Columbia Water Center
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ASSESSING THE HAZARD AND EXPOSURE OF DAMS IN THE U.S.

INTERIM REPORT FOR THE GLOBAL RISK INSTITUTE (GRI)

ADVANCES FROM APRIL – OCTOBER 2019

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OCTOBER, 2019

FOREWORD

We are developing a framework for rapidly assessing the probability and magnitude of the impacts of a dam failure. The concern arises from the increasing intensity and frequency of rainfall under climate change that could lead to the overtopping and failure of the very large inventory (>85,000) of aging dams (median age 67 years vs design life of 50 years) in the USA. A dam failure could lead to a flood that is substantially larger than the 100 year flood that could occur from a rainfall event, and may lead to a cascading failure of downstream electric power plants, bridges, dams, highways, water treatment plants and other critical infrastructure. The approach intends to provide a preliminary ranking of the priority areas of concern and can be generalized to other countries.   An intended application is for a *portfolio level* risk analysis by investors, asset managers, and insurance providers.

The focus of this interim report is on the estimation of the consequences of a dam failure including financial losses, affected critical infrastructure, and population. A framework is proposed to improve the current dam hazard classifications to gain visibility as to the types of risks that could emerge from a failure and to rank the dams as to the level of concern based on disruption and financial loss.

A detailed regional analysis is performed to shed light on the kinds of financial impacts that may emerge as a concern, and for which public data is available. The Cumberland River Basin in the Southern United States is used as an example. This basin has multiple interconnected dams that serve different purposes including electricity generation, recreation, water supply, and flood control.

Dam break analyses were pursued to compare the inundation that would result from the failure of a dam in Nashville, TN., to the FEMA 100 and 500 year flood plain maps

The next stage of the project will focus on assessing the probability of failure by overtopping, which is linked to clustering of extreme precipitation events, long term wet periods, reduction of dam capacity due to sedimentation, and inappropriate design for a changing climate. A discussion of how this would be applied for portfolio risk analysis is provided at the end of the report.

Background

The financial risk associated with the failure of dams is largely unmapped, due in part to the complexity of the chain of events triggered by the failure of a major dam or levee [1], the lack of data [2], and the difficulty of estimating the probability associated with a failure [3–5].

There are over 90,000 dams in the US National Inventory of Dams (NID) [6]. State dam safety programs vary significantly in staffing and quality [7]. The number of dam safety inspectors can be as low as 1 for every 3000 dams in some states. The Association of State Dam Safety Officials estimates that it would cost US$64 billion to rehabilitate all federal and non-federal dams, and the U.S. Army Corps of Engineers estimated $25 billion are needed just to address deficiencies in the dams they operate [8]. In 2019 FEMA's National Dam Rehabilitation Program has a grant pool of $10 million for all dams classified as high hazard potential in the U.S. [9]. By contrast the repair of one of Oregon's dams alone is estimated at $80 million [10]. Other countries face similar challenges.

Given the budgetary and personnel constraints, a method to prioritize funding allocation that accounts for the likelihood and consequence of dam failures is needed. Dam hazard classifications based on probable loss of life, and social and economic disruptions exist in the U.S. but variations among federal agencies and states make it difficult to develop a consistent national assessment of dam hazards [11,12]. In general, the characterization of probable loss of human life in dam hazard classifications is clearer than the potential economic losses and critical infrastructure damage. This is partially due to the accessibility to demographics data and because loss of life is an immediate priority in hazard classifications (as it should be). However, the financial impacts of a dam failure can be quite significant, and these are heightened in extreme events, when other critical infrastructure can fail.

Different approaches have been proposed to improve dam hazard classifications, most notably multi-criteria decision analysis (MCDA) techniques, since they can include variables expressed in different units (monetary, impacted population, damaged infrastructure, etc.);[13–15]). MCDA models rank decision options based on a set of evaluation criteria and the importance of each criterion is represented by weights usually elicited from experts or stakeholders [17], and summarized in a decision matrix. The analytic hierarchy process (AHP)[18] is the most popular MCDA technique in the academic literature for dam risk ranking [15], integrating quantitative and qualitative measures, and personal preferences in performing decision analyses.

In regards to insurance mechanisms to cover flood losses, the US flood insurance rate maps (FIRMs) determine the cost of flood insurance through the National Flood Insurance Program (NFIP) managed by FEMA. NFIP considers the 1 in 100 year flood return period as base to delineate flood areas [19]. The damages of dam failure could potentially be much greater the 1 in 100-year flood area in the NFIP but FIRMS, although available throughout the U.S., does not consider dam failure. We provide an example of the estimated damages in the 1 in 100-year flood zone and 1 in 500-year flood zone with and without including a dam failure for Nashville, TN. FEMA's updates to the flood risk maps typically cost over $2 million per county, so a comprehensive analyses of dam break induced flooding and impacts that cover more than 85,000 dams, in over 3000 counties across the country would be quite expensive (> $6 billion) and would most likely highlight the need for significantly higher additional investments for risk mitigation to cover just the most critical locations. If nothing is done, and some of the more significant dams were to fail, in addition to the loss of life, large damages may occur to downstream critical infrastructure (e.g., other dams, electric power plants and transmission infrastructure, highways, bridges, water and wastewater treatment plants), whose repair and replacement costs would also emerge as an issue. The lack of a comprehensive analysis of this risk, and its securitization mechanisms, is a considerable concern as the confluence of the increasing fragility of the dams, and the increasing risk of high precipitation events, manifests as a higher probability of failure and downstream impact.

A framework to identify "hot spots" beyond the current dam hazard classifications is proposed. The framework uses publicly available dam break and consequence tools developed by the US Army Corps of Engineers (USACE) and FEMA, and national infrastructure datasets. The Decision Support System for Infrastructure Security Lite (DSS-WISE™Lite)[20] is used to simulate dam failures to estimate the inundated area and the affected population. The building inventories and depth-damage curves in FEMA's

Hazard-US (HAZUS) software are used to estimate the direct financial losses. Other national databases of critical infrastructure are also used in the analysis. The AHP method is applied to obtain the dam hazard ranks considering the following decision criteria:

C1-Direct economic losses - Includes the depreciated replacement costs of residential, industrial, commercial, government, religious, and agricultural infrastructure, and the dam replacement cost. These are estimated with building inventory databases included in FEMA's Hazard-US (HAZUS) software, and an approximation of dam replacement costs as a function of storage [23]. HAZUS is computationally and time intensive and an ArcGIS license is needed to use it, therefore the loss estimation analyses proposed in the framework were executed in the open-source software R, extracting datasets from HAZUS and using the depth-damage functions from the R package called Hazus [24].

C2 -Economic risk of infrastructure – Number of utilities with damages greater than 40% including wastewater treatment plants (WWTP), power plants (PP), Airports (Air), and electric substations (ES). These were obtained from national infrastructure datasets. Replacement costs for these infrastructure were not available nationwide, but the number of buildings with high percent damage can inform the prioritization of insurance providers, property owners, and government officials.

C3-Miles of major roads and railroads – Obtained from national datasets. This estimation does not consider the inundation depth.

C4-Tons/day of commodities in affected navigation routes – obtained from national datasets.

C5- Number of other dams and sites with potential hazardous waste defined under the Resource Conservation and Recovery Act (RCRA) referred as RCRA sites.

C6 -Affected power generation in megawatts – obtained from national datasets.

C7-Affected population – obtained from the human consequence module included in DSS-WISE™Lite.

We introduce the dam break-financial consequence framework using a test case in the Cumberland River Basin, that lies in the Southern USA and drains the western slope of the Appalachian mountains. This basin has multiple interconnected dams that serve different purposes including electricity generation, recreation, water supply, and flood control.

Lastly, we discuss how clustered extreme events can lead to multiple dam failures within a region, including cascading dam failures, and indicate how this may translate into a fat tail risk for regionally invested insurance portfolios.

Description of the study area

The Cumberland River Basin (CRB) extends in parts of Kentucky and Tennessee. There are 352 dams within the basin and 107 of them are classified as high hazard. The ten largest dams in the CRB are operated by the USACE as an integrated system. All of them are classified as High hazard potential in the NID, but the specifics of what is at risk is not clear from this classification. Figure 1 shows the connectivity of the dams. The biggest urban center in the basin is the city of Nashville.

Rankings were estimated for five of the ten USACE operated dams: Center Hill, Cordell Hull, Old Hickory, Dale Hollow, and Percy Priest.

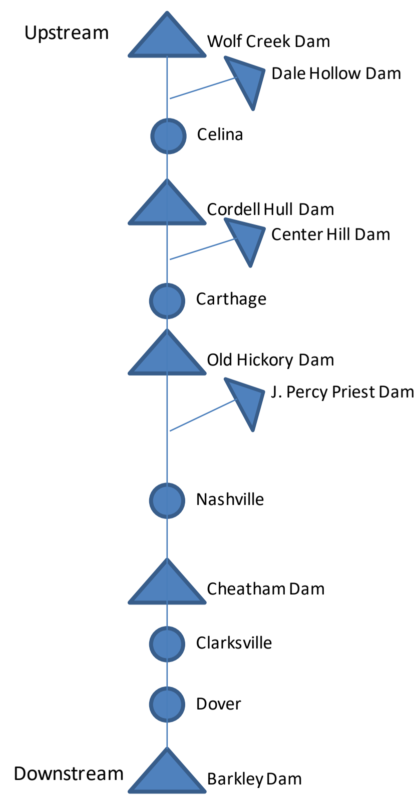

Figure 1 Diagram of USACE dams in the Cumberland River Basin. Image modified from [21]

Results

Figures 2 and 3 show the criteria results for each dam. In general, the failure of J Percy Priest Dam scores higher across the criteria because of its proximity to the city of Nashville, however some criteria such as the dam replacement cost, impacted megawatts, and the presence of dams within the inundation area are higher for other dams.

The final hazard ranking in descending order is J Percy Priest, Center Hill, Cordell Hull, Old Hickory, and Dale Hollow Dam, assuming equal weights for the criteria. This ranking is sensitive to the chosen weights and a sensitivity analysis on the weights could be performed.

Overall, this framework provides better granularity of the exposure than the current dam hazard classifications. All the dams in the test case are ranked as High Hazard in the NID, however as seen in the results, the individual consequences of failure are not the same across them.

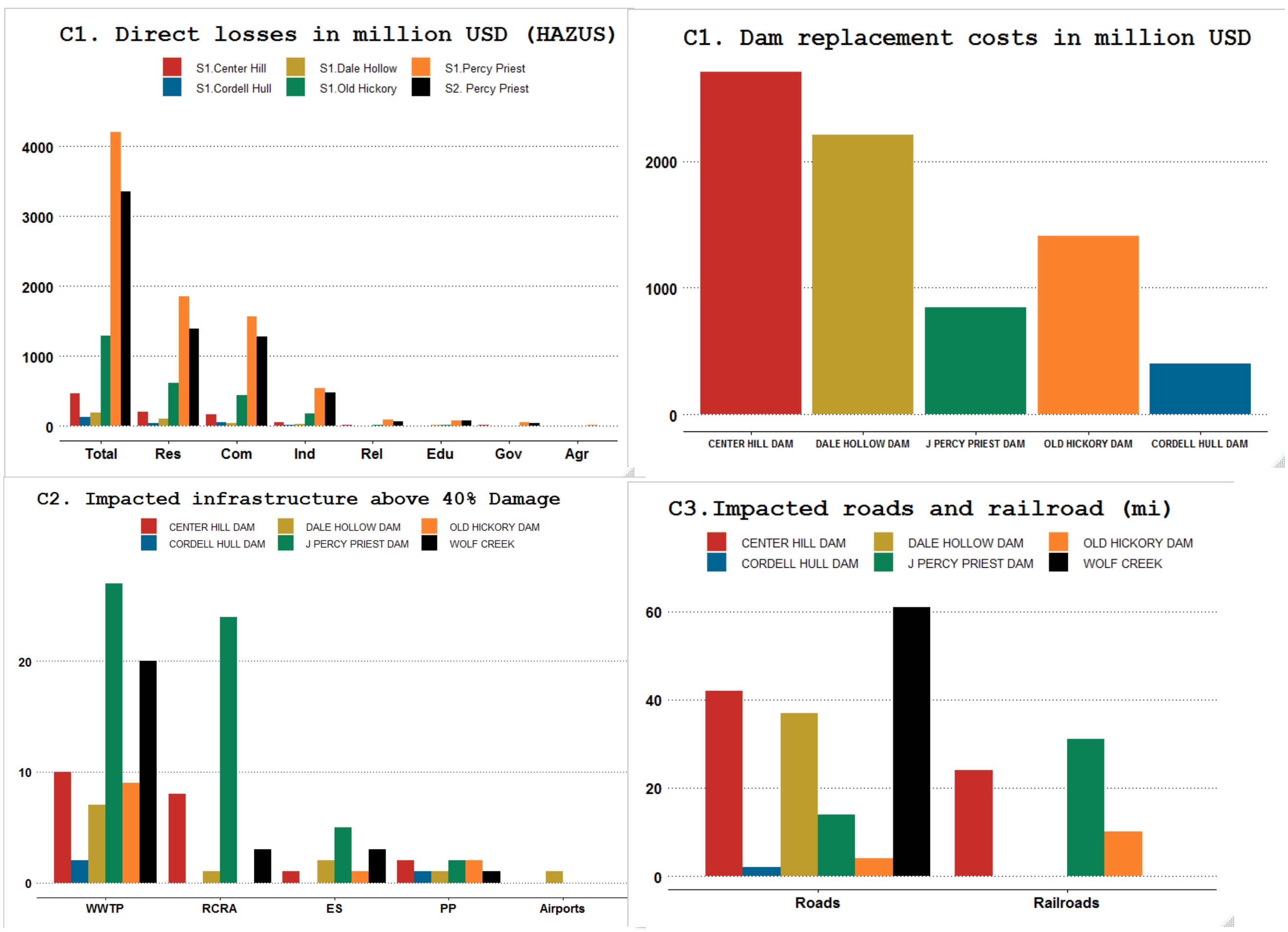

Figure 2 Results of the decision criteria C1-C3.

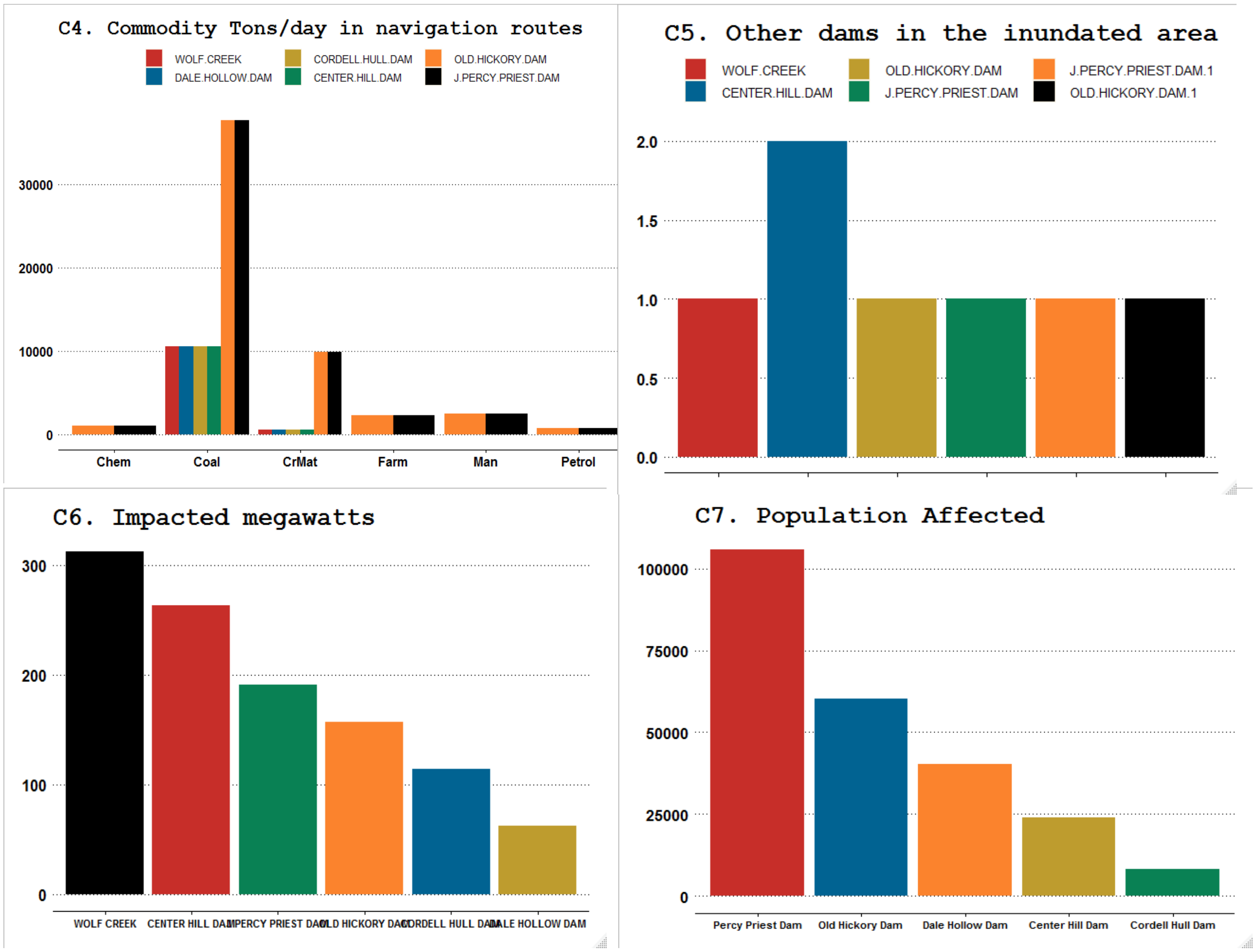

Figure 3 Results of the decision criteria C4-C7.

Analysis of losses using FIRMs (1 in 100 years and 1 in 500 years) and J Percy Priest failure in Nashville

The objective of this analysis was to put into perspective the differences in damages and insurance needs included in the flood inundation rate maps (FIRMs) and those resulting from a dam failure. Given that J Percy Priest has a higher hazard ranking than the other dams, we used its inundation area to compare it to the flood maps. We constrained the analysis to the boundaries of Nashville's Urban Service Districts for comparison purposes, given that it is the largest urban area in the test case region. The infrastructure within the FIRMs (nominal 100 year and 500 year floods) in Nashville was compared with the inundation area of Percy Priest's Dam failure *plus* the FIRMs areas. This analysis only considers criteria C2 to C6. The flood insurance rate maps obtained for Kentucky did not include flood depth for most of the areas, so in this crude comparison we only take into account the number of facilities within the inundation zone without estimating damages as a function of inundation depth. It is evident from the results in Table 1 that the potential damage in electricity supply, wastewater treatment plants, and losses associated to commodity trading in impaired navigation routes could be much greater than the FIRM maps alone. The exposure of hazardous sites (RCRAs), electric substations, and damaged miles of major roads and railroads is also greater. The commodity most impacted would be coal (Table 2), which in turn could affect other sectors. This shows that damages incurred by the failure of J Percy Priest dam would be greater than those considered in the FIRM zones, which could likely be uninsured.

Table 1 Infrastructure affected in Nashville in different inundation scenarios

Inundation Extent	MWs	WWTPs	Roads (mi)	ES	Railroad (mi)	RCRA sites	Tons/day in Navigation route
DFIRM 100 year flood	0	16	2.3	6	6	1	0
DFIRM 100 year flood	0	28	4.3	12	14	4	0
DFIRM 100 year flood and Percy Priest Dam	33.8	52	7.8	14	20	6	53,987
DFIRM 500 year flood and Percy Priest Dam	33.8	54	8.4	16	21	6	53,987

*MWs=Megawatts, WWTPs=Wastewater treatment plants, ES=Electric substations, RCRA=hazardous sites

Table 2 Commodities (in ton/day) transported in the affected navigation route**s** in Nashville in case of failure of Percy Priest**.**

Coal	Petrol	Chem	CrMat	Man	Farm	Mach
37,674.6	724.5	1,020.1	9,864.4	2,466.0	2,236.8	0.4

*Chem=Chemical materials, CrMat=Construction materials, Farm=agricultural products, Man=Manufactured goods

The Portfolio Risk Perspective

From a portfolio perspective, particularly for correlated risks such as dam failures that result from extreme weather events or prolonged wet spells within a region, risk scoring methods may not be appropriate [22]. Funding allocations in this case need to have a portfolio approach instead of looking at dams separately. The same applies when setting insurance premiums or analyzing investments. Optimizing the selection of risk- reduction opportunities as a subset or portfolio (be it as funding for dam maintenance or in investments) is more effective for risk reduction per resources spent than scoring when correlated consequences are involved[22]. The optimization has to consider the interdependencies of risk reduction activities.

Consider a portfolio of dams and/or other critical infrastructure elements whose failure could lead to a cascading failure of other systems with some probability. For assessing the risk profile across such a portfolio, one needs to consider the combinatorial probabilities for the joint failure of each set of assets at risk, and the subsequent impacts of such a failure. In the specific case of interest here, the river system can be considered as a convergent, dendritic (or tree like) network. As illustrated in the representation in Figure 1, several of these dams are located in "parallel" on this network, i.e., there are no other dams upstream of them (e.g. Dale Hollow). Others, are located in series, i.e., one or more dams are upstream of a dam of interest (e.g. Cordell Hull, Old Hickory Dam). Dams that are in parallel, may or may not experience an overtopping event simultaneously, with a certain probability. For K such dams, the probability of two or more experiencing such an event can be derived based on regional precipitation and streamflow data, and used with the potential probability of failure on overtopping, to assess the joint probability distribution of failure of multiple such dams. A regional extreme precipitation event is of concern in this case, and these probabilities would be derived from the associated data. For dams in series, one needs the conditional probability of overtopping of the downstream dam, given that one or more of the upstream dams has failed (or not). This can also be derived from regional precipitation or streamflow records. Once these are estimated, one can examine all potential failure pathways in the portfolio, and score the probability and the potential loss associated with each pathway to derive a probability weighted measure of portfolio risk. Within the portfolio, one could identify the network links that contribute the highest expected loss along each of the metrics defined earlier. This procedure would then provide a mechanism for aggregated and disaggregated portfolio risk analysis that builds directly off the site level analysis presented earlier.

Closing Remarks

The objective of the first part of the project was to develop a framework to estimate the consequences of a dam failure. The next stage will focus on the portfolio risk approach discussed in the previous section. At a national scale, we do not expect cascading failures across different river basins. However, positive and negative correlations in extreme rainfall exist across the country, and these correlations could be used to assess the annualized portfolio risk across a set of dams at the national scale. However, at the moment we are not taking this into consideration since we believe that river basin level analyses are of more direct interest in terms of regional economic development.

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