CLIMATE EXTREMES, AGING DAMS & LEVEES AND CASCADING FAILURE IMPACTS

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In October 2015, South Carolina (SC) experienced an estimated 1 in 500 year storm event[1], and 36 regulated dams failed as a result of the storm[2]. The subsequent flooding due to the storm and dam failures resulted in 19 deaths, the closure of all highways in Columbia, and the closure of 120 km of the critical north-south Interstate 95 highway that connects the east coast of the US. Nearly 30,000 people were without power in the state. Damage losses were estimated at US$1.5 billion [2]. In 2016, 20 regulated dams in SC failed during Hurricane Matthew, and 11 more in 2018 with Hurricane Florence.

Aging dams and levees, in combination with an increasing frequency of climate extremes pose an unprecedented risk to communities around the world. The financial risk associated with the failure of such assets is unmapped, due in part to the complexity of the chain of events triggered by the failure of a major dam or levee, and of the difficulty of estimating the probability associated with such a failure. Just in the US, there are over 88,000 dams with height taller than 15 m, and a median age of ~70 years (Figure 1), well longer than the nominal 50 year design life of most of these structures. In 2016, the Association of State Dam Safety Officials estimated that it would cost US$60 billion to rehabilitate all the dams that needed to be brought up to safe condition[3].

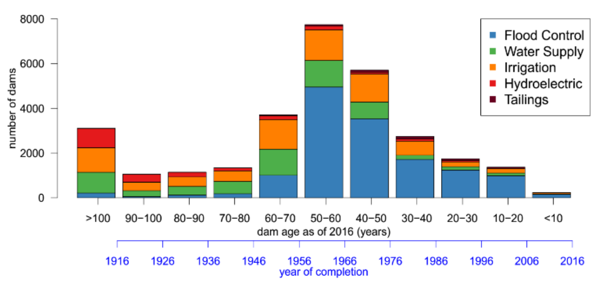

Figure 1 . Age of dams (from National Inventory of Dams database) with primary uses of flood control, water supply, irrigation, hydroelectric or tailings dams.

Nearly a third of the dams fail due to overtopping, an event whose likelihood increases as the potential for severe storms increases. The shear strength of a dam decreases with age, and as more of the reservoir fills with sediment, the capacity for flood storage is reduced. A dam failure can damage downstream assets such as thermoelectric plants, water and wastewater treatment plants, airport, bridges, highways, as well as other dams. The failure of such critical infrastructure can lead to a cascading failure of other critical services such as hospitals, emergency response, and supply chains. Immediate losses can include damage to life and property, but a dam failure can also lead to longer term losses related to access to water, flood control, electricity and transportation services[4], that go beyond remediation and reconstruction costs. Rigorous modeling of the mechanisms of dam failure and exposure is data intensive and time consuming. As a result, much of this risk is not priced and goes without discussion in the context of climate change, public safety, or financial risk management.

The overall goal of the study being conducted by the Columbia Water Center 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 this project, climate risk models are being developed to identify critical events that can trigger a dam failure, including their return period. On the exposure side, existing tools and methodologies developed by US agencies to estimate inundation areas and expected losses are under review to define the optimal applications for our proposed framework (Figure 2). This first report summarizes the objectives and highlights of the study to this point.

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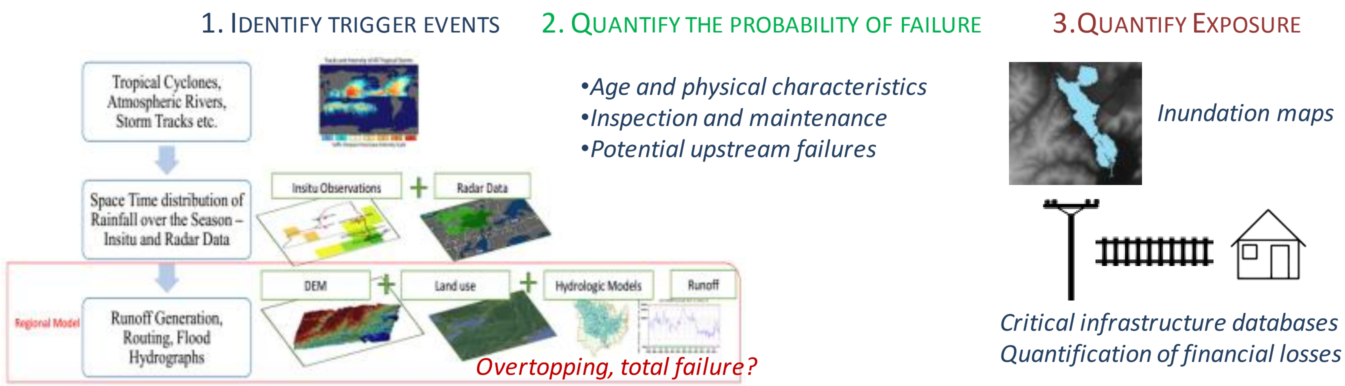

Figure 2. Conceptual framework

CLIMATE RISK

Hydrologic design criteria for dam safety are generally based on local precipitation-frequency analyses or on a single "maximum" event called the probable maximum flood (PMF)[5]. The use of the PMF or a single flood event to evaluate the risk of dam overtopping has been questioned, arguing that in many cases the occurrence of a series of smaller floods has been more damaging, and a probabilistic approach has been proposed as an alternative[(5)]. Globally, overtopping is the leading cause of dam failure.

In the US, overtopping has been identified as a risk for some federally managed dams (e.g. Addicks Dam near Houston, Texas[(6)]), or is being addressed through upgrades (e.g. Folsom Dam[(7)]).However, only about 3% of dams in the US are federal and the status of updated risk analyses for the non-federal dams is not clear. Additionally, many dams were designed using relatively short instrumental climate records, and may be at risk of being under-designed if the period of record considered in the analysis of the flood event was anomalously dry.

The existing and projected risks of storms that could result in overtopping and catastrophic dam failures justify an investigation of their characteristics (spatial and temporal), causes, and predictability.

In our study, we consider rainfall events ranging from a single high intensity event to recurrent and persistent anomalous rainfall over a season or longer. Such rainfall events could stem from a variety of atmospheric drivers (e.g. hurricane induced events in the east and large scale moisture transport through atmospheric rivers in the west). The failure of the spillway of the tallest (770 ft) US dam, Oroville, in February 2017 corresponded to overflows generated by persistent rainfall, rather than one extreme event. Nearly 200,000 people were evacuated and the cost of repairs has exceeded $1 billion. An animation of the impact if the spillway had fully failed has been developed by UC Irvine and the Sacramento Bee.

To explore the triggers of regional extreme events, we analyzed their connection with large-scale climate patterns such as moisture transport. A CNN (Convolution Neural Network), which is a deep learning model, was developed to predict regional extreme rainfall from global patterns of moisture transport. Assessing how the risk of storms that lead to overtopping changes over space and time can improve risk characterization, reservoir management, and flood insurance pricing[(8)].

EXPOSURE

Apart from climate variability and change, dam failure risks have been heightened by increased development in flood plains[9, 10] as changes in land use increase runoff peaking and volume[8]. Additionally, some socio-economic processes, like population growth and economic development, may change at a faster pace than long-term physical changes such as climate change[11]. This translates into a dynamic change in the exposure for populations and infrastructure networks. For example, if the Folsom Dam in California failed, critical highways, power production, water supply, and oil and gas facilities could be impacted. In this region an earthquake rather than an extreme rainfall event could be the trigger for failure. Consequently, it is useful to separately analyze exposure on failure and triggers of failure.

Multiple approaches have been developed to estimate the exposure and expected losses of dam failure [12,13,14,15]. Hazus is FEMA's methodology for estimating potential losses from disasters, such as floods. It uses geographical information systems (GIS) to estimate the physical, economical, and social impacts of natural disasters [13]. Assessing the short term property loss and impact from dam failure flooding can be accomplished using a Hazus-like approach. However, the long term loss of water supply and flood control, as well as loss of use of ancillary infrastructure that is impacted needs innovative methods to price and value [14].

State dam safety regulations usually require indundation maps to be provided for only a specific dam failure scenario[16] . The perspective of most dam-risk studies is typically to do a flood risk analysis of a specific asset. A critical extension of past work in loss estimation is that we are interested in assessing portfolio risk as manifest in multiple events occurring over a designated portfolio in the same year. Clustering of flood events increases the likelihood of a high number of damage claims within a short period of time[11]. Consequently, instead of just looking at the event and loss analysis at a given asset as has been the focus in past studies we are developing a model that will look at the joint probability of trigger events across all sites of interest in a portfolio, and then deriving the probability distribution of the joint loss. This aspect is most relevant from a financial risk perspective to the holder of a set of policies covering these assets or from a catastrophic fat tail risk perspective.

The next phase of this study will continue the development of the rapid loss assessment methodology including test cases. We will follow these steps:

1) Consider the 1/100 and 1/500 year inundation maps provided by FEMA- they exist almost everywhere in the US and hence are a useful benchmark.

2) Identify assets that lie in these inundation zones – critical infrastructure elements such as bridges, airports, highways, power plants, dams, levees, water /wastewater treatment plants, major power transmission /transformer stations etc. Nominally the risk associated with their flooding is 1/100 or 1/500, but usually a fact that is usually overlooked is that that if an event happens along a river all of them experience that event at the same time.

3) Consider that climate change/variability translates into clustering of extreme events in space and time and increases in their frequency, at least for a few years - i.e., the risk may be much greater than 1/100 or 1/500 years. This analysis integrates the climate risk models mentioned previously.

4) Assess the added impact of dam failure by overtopping. We will assume that the river below a dam is at least at bank full stage and in flood (the inundation is already in the 1/100 year zone), and a relatively rapid release of the volume of the dam occurs. The questions we will address are: when the dam fails, how far below does the inundation reach? The 1/500 year inundation or further? If there is a dam downstream of the first dam, what happens if it also fails from overtopping? This will be

demonstrated through a few cases of modeling in representative channels with simplified assumptions.

5) For each dam in question, quantify the total MW of power, m^3 of water/wastewater capacity etc. and estimate the economic losses (direct and indirect) of each type of impact. We will use Hazus and the DHS recommended approach[13,14] for this estimation.

At the moment of writing this report, we have collected precipitation and streamflow data, digital elevation models (DEMs), infrastructure data (power plants, highways, water and wastewater treatment plants), and FEMA's inundation maps. We acquired data for 22,904 rainfall stations (GHCN) and 23,494 streamflow gages (USGS). We developed the CNN model for extreme rainfall.

A preliminary assessment of New York State's exposure to dam failures was started. 5,800 dams, power plants and wastewater treatment plants were mapped along FEMA's inundation areas for New York State (Figure 3). Individual dams were classified using a risk score based on the potential severity of damages caused by their failure, with and without considering the cascading effect of failure from upstream dams. With this effect, the number of dams in the Low, Medium, and High hazard increase (Figure 4). Power shortages were also estimated from the 1/100 and 1/500 flood maps. We will continue with the assessment of dam failure, and the estimation of economic losses.

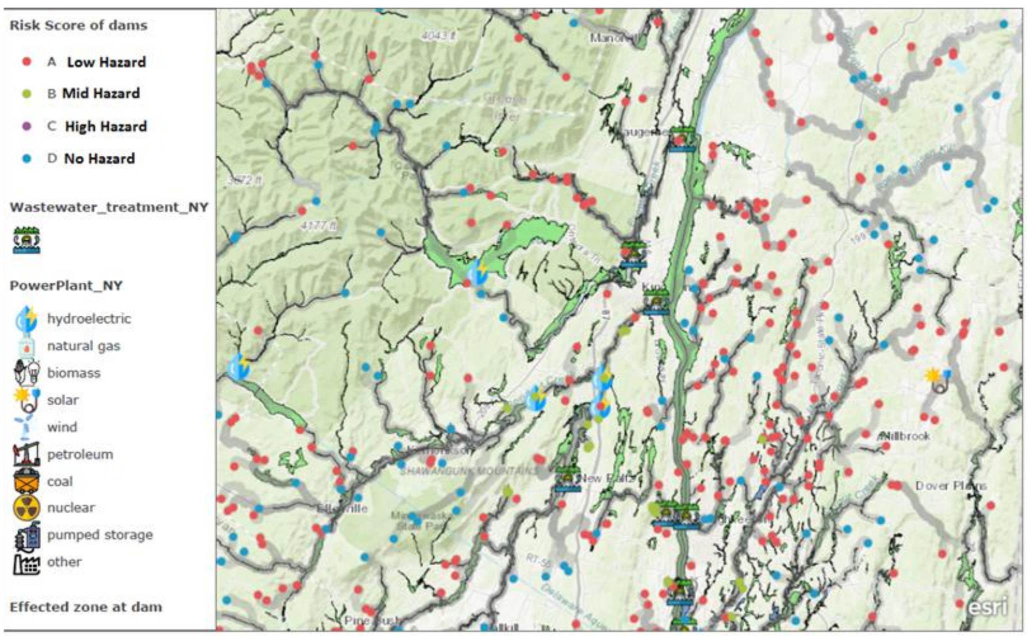

Figure 3 Dam risk scores, inundation areas and critical infrastructure at risk (NY state sample).

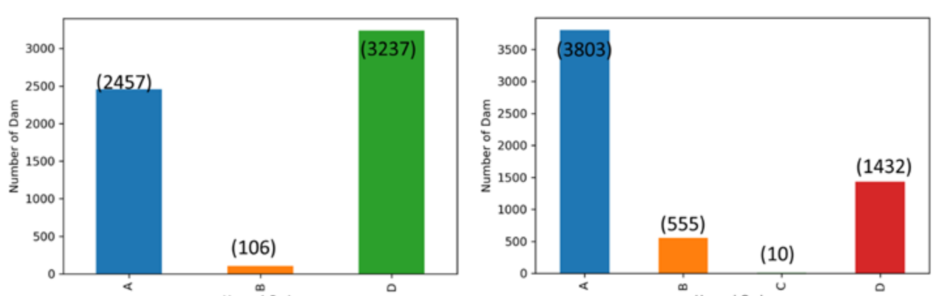

Figure 4 Risk score; no cascading effect (left) and cascading effect (right)

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SUMMARY

The failure of aging dams and levees constitutes a significant risk for downstream communities and critical infrastructure. We are developing a multi-pronged approach to rapidly identify the potential financial exposure from existing dams, in case they failed. This entails the identification of critical assets at risk in the event of failure using available data sets from public sources as well as satellite remote sensing. A simplified approach for exposure assessment that allows a rapid indexing of the potential financial exposure without the need for detailed hydraulic modeling and scenario analysis is being piloted, recognizing the large number of dams across the country, and in Europe that may be at risk. Preliminary applications of this idea to the state of New York, have resulted in a hazard impact rating for each dam and each county at risk. This analysis is being verified and tested.

Separately, we have developed methods for the assessment of the risk of precipitation events that could lead to overtopping of dams – one of the dominant risk mechanisms. The idea here is to focus on the atmospheric mechanisms of concern, so that the changes in the probabilities of these mechanisms under climate change or clustering can be identified and used to assess the potential change in risk.

A third part that is important is to assess the state of each of the dams so that their propensity for failure (not just age) due to the state of maintenance can be assessed. We have not found a data base or an approach to do this at this time, and are still exploring options. The recent failure of tailing dams associated with a Vale operated mine in Brazil highlights that even where dam safety inspections have been performed and the dam was certified as safe, a catastrophic failure can occur. Our current thinking is that given the difficulty of getting a reliable assessment of the safety condition for a dam, an approach that focuses on exposure and vulnerability based on data driven metrics, may be more useful in any case, as part of the development of a financial securitization recommendation. The potential losses from dam failure impact can easily reach a threshold that makes sense from the perspective of Insurance Linked Securities or Parametric Insurance products, and defining the parameters for such a product may motivate better disclosure on asset condition, especially if the pricing assumed that the dam failure impact needed to be fully insured.

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