Columbia Water Center
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CLIMATE EXTREMES, AGING DAMS & LEVEES AND CASCADING FAILURE IMPACTS

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FOREWORD

This report summarizes the advances of the project since the last report submission of February 2019.

The overall goal of this study is to develop a framework for rapidly assessing the hazard (i.e. the probability and magnitude of a dam failure) and the exposure (what gets affected by a failure), scalable over many regions for a preliminary ranking of the priority areas of concern. The intended application is for a *portfolio level* risk analysis by investors, asset managers, and insurance providers.

In the first stage (2018), a climate risk model was developed to detect the atmospheric drivers of storms that could trigger a dam failure in the conterminous United States. Additionally, a dam risk score was proposed to rank individual dams according to the potential severity of damages caused by their failure, with and without considering the cascading effect of failure from upstream dams. The risk score could take values between 0 and 1.5 and was obtained with the elements described in Figure 1. This was exemplified with the analysis of 5,800 dams located in New York State. While this risk score can be a helpful first screening of the dams, its calculation had some important gaps. First, the inundation area in case of failure was not estimated using dam break analysis; it was subjectively defined with a buffer area around a downstream channel. The buffer extent was not linked to the characteristics of the dam (the same buffer area was used across dams) or the topography. Second, the element number 7 in Figure 1 (number of dams downstream that could be affected) was not based on analysis of the flow that could be released from an upstream dam and how this could affect it.

number	item	Criterion
①	Number of Power Plant on inundation	If =0 , score is 0 │ =1 , score is 50 │ =2 , score is 75 │ =>3 , score is 100
②	Total MW of damage on inundation(MW)	=0 MW , score is 0 │ <300 MW, score is 50, < 600 is 55, < 900 is 60, < 1200 is 65, < 1500 is 70, < 1800 is 75, < 2100 is 80, < 2400 is 85, < 2700 is 90, > 2700 is 100
③	Total Population (in thousands)	=0, score is 0 │ <10000, score is 50, < 20000 is 55, < 30000 is 60, < 40000 is 65, < 50000 is 70, < 60000 is 75, < 70000 is 80, < 80000 is 85, < 90000 is 90, > 90000 is 100
④ (4-1, 4-2, 4-3, 4-4)	Relative Transmission Line Density (Km)	=0, score is 0 │ <10000, score is 50, < 20000 is 55, < 30000 is 60, < 40000 is 65, < 50000 is 70, < 60000 is 75, < 70000 is 80, < 80000 is 85, < 90000 is 90, > 90000 is 100
	Relative Pipeline Density (Km)	=0, score is 0 │ <10000, score is 50, < 20000 is 55, < 30000 is 60, < 40000 is 65, < 50000 is 70, < 60000 is 75, < 70000 is 80, < 80000 is 85, < 90000 is 90, > 90000 is 100
	Relative Railroad Density (Km)	=0, score is 0 │ <10000, score is 50, < 20000 is 55, < 30000 is 60, < 40000 is 65, < 50000 is 70, < 60000 is 75, < 70000 is 80, < 80000 is 85, < 90000 is 90, > 90000 is 100
	Relative Road Density (Km)	=0, score is 0 │ <10000, score is 50, < 20000 is 55, < 30000 is 60, < 40000 is 65, < 50000 is 70, < 60000 is 75, < 70000 is 80, < 80000 is 85, < 90000 is 90, > 90000 is 100
⑤	100yr flooding area	Weight 20%
⑥	500yr flooding area	Weight 30%
⑦	Number of dams in flooding area linked to a breach of dam	=1 , score is 50 │ =2 , score is 75 │ =>3 , score is 100

Step 1(T1)=(①*0.25 + ② * 0.25 + ③*0.25 + ④*0.25)/100 where, ④*0.25 = ((4-1)*0.25+(4-2)*0.25+(4-3)*0.25+(4-4)*0.25))
Step 2(T2)=T1+T1*0.2 if a dam is in ⑤
T1+T1*0.2 if a dam is in ⑥

Risk Score=T2+(⑦/100)*0.2

Figure 1 Risk Score estimation from 2018 report

Therefore, the main focus of the past three months has been on improving the estimation of the exposure in case of failure. Existing tools and methodologies developed by US agencies were reviewed and tested using the Cumberland River Basin, a tributary of the Ohio River Basin as test case. We found that many programs were needed to perform the analysis (HEC-HMS, DSS-WISE, ResSim ArcGIS Pro, R, ResSim and Hazus), some of them were slow and unstable and required intense data manipulation. The results of the test case are provided in this report. In order to make this a rapid and scalable framework, the process needs to be streamlined. The focus of the following stage will be on a) the estimation of the probability of overtopping, and b) trying to make the exposure estimation more accurate and efficient.

Review of available tools

Probability of overtopping

Overtopping occurs when the inflow to the impoundment exceeds the available storage and the capacity of the discharge outlets (spillways, orifices, gates). A hydrology model is needed to translate precipitation to runoff and therefore estimate the probability of a precipitation event leading to overtopping of a dam. We reviewed the capabilities of the hydrology and hydraulic model HEC-HMS, which is used by the US Army Corps of Engineers (USACE). This model also allows estimating the flows and storage-discharge relationships of interconnected dams.

Dam break simulations

There are different types of dams and each of them have different modes of failure. Concrete gravity dams tend to have a partial breach while concrete arch dams tend to fail suddenly and completely. Embankment dams on the other hand do not usually have a complete or sudden failure. In the case of embankment dams, once a breach is initiated, the discharging water erodes a portion of the downstream face of the dam until the reservoir is depleted. The two primary tasks in the analysis of a potential dam failure are 1) the prediction of the reservoir outflow hydrograph, and 2) the routing of that hydrograph downstream to determine dam failure consequences (Golder, 2017).

A variety of tools are available to estimate the outflow hydrograph and the inundated area, and they have various levels of complexity. For example, HEC-RAS developed by the USACE is considered as one of the best tools but requires multiple parameters that are often not known. It is complex and time consuming. DSS-WISE can model dam break inundation analyses but not failure of interconnected dams (although this capability is planned for the next version). DSS-WISE is easy to use and fast but it gives a less precise approximation of the inundation area compared to the results provided by HEC-RAS when the input information is available. Both of them were tested and given the complexity, time, data requirements, and the scalability wanted for this project, DSS-WISE was the tool of choice to estimate the inundation area of selected cases.

The starting conditions in our simulations are set so the dams are full in the time of failure (assuming flood conditions). However, DSS-WISE does not allow to input the initial conditions in the river downstream of the dam, which we would like to simulate as being in flood stage, and does not simulate backwater either. Therefore, the resulting inundation area may be less than if flooding conditions prior to the dam break are simulated, but still much greater than the flood inundation areas included in the flood insurance rate maps (DFIRMs) released by the federal emergency management agency (FEMA). We demonstrate this in the test case of Dale Hollow Dam in the Cumberland River Basin.

Estimating financial exposure

Hazus is a program developed by FEMA to estimate the financial consequences of floods. It can't model dam breaks but the depth-area grids of dam break simulations obtained in other programs such as DSS-WISE and HEC-RAS can be used as input. Hazus has an inventory of buildings and critical infrastructure in each region at the census block scale, which is used to calculate flood potential damage based on depth-cost curves. We found the software to be very slow and unstable so we used its building inventories and cost-depth curves but performed the calculations external to the program.

The financial exposure estimation presented in the test case focuses only on property damage, excluding other indirect costs such as power outages, costs and time to rebuild the dams, bridges, and roads, and water supply interruptions. We plan to incorporate more of these indirect costs in the next stages of the project.

The diagram in Figure 2 shows the method followed in the analysis. The three dam break scenarios considered were: S1 sudden and complete failure (discharge calculated by DSS-WISE); S2 complete failure (discharge calculated for an overtopping event in

HEC-HMS and inundation area modeled in DSS-WISE); S3 partial failure (discharge calculated in DSS-WISE using parameters for breach formation calculated from empirical equations).

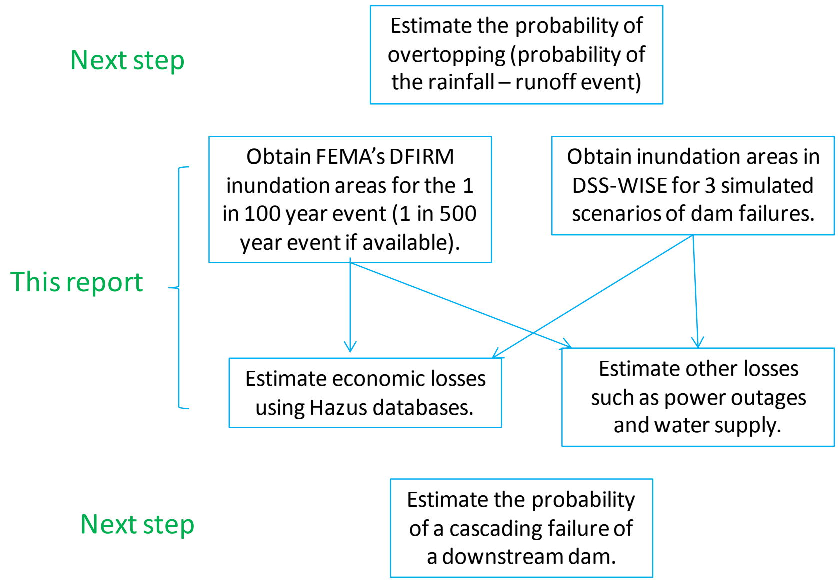

Figure 2 Process flow

Analysis

To define our test case we first classified more than 70,000 dams in the National Inventory of Dams (NID) by attributes that can increase the risk of failure:

- Group 1 : No emergency plan, not owned by a federal agency, age greater than 50 years, dam type different than concrete, and storage >5,000 acre-ft.
- Group 2 : No emergency plan, age greater than 50 years old, dam type is different than concrete, and NID storage >1,000 acre-ft.
- Group 3: NID storage>50,000 acre-ft.

Then, we focused on a region that had multiple interconnected dams that serve different purposes including electricity generation, recreation, water supply, flood control, etc., and that are located in areas prone to flooding. We selected the Cumberland River Basin which discharges to the Ohio River (Figure 2). It has multiple interconnected dams larger than 50,000 acre- feet (Group 3) and a history of flooding. For example, in May 2010, there was a two day storm estimated to be far greater than a thousand year rain event. The J. Percy Priest dam, located just upstream of Nashville, was nearly overtopped during this event. The navigation project, Cheatham Lock and Dam was overtopped.

The set of selected dams are managed by USACE so information of their physical attributes and management is available. These are "best case" dams in terms of data availability. The connected system of dams in Cumberland River Basin is included in the Appendix. The Dale Hollow dam in the upper part of the basin was used to test the tools mentioned in the previous section, but this system of dams will be used in future analyses.

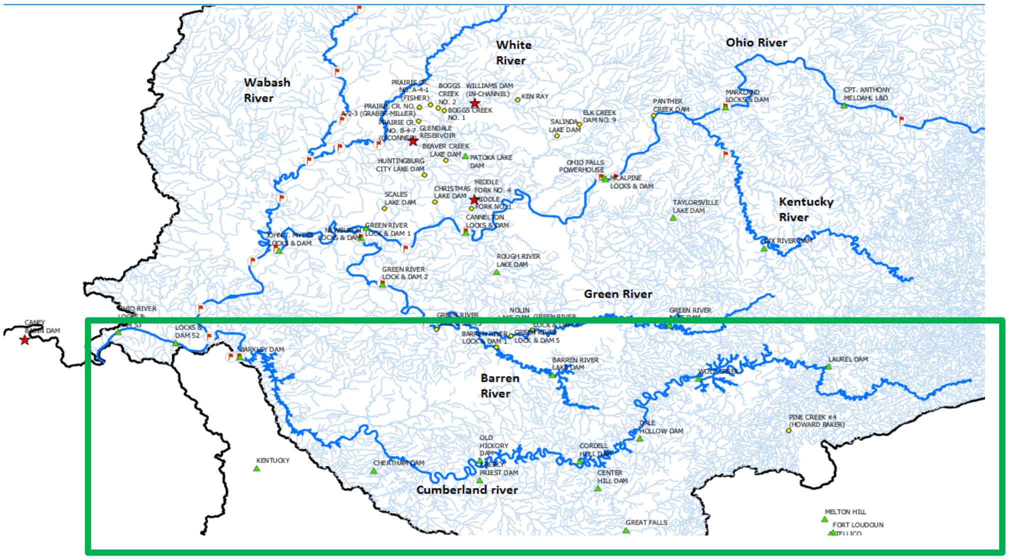

Figure 3 Test case area – Cumberland River Basin. Green triangles represent Group 3 dam locations

Results

DSS-WISE inundation area simulations

In Figure 4 is noticeable that the 1 in 100 year DFIRM flood area mainly occurs as backwater effect from the dam and some areas downstream, but the extent of the flood is much greater in the dam break S1. The maximum flood depth (H max) is pictured in S1 and it is quite dramatic just downstream of the dam as would be expected, this is where the city of Celina is located and would be greatly damaged in case of a dam failure. The flood extents in S2 and S3 are included in the Appendix. Depending on the simulation parameters the extent and depth of inundation varies; S2 has the greatest flood distance (43.8 miles). However, the outflow hydrograph for that simulation was obtained from an un-calibrated HEC-HMS model and it requires further revision. The Nashville district of the USACE kindly provided their calibrated HEC-HMS model and their ResSim model recently so we hope to make improvements in the estimation of S2 to compare if the results given by DSS-WISE are really that different and select the best method for future test cases. S1 for Cordell Hull, Wolf Creek, and Center Hill Dams were also ran in DSS-WISE but the results will be included in the next progress report.

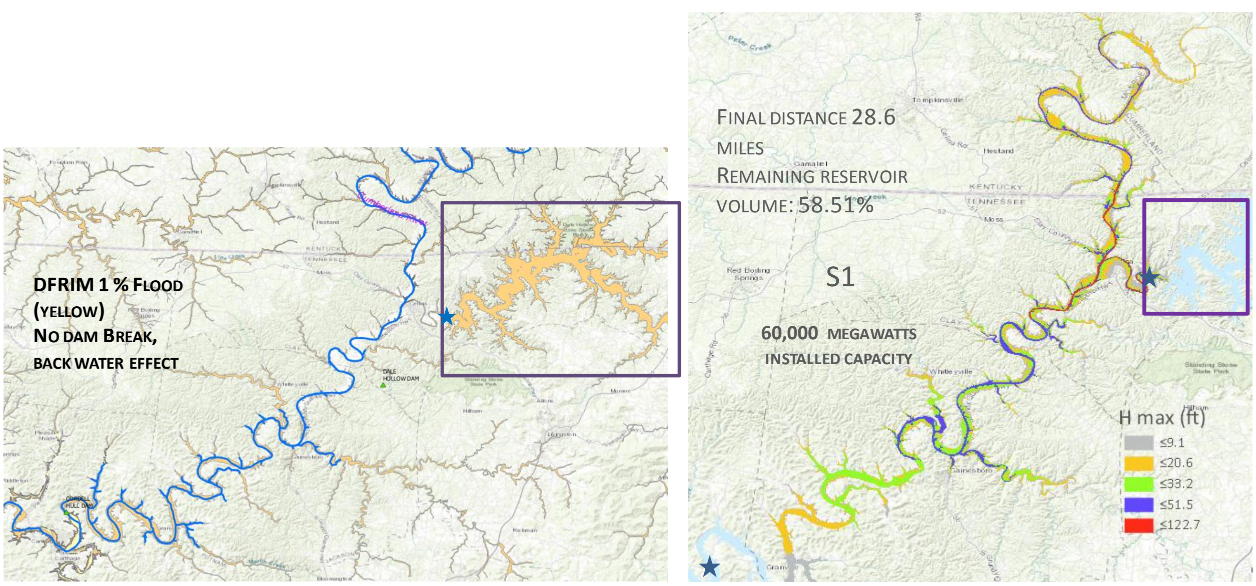

Figure 4 DFIRM I in 100 year flood at Dale Hollow (left) and DSS-WISE results from scenario 1 (complete and sudden failure (right)

Financial loss estimation

The percent inundation is calculated at each census block, and the maximum and average flood depths are extracted from the inundation results. The Hazus database containing the depreciated exposure (in million USD) of buildings per census block is overlaid with the percent inundated area and height. Then, the percent damage of the buildings is estimated with Hazus damage-depth curves, which differentiate by type of building. The loss is the multiplication of the %damage and the building value.

The aggregated results by building occupation are shown in Table 1. Results from S2 were not included because as mentioned previously, the inundation area needs to be reviewed. The test case area does not have a large population density. It is important to mention that the loss results included in the DFIRM scenario are not adjusted to depth, therefore this assumes that all buildings are a complete loss which is an overestimation. Additionally, because DSS-WISE cannot simulate backwater effects during flood conditions (seen in Figure 4 left), the inundation behind the dam would have already occurred prior to the failure and therefore the estimated losses of the dam break scenarios are higher. Overall, there is a bigger difference between DFIRM losses and those incurred from a dam break but the process of loss estimation still needs to be refined to reflect this, and also include indirect costs.

Table 1 Building damage losses on the affected counties in Tennessee in million USD

Scenario	Total	Residential	Commercial	Industrial	Agricultural	Religious	Government	Education
S1	196.22	101.14	41.03	24.68	0.59	8.01	8.63	12.15
DFIRM*	139.12	72.46	48.81	7.37	0.94	3.39	2.18	3.97
S3	166.42	84.29	34.16	23.11	0.33	6.65	7.69	10.19

** DFIRM losses are not adjusted to depth so in reality they would be less than this (this assumes complete damage).*

CONCLUSIONS

- There is great uncertainty in the financial exposure estimation of a dam break depending on the model, parameters used, and in the consequences database. However this preliminary approach gives an indication of how the financial consequences of dam failure can be much greater than the estimated DFIRM.

- This was a period dedicated to understand and test the tools available to calculate the probability and consequences of a dam failure. Many programs were needed to perform this analysis (HEC-HMS, DSS-WISE, ResSim ArcGIS Pro, R, and Hazus), some of them slow and unstable or requiring intense data manipulation. The process has to be streamlined to be able to analyze multiple dams and achieve the scale desired in this project.

NEXT STEPS

- Refine the loss estimation procedure to include indirect costs and consider backwater effects. Obtain flood depth from DFIRM maps when available to adjust the loss estimation.

- Test the methodology to obtain the probability of overtopping using precipitation – runoff models. Continue the test case of Cumberland River Basin using USACE's HEC-HMS model.

- Model the probability of cascading effects using the recently acquired ResSim model from USACE's Cumberland projects and the HEC-HMS.

- Device a way to streamline the process to make it faster and require less software.

Acknowledgments

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References

FEMA flood map service: HAZUS https://msc.fema.gov/portal/resources/hazus

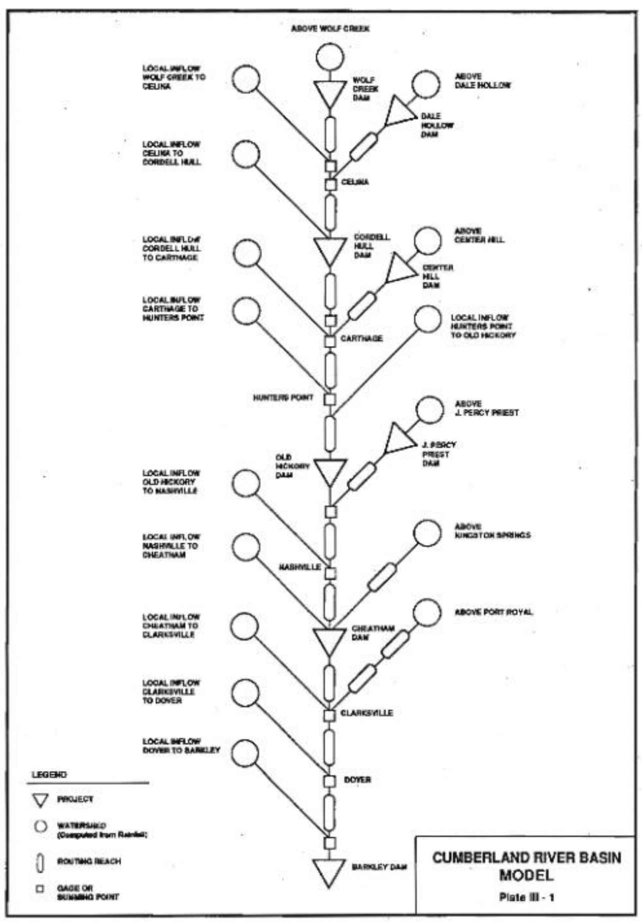
Dams Sector: Estimating Economic Consequences for Dam Failure Scenarios, US Department of Homeland Security, September 2011

Golder (2017), Inventory and Assessment of Dams in Newfoundland and Labrador Year Two

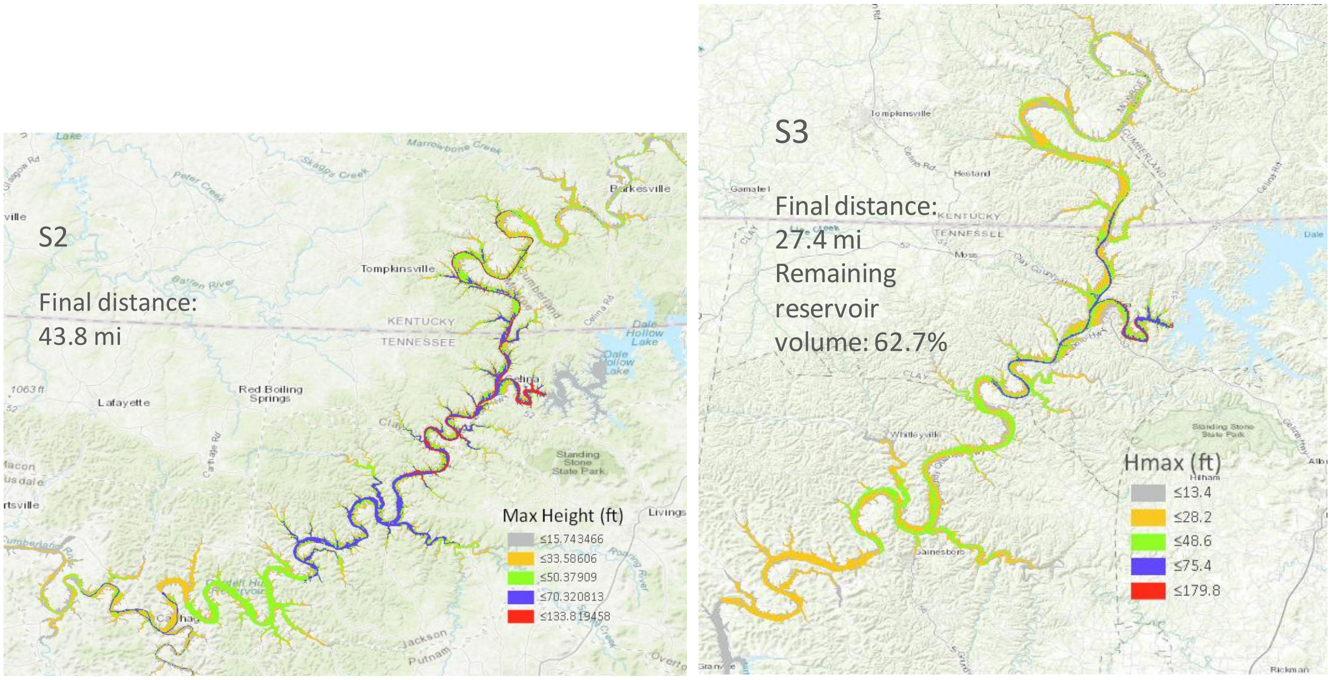
After Action Report: May 2010 Flood Event Cumberland River Basin, 1-3 May 2010, Great Lakes and Ohio River Division https://www.hsdl.org/?abstract&did=21310

DSS-WISE TM Lite: Web-based Automated Dam -Break Modeling/Mapping, FEMA Fact Sheets, https://dsswiseweb.ncche.olemiss.edu/index.php

Appendix



A1. Diagram taken from: the Master Water Control Reference Manual of Cumberland River Basin, USACE



A2. DSS-WISE results for scenario 2 (left) and scenario 3 (right).