Assessing the Exposure of Critical Infrastructure and Other Assets to the Climate Induced Failure of Aging Dams in the U.S.

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A changing climate presents us with the potential for more frequent and more intense precipitation extremes and hence an increasing risk for floods and droughts. Dams and levees have been used as one of the measures for flood control, and dams are also used for buffering drought risks. **However, the flood retention capacity of dams and levees has the risk of being overwhelmed by the increased frequency and intensity of floods. This combined with reduced storage due to sediment buildup, structural aging, poor maintenance, faulty design, and development in floodplains has increased the risk of dam and levee failure, and the subsequent impact on critical infrastructure and populations that are downstream.** These risks are largely unpriced at this time.

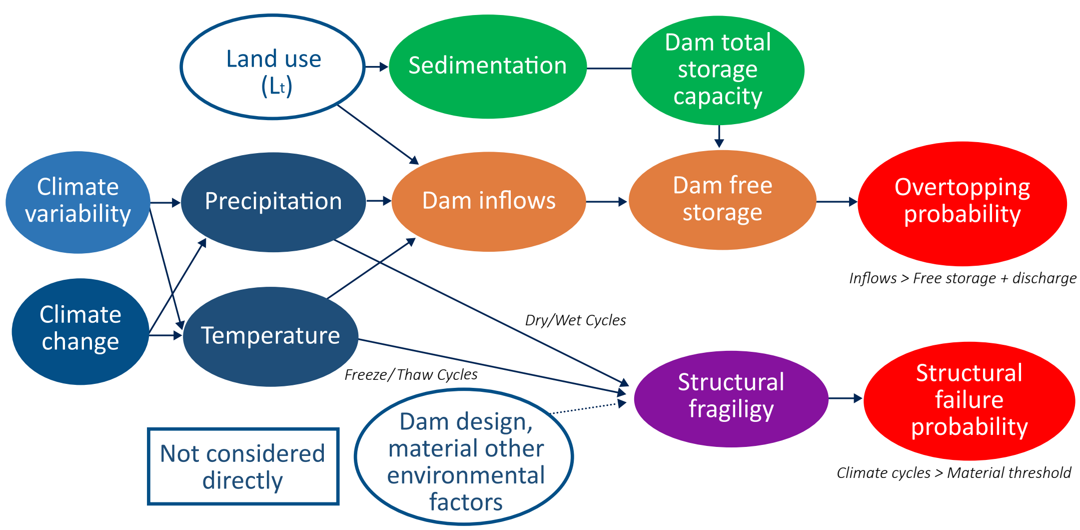
Recent floods and dam failures in Canada have shown the catastrophic social and financial impacts that these events can have. In 2019, extreme rainfall and snowmelt led to flooding of the Muskoka River, and a dam in Bracebridge overtopped[1]. Residents of the area suffered $900-million in damages and local politicians complained that the water management plan was outdated; there were two 1 in 100 year floods in six years[2]. In 2017, excessive rainfall caused Lake St. Louis to exceed flood stage and breach dikes, flooding large areas near Montreal[3] and elsewhere in Quebec. Water releases from the Moses-Saunders Power Dam caused downstream damages all the way to New York State and lawsuits ensued[4]. Development in flood plains have increased the exposure to floods and therefore to levee and dam failures. Ste-Marthe-sur-le-Lac is an example of this, where a dike failed and resulted in the inundation of more than 2,500 homes built in the floodplain of a lake[5]. Poor dam maintenance has also led to failures. The dam failure in Chicoutimi in 1996 resulted in the evacuation of more than 16,000 people, 7 deaths, and an estimated CA$1.5 billion in damages; its failure was attributed to poor maintenance[6].

Dam in Downtown Bracebridge Ontario, Sunday, April 28, 2019. Fred Thornhill/THE CANADIAN PRESS

1 https://nationalpost.com/news/canada/armed-forces-in-bracebridge-ont-to-help-battle-rising-floodwaters
2 https://www.theglobeandmail.com/news/toronto/muskoka-residents-seek-900-million-from-ontario-in-water-damages/article31918744/
3 https://www.nytimes.com/2017/05/08/world/canada/montreal-quebec-flooding.html?_r=0
4 https://www.lockportjournal.com/news/local_news/rising-waters-bring-lawsuits-against-u-s-canada/article_70c4c0ce-8038-542a-91e0-a821077e731b.html
5 https://montrealgazette.com/news/local-news/dike-in-ste-marthe-sur-le-lac-was-inspected-but-failed-anyway/
6 https://www.cbc.ca/news/canada/montreal/saguenay-quebec-floods-20-year-anniversary-1.3684983

The potential risk of failure of dams is not established. Neither is the potential impact of the failure in terms of the value of the loss of services provided by the dam, or the downstream impacts on asset, population and reconstruction needs, or the cascading impact across the national and regional economy. In the United States, there is a very large inventory (>90,000) of aging dams with a median age of nearly 60 years, compared to a nominal design life of 50 years. 15,491 of these dams are listed as high risk, indicating substantial impacts if they were to fail. There is concern over the potential failure of one or more of these dams through the dual threat of climate change and increasing fragility, but there are no formal analyses covering even the dams designated as high risk. The research presented here represents the first effort to develop an approach in this direction. **We focus primarily on identifying methods for the rapid quantification of the time-dependent trigger probability for dam failure, and of the critical infrastructure that would be impacted if the dam fails.** We provide context on the pressing situation of dams in the United States, which originally motivated this research. However, the framework we present can be applied to dams in other geographies.

Time-Varying Triggers and Probability



HOW WE DO IT

Inter-annual & decadal predictions.	Long termpredictions.	Yearly storage loss rate.	Flood Volumes	Elevation probability	Embankment Dams
Satistical models using regional climate drivers	Statistical models with GCM-derived climate predictors	From situation surveys	Extreme value analysis **Dam discharge** Elevation-discharge curves	Elevation time series **Dam storage** Elevation-storage curves	SPEI index (Dry/Wet Cycles) **Concrete Dams** Temperature variability

ARE THERE TRENDS? ARE THEY DIFFERENT NOW THAN WHEN THE DAM WAS DESIGNED?

Time-Varying Triggers Consequences — Portfolio at Risk

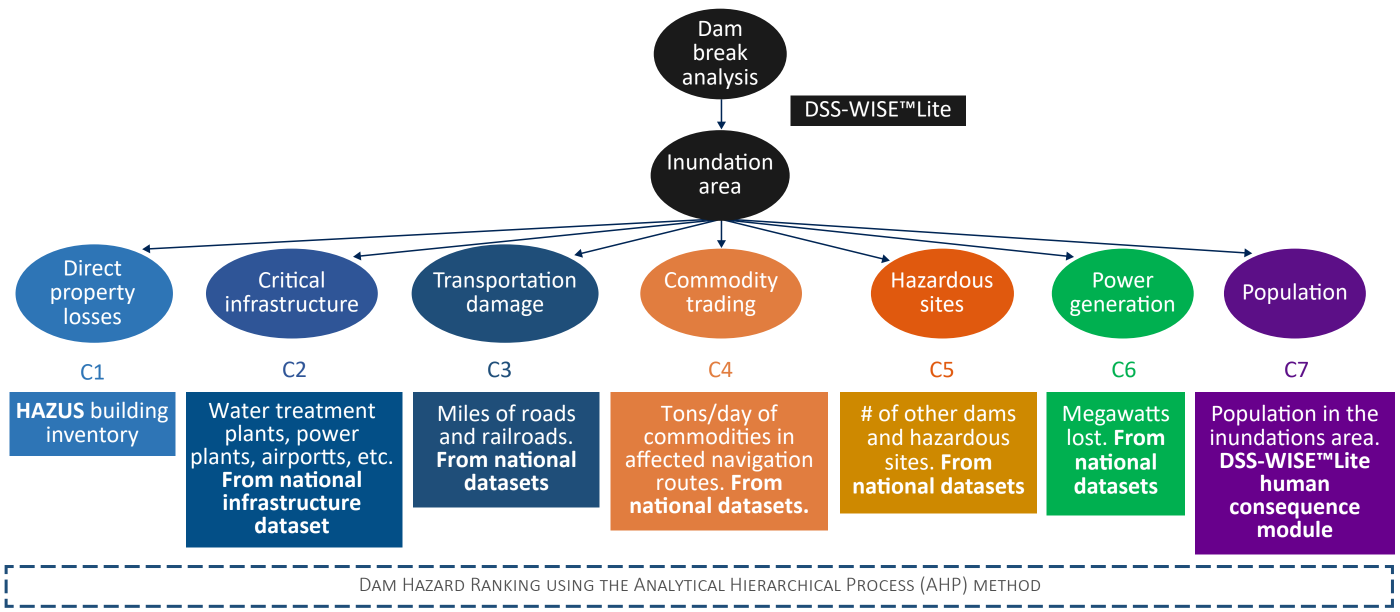


Figure 1. Proposed Framework for the Estimation of the Probability and Consequences of Dam Failures

Using dams in the Cumberland River Basin as a pilot, we show the application of the framework (represented in Figure 1) to quantify the causal network of the climate and age-induced changing risk of dam failures, and prioritize different dams or regions in terms of potential financial impact. This provides the foundation for a comprehensive national risk estimation and prioritization effort for financial and other mitigation actions.

For the dams included in our test case, **we found that there is an increasing trend in the number of events that could lead to overtopping**. **Also storage loss due to sedimentation may be shifting the return periods assumed for critical dam storage elevations** (i.e. the probability of being at the top of the flood storage elevation), which increases the probability of overtopping as even smaller, more recurrent flood volumes can exceed the remaining free storage. We also find that **the 100 and 500-year flood plains usually considered for insurance purposes would likely be overwhelmed by a dam break for several river miles below the dam, and that current dam hazard classifications do not give visibility to the different types of hazards that each of them poses**. In our case study, all the dams were classified as High Hazard, yet the financial impacts of the failure of each of them were strikingly different.

We highlight that at this point, there is no clear understanding of the scale of the economic disruption that would be caused by the dam failures consequent to climate induced triggers. While we are able to provide a preliminary approach to trigger probability quantification, and the mapping of the vulnerability of critical infrastructure, population centers, and toxic waste sites to flooding from dam failure, **the resources available have constrained our ability to develop and test a strategy for the aggregate financial risk faced by the USA nationally or regionally from such failures. An approach to address this challenge would require a quantification of both the life and property losses as well as the supply chain effects and larger scale propagation of the loss of regional services provided by the infrastructure or of the national relief efforts that would result from the disruption, or of the reconstruction needs that are generated. Linkages to economic and valuation models that would allow such a quantification are still needed, and would constitute a contribution to the narrative on climate change impacts, as well as on the national investment needs for aging infrastructure.**

The image below summarizes the data and analyses needed to develop a comprehensive dam risk model that could provide a stochastic catalog of loss for use with financial instruments for risk management or for traditional insurance type of applications. We expect to continue work in this direction, and recognize that a much more substantial effort at data collection and analysis is needed than was feasible in our pilot, which has developed and exemplified a road map and formal approach that can be taken for the analysis.

CLIMATE EXTREMES

ANALYSIS OF EXTREME EVENTS RETURN PERIODS

Regional climate models

Precipitation and temperature data

Streamflow data / dam inflows

DAM FAILURE

PROBABILITY

Dam characteristics, age, sedimentation rate, operational data, maintenance, current physical conditions

INUNDATION AREA

Dam characteristics, dam break inundation model
(very time consuming)

CASCADING DAM FAILURE/FAILURE OF MULTIPLE DAMS IN THE REGION

REGIONAL FINANCIAL EXPOSURE

DIRECT FINANCIAL LOSSES

Infrastructure replacement costs (including dam reconstruction), elevation-damage curves

Agriculture losses

INDIRECT FINANCIAL LOSSES FROM:

Transportation interruption: supply chains, jobs, tourism, etc. loss of dam services
Power cuts
Water/ wastewater cuts
Release of toxic materials

ECONOMIC LOSS PROBAGATION
TO DIFFERENT SECTOR/CASCADING EFFECTS

Model money flow:

Input-output models (I-O)

Computable general equilibrium models (CGE)

Bayesian networks to assess uncertainty and risk propagation

Scenarion analysis of economic development

Costs of inaction