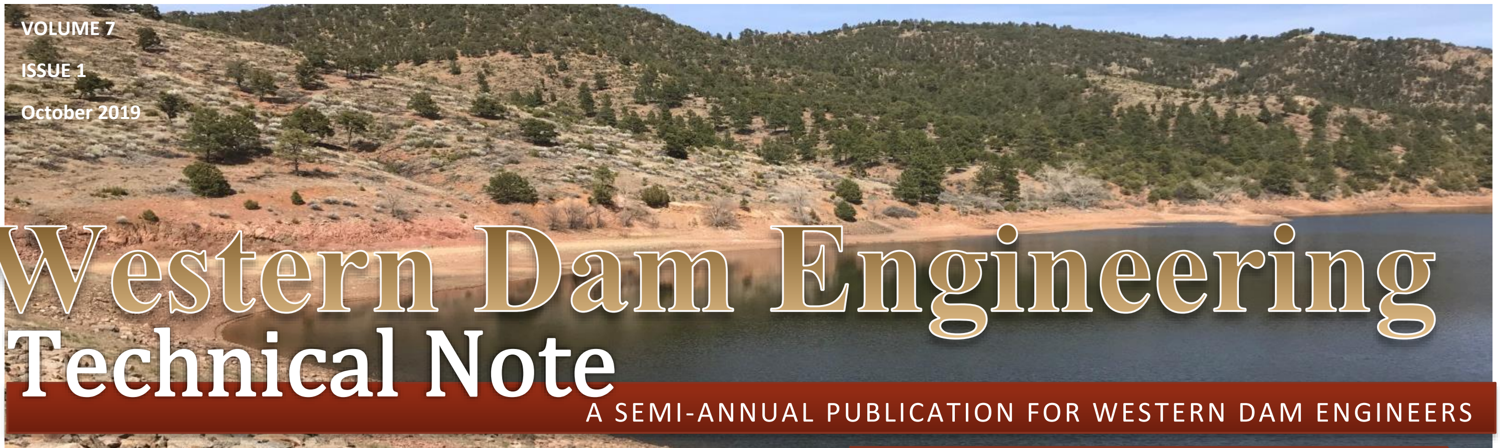

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# Western Dam Engineering Technical Note

A SEMI-ANNUAL PUBLICATION FOR WESTERN DAM ENGINEERS

In this issue of the ***Western Dam Engineering Technical Note***, we present articles on **an alternative method for completing a breach analysis and consequence estimation**, and **a PMP tool discussion**. This newsletter is meant as an educational resource for civil engineers who practice primarily in rural areas of the western United States. This publication focuses on technical articles specific to small and medium dams. It provides general information. The reader is encouraged to use the references cited and engage other technical experts as appropriate.

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- New Mexico Office of the State Engineer

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## Good to Know

**Upcoming ASDSO Webinar Dam Safety Training:**

- *Intro to Overtopping Protection Systems, 11/12/19*
- *Filters and Drainage Systems for Embankment Dams, 1/14/20*

**Upcoming Classroom Technical Seminars:**

- *Stability Analysis of Embankment Dams, Phoenix, AZ March 24-26, 2020*
- *HEC-RAS, Austin, TX, May 5-8, 2020*

**Upcoming Conferences:**

- *ASDSO Southeast Regional Conference, Charleston, SC; May 11-13, 2020*

**ASDSO Training Website Link**

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## In this Issue

# Wise Up: DSS-WISE™ LITE as an Alternative Method for Breach Analysis and Consequence Estimation

*By: Alan Turner, PE, CFM, & Chris Shrimpton, PE*

## Introduction

DSS-WISE™ Lite (DSS-WISE) is a web-based, automated two-dimensional dam break flood modeling and mapping tool with the capability of completing dam break analyses via a web-based platform and computing the potential breach inundation consequences downstream of the subject dam. DSS-WISE is a robust numerical model that uses fully dynamic shallow water equations. The numerical model uses a state-of-the-art upwind numerical scheme that can handle all flow regimes, wet/dry interfaces, and discontinuities [6]. The upwind numerical scheme is parallelized dividing and executing the DSS-WISE model computations on multiple computer cores at once. This parallelization supports excellent computational speed, allow for the potential of operational real-time simulations of potential emergencies, and rapid results for multiple simulation runs at a minimum of effort and cost [6]. DSS-WISE also has a Human Consequences Module (HCOM) that calculates an estimation of day and night population at risk (PAR) within the dam break inundation zone. This information is valuable as input into risk informed decision making (RIDM) processes such as semi-quantitative risk analysis (SQRA).

The National Center for Computational Hydroscience and Engineering (NCCHE) at the University of Mississippi, develops, administers, and supports DSS-WISE. The United States Federal Emergency Management Agency (FEMA) supplies financial support for the development, operation, and maintenance of the DSS-WISE web-based [6]. DSS-WISE assists FEMA and the Department of Homeland Security (DHS) Science and Technology Directorate (S&T) to achieve their mission by addressing these challenges listed above through free-of-charge web-based tool that is available 24/7 to stakeholders of dams sector for both the preparedness and response to flood hazard [6].

This article will introduce the DSS-WISE web-based modeling platform, discuss the input parameters, model tools, population at risk, and inundation results.

## Can Anyone use DSS-WISE?

One of the major goals of DSS-WISE is to simplify the process of running dam breach models. Currently 17.1% of High Hazard Dams on the U.S. Army Corps of Engineers (USACE) National Inventory of Dams (NID) do not have an up-to-date EAP [15]. This issue grows larger when you focus on all dams as depicted in Figure 1 below [14].

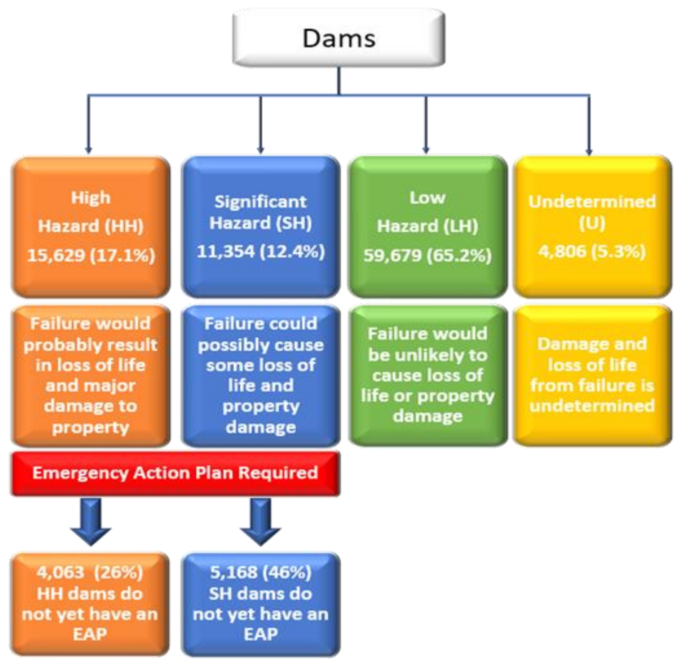


**Figure 1. Statistics on EAP's for Dams in the NID [14].**

DSS-WISE is a tool to help dam safety officials create dam break simulations, with a minimum of input data and limited modeling experience, that develop basic information on dam breach discharges, volumes, inundation mapping, flood arrival times, and estimates of population at risk (PAR) and flood hazard maps for humans [6]. Results and data provided by this tool allow dam owners, and state dam safety programs to efficiently produce EAPs and understand downstream impacts for dams that lack dam breach information.

FEMA and NCCHE grant state dam safety programs access to the DSS-WISE system, with state dam safety programs serving as administrators for access to the

DSS-WISE online tool. Users request access through the DSS-WISE portal, which notifies the dam safety administrator in the region of the dam of interest. State programs review the request and control who may access the system to run simulations under their group. Policies vary by state, but many states will grant access to engineers who are helping dam owners in their state or who are aiding the state program itself. A private dam owner who has the technical skills to develop a dam breach analysis with DSS-WISE could also request and receive access. In general, it is not the intent of the DSS-WISE program to be publicly available. The web-based computational platform, and administration by state agencies, limits the number of users so that the two 16-core computer servers that are performing the simulation support efficiency for emergency and real time dam breach analyses. NCCHE guarantees the privacy and security of the data.

## What is DSS-WISE?

As discussed previously, DSS-WISE is a web-based numerical model for simulating dam breaks using as-designed reservoir information including maximum and normal pool water surface elevations and corresponding volumes, and as-built information such as crest elevation and hydraulic height. Alternatively, DSS-WISE can accept externally-generated breach hydrographs in place of physical dam characteristics to simulate a dam breach. The intent of the program is to provide inundation mapping and PAR information from a dam breach analysis with minimum input data and limited modeling experience.

Due to the robust and efficient numerical scheme, simulation times are typically less than one hour for most cases, but are dependent on the size of the chosen grid (cell sizes can range from 15 ft to 200 ft at 1-ft increments.), length of the simulation (in number of days), and mileage downstream from the dam break (DSS-WISE can model up to 390 miles downstream from a dam) [14].

With the release of an updated version of DSS-WISE on October 9, 2019, DSS-WISE now adds the ability to incorporate high resolution digital elevation maps (DEM) [13]. With this recent upgrade, the DEM layer with the highest resolution assigns the elevation to the computational grid. The new computation grid development scheme layers the highest resolution DEM which has the highest priority for sampling to the lowest resolution DEM which has the lowest priority for sampling. Figure 2 depicts The DEM generation scheme [5]. Currently DSS-WISE has the following DEMs available for use in the model [13]:

- USGS 1-m LIDAR-based DEM raster (Coverage includes the Continental U.S. (partial) and Puerto Rico (almost complete))
- USGS 1/9 arc-second DEM raster (Coverage includes the Continental U.S. (partial), Alaska (partial) and Guam)
- USGS 1/3 arc-second DEM raster (Coverage includes the Continental U.S. (complete), Alaska (partial), Hawaii, American Samoa, Puerto Rico, U.S. Virgin Islands, Guam, and Northern Mariana Islands)
- USGS 1 arc-second DEM raster (Coverage includes the Continental U.S., Alaska, Hawaii, American Samoa, Puerto Rico, U.S. Virgin Islands, Guam, Northern Mariana Islands, Canada, and Mexico)
- USGS 2 arc-second DEM raster (Coverage includes Alaska (complete))

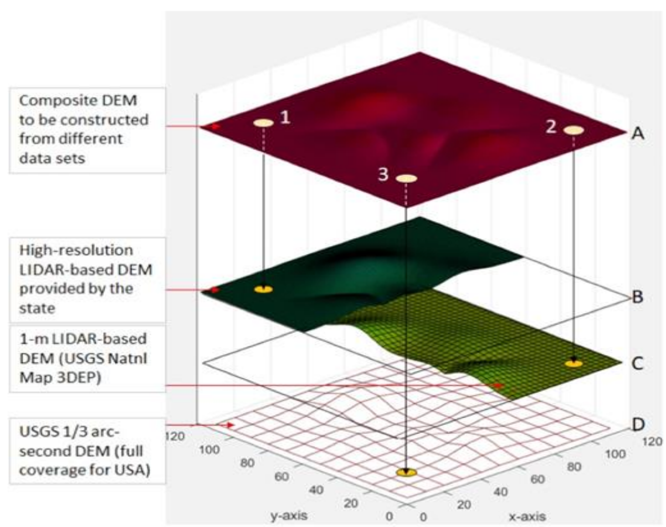


**Figure 2. Composite DEM Creation Scheme [5]**

DSS-WISE also includes The Human Consequences Module (HCOM) which allows the user to estimate PAR and other economic and environmental consequences of breach inundation. HCOM supplies more information on a dam break including:

- How fast and how far will the flood propagate;
- The flooding depth, velocity, and specific discharge (depth × velocity) at prescribed critical sections;
- The hazard levels and consequences for humans;
- Shape file and Google Files (kmz) for easy visualizations and use in EAPs; and
- The level of damage to properties, infrastructure, and the environment downstream.

Figure 3 below depicts the DSS-WISE modules and logic flow path that for DSS-WISE model development and processing [14].

## Where do I begin?

A sponsoring agency or state (usually a dam safety official) controls access to DSS-WISE. Access and approvals are rapid, and once accepted, DSS-WISE assigns the defined area based on state or regional boundary to the user. This allows the user to focus on the collection of data and initiation of a dam break analysis for any facility within the assigned domain. Model runs can extend beyond the boundaries of the area assigned to the user as the user specified distance from the breach point defines the computational domain. The user then defines the location and geometric properties of the dam and reservoir, locations of observation cross sections for data reporting and potentially, a breach hydrograph. Dam owners, state regulatory agencies, and the NID can be excellent sources for geometric and dam break information to use as input information for DSS-WISE. Cross-referencing data (when possible) from multiple sources is a good rule of thumb to confirm the accuracy of DSS-WISE input data. Modeling data includes hydraulic height, maximum, normal, and failure pool elevations and corresponding volumes. Sections where discharge hydrograph information will have value, should also be located prior to data input.

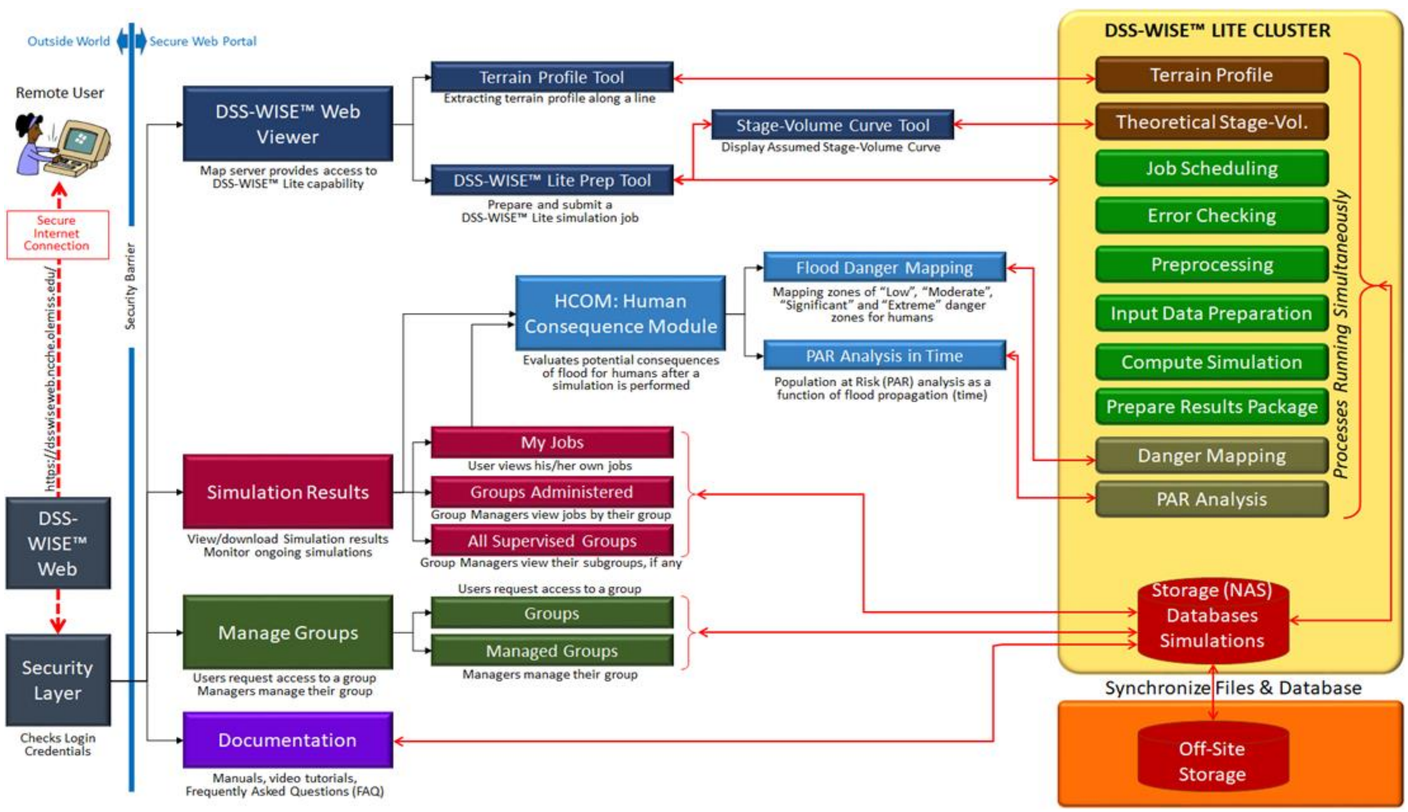


**Figure 3. DSS-WISE Model Logic and Modular Flow Path [14]**

## Let's Build a Model!

To begin developing a DSS-WISE dam break simulation you first need to request access from the "Group Manager" from your state or region through the following website:

https://dsswiseweb.ncche.olemiss.edu

Select the new user registration button (or Log In button if an existing user) and fill out your information. You will receive and email with link to click to confirm your email address. Verify your email address and access the website again to log in to your account and request membership to a group. Finally, select the group that has your dam of interest. This action sends a request to the state DSS-WISE administrator to approve access and once approved, you are ready to begin inputting your reservoir information. DSS-WISE needs a modern browser to run and you should access the platform with one of the following browsers:

1. Google Chrome
2. Firefox
3. Microsoft Edge

DSS-WISE will not function on Internet Explorer. If one browser is giving you issues, try a different one.

Clicking on the DSS-WISE Web Viewer button (shown below) enters you into the model set up and launch online platform.


Select your group after clicking the DSS-WISE Prep Tool opens the scenario description box, prepopulates the map with NID data, and highlights your group's active domain as shown on Figure 4.

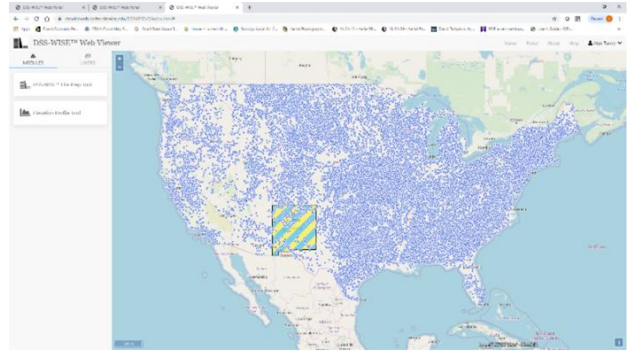

**Figure 4. DSS-WISE Landing Page**

Selecting "Next" leads you through the remaining data input information as described below.

### Simulation Type Tab (Figure 5):

*Reservoir Simulation* – Input physical information including hydraulic height, dam crest elevation, maximum, normal, and failure elevations and corresponding volumes, breach parameters, simulation time and simulation parameters to develop the breach failure parameters for the model.

*Hydrograph Simulation* – Input a breach hydrograph developed outside of DSS-WISE as well as, dam information, crest elevation, breach location, and simulation parameters to run a known breach simulation.

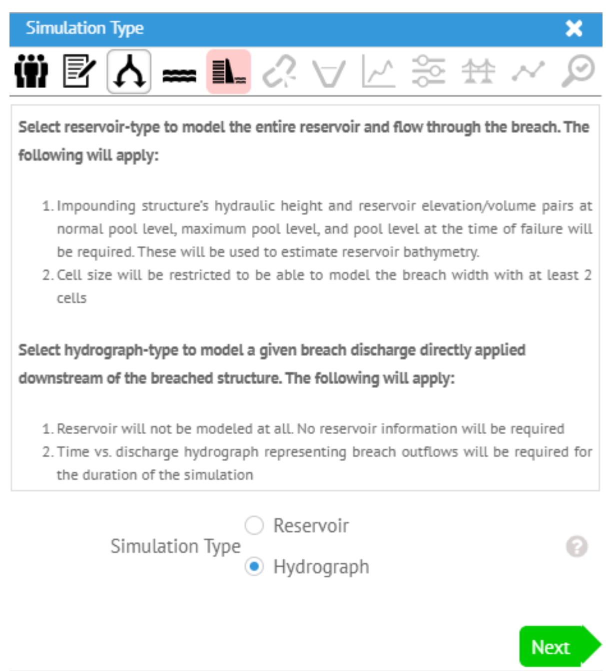


**Figure 5: Simulation Type Data Entry Tab**

## Reservoir Information Tab (Figure 6):

For a reservoir simulation, the user defines the reservoir pool in this tab. Hydrograph simulations do not need the reservoir pool definition. The user enters latitude and longitude of the reservoir pool by clicking a point in the reservoir and adds the maximum and normal storage elevation and volume. The maximum storage elevation must be greater than the DEM elevation of the selected reservoir point.

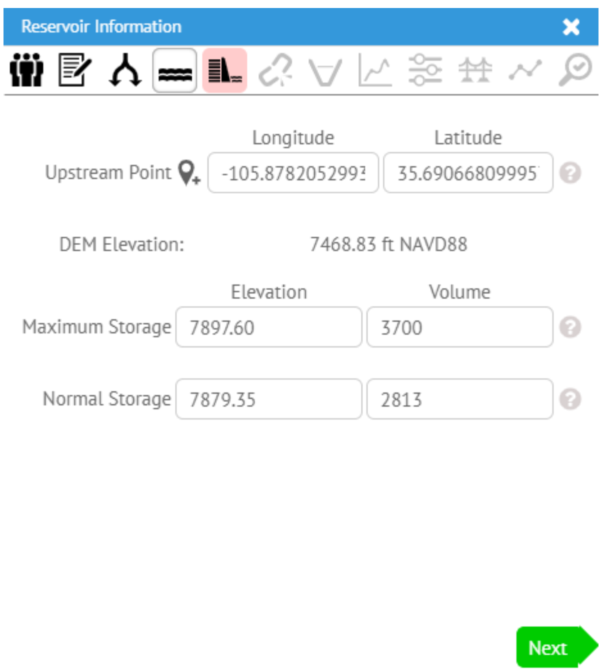


**Figure 6. Reservoir Information Data Entry Tab**

## Impounding Structures Tab (Figure 7):

The impounding structures tab provides the location for the definition of the impounding structures for the analysis for both reservoir simulation and hydrograph simulation methods (breaches can only occur at one structure at a time for a given simulation). The user enters the impounding structure name, impoundment type (embankment, gravity, or arch), hydraulic height (height of impoundment from downstream toe to maximum water surface elevation), crest elevation, and draws the centerline of the crest directly in the DSS-WISE simulation preparation page.

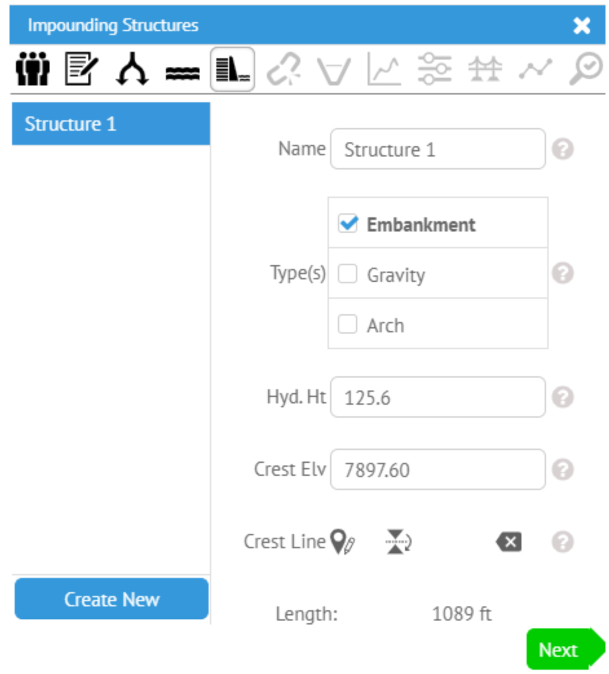


**Figure 7. Impounding Structures Tab**

## Conditions at Failure Tab (Figure 8):

The conditions at Failure Tab defines the reservoir breach parameters. This includes the breach location (selected by clicking a point on the map), the type of breach (sudden and complete or partial breach), reservoir storage and volume at breach, for the reservoir simulation method only. The conditions at failure tab is not used for the hydrograph method.

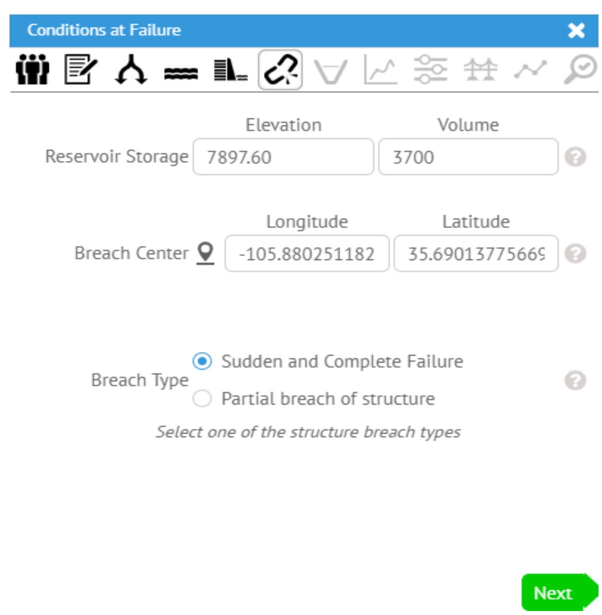


**Figure 8. Conditions at Failure Tab**

## Partial Breach Information (if selected) (Figure 9):

The user will enter the breach invert, breach width and breach formation time. The choice of sudden and complete failure prevents data entry on this tab. A future upgrade to DSS-WISE plans to incorporate a partial breach parameter calculator to the Partial Breach Information tab. Currently this functionality is not operational, and the user should calculate the breach parameters outside of the program using the following methods:

- MacDonald and Langridge-Monopolis [10];
- Froehlich [7], [8], [9];
- or Von Thun and Gillette [10].

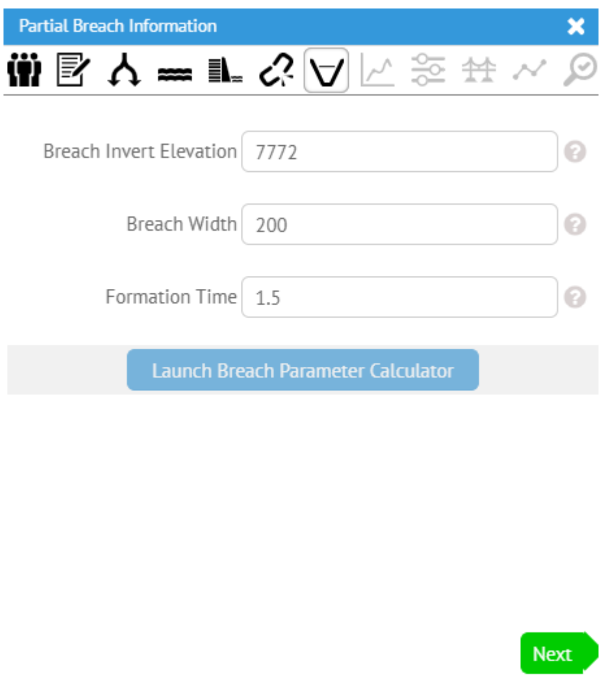


**Figure 9. Partial Breach Information Data Entry Tab**

## Hydrograph Breach Information (if selected) (Figure 10):

This tab defines the breach hydrograph developed with outside software (USACE HEC-HMS, for example). The user enters the data as a time vs. discharge paired data series.


**Figure 10. Hydrograph Breach Information Tab**

## Simulation Parameters (Figure 11):

This tab is where the simulation parameters are input including simulation cell size, downstream simulation distance in miles (defines computational domain) from the specified breach center, and simulation duration in days. The choice of simulation parameters can affect the simulation run time.

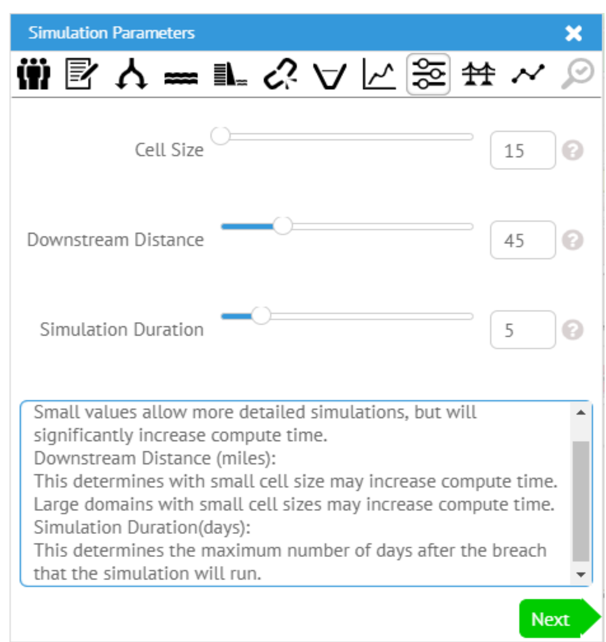


**Figure 11. Simulation Parameters Data Input Tab**

## Bridges (optional) (Figure 12):

The DSS-Wise model will run without the addition of Bridges. Defining bridges in the grid removes embankment artifacts from the DEM that could artificially constrict the floodplain. The bridge tab includes the center point of the dam (selected on the screen), span length of the bridge, and name of the structure. This creates a rectangular "block out" that will remove any obstructions below the clear span of the bridge from the DEM and interpolates the blocked-out area with information upstream and downstream of the bridge. Bridge data can be developed with information from the included National Bridge Inventory (NBI) data provided in DSS-WISE in absence of better information.

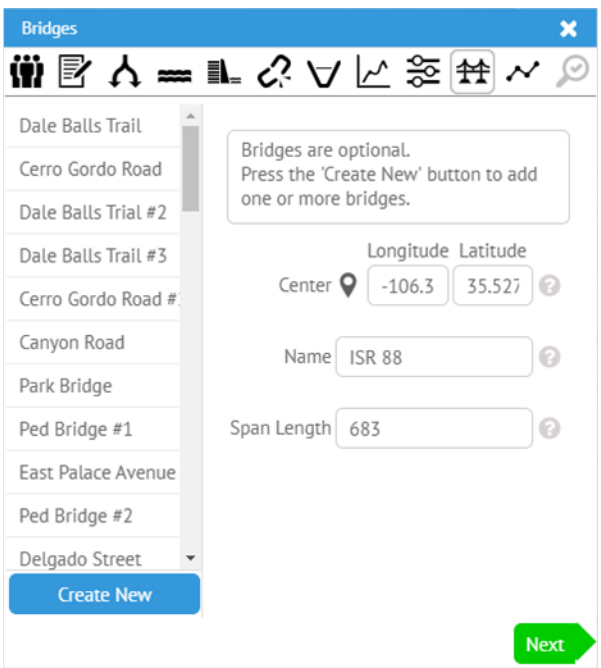


**Figure 12. Bridges Data Input Page**

## Observation Lines (optional) (Figure 13):

Observation lines are lines of interest where the user can extract the discharge hydrograph at critical cross sections. This information is essential in developing an EAP. The user can draw lines downstream of the dam where flow information is desired following the DSS-WISE convention. The convention for observation line development is if you were to stand on the first vertex and walk toward each successive vertex, the positive direction will be to your right. When drawing an observation line or dam crest line, a dashed line parallel to the solid line indicates the downstream, or "Q+" direction If you see the dashed line on the upstream side of the line you drew, there is a "flip line" button which will reverse it for you. A user can define a maximum of ten (10) observation lines for each DSS-WISE run.

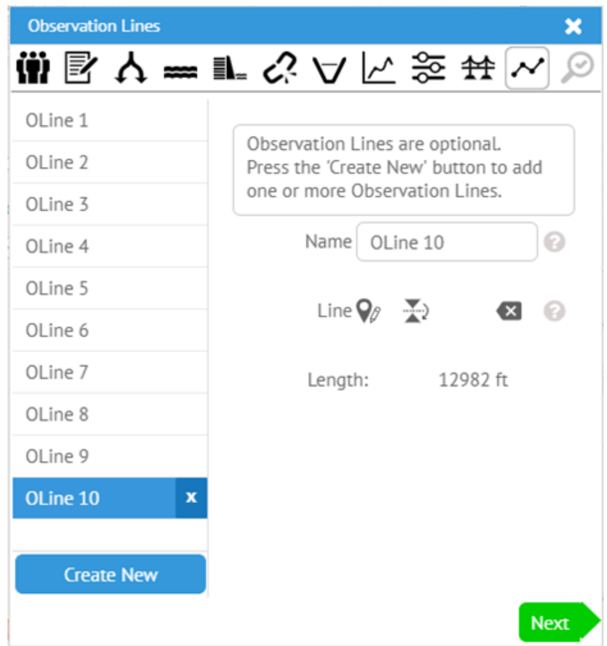


**Figure 13. Observation Lines Input Tab**

Uploading the simulation to the web servers for processing and development occurs after entering all the input data on each tab. The tool will let you know the number of simulations in the queue ahead of you and the approximate time for your model run as depicted on Figure 14.

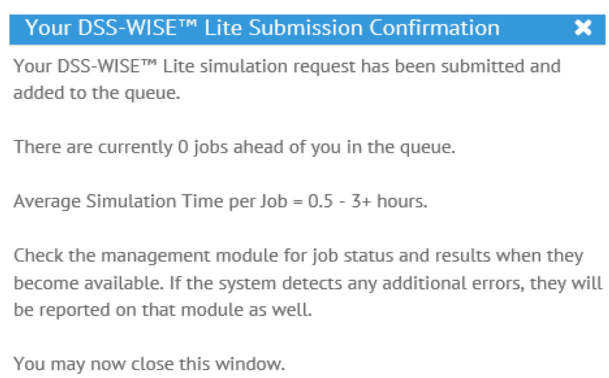


**Figure 14. DSS-WISE Run Window**

## Tips, Tricks, and Limitations

The DSS-WISE Tool employs several publicly available datasets to develop model input parameters. These datasets include Landsat and Landcover data, USGS DEMs, NBI, NID, and the USACE's National Levee Database (NLD). DSS-WISE uses this data behind the scenes to develop the modeling grid, stage/volume information, dam information and Manning's n value and typically does not need user intervention. The following describes the sources of publicly available data found in DSS-WISE.

As described above, the most recent release of DSS-WISE (October 9, 2019) incorporates the ability to sample hi-resolution DEM data provided by the USGS [16]. This new system is modular and future upgrades will include the ability to include group specific DEM data [13]. Currently available DEM datasets include:

- USGS 1-m Light Detection and Radar (LiDAR) based DEM
- USGS 1/9 arc-second DEM raster
- USGS 1/3 arc-second DEM raster
- USGS 1 arc-second DEM raster
- USGS 2 arc-second DEM raster

DSS-WISE develops Manning's n values for the modeling domain using the USGS National Land Cover Data (NLCD) set [11]. The most recent upgrade of DSS-WISE uses the recently released 2016 NLCD set [13]. Earlier versions of DSS-WISE have relied on the 2011 NLCD set. The user cannot change the predefined Manning's n values developed by DSS-WISE that are based on NLCD Classifications [12].

The current release of DSS-WISE limits the modeler to the DEM and land use information that is available in the USGS DEM data and the NLCD2016 data available for the region of interest. Thus, the user cannot interact or change the DEM to account for any irregularities. The limitations of the current DEM at some locations can cause problems with modeling of breach simulations for small dams. The application of a breach hydrograph simulation in place of a reservoir breach simulation bypasses this issue for small dams and reservoirs.

In some cases, the existing DEM surface that is available to DSS-WISE will not fully capture constructed channels or other natural features that may affect flooding. The user should recognize this limitation and where it occurs. Creation of unacceptable inundation or modeling results due to the limitations of the DSS-WISE input parameters, may lead the user to explore more detailed modeling platforms. However, experience from many state dam agencies shows DSS-WISE produces results that are much better than a "rough approximation." The results from DSS-WISE are extremely useful for inundation mapping for EAPs. The University of Mississippi is evaluating the addition of a way for the user to input his or her own model surface for simulation in the future.

There are also several tools built within DSS-WISE to help the user build and develop their model. The viewer and model development platform include several layers and overlays. The user can toggle these layers on and off including web based aerial imagery, open street maps, and elevation DEMs. In addition, there is an Elevation Profile Tool, depicted in Figure 15, that allows the user to develop a cross section that queries the underlying DEM data. The user should use the elevation profile tool during the development of the model to confirm DEM and NID information against as-built information and to assess the reasonability of dam break parameters and inundation results.

Finally, there is a Reservoir Elevation-Volume Tool. This tool provides the user with a back check of the stage-storage information coded into DSS-WISE as compared to as-built information for the dam and stage-storage data for the reservoir. Figure 16 depicts the information provided from the Reservoir Elevation-Volume Tool.

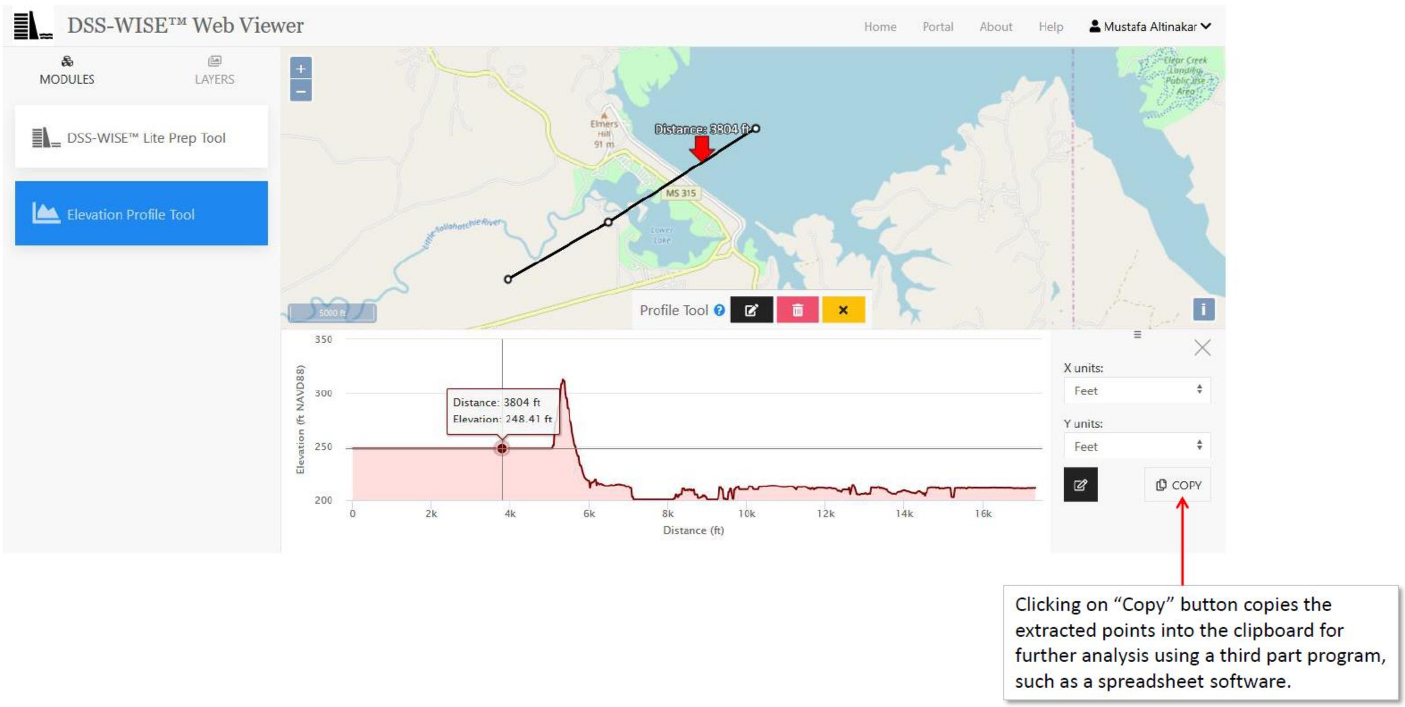


**Figure 15. Elevation Profile Tool [14]**

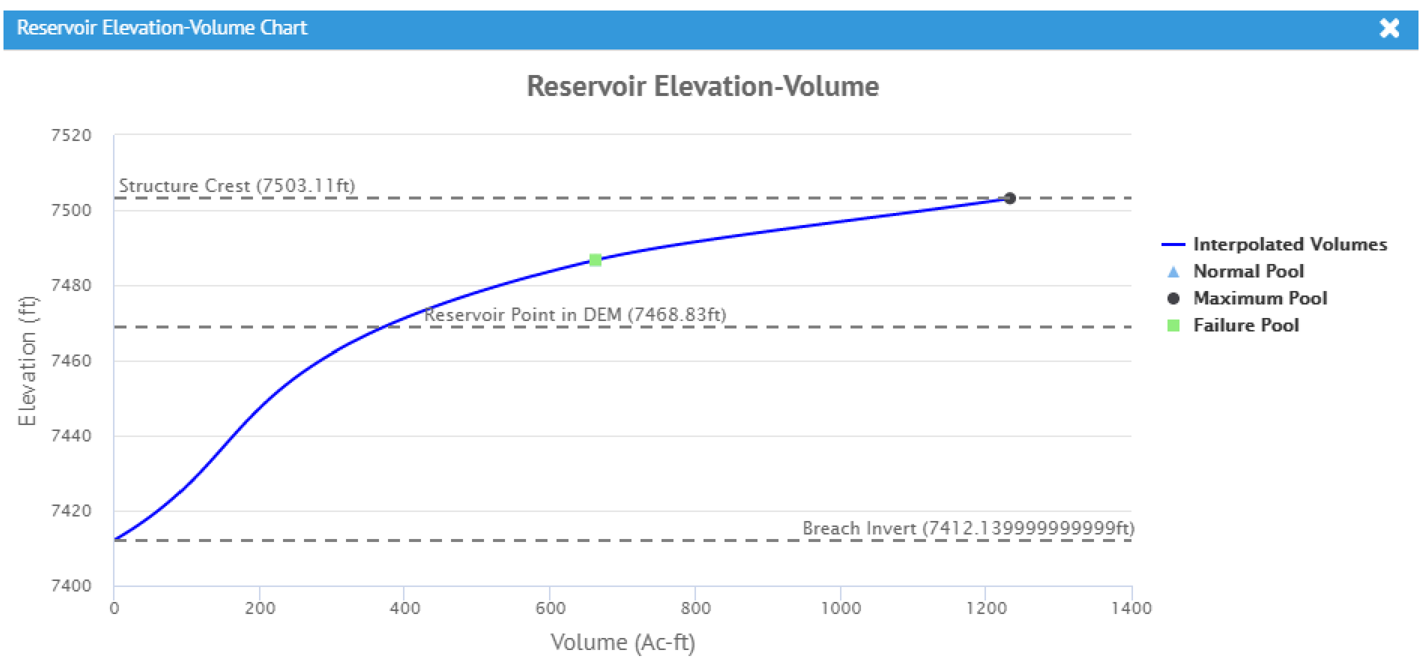


**Figure 16. Reservoir Elevation Volume Tool**

## What do I get after a DSS-WISE Run is Complete?

After the DSS-WISE simulation has completed, the tool produces several outputs in a zipped Simulation Results Package. Figure 17 below shows the results provided by the DSS-WISE Tool. These results supply a full description of the simulation including assumptions and runtime parameters, and GIS information to develop post-simulation figures and computations.

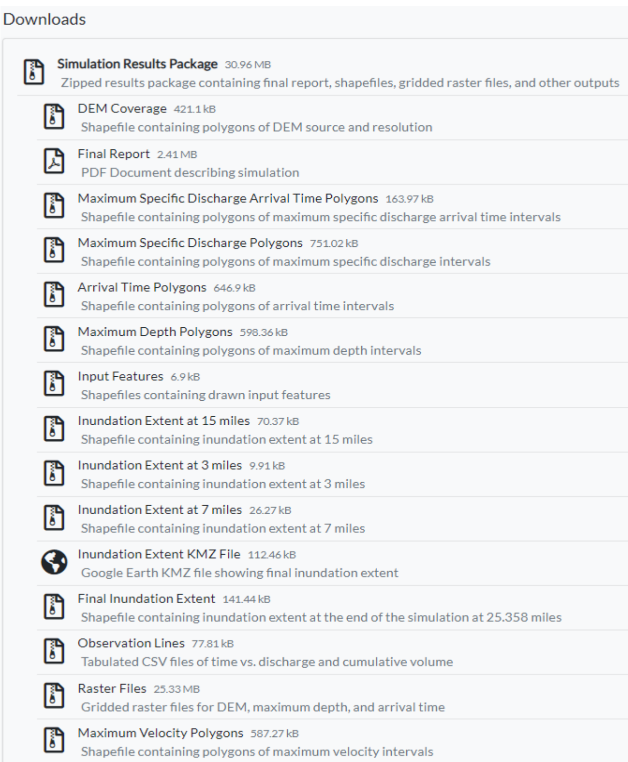


**Figure 17. DSS-WISE Output Information**

## How do I find the Human Impacts? Ask DSS-WISE HCOM.

HCOM is a post processing tool that can run after a DSS-WISE simulation has successfully run. HCOM assess downstream PAR (nighttime and daytime) and hazard potential. HCOM starts with a click of the button from the results screen and uses the output from DSS-WISE merged with publicly available information on census and population trends (daytime and nighttime). HCOM develops flood hazard maps for humans (but also indirectly for structures) and calculates the nighttime and daytime PAR counts to aid in emergency response and evacuation planning.

DSS-WISE HCOM computes the flood hazard risk by partitioning the inundation area into zones of pre-defined potential danger classes for humans. The resulting map generated by DSS-WISE includes polygon shapefiles of hazard and risk that any GIS supported program can open. The polygons correspond to distinct levels of potential danger for humans caught outdoors and indoors.

The potential danger classes are based on the ranges of the value of the maximum specific discharge, $qmax$, which is equivalent to the maximum value of the product of depth and velocity, $DVmax$ [14].

The hazard levels for humans caught outdoors as adapted from (Cox, Shand, & Blacka, 2010) defines the potential flood hazard levels for humans in DSS-WISE. Figure 18 defines these hazard classifications. For humans who are indoors during the flood, DSS-WISE assumes that the potential danger is associated with the collapse of the building [3].

**Table 2. Potential flood hazard levels for humans caught outdoors by the flood (adapted from Cox et al. 2010).**

| $DV_{max}$ | | | | Potential Hazard Category | Explanation | | |
|---|---|---|---|---|---|---|---|
| $m^2/s$ | | $ft^2/s$ | | | Adults | Children | Infants, Small Children and Frail/Older Persons |
| from | to | from | to | | | | |
| 0.0 | 0.4 | 0.0 | 4.3 | HZ01 Very Low Hazard: Shallow flow or deep standing water | Low Hazard | Low Hazard | Extreme Hazard Dangerous to all Infants, small Children and Frail/Older Persons |
| 0.4 | 0.6 | 4.3 | 6.5 | HZ02 Low Hazard: Dangerous to Children | | Significant Hazard; Dangerous to most Children | |
| 0.6 | 0.8(2) | 6.5 | 8.6(2) | HZ03 Moderate Hazard: Dangerous to some adults | Moderate Hazard: Dangerous to some adults | | |
| 0.8 | 1.2(3) | 8.6 | 13(3) | HZ04 Significant Hazard: Dangerous to most adults | Significant Hazard: Dangerous to most adults | Extreme Hazard: Dangerous to all children | |
| 1.2(3) | | 13(3) | | HZ05 Extreme Hazard: Dangerous to all | Extreme Hazard: Dangerous to all | | |

1) Small children, children and adult categories are defined based on $height(H) \times mass(M)$
Small children: $H \times M \leq 25l(m.kg.)$ $H \times M \leq 181(ft.lb.)$
Children: $25 < H \times M(m.kg.) \leq 50$ $181 < H \times M(m.kg.) \leq 362$
Adult: $50 < H \times M(m.kg.)$ $362 < H \times M(ft.lb.)$

2) Recommended upper limit of tolerable working flow regime for trained safety workers or experience and well-equipped persons

3) Above this value, the hazard is extreme according to majority of the past studies.

**Figure 18. Potential Flood Hazard Levels for Humans for DSS-WISE [2]**

The approach neglects the potential of drowning in the structure and only the collapse of the building defines the human life hazard. Thus, the user can evaluate potential structural damage in the flood hazard area by using the map of potential flood hazard for people caught indoors [14]. Figure 19 depicts the $DVmax$ used by DSS-WISE in calculating the potential collapse of different buildings [1].

| Building Type | $q_{max} \equiv DV_{max}$ ($m^2/s$) | ($ft^2/s$) |
|---|---|---|
| Poorly Constructed Building | 5 | 54 |
| Well Built Timber Building | 10 | 108 |
| Well Built Masonry Building | 15 | 162 |
| Concrete Building | 20 | 215 |
| Large Concrete Building | 35 | 377 |

**Figure 19. $DVmax$ for Evaluation of Potential Structural Damage [1]**

Finally, DSS-WISE creates mapping of potentially lethal flood zones (PLFZs) for humans, developing polygons that include pre-defined potential lethality classes for children and adults. The maximum depth, $hmax \equiv Dmax$, and maximum specific discharge, $qmax \equiv DVmax$ defines the distinct levels of potential lethality that stored in the resultant polygon shape files [14].

Figure 20 shows the definition of PLFZs for distinct categories of people caught outdoors, or inside cars, mobile homes, and typical residential structures [4]. The results produced by DSS-WISE Lite can be used to produce other PLFZ maps for these categories on a GIS software.

Table 4. Definition of potentially lethal flood zones (PLFZs) for different categories (Feinberg, 2017).

| Category | Color Code | $D_{max}$ $(ft.)$ | | $DV_{max}$ $(ft^2/s)$ |
|---|---|---|---|---|
| Children caught outdoors (tent camping, fishing, hiking, etc.) | | ≥2 | or | ≥5.4 |
| Adults caught outdoors (tent camping, fishing, hiking, etc.) | | ≥4 | or | ≥6.5 |
| Motor vehicle (compact car) floating | None | ≥1 | or | ≥4.3 |
| Motor vehicle (compact car) sliding/toppling | None | | | ≥5.4 |
| Mobile homes | None | ≥2 | or | ≥30 |
| Typical residential structures | None | ≥4 | or | ≥75 |

**Figure 20. Definition of potentially Lethal Flood Zones (PLFZs)**

A downloadable zipped Simulation Results Package holds the outputs from the HCOM tool. After the HCOM has completed running, DSS-WISE displays a summary of HCOM calculations as shown on Figure 21.

Human Consequences: Finished
Sep 19, 2019 10:23:33 am 31 mins

| | |
|---|---|
| Nighttime PAR: | 3,449 |
| Daytime PAR: | 10,874 |
| Inundated Area: | 2,361 acres |
| New Mexico counties: | 2 |

**Figure 21. DSS-WISE HCOM Output Summary**

Figure 22 depicts the files developed by HCOM. These results supply a full description of the simulation including assumptions, runtime parameters, and GIS information.

Human Consequences Results Package 3.62 MB
Zipped results package containing final report, shapefiles, gridded raster files, and other outputs

HCOM PAR Analysis Results 88.21 kB
MS Excel spreadsheet containing tabulated results of population at risk analysis

HCOM PAR by Census Blocks 361.17 kB
Shapefile containing polygons of census blocks in the inundation extent

HCOM Daytime Population Density 15.91 kB
Shapefile containing polygons of daytime population density derived from LANDSCAN data

HCOM Final Report 4.1 MB
PDF Document describing the results of this HCOM calculation

HCOM Hazard Level to People Indoors 47.74 kB
Shapefile containing polygons of hazard levels to people caught indoors in the flooded extent

HCOM Nighttime Population Density 14.14 kB
Shapefile containing polygons of nighttime population density derived from LANDSCAN data

HCOM Hazard Level to People Outdoors 427.91 kB
Shapefile containing polygons of hazard levels to people caught outdoors in the flooded extent

HCOM Potentially Lethal Flood Zones 146.75 kB
Shapefile containing polygons of flood zones potentially lethal to adults and children

**Figure 22. Output files from DSS-WISE HCOM**

## Conclusion

DSS-WISE is a simplified inundation mapping tool with minimal input parameters to estimate downstream flooding and consequence parameters. DSS-Wise is a Tier 1, or a Preliminary Risk Assessment dam breach simulation model, provided by FEMA free of charge, as a tool to help state dam safety programs and the dam safety community in understanding the potential risk of dams.

This powerful tool can provide a rapid analysis of breach simulations that can serve as a check of more detailed analyses, to understand the potential benefits of reservoir upgrades or, in many cases, to produce an inundation map and Human Consequences mapping for an Emergency Action Plan.

This flexible tool is not right for analysis of small dams that are not well defined within the limitations of the underlying DEM grid. However, this amazing tool should be in every dam safety toolbox to help in dam breach flood mapping and evaluation to minimize damage and loss of human life in the United States. Consult with your local dam safety program for access and guidance.

## References

[1] BCH. (2006). Life Safety Model system V 1.0, Guidelines, Procedures, Calibration and Support Manual. Technical Report. Engineering Report E310. British Columbia: British Columbia Hydro (BCH).
[2] Cox, R. J., Shand, T. D., & Blacka, M. J. (2010). Australian Rainfall and Runoff, Revision Project 10: Appropriate Criteria for People. AR&R Report Number P10/S1/006. Engineers Australia, Water Engineering: ISBN 978-085825-9454. Retrieved from arr.ga.gov.au/arr-guideline/revision-projects/project-list/projects/project-10
[3] DHS. (2011). Dams Sector: Estimating Loss of Life for Dam Failure Scenarios. Washington D.C.: U.S. Department of Homeland Security.
[4] Feinberg, B. (2017). Using Potentially Lethal Flood Zones to Assess Downstream Impacts from Dam Failure. Presentation at National Dam Safety Training Seminar.
[5] FEMA. (2018a). DSS-WISE™ Lite: Flood Modeling and Simulation Capability Enhancements for Dams. (FEMA, Ed.) Retrieved from Federal Emergency Management Agency Media Library
[6] FEMA. (2018b). DSS-WISE™ Lite: Web-based Automated Dam-Break Modeling/Mapping. Retrieved from Federal Emergency Management Agency Media Library
[7] Froehlich, D. C. (1995a). Peak Outflow from Breached Embankment Dam. Journal of Water Resources Planning and Management, 121(1), 90-97.
[8] Froehlich, D. C. (1995b). Embankment Dam Breach Parameters Revisited. 1995 ASCE Conference on Water Resources Engineering (pp. 887-891). New York: ASCE.
[9] Froehlich, D. C. (2008). Embankment Dam Breach Parameters and Their Uncertainties. Journal of Hydraulic Engineering, 134(12), 1708-1720.
[10] MacDonald, T. C., & Langridge-Monopolis, J. (1984). Breaching Characteristics of Dam Failures. Journal of Hydraulic Engineering, 110(5), 567-586.
[11] MRLC. (2019a). National Land Cover Data Site. (MRLC) Retrieved from Multi-Resolution Land Characteristic Consortium
[12] MRLC. (2019b). National Land Cover Database 2016 (NLCD2016) Legend. (MRLC) Retrieved from Multi-Resolution Land Characteristics Consortium
[13] NCCHE. (2019a). New Major Release with High Resolution DEM Capability. (M. Altinakar, Ed.) Retrieved from DSS-WISE™ Web Documentation
[14] NCCHE. (2019b). ASDSO 2019 Conference Orlando Short Course Materials. (M. Altinakar, Ed.) Retrieved from DSS-WISE™ Web Documentation
[15] USACE. (2019). U.S. Army Corps of Engineers National Inventory of Dams. (USACE, Editor, USACE, Producer, & USACE) Retrieved from National Inventory of Dams Interactive Map & Charts
[16] USGS. (2019). National Geospatial Program. Retrieved from National Geospatial Program
[17] Von Thun, J. L., & Gillette, D. R. (1990). Guidance on Breach Parameters, Unpublished Internal Document. Denver: U.S. Bureau of Reclamation.

# A Tool for Every Job:
## Statewide Probable Maximum and Extreme Precipitation Estimation

*By: Hayden LoSasso, EI; Erik Sutherland, EI; Chad Vensel, PE*

## Introduction

Have you ever toiled over a Hydrometeorological Report (HMR) to estimate probable maximum precipitation (PMP) depths only to wonder: "Isn't there a better way?" Well friends, there is a better way – for some locations, at least. Since about 2008, states across the country have been completing statewide PMP studies and developing associated PMP Tools [1]. These updated studies and tools represent significant advancements and refinements in PMP estimation and are critically important to the dam safety community, which rely on these data to develop inflow design floods (IDFs) as part of the design, assessment, and regulation of new and existing dams.

This article focuses on these updated PMP studies, their associated PMP Tools, and comparisons between PMP estimates based on historical (i.e., HMRs) and PMP Tool methodologies. Although, PMP studies across the country are discussed, this article focuses on the Western States (i.e., Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming).

## A Quick Review of the PMP and Historical Estimation Methodologies

The IDF and design precipitation were discussed in Volume 1, Issue 3 of the Western Dams Engineering Technical Note series article "When it Rains Does it Pour? Design Precipitation Depths for Dam Safety" [14]. Let's quickly refresh and expand upon some of the key points of this previous article.

As defined in the HMRs, the PMP 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." The PMP is generally developed using a "storm based" approach, which includes identification of extreme precipitation events that have occurred in regions of similar geographic and meteorological characteristics to a given location of interest. Detailed evaluation of these storms allows for transposition of precipitation from the original location to the location of interest. The deterministic storm based PMP is developed through the examination, maximization, and transposition of these historic extreme storms.

PMP estimates have historically been derived from the HMRs, which were first developed by the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) in the late 1930s and last updated in the 1990s [13]. Figure 1 presents the delineations and applicability of various HMRs to locations across the United States. In general, HMRs 49, 51, 52, 53, 55a, and 57 are applicable to the Western States. HMRs provided reasonable PMP estimates in their time but have since become increasingly outdated and NOAA does not currently have a plan, mandate, or the funding to update the HMRs.

As an alternative to the HMRs, site-specific and statewide PMP studies have been completed at various locations since the 1980s. These site-specific studies include updated extreme storm data, updated climatologies used to adjust storms, more detailed evaluations of site-specific characteristics and features and, in some cases, they provide significantly different PMP estimations for a given location than those of the HMRs.

## Why PMP Tools?

In the two decades since the last HMR update, scientific advances and increases in computing power have enabled public sector scientist's, mathematicians, and engineers to make improvements in the methodologies of extreme rainfall estimation. With dam overtopping due to inadequate spillway capacity being a high probability failure mode, spillways are the most critical appurtenance related to risk and public safety of dams. Spillways are also one of the most expensive construction elements on a dam. State of the practice precipitation estimation methodologies provided by site-specific, statewide or regional studies provide confidence to regulators and dam owners alike that safety is being adequately addressed in the most scientifically justifiable and economically feasible means possible.

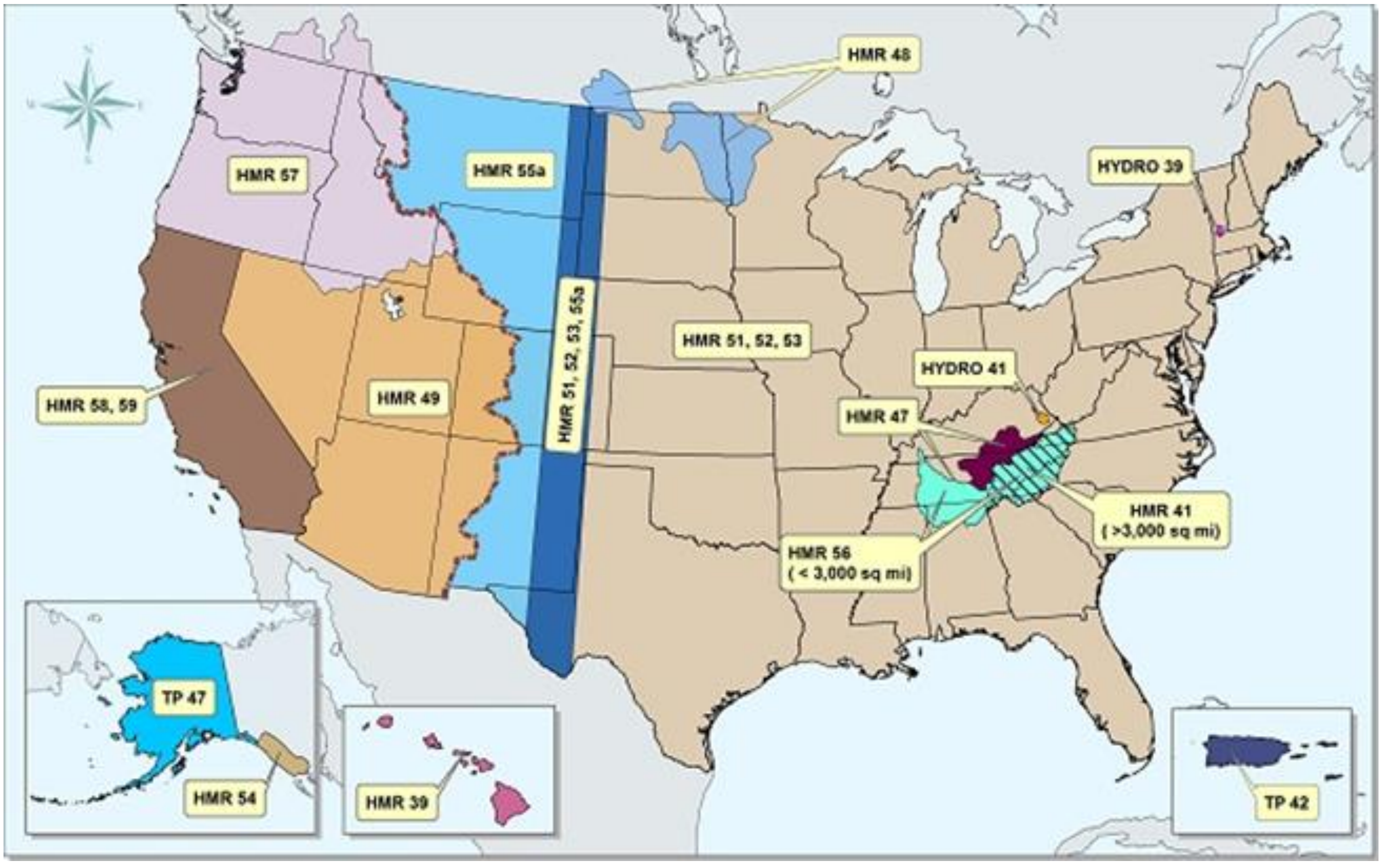


Figure 1. **National Weather Service HMR Region Map** (https://www.nws.noaa.gov/oh/hdsc/studies/pmp.html)

As discussed further in this article, HMR based PMP estimates have been shown to vary significantly from those of site-specific and statewide studies. Consequently, there have been numerous cases where necessary dam safety modifications were identified based on an IDF using HMR PMP estimates, but after estimation of site-specific/statewide PMPs, it was determined that the size, scale, and scope of the modifications could be reduced (or expanded).

Site-specific PMP studies are currently the most robust and comprehensive means to estimate the PMP. Fortunately, with the increase in computing power and use of geographical information systems (GIS), statewide PMP Tools using the same methodologies as a site-specific study, but covering a wider (i.e., state) domain, produce similar results. Statewide PMP Tools provide advantages over HMR and site-specific based PMP estimation methodologies including:

- The ease of use of statewide tools enables regulators and engineers to generate PMP estimates in a matter of minutes and hours rather than hours and days (i.e., HMR based estimates) or weeks and months (i.e., site-specific study-based estimates);
- The cost to generate PMP estimates is substantially less than HMR and site-specific study methodologies;
- The flexibility to add future extreme precipitation events to regional storm databases and corresponding PMP estimates, thereby, maintaining the relevance of the PMP studies through time;
- An additional approximately 20 to 40 years of storm data, including more robust and comprehensive data sets;
- Advancements in the science of individual storm grouping (i.e., storm-typing) into local storms, mesoscale storms with embedded convection (MEC), mid-latitude cyclones (MLC) and tropical storms remnants (TSR);
- Site-specific characteristics and features (e.g., elevation, orography, etc.);

- Use of familiar methodologies similar to those of HMR and site-specific studies, but builds on these methodologies by implementing state of the practice understanding;
- Updated, high resolution areal reduction factors and temporal and spatial distributions;
- Consistency and continuity of PMP estimates at a given location and time, across a given state PMP Tool domain, and neighboring state PMP Tool domains;
- PMP tool output provides thorough documentation of storm data including adjustment factors, allowing for greater understanding of controlling events and final results; and
- Independent expert reviews and beta testing have been completed. This allows for modern PMP Tools to be widely accepted across the various dam regulatory agencies.

## Who Has PMP Tools?

Currently eight states have completed statewide PMP studies (refer to Figure 2) that are publicly available: Arizona [2], Colorado [3], Nebraska [6], New Mexico [7], Ohio [8], Texas [9], Virginia [11], and Wyoming [12]. Another five states have completed studies that are not yet publicly available, but will be soon: Pennsylvania, Oklahoma, Arkansas, Louisiana, and Mississippi. Additionally, North Dakota is currently in the process of conducting their own statewide PMP study.

The PMP studies for these states provide a GIS based tool to generate PMP estimates. The exceptions are Nebraska and Ohio, whose statewide studies do not include a GIS PMP tool and some additional analysis is necessary to develop PMP estimates for a given location.

It should be noted that Utah has not completed a statewide PMP study but has developed updated guidance for PMP estimation using HMR 49 [10]. Montana continues to use the HMRs without correction/modification, but incorporates a risk based decision process for selecting IDFs.

## How Do PMP Tools Work?

Statewide PMP Tools are GIS based applications that query geodatabases created through detailed storm analyses conducted on a grid of the study area. Depth-area-duration (DAD) tables are generated in the analysis as are adjustments factors for maximization, transposition and geography. The data are output to gridded points within the study domain via a GIS interface and PYTHON script to transpose, maximize, and adjust historical storms to the user defined basin. The processes by which PMP data are developed provide consistent and reproducible results.

The PMP Tools can be easily accessed and downloaded from the respective state's website and locally saved to a location that can be accessed by ArcMap desktop. The PMP Tools contain a series of geodatabase files used in PMP development: the storm depth-area-duration tables, storm adjustment tables, temporal distributions, and a storm list. The process to obtain PMP estimates using a PMP Tool is simple and user-friendly:

1) Open the PMP Tool script in ArcMap.
2) Select a basin shapefile/feature class to outline the area of interest. The shapefile must have a compatible surface map projection for the Arizona and Wyoming PMP Tools.
3) Select the desired storm types and durations and verify that they are appropriate for the drainage area of the input basin – larger basins may need to be sub-divided to accommodate shorter duration, smaller area local storms.
4) Adjust other available user options, as desired, or adopt default settings (i.e., PMP area, border weighted average, sub-basin averages, etc.)
5) Run the PMP Tool.
6) Output data is stored in a geodatabase. Output files can be opened, viewed, and copied from ArcMap.

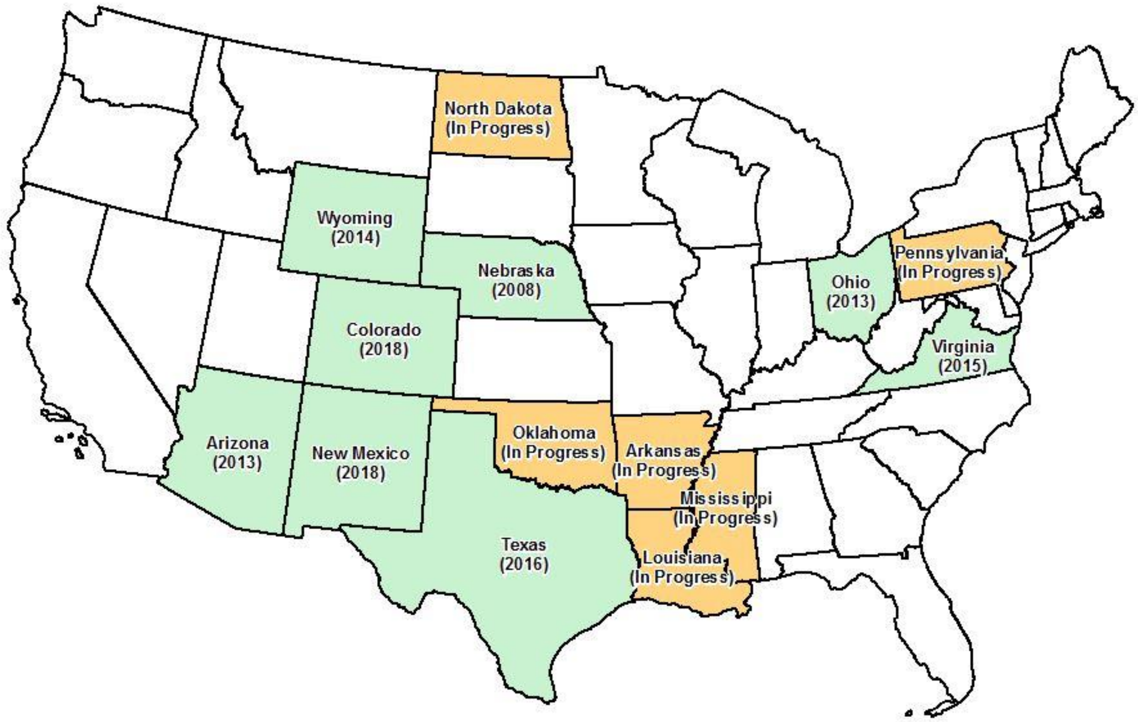


**Figure 2**. **Statewide PMP Studies and Year Completed (all statewide studies have been completed by Applied Weather Associates)**

Output files depend on which state PMP Tool is being used, but generally include PMP depth rasters, basin/sub-basin precipitation depth tables, temporal distribution tables, and a grid centroid point file (containing grid ID, latitude, longitude, analysis zone, elevation, PMP depth durations, and the contributing storm ID). An example output displaying basin shapefile, grid centroids, and PMP depth raster is presented on Figure 3. A summary comparison of input and output data for the Western States PMP Tools is presented in Table 1.

Run times vary based on computer processing, basin size, and storm selections, but generally vary from a few minutes to a few hours.

The ease and usability of these PMP Tools continues to advance significantly. During each subsequent statewide study, PMP tools are updated and improved with more user-friendly input/output processes and ease-of-use advancements. However, GIS software version control has become an issue for the older statewide studies and will continue to be problematic as new states are completed. In addition, as each statewide study is completed, new types of output are developed that may not have been included in older versions (e.g. Table 1).

To overcome this, Applied Weather Associates (AWA) has teamed with several of the states to develop a single web interface, the AWA PMP Portal, which will provide PMP Tool output through the cloud via web interface. This will allow users to obtain basin PMP without the use of ArcGIS Desktop, preventing version and compatibility issues and significantly increasing ease-of-use. GIS output files will still be available through the web interface. Changes to PMP, based on storm database updates or additions, will be universally available to all users. The AWA PMP Portal is currently in development and expected to be available to users starting in 2020.

## PMP Estimation Comparisons

The statewide PMP studies revised and refined several PMP estimation methodologies and factors used by the HMRs. This makes direct PMP estimate comparisons difficult. However, general trends are highlighted and described in greater detail below.

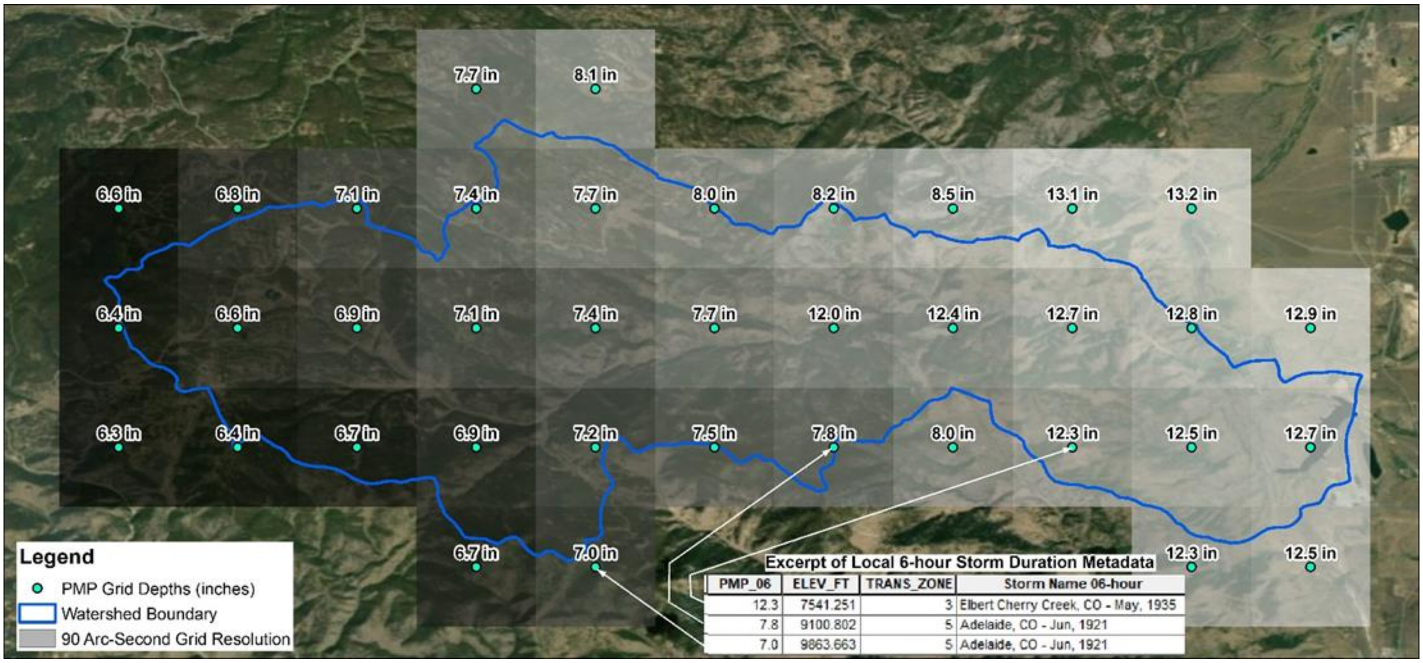


**Figure 3. Hour General Storm Gridded PMP Basin Example (Note variation in precipitation depth across watershed and with elevation)**

**Table 1. Western States PMP Tool Comparisons**

| | Input | Output | Grid Resolution | Temporal Distribution |
|---|---|---|---|---|
| **Arizona** | Drainage Basin Shapefile (ArcMap v10.0 or later) | PMP Grid Point Estimates, Basin Average Depths | 90 Arc-Seconds | General Frontal, Tropical, and Local Storm (Provided in tool output) |
| **Colorado - New Mexico** | Drainage Basin Shapefile (ArcMap 10.4 or later) | PMP Grid Point Estimates, Basin Average Depths, & Sub-basin Average Depths | 90 Arc-Seconds | Local, General, and Hybrid for East and West of Continental Divide (Provided in tool output) |
| **Wyoming** | Drainage Basin Shapefile (ArcMap v10.2 or later) | PMP Grid Point Estimates, (Manual basin average calculation required) | 90 Arc-Seconds | Local, General, and Hybrid for East and West of Continental Divide (Requires manual development using separate documentation) |

## General Trends

The HMR studies were conducted on large scale and regional areas, whereas, statewide PMP studies are conducted on smaller scale grids that can capture natural meteorological variabilities due to terrain and elevation changes occurring over short distances. As such, the statewide PMP estimates result in a wide range of both reductions and increases as compared to HMR estimates. Whether or not the PMP estimates increase or decrease at a given location is interesting but should not be the goal of a statewide or regional study. The impetuous for conducting a study and producing PMP tools for the 21st century is to provide scientifically defensible results founded on state of the practice methodologies.

For both local and general storms, HMR 55a PMP estimates tend to be greater than statewide PMP estimates, especially in regions with high elevations and protected interior valleys. The greater HMR 55a estimates are also reflected in the differences between it and HMR 57, where the difference between two adjacent points of the two study domains has been found to be greater than 50 percent. Such differences are not encountered using the statewide PMP methodologies.

The HMR 51 PMP estimates also tend to be greater than statewide PMP estimates for both the local and general storms.

Conversely, HMR 49 PMP estimates have been found to be both greater and lesser than statewide PMP estimates. However, HMR 49 PMP estimates generally tend to be lesser than statewide PMP estimates, especially for the general storm. This trend was likely attributable to the lack of general storm data used in HMR 49, which included a total of only five general storms to define the PMP across the entire study domain.

It should be noted that study locations within these regions may produce results that are inconsistent with the general trends discussed above and that temporal accumulation patterns also have a significant impact on final flood runoff characteristics. Statewide PMP studies provide updated temporal accumulation patterns by storm type and region and for durations from 5-minutes through several hours. This is another significant improvement from data provided in the HMRs.

## Arizona

HMR 49 covers the entire state of Arizona and is the oldest "current" HMR (last published/updated in 1977) applicable to the Western States.

General comparison trends between HMR 49 and the Arizona statewide PMP study (completed in 2013), for a 10 square mile watershed, indicate:

- Based on evaluation of 38 locations in the HMR 49 domain:
    - Of 6-hour local storm PMP estimates, 26 were reduced by an average of 20 percent and 10 of the estimates were increased by an average of 17 percent based on the statewide PMP estimates; and
    - The 24-hour general storm PMP estimates were reduced by an average of 56 percent based on the statewide PMP estimates.

## Colorado-New Mexico

The majority of Colorado and New Mexico are covered by HMR 55a (last published/updated in 1988) with areas west of the Continental Divide covered by HMR 49 and some of the eastern plains covered by HMR 51 (last published/updated in 1978).

General comparison trends between HMRs 49, 51, and 55a and the Colorado statewide PMP study (completed in 2018), for a 10 square mile watershed, indicate:

- Based on evaluation of nine locations in the HMR 55a domain:
    - The 6-hour local storm PMP estimates were reduced by an average of 23 percent based on the statewide PMP estimates; and
    - The 72-hour general storm PMP estimates were reduced by an average of 44 percent based on the statewide PMP estimates.
- Based on evaluation of 27 locations in the HMR 49 domain:
    - Of the 6-hour local storm PMP estimates, 16 were reduced by an average of 19 percent and 11 of the estimates were increased by an average of 16 percent based on the statewide PMP estimates; and
    - Of the 24-hour general storm PMP estimates, 21 were reduced by an average of 21 percent, 3 of the estimates were increased by an average of 5 percent, and 3 of the estimates remained the same based on the statewide PMP estimates.
- Based on evaluation of locations in the HMR 51 domain:
    - The 6-hour local storm PMP estimates were reduced by an average of 22 percent based on the statewide PMP estimates; and

- The 72-hour general storm PMP estimates were reduced an average of 39 percent based on the statewide PMP estimates.

## Wyoming

The majority of Wyoming is covered by HMR 55a with areas west of the Continental Divide covered by HMR 49 and HMR 57 (last published/updated in 1994) and some of the eastern plains covered by HMR 51.

General comparison trends between HMRs 49, 51, 55a, and 57 and the Wyoming statewide PMP study (completed in 2014) estimates indicate:

- Wyoming was particularly susceptible to HMR inconsistencies where some watersheds were covered by 3 different HMRs producing vastly different PMP estimates;
- Based on evaluation of 13 locations in the HMR 55a domain:
  - The 1-hour (1 square mile) local storm PMP estimates were reduced by an average of 46 percent based on the statewide PMP estimates; and
  - The 24-hour (10-square miles) general storm PMP estimates were reduced an average of 43 percent based on the statewide PMP estimates.
- Based on evaluation of 3 locations in the HMR 49 domain:
  - The 1-hour (1 square mile) local storm PMP estimates were reduced by an average of 12 percent based on the statewide PMP estimates; and
  - The 24-hour (10 square miles) general storm PMP estimates were increased by an average of 34 percent based on the statewide PMP estimates.
- Based on evaluation of 2 locations in the HMR 57 domain:
  - Of the 1-hour (1 square mile) local storm PMP estimates, 1 was reduced by 17 percent and 1 was increased by 29 percent based on the statewide PMP estimates; and
  - The 24-hour (10 square miles) general storm PMP estimates were increased an average of 16 percent based on the statewide PMP estimates.

## Utah

Utah is predominantly covered by HMR 49 with a small area covered by HMR 57 in the most northwest corner of the state. Utah developed updated guidance for local storm PMP estimation using HMR 49 in 1995. In 2002-2003 updated guidance for general storm PMP estimation was developed. The revised guidance includes refinements generally consistent with those of other statewide PMP studies and generally results in PMP estimates less than those estimated using HMR 49 alone. Currently, these methodologies are under review by the state climatologist to provide recommendations for updating and revising PMP estimation in the state.

## Other States with Statewide PMP Studies

Other states with completed statewide PMP studies include Nebraska, Ohio, Virginia, and Texas, which are all predominantly covered by HMR 51. The western portions of Nebraska and Texas are covered by HMR 55a. General trend comparisons across these states indicate reductions in both local and general storm PMP estimates based on the use of statewide PMP studies. Reduction percentages vary by state but are generally greater than about 15 percent and less than about 40 percent.

# Precipitation-Frequency Tools

Precipitation frequency estimates are used to support PMP development for regional studies and evaluations associated with extreme precipitation events (e.g., risk assessments). NOAA Atlas 14 data can be used in support of some of these types of assessments, but additional analysis is often required to develop updated and more refined data sets.

The Colorado-New Mexico Regional Extreme Precipitation Study (REPS) included development of regional precipitation frequency estimates for extreme precipitation [3]. This study provides an independent check of deterministically derived PMP estimates and also forms the basis for probabilistic risk analysis studies. A precipitation frequency tool (PF Tool) was developed to capture the results of this study.

The PF Tool runs on a web-based server called MetPortal [4]. Similar to the PMP Tool, input data requirements for the PF Tool include a basin shapefile or point coordinates (in the WGS84 geographic coordination system). Output data includes depth-duration relationships for AEPs ranging from 1 in 10 to 1 in 10,000,000 with 90 percent confidence bounds.

The estimation of extreme precipitation at infrequent probabilities of occurrence is an important advancement in the progression of dam safety evaluations. On this basis, the PF Tool results can be used to estimate the AEP of the PMP to support risk-based decision making (RIDM) for dam safety evaluations. However, it is good practice to exercise caution and evaluate sensitivity when assigning an AEP to the PMP.

## Conclusion

Advancements and refinements in extreme precipitation (e.g., PMP, etc.) understanding and estimation have shown that historical and outdated methodologies (e.g., HMRs) are no longer adequate or consistent with the current state of the practice. Statewide PMP and extreme precipitation studies and their associated estimation tools are valuable additions to the dam engineer's toolbox. These tools can be used by dam safety practitioners across the community to quickly and easily develop an estimate of extreme precipitation consistent with current state of the practice and an associated understanding of hydrologic regulatory conformance and risk.

Many statewide studies have indicated reductions in PMP estimates as compared to associated HMR PMP estimations. This could be beneficial to owners of new or existing dams. However, increases in PMP estimations have also been noted in some locations (e.g., locations within the HMR 49 study domain). Regardless of whether PMP estimates increase or decrease, the key point is that the tools described herein represent state of the science methodologies and are defensible from a public safety standpoint and economically justifiable for engineers and dam owners.

So, wonder no more friends – statewide studies and their associated tools are here to stay and provide a better way to estimate extreme precipitation. If they aren't already available in your state, they're likely coming soon, so stay tuned…

## References

[1] Applied Weather Associates (AWA), Probable Maximum Precipitation Studies. http://www.appliedweatherassociates.com/
[2] Arizona Department of Water Resources, Dam Safety, https://new.azwater.gov/dam-safety/
[3] Colorado Division of Water Resources, Department of Natural Resources,http://water.state.co.us/damsafety/dams.asp
[4] MetStat, Inc., MetPortal CO-NM Precipitation Frequency, 2018. https://conm-reps-gui.shinyapps.io/metportal/
[5] The Montana Department of Natural Resources & Conservation, http://dnrc.mt.gov/divisions/water/operations/dam-safety
[6] Nebraska Department of Natural Resources, https://dnr.nebraska.gov/dam-safety/
[7] New Mexico Office of the State Engineer, Dam Safety Bureau, http://www.ose.state.nm.us/dams/conmpf.php
[8] Ohio Department of Natural Resources, http://water.ohiodnr.gov/safety/dam-safety#ADD
[9] Texas Commission on Environmental Quality, Dam Safety Program, https://www.tceq.texas.gov/compliance/investigation/damsafetyprog.html
[10] Utah Division of Water Rights, Dam Safety, https://www.waterrights.utah.gov/daminfo/default.asp
[11] Virginia Department of Conservation and Recreation, Dam Safety and Floodplains, https://www.dcr.virginia.gov/dam-safety-and-floodplains/pmp-tool
[12] Wyoming State Engineer's Office, Safety of Dams, https://sites.google.com/a/wyo.gov/seo/surface-water/safety-of-dams
[13] National Weather Service (NWS). Probable Maximum Precipitation (PMP) Documents, https://www.nws.noaa.gov/oh/hdsc/studies/pmp.html
[14] Western Dam Engineering Technical Note. Volume 1, Issue 3, "When it Rains Does it Pour? Design Precipitation Depths for Dam Safety," 2013.