Risk Informed Inundation Mapping

David C. Curtis, Senior Vice President, WEST Consultants, Folsom, CA, dcurtis@WESTconsultants.com
Brent Travis, Director of Applied Research, WEST Consultants, Tempe, AZ, btravis@WESTconsultants.com
Gyan Basyal, Staff Engineer, WEST Consultants, Tempe, AZ, gbasyal@WESTconsultants.com

Abstract

Risk informed inundation mapping provides information and context to rare low probability high consequence events. Traditional deterministic hydraulic modeling produces a single water surface mapped to the local terrain, even though there are significant uncertainties in some of the underlying model parameters. In the case of dam breach modeling, parameter choices such as breach geometry (bottom width, elevation, and side slopes), the weir coefficient, breach formation time, and initial piping elevation can all significantly impact the breach discharge hydrograph and influence stages routed downstream. Choices for channel and overbank roughness, bridge parameters, culverts, in-line structures and floodplain encroachments further impact downstream stages and mapped areas.

For purposes of dam breach inundation mapping these breach parameters are often assumed at their most conservative values. This creates a worst-case scenario for the potential extent of inundated areas. However, given that a dam breach is likely to be a low-probability event (often less than the 1% chance event), this worst-case scenario will substantially lower this probability. This may be inconsistent with the risk tolerance of the decision makers.

Understanding the impacts of the range of possible parameter choices provides important context to the mapped results. One way to evaluate this context is through a direct simulation of through a Monte Carlo approach. This approach, which varies the parameters according to their distributions and typically executed with thousands of scenarios to stabilize the statistics, facilitates risk assessments of the resulting inundation maps.

Examples of risk-based inundation mapping will be presented and discussed. The results provide important context to risk to specific floodplain structures and support improved prioritization of mitigation resources.

Introduction

Probabilistic Mapping Approach

Traditionally, selection of the breach parameters is done deterministically by

1. Estimating the size, shape, and timing of the dam breach using empirical equations;
2. Performing a sensitivity analysis assuming a reasonable range of these parameters; and,

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3. Selecting conservative values (e.g. those values that appear to increase the magnitude of the breach outflow hydrograph).

This three-step approach may well represent the worst-case scenario but given the inherent unlikelihood of these worst-case features all occurring at once does not match most reasonable risk-based decisions.

A reasonable, alternative method for selecting the breach parameters is a probabilistic approach. This approach varies the dam breach parameters through predefined probability density functions. By considering a large set of model simulations (events), statistical distributions of outcomes of interest can be generated. Examples include the dam breach hydrographs, floodwave arrival times, and stage hydrographs, among others.

Studies such as Vorogushyn, Merz, Lindenschmidt, and Apel, (2010) and Tsai, Yeh, and Huang (2019) have shown that statistical consideration of these outcomes can have a pronounced impact on downstream flood mapping. These studies utilized specifically developed software that coupled stochastic input and 1-dimensional and 2-dimensional floodplain delineation. As proof of concept this work is critical, but from a practical standpoint difficult to apply to engineering studies where existing, publicly available freeware models such as the United States Army Corps of Engineer's Hydrologic Engineering Center's River Analysis System (HEC-RAS) are standard and accepted by numerous government agencies. Probabilistic floodplain mapping is thus more easily implemented using HEC-RAS or other accepted hydraulic and hydrologic modeling software.

Assuming agency acceptance of the floodplain mapping software, the first step in probabilistic consideration becomes the careful selection of the corresponding dam and levee breach statistical distributions. This often involves meeting with project stakeholders such as the dam owners, the Federal Emergency Management Agency (FEMA), the Federal Energy Regulatory Commission (FERC), and others. After consideration of the potential failure mode statistical distributions, stakeholders can discuss the distributions and corresponding factors to determine if they are appropriate given the failure mode, construction of the dam, inflow hydrograph, reservoir size, applicable guidelines, and other factors. Assuming a consensus is achieved, modeling by Monte Carlo simulation can then executed to developed probabilistic outcomes.

Modeling Procedures

In recognition of the need to improve flooding risk assessment for dam and levee breach evaluations, new software was developed that directly incorporates probabilistic aspects of all major components consistent with Monte-Carlo type simulations. The resulting product, tentatively named RiskRAS (formerly SimRAS 2D), is a multipurpose, graphical user interface (GUI) based HEC-RAS simulation tool with a simple graphical interface. It allows the user to assign a statistical distribution to one or more key parameters in the chosen HEC-RAS 1D or 2D model (see examples shown in Figure 1 below).

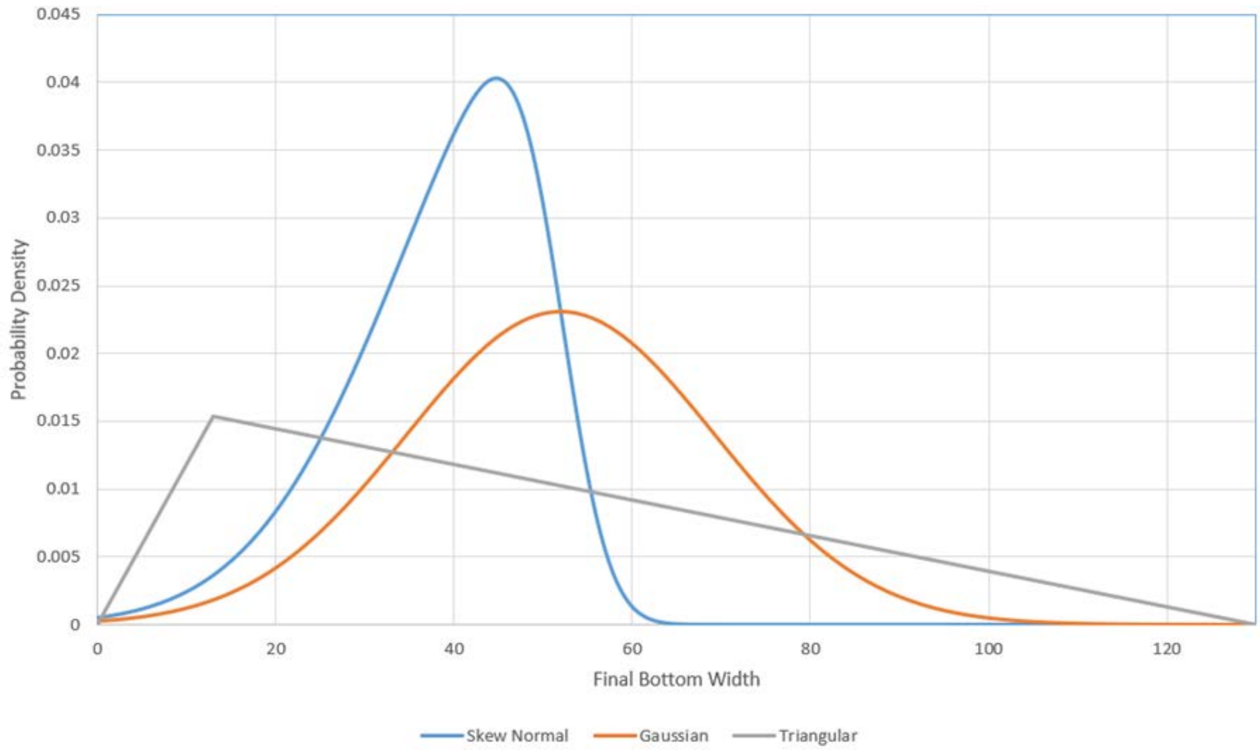

Figure 1. Example available statistical distributions in RiskRAS

Completely automated, RiskRAS runs the HEC-RAS model multiple times, selecting randomized values of the key parameters for each run (consistent with a Monte Carlo analysis). When complete, the results can be used to determine the risk of a particular event occurring, evaluate parameter sensitivity, and/or determine most likely outcomes. RiskRAS is written in Python language utilizing reliable and well tested libraries. Some specific features are as follows:

- Easy to use GUI interface minimizing the learning curve, promoting efficient, error-free simulations.
- Facilitation of statistical distribution type and parameter selection with dynamic plots.
- Guided input selection.
- Instant results reported through dynamic tables and figures.
- Python based programming allows easy modification for individual projects.
- Live feedback during simulation.
- Utilizes HEC-RAS standard database (HEC-DSS) for all parameter and results storage.

Beyond the present application, RiskRAS can also be used for:

- Dam Break Modeling
- Levee Breach Modeling
- River Model Sensitivity Analyses
- Emergency Action Planning
- Uncertainty Analysis
- Risk Analysis
- Design of Simulated Experiments
- Floodplain Delineation

The results of a RiskRAS application (each typically referred to as a realization) are stored within the HEC-DSS database along with the randomly generated parameters. Thus, all vital simulation information can be easily accessed from within HEC-DSSVue. Further analysis of the results can be accomplished both through HEC-DSSVue (e.g., tabulation, plotting) as well as via the currently implemented RiskRAS post-processing tools. These tools include direct floodplain mapping and statistical analyses. For example, Figure 2 displays the results of one RiskRAS study of flow exceedance (e.g., the 1% flow exceedance is equivalent to the 100-year storm) due to five stochastically selected breach parameters: final bottom width, left side slope, right side slope, weir coefficient, and formation time. A pronounced, albeit statistically noisy, relationship is seen between final bottom width and formation time. The former parameter indicates the breach width appears to be positively correlated with the rarity of the flood event. The latter displays the opposite effect, specifically that rarer storms tend to be exceeded by shorter progression times. The other factors appear to have little effect. Note that this analysis was for only one dam; other locations will likely have different outcomes.

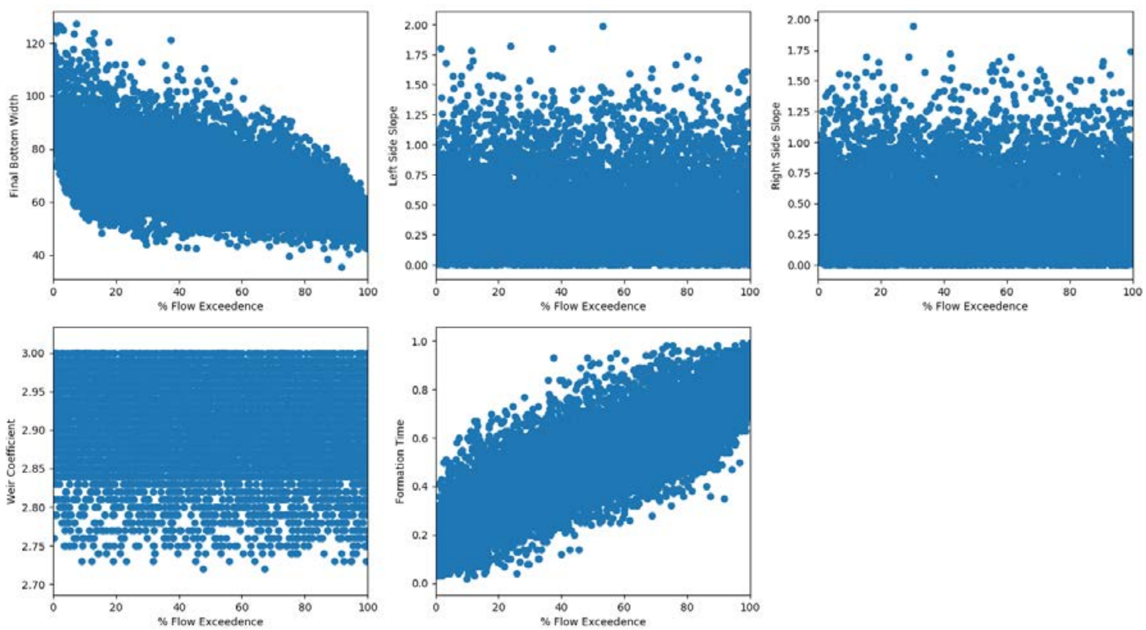

Figure 2. Examples of the post-processing capabilities in RiskRAS

Application of Probabilistic Mapping

As a test of the overall approach to risk informed inundation mapping in general and RiskRAS in particular, probabilistic analysis was performed at a hydroelectric, concrete gravity dam located in Montana (Figure 3). The first step of this ongoing project is to understand how high flows downstream of the dam might vary due to a breach and then determine how these flows relate to an exceedance risk.

Figure 3. Aerial photo of the Montana hydroelectric project

Following development of the hydrology and a HEC-RAS hydraulic model, RiskRAS was utilized for the risk analysis. Specifically, 10,000 Monte Carlo scenarios were executed with the outflow tracked as the outcome of interest. [Details of this effort will be described within as the Travis, Basyal, Bahner and Wahlin (in press) conference paper accepted for the Proceedings of United States Society on Dams 2019 Conference and Exhibition, April 8 – 11, 2019.] The results were ranked and the risk of exceedance of each assigned accordingly. Overall, high variation was seen among the outflows (Figure 4). In particular, it is seen that the breach outflow risk becomes quite sensitive in the design range, with the 1% chance of exceedance breach outflow of 18,500 cfs about 20% higher than the median breach outflow of 15,500 cfs, and the 0.01% chance of exceedance flow even higher at 20,500 cfs. Hence, the risk analysis indicates that the deterministic value originally chosen for the project (25,500 cfs) would correspond to a chance of exceedance far smaller than 0.01%. The comparison to hydrology would be that the deterministic value is far greater than 10,000-year hydrologic event.

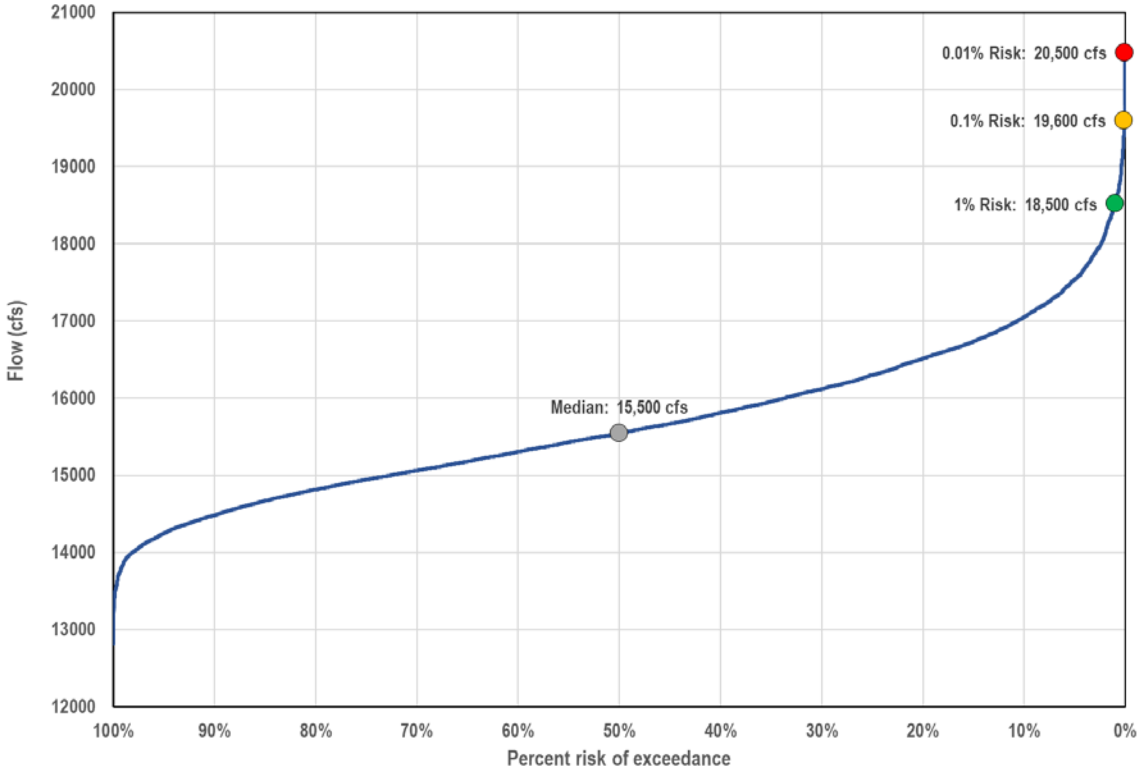

Figure 4. RiskRAS risk analysis results for Montana Dam

Following identification of flow exceedance risk, floodplain mapping proceeded as normal for each of the flows of interest. The results for a particular section of the floodplain is shown in Figure 5. The worst-case (25,500 cfs), 1% risk (18,500 cfs), and median risk (15,500) floodplain delineation are shown.

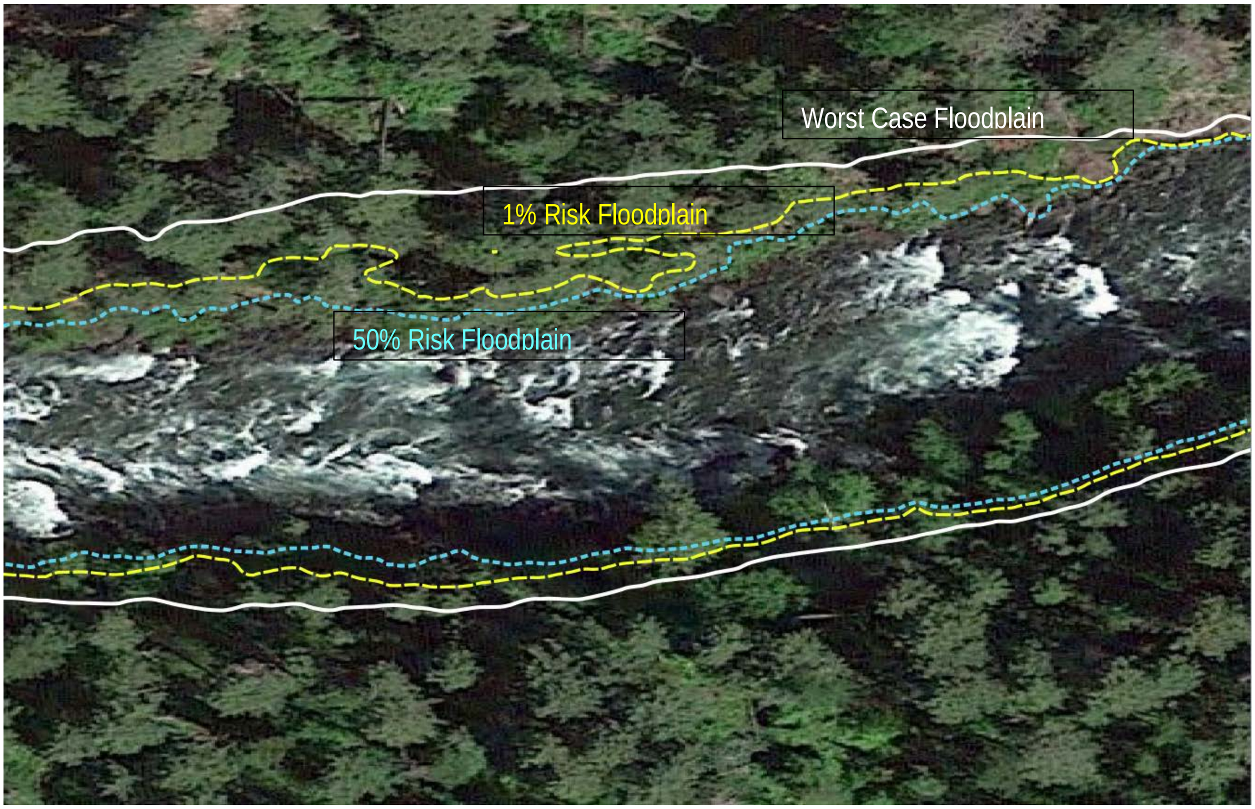

Figure 5. Probabilistic mapping example

Conclusion

This general overview of probabilistic floodplain mapping shows how the procedure can assist floodplain managers make informed, risk-based decisions regarding floodplain extents from typically highly uncertain dam breach scenarios. The associated tool – RiskRAS – can facilitate the approach which, by directly accounting for individual breach component uncertainty, provides direct, quantitative results well suited for risk-based floodplain management.

References

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