to the average point estimates within the subject area. Currently, the depth-area-duration curves from the U.S. Weather Bureau's Technical Paper No. 29 can be used for this purpose and is recommended by NOAA Atlas 14. The NWS is investigating the areal reduction factors for NOAA Atlas 14 and may issue new areal reduction factors in the future.

Probable Maximum Precipitation Events

The PMP, as defined in the HMR documents, is "theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year". No recurrence interval is assigned to the PMP.

For Colorado, Montana, Utah, and Wyoming, the PMP east of the Continental Divide is derived using the methodology in HMR 55A; the PMP west of the Continental Divide is derived using HMR 49 or HMR 57. The PMP studies developed by NOAA and NWS are shown in **Figure 7** by geographical location in the United States and are available online through NOAA.

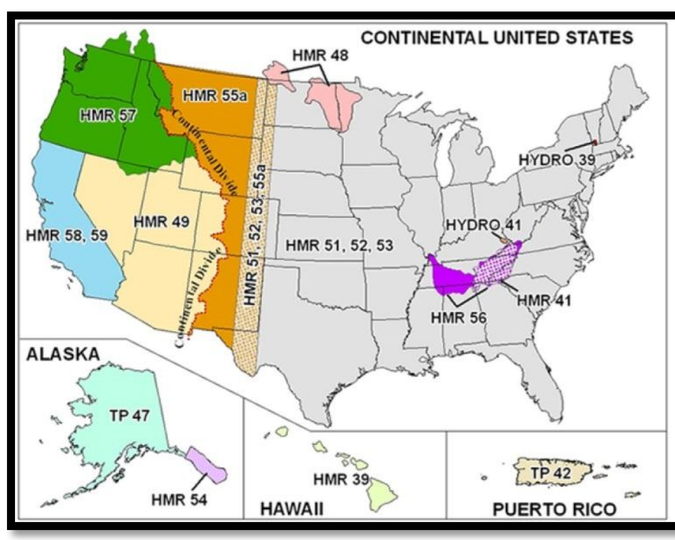


Figure 7: Available PMP Studies

Utah has published two updates to HMR 49:

- "2002 Update for Probable Maximum Precipitation, Utah 72 Hour Estimates to 5,000 sq. mi. - March 2003" (USUL)
- "Probable Maximum Precipitation Estimates for Short Duration, Small Area Storms in Utah - October 1995" (USUS)

These augment, not supersede, HMR 49 and are intended only for use in the state of Utah.

HMRs 55a, 49, and 57 provide precipitation values for a local storm (thunderstorm) with 6 hours of duration and a general storm with 72 hours of duration. The results from both the general and local storm should be used in hydrologic trials to determine the critical design values.

The HMR methods require obtaining index precipitation from maps, and then adjusting precipitation depths for drainage area size, elevation, and orographic effects specific to the watershed being studied.

An alternative to the HMR documents for PMP estimates is a site-specific analysis. Colorado has developed an Extreme Precipitation Analysis Tool (EPAT) and is currently conducting a formal 3rd party meteorological peer review set for completion in April 2014. In general, a site-specific analysis is not readily achievable for small dam owners and because it typically requires a custom analysis by a consultant engineer/meteorologist.

Conclusions

To determine design precipitation depths for precipitation frequency events, NOAA Atlas 2 and/or Atlas 14 are available (Montana also uses USGS WRI Report 97-4004). NOAA Atlas 14 is an update and supersedes NOAA Atlas 2 in Utah and Colorado, while no update is currently planned for Montana or Wyoming. One advantage of NOAA Atlas 14, the precipitation depths can be easily obtained online using NOAA's Precipitation Frequency Data Server.

PMP estimates can be estimated using HMR methods. Precipitation for both the local and general storms is derived for hydrological evaluation. An alternative to the HMR methods is a site-specific extreme precipitation analysis. Site-specific analysis is not easily achieved and typically requires a custom analysis by a consultant engineer/meteorologist.

Selecting the design precipitation is the first step in the hydrologic analysis used to size the dam and spillway. If the dam and spillway are not sized appropriately, an extreme precipitation event can lead to dam overtopping and failure. As the recent precipitation event in Colorado shows, large or rare precipitation events can occur and when they do, the importance of appropriately selecting the design precipitation for a given dam is reinforced.

References (with Links where available)

Colorado Rules and Regulations for Dam Safety and Dam Construction, January 01, 2007.

Colorado Launching Massive Emergency Dam Inspection Program, The Denver Post, by David Olinger, September 23, 2013.

Montana Dam Safety Rules and Regulations, Rule 36.14.502 - Hydrologic Standard for Emergency and Principal Spillways, November 5, 1999.

Regional Analysis of Annual Precipitation Maxima in Montana, USGS Water-Resources Investigations Report: 97-4004, by Charles Parent, 1997.

Utah Requirements for the Design, Construction and Abandonment of Dams, R655-11-4 Hydrologic Design, August 01, 2013.

Wyoming Surface Water Regulations and Instructions, Chapter 5 - Reservoirs, 1977.

NOAA Data Links

Current NWS Precipitation Frequency Documents (Including NOAA Atlas 2 and NOAA Atlas 14):
http://www.nws.noaa.gov/oh/hdsc/currentpf.htm

Current NWS Probable Maximum Precipitation Documents (Including HMR 55A, HMR 49, and HMR 47):
http://www.nws.noaa.gov/oh/hdsc/studies/pmp.html

HDSC Exceedance Probability Analysis for Select Storm Events:
http://www.nws.noaa.gov/oh/hdsc/aep_storm_analysis/index.html

Areal Reduction (Technical Paper No. 29):
http://www.nws.noaa.gov/oh/hdsc/Technical_papers/TP29P4.pdf