State of Colorado

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

GUIDELINES FOR HYDROLOGIC HAZARD ANALYSIS

Revision Date: January 21, 2020

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Section 1. **Background**

1.1 The 2020 Colorado *Dam Safety Rules and Regulations for Dam Safety and Dam Construction* (2020 Rules) change the basis of spillway sizing from Sunny Day Hazard and Dam Size (2007 Rules) to Hydrologic Hazard, which is defined as follows:

1.1.1 Hydrologic Hazard. Potential consequences downstream of a dam caused by floodwaters released by overtopping failure of the dam. Hydrologic Hazard establishes design criteria for spillway size.

1.1.2 Hydrologic Hazard will be interpreted by the State Engineer's Office to be applicable to all plausible hydrologic failure modes, and shall be used to establish Inflow Design Flood (IDF) criteria for spillway size, spillway hydraulics, and other features associated with hydrologic loading.

1.2 The reasons for the change to Hydrologic Hazard are as follows:

1.2.1 The principle determinant of spillway sizing criteria and related design features for dam safety should be the consequences that would occur if a dam fails during a hydrologic event.

1.2.2 The 2007 Rules used fractions of probable maximum precipitation (PMP) for the IDF based on sunny day hazard and dam size. Fractions of PMP were intended to represent a sliding risk scale. Sunny day hazard and dam size were surrogates for hydrologic hazard because the former were readily available data. Generally, a larger dam and reservoir were assumed to pose a larger incremental flood hazard from overtopping failure than a small dam and reservoir for a given sunny day hazard classification. However, the September 2013 Colorado floods suggested this assumption may not always be valid and it leaves actual overtopping flood hazard unknown.

1.2.3 FEMA P94, "Selecting and Accommodating Inflow Design Floods for Dams" (2013) recommends eliminating arbitrarily selected composite criteria or percentages of hydrologic events for spillway sizing criteria (p. 7) due to the resulting inconsistent levels of spillway risk and reliability.

1.2.4 FEMA P94 recommends spillway design floods should be designed based on hazard potential and not on any classification system based on dam or reservoir size (p. 11).

1.2.5 Hydraulic modeling software, topographic data, and population data are now readily available to allow overtopping dam breach and consequence analysis to be performed with a reasonable amount of effort.

1.3 Hydrologic Hazard versus Incremental Damage Analysis: The Hydrologic Hazard spillway sizing approach is based directly on overtopping (or other hydrologic failure mode) dam breach consequences and so takes the place of the former Incremental Damage Analysis (IDA) rule from the 2007 Dam Safety Rules. The old IDA approach required spillway design size to be increased until incremental consequences from overtopping dam failure were essentially negligible, regardless of failure likelihood. The new Hydrologic Hazard approach uses consequences to determine an IDF magnitude such that risk (likelihood of failure x consequences) is acceptably low.

1.4 Hydrologic Hazard versus Hazard Classification: The Colorado Dam Safety Branch made the decision to keep Hydrologic Hazard separate from a dam's Hazard Classification because floods and hydrologic loading are unusual conditions in our arid and semi-arid climate.

1.4.1 A dam's Hazard Classification will continue to be based on sunny day hazard potential and is the basis for the Colorado Dam Safety Branch's inspection frequency and static design criteria.

1.4.2 Hydrologic Hazard is intended to be used for spillway sizing, spillway hydraulic design, and other design features associated with hydrologic loading during the IDF. It may also be used for emergency planning purposes.

1.5 Applicability and Determination of Spillway Deficiency:

1.5.1 Hydrologic Hazard and Rule 7.2 of the 2020 Rules shall be used to determine the IDF design criteria for new dams, dam enlargements, and for remediation of any existing dam that is determined to have a deficient spillway size or other safety deficiency associated with hydrologic loading.

1.5.2 At the recommendation of FEMA P94 (pg. 12), "grandfathering" of spillway sizes for existing dams has been eliminated from the 2020 Rules because it is indiscriminate. Instead FEMA P94 (pg. 12) recommends that dam safety regulations and guidelines should include considerations of safety and risk when determining whether dam owners should be required to upgrade existing dams/spillways.

1.5.3 Evaluation of spillway size deficiencies for existing dams will be performed in accordance with the 2020 Rules, Rule 5, which may include safety inspections and potential failure mode analysis (PFMA) to determine whether risk associated with overtopping or other hydrologic dam failure mode is unacceptably high and requires action to reduce the risk to an acceptable level. See Section 3 below for further discussion about hydrologic evaluation of existing dams.

Section 2. **A Procedure for Determining Hydrologic Hazard**

2.1 A presumptive Hydrologic Hazard classification of *Extreme* (see the 2020 Rules, Rule 4.15) may be taken for design purposes with no further justification. *Extreme* Hydrologic Hazard requires an IDF based on probable maximum precipitation (PMP) in accordance with the 2020 Rules, Rule 7.2, Table 7.1.

2.2 Otherwise, Hydrologic Hazard determination involves an overtopping dam breach analysis (or breach by other plausible hydrologic failure modes), associated flood routing, and consequence analysis. Consequence analysis includes estimating population at risk (PAR), warning adequacy, fatality rates, and expected life loss.

2.3 A spillway size must be assumed as a starting place for Hydrologic Hazard analysis. For an existing dam the existing spillway size should be used. For new dams or reservoir enlargement projects, a spillway sized to pass the flood from the Critical 1% annual exceedance probability (AEP) storm should be assumed because this is the minimum IDF allowable under the 2020 Rules for any Hydrologic Hazard category.

2.4 Hydraulic modeling for Hydrologic Hazard analysis can be performed using the following publically available resources:

2.4.1 U.S. Army Corps of Engineers' HEC-RAS software: https://www.hec.usace.army.mil/software/hec-ras/

2.4.2 Decision Support System for Water Infrastructure Security Web (DSS-WISE), which is an on-line dam breach, flood routing, and hazard evaluation tool developed by the University of Mississippi with funding from U.S. Department of Homeland Security. Users must register for a log-in associated with Colorado at: https://dsswiseweb.ncche.olemiss.edu/index.php Use the green, "Click to Request Access" button and submit the necessary information. Access will be granted by the Colorado Group manager.

2.5 Overtopping dam breach model parameters should be determined in accordance with the Colorado Dam Safety Branch's "Guidelines for Dam Breach Analysis", Table 3 or other methods acceptable to the State Engineer. Also, reference "Guidelines for Dam Breach Analysis", Section 3.2, Overtopping Failure of Earthen Dams.

2.5.1 Justification shall be provided for beach parameters associated with other hydrologic failure modes.

2.5.2 HEC-RAS currently has a dam breach parameter calculator, which can be used in conjunction with the Colorado Dam Safety Branch's breach guidelines. The calculator includes various methods, which provides an opportunity for sensitivity analysis.

2.5.3 DSS-WISE may also be used for dam breach simulations. Currently the user must supply dam breach parameters.

2.5.4 Spillway flooding should be modeled appropriately along with the hydrologic dam failure mode. Spillway flooding may be assumed as steady state flow or may be based on an inflow flood hydrograph for the drainage basin. If an inflow flood hydrograph is used, the peak routed reservoir stage should generally correspond to the initiation of dam failure.

2.6 Modeling of the routed dam failure floodwave must be extended through the downstream floodplain to a point where no further damage (or incremental damage) is expected. Routing should be performed to an appropriate level of detail, as discussed in "Guidelines for Dam Breach Analysis", Section 6.

2.6.1 HEC-RAS 2-dimensional (2D) analysis is an acceptable method for dam breach flood routing in areas where adequate topographic data is available.

2.6.1.1 LiDAR data and other high resolution topographic data should be used where available. USGS NED 10 meter DEM data are available for all locations in Colorado and are generally acceptable for evaluation of Hydrologic Hazard.

2.6.1.2 2D model roughness parameter values may be assigned using the National Land Cover Database gridded land cover data. Recommended values are provided in Table 1.

Table 1: Recommended Mannings "n" roughness values by NLCD land use

NLCD Code	Land use description	Recommended "n" value
11	Open Water	.032
21	Developed, open space	.046
22	Developed, low intensity	.095
23	Developed, medium intensity	.104
24	Developed, high intensity	.147
31	Barren land rock/sand/clay	.033
41	Deciduous forest	.115
42	Evergreen forest	.122
43	Mixed Forest	.109
52	Shrub/scrub	.082
71	Grasslands/herbaceous	.037
81	Pasture/hay	.04
82	Cultivated crops	.047
90	Woody wetlands	.095
95	Emergent herbaceous wetlands	.075

2.6.2 DSS-WISE may also be acceptable for performing dam breach floodwave routing for Hydrologic Hazard evaluation.

2.6.3 Hydrologic Hazard is based on dam failure during flood conditions, therefore assumptions may be needed regarding downstream concurrent tributary flooding. Since concurrent flooding conditions are unpredictable, a sensitivity approach is recommended.

2.7 Consequence Estimation: Life loss consequences associated with the routed overtopping (or other hydrologic failure mode) dam breach floodwave should generally be estimated using the USBR's "RCEM -- Reclamation Consequences Estimation Methodology". Life loss estimation by RCEM is calculated as the product of fatality rate and population at risk (PAR).

2.7.1 Consequences may be determined either based on total flood depth from the overtopping dam breach flood or based on the incremental flood depth between the overtopping dam breach flood and the spillway base flood immediately prior to dam failure (Rule 7.2.2).

2.7.2 PAR may be determined using aggregate demographic data (e.g. U.S. Census data or Colorado Dam Safety Branch Social Vulnerability Tool data) or by an inventory of actual structures. Table 2 provides guidance on PAR per structure type/exposure. The demographic statistics method may be more applicable to densely populated areas, while the inventory of individual structures is more suited to rural areas.

Table 2: Suggested PAR by structure type and exposure(1)

Structure Type / Exposure	Suggested PAR(2)	Structure Type / Exposure	Suggested PAR(2)
Home	3.0	Hospital	Varies
Cabin	1.5	Main local road / minor state highway	2
Duplex	5	Major state road / minor federal highway	4
Apartment	Varies	Major federal highway	8
Commercial	Varies	Railroad, freight traffic	3
School	Varies	Railroad, passenger	20

(1) Reference NRCS "Guidance for Completion of Evaluation of Potential Rehabilitation Projects", Updated July 6, 2013, and "PAR Computation Worksheet"
(2) Suggested PAR should be checked against local data or field verified as needed to ensure reasonableness.

2.7.2.1 Dam owners should be aware that PAR, and particularly the structure-inventory method described above, may be subject to change if new development occurs in the dam breach floodplain in the future (i.e. hazard creep). Hazard creep may necessitate re-evaluation of Hydrologic Hazard and spillway adequacy.

2.7.2.2 Incremental Hydrologic Hazard analysis may be based on incremental PAR, which is the increase in PAR associated with overtopping dam failure above and beyond the PAR associated with the spillway base flood immediately prior to dam failure.

2.7.3 Warning to the population at risk must be evaluated in terms of timing and quality. Adequate warning time should be considered relative to expected flood wave arrival time, which may vary by structure or downstream reach. Judgment is required to make the case for warning adequacy (see RCEM manual). Warning adequacy is used to determine fatality rates by RCEM Figure 3 (Little or No Warning) or Figure 4 (Adequate Warning).

2.7.4 Fatality rates are estimated from RCEM Figure 3 or Figure 4 as a function of floodwave depth x velocity product (DV). Two methods are generally recommended for extracting DV and estimating fatality rates.

2.7.4.1 Method 1 – RCEM using point DV data at structures: This approach uses 2D point (or cell) DV results at each structure in the inundation area to estimate structure-by-structure fatality rates and life loss. This method may be conducive to the structure-inventory PAR method discussed above. Depth and velocity values can be extracted at shapefile point features from HEC-RAS using RAS Mapper. Likewise ArcMap can be used to extract DSS-WISE DV raster grid values at shapefile points.

2.7.4.2 Method 2 – RCEM using reach-average DV-estimates: This approach divides the downstream inundation area into reaches of similar hydraulic and warning time characteristics. Typical or average reach DV values may be used. DV may be calculated from section averages at profiles in HEC-RAS's RAS Mapper, at observation lines in DSS-WISE, or simply as routed peak breach discharge divided by floodplain top width. This method may be conducive to the aggregate demographic data method of PAR estimation discussed above or to the structure-inventory PAR method.

2.7.5 Life loss is estimated as the product of fatality rate and PAR, either on a structure-by-structure or reach basis and is then summed over the entire inundation area. Incremental analysis may be based on incremental PAR (discussed above) or incremental life loss (overtopping dam failure life loss minus spillway base flood life loss).

2.7.6 Economic and other damages should be evaluated where flooding is expected at uninhabited structures and infrastructure, but there is no expected life loss, or where expected floodwave DV at habitable structures is so low that estimated fatality rate and life loss are zero. The Colorado Dam Safety Branch's "Guidelines for Hazard Classification" provides guidance on evaluating such damages.

2.8 Hydrologic Hazard is categorized directly from overtopping (or other hydrologic failure mode) dam breach consequences according to the following definitions from the 2020 Rules, Rule 4.15:

2.8.1 **Extreme.** Life loss potential of 1 or more.

2.8.2 **High.** Life loss potential of less than 1.

2.8.3 **Significant.** No life loss potential but significant damage is expected to occur.

2.8.4 **Low.** No life loss potential or significant damage is expected to occur

2.9 IDF selection for Spillway Sizing: The prescriptive IDF Critical Rainfall shall be selected from the 2020 Rules Table 7.1 for the appropriate Hydrologic Hazard category.

2.9.1 Deterministic PMP should generally be obtained using Colorado's Regional Extreme Precipitation Study (REPS) PMP Evaluation Tool. Probabilistic design rainfall should generally be obtained using the REPS MetPortal Precipitation Frequency tool. See the Colorado Dam Safety Branch's "Guidelines for Use of Regional Extreme Precipitation (REPS) Rainfall Estimation Tools" for details.

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

2.10 Spillway Sizing: Spillway sizing based on Hydrologic Hazard is an iterative process that begins from the assumed spillway size (see Section 2.3 above). Firstly, develop drainage basin hydrology in accordance with the Colorado Dam Safety Branch's "Hydrologic Basin Response Parameter Estimation Guidelines" and check whether the spillway size can safely route the hydrograph for the prescriptive IDF from the 2020 Rules, Table 7.1.

2.10.1 If yes, then the spillway size is adequate.

2.10.2 If no, then the spillway design size should be increased iteratively until it can safely route a hydrologic event equaling or exceeding that required for the Hydrologic Hazard category by 2020 Rules Table 7.2, or conversely until the Hydrologic Hazard is reduced to where the routed hydrologic event is acceptable. The resulting hydrologic event is the IDF for the dam. The following is an example:

> An existing dam's spillway was determined to safely convey the 0.3% AEP (i.e. 333-YR average recurrence interval) flood. Overtopping dam breach incremental consequences were estimated at a life loss of 15, which was determined to pose an unacceptably high risk to the downstream public and was categorized as *Extreme* Hydrologic Hazard using 2020 Rules, Rule 4.15. Using the 2020 Rules Table 7.1, the prescriptive IDF for *Extreme* Hydrologic Hazard is the Critical PMP flood. Therefore, the spillway design size was enlarged to convey the Critical PMP runoff hydrograph, as routed through the reservoir. But when the incremental overtopping consequences were rechecked for the new spillway design size, the dam's Hydrologic Hazard was found to be *High* (life loss potential less than 1). The designer may either stop here and conservatively use the spillway sized to convey the PMP flood or the designer may iteratively reduce the spillway design size to the smallest size for which the Hydrologic Hazard is *High* while meeting or exceeding the 0.01% AEP IDF (from Table 7.1). The IDF developed in this manner will be between the PMP and the 0.01% AEP storm with an expected life loss of less than 1.

2.11 Early Warning: If a spillway size is found to be inadequate to safely convey the prescriptive IDF from the 2020 Rules Table 7.1 for the dam's Hydrologic Hazard due to an assumption of "little to no warning", then consideration may be given to improving warning time and quality in order to reduce expected life loss and justify an assumption of "Adequate Warning", in accordance with the USBR's RCEM manual. Hydrologic Hazard is based on dam failure during flood conditions, so it may be possible to detect and provide early warning of such flood conditions by instrumentation and monitoring, emergency planning, communications, and emergency action plan (EAP) exercises. Any proposed early warning system that would serve to reduce expected life loss consequences from overtopping (or other hydrologic failure mode) dam failure must be prepared in a written plan, reviewed and approved by the Colorado Dam Safety Branch. The warning system plan must be coordinated with local and state emergency managers and the downstream public within the inundated area who would need to be warned. An early warning plan must include dam breach inundation mapping for overtopping failure (or other hydrologic failure mode) and inundation mapping for the spillway flood immediately prior to dam failure (to help with evacuation planning). The final plan must be fully implemented and must be exercised annually with the Colorado Dam Safety Branch, emergency managers, and affected downstream residents. Early warning system plans must be included in the dam's EAP. Approved and implemented early warning systems will be tracked in the Colorado Dam Safety Branch's DAMS database.

Section 3. <u>Evaluation of Spillway Adequacy for Existing Dams</u>

3.1 As discussed in Section 1 above, hydrologic adequacy of spillways and related features of existing dams will be performed in accordance with the 2020 Rules, Rule 5, *Determination of Safe Storage Level*. This may include safety inspections and potential failure mode analysis (PFMA) to determine whether risk associated with overtopping or other hydrologic dam failure mode is unacceptably high and requires action to reduce the risk to an acceptable level.

3.2 The Colorado Dam Safety Branch's risk-based evaluation of an existing dam's spillway (or other hydrologic features) involves development of a hydrologic hazard curve, estimation of life loss consequences, and a qualitative risk evaluation.

3.3 A hydrologic hazard curve is a likelihood plot of different reservoir stages. It should not be confused with *Hydrologic Hazard* category, discussed above. The hydrologic hazard curve plots maximum reservoir stages from modeled flood routing against annual exceedance probabilities of the associated design storm events.

3.3.1 The REPS MetPortal Precipitation Frequency (PF) Tool can be used to develop a PF curve/table over an AEP range of 10^{-1} to 10^{-7} and a design storm temporal pattern for each storm type. MetPortal storm types are the 2-hour Local Storm (LS), 6-hour Mesoscale with Embedded Convection (MEC), and 48-hour Mid-latitude Cyclone/Tropical Storm Remnant (MLC/TSR).

3.3.2 LS, MEC, and MLC/TSR storm types were determined to be independent storm types by the REPS study. **Therefore, all three design storm types must be run to determine the critical case (i.e. highest routed reservoir stage) at each AEP.**

3.3.3 A hydrologic hazard curve can be developed by plotting the maximum reservoir stage of the critical design storm at each AEP. The combination of seven AEP estimates for each of the three storm types results in 21 design storms that must be run in a rainfall-runoff model in order to generate the full hydrologic hazard curve.

3.3.4 The intersection of the dam crest elevation and hydrologic hazard curve can be used to determine the likelihood (i.e., AEP) of dam overtopping.

3.3.5 An example hydrologic hazard curve is shown below in Figure 1.

3.4 Next, life loss consequences for overtopping dam failure (or other hydrologic failure mode) are estimated in the manner described in Section 2 above.

3.5 Using the Colorado Dam Safety Branch's Comprehensive Dam Safety Evaluation (CDSE) Tools, *Failure Likelihood Rating* and *Consequence Category* can be assigned based on the dam overtopping AEP and expected Life Loss. The CDSE Tools aid the assignment of *Failure Likelihood* with worksheets for potential failure mode event trees and adverse and positive factors. CDSE Tools are available at the Colorado Dam Safety Branch website as shown in Figure 2: http://water.state.co.us/damsafety/dams.asp

3.6 Finally, a qualitative risk assessment can be made by plotting Likelihood of Failure against the Consequences Category for overtopping dam failure (or other hydrologic failure mode). An example is shown in Figure 3 below. Given the 3×10^{-3} AEP (High Failure Likelihood) shown on the hydrologic hazard curve in Figure 1 and assuming there is an associated life loss estimate of 15 (Level 3 Consequences Category), the overtopping failure mode for this example plots above the acceptable risk line.

3.7 For the example in Figure 3, the Colorado Dam Safety Branch would work with the existing dam's owner and take necessary regulatory action to reduce the risk of overtopping dam failure. The CDSE Tools provide detailed written guidance on potential actions based on Failure Likelihood category. For the unacceptable risk shown in our example case, the dam owner's Engineer would follow the Hydrologic Hazard spillway sizing procedure, discussed in Sections 1 and 2 above, to design a spillway that complies with the 2020 Rules, Rule 7.2.

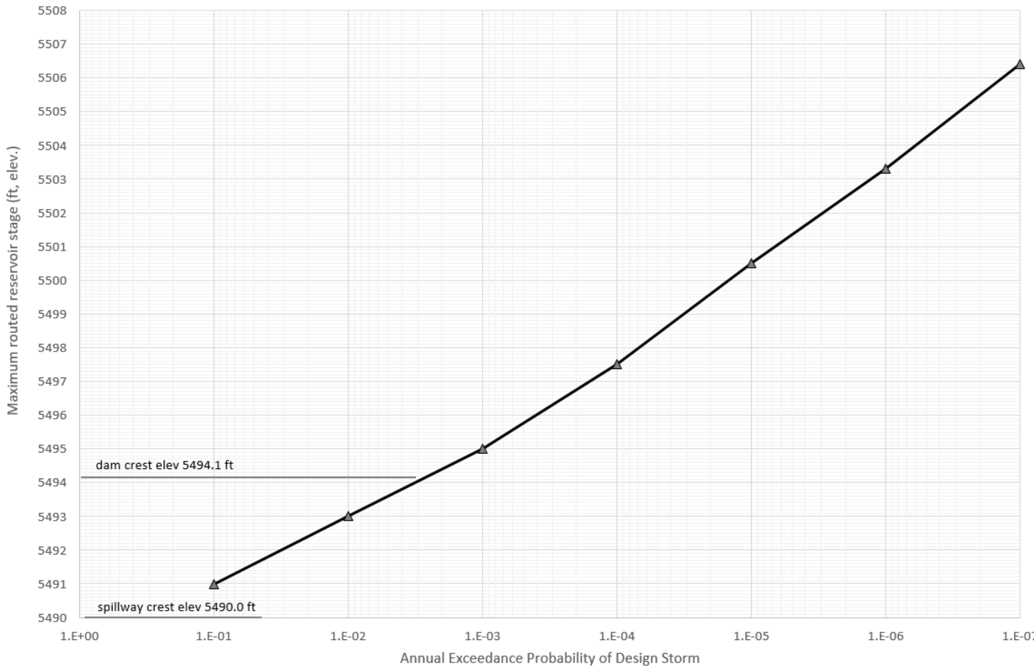

Figure 1: Example hydrologic hazard curve based on maximum reservoir stage for critical REPS MetPortal PF design storm at each AEP

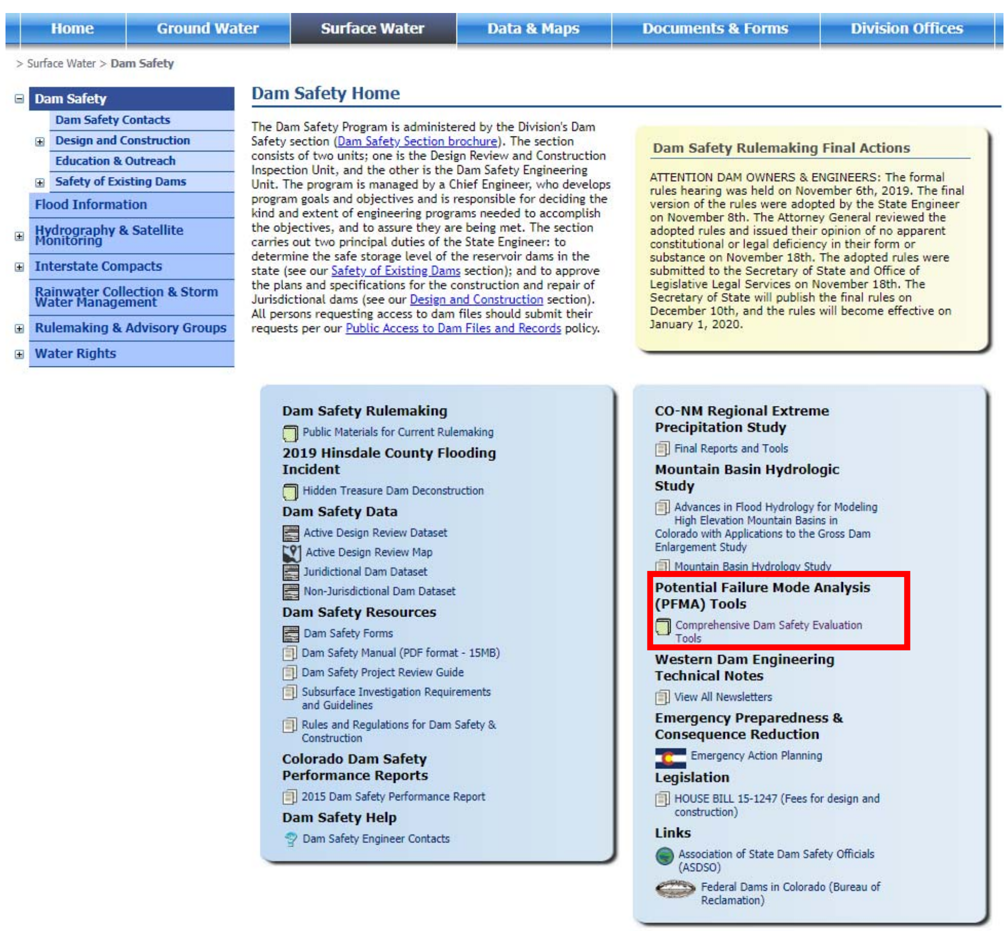

Figure 2: Colorado Dam Safety Branch's CDSE Tools available at http://water.state.co.us/damsafety/dams.asp

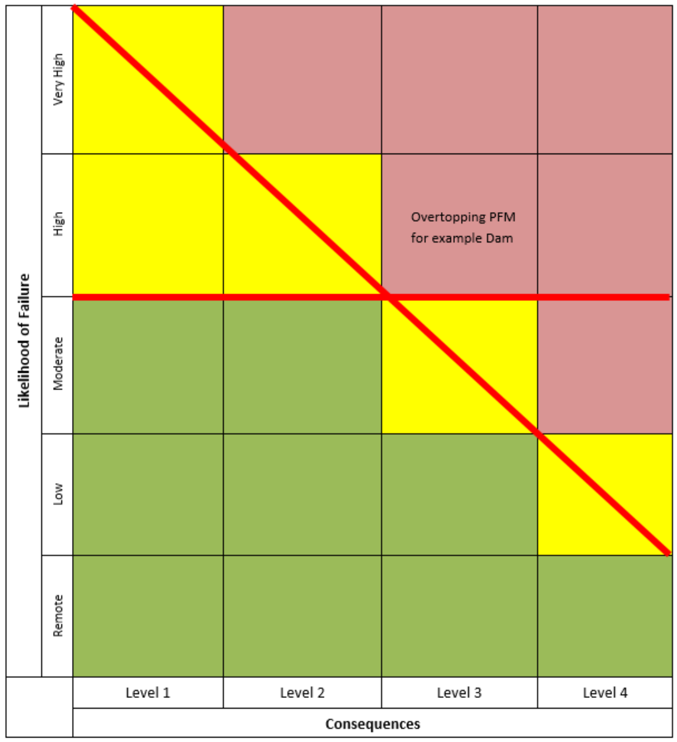

Figure 3: CDSE Tools quantitative risk assessment chart for the example overtopping potential failure mode (PFM)

Section 4. References

4.1 *Guidelines for Dam Breach Analysis*, Colorado Dam Safety Branch, 2020

4.2 *Guidelines for Hazard Classification*, Colorado Dam Safety Branch, 2020

4.3 *Rules and Regulations for Dam Safety and Dam Construction*, 2020

4.4 *Reclamation Consequence Estimating Methodology*, USBR, July 2015

4.5 *Colorado-New Mexico Regional Extreme Precipitation Study Summary Report, Volume 1*, Colorado Department of Natural Resources and New Mexico Office of the State Engineer, November 30, 2018.

4.6 *Guidelines for Use of Regional Extreme Precipitation Study (REPS) Rainfall Estimation Tools*, January 2020.

4.7 *Hydrologic Basin Response Parameter Estimation Guidelines*, Colorado Dam Safety, 2008