# Vulnerability of large dams considering hazard interactions
## Conceptual application of the Generic Multi-Risk framework

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ABSTRACT: The potential risks associated with dams are often kept in check through the adoption of demanding design criteria, frequent surveillance efforts, and the commission of maintenance and retrofitting operations. Although this approach's effectiveness is time-tested, it circumvents the probabilistic characterization of the system's response to different hazards and, to an even greater extent, to their combinations (multi-risk assessment). This background poses a challenge when the goal is to quantify the risks associated with a given infrastructure or to identify critical chains-of-events.
The Generic Multi-Risk (GenMR) framework is a probabilistic technique based on the sequential Monte Carlo method and the hazard correlation matrix concept. It presents a powerful and flexible way to characterize the often broad range of risks associated with complex systems. The present work takes advantage of the GenMR framework's capability to cope with the difficulties underpinning the assessment of the risks associated with a large dam system and describes its conceptual application. In order to simulate the system and estimate the contribution of hazard interactions to the overall risk, it accounts explicitly for the probabilistic nature of the problem, the evolution of reservoir volumes, and the state of the main system's components as they are affected by individual and/or multiple hazards.

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# Introduction

Large dams are complex, dynamical structures, with reservoirs often retaining massive volumes of water. If, on the one hand, they yield noteworthy benefits to society and the economy, on the other hand, they can entail acknowledgeable risks.
Professionals familiar to dam design, operation, surveillance, and maintenance have for long been aware of such risks. Arguably – with a reduced number of disasters set aside – they have been very successful in guaranteeing the integrity of the both the large structures and their reservoirs, ultimately protecting the potentially affected areas downstream.
Traditionally, safety design criteria for large dams have been based on deterministic approaches [1]. According to that paradigm, safety is ensured through the detailed study of reference scenarios that the dam system must withstand while guaranteeing prescribed degrees of functionality. Although historically effective in keeping dams safe, the thorough evaluation and adaptation to demanding representative scenarios does not possibly cover all the situations that may lead to failure. Also, it does not lead to a quantitative measure of the overall risk associated with the dam.
Probabilistic methodologies to safety evaluation have also been proposed e.g. [2,3]. They promote quantitative measures of risk and have the potential to provide insight into what are its predominant sources. As such, they theoretically allow for a more efficient allocation of resources in what concerns risk reduction strategies. Mostly, they can be useful when complementing traditional approaches [1].
Probabilistic risk assessments of dams have been carried out resorting to a number of different strategies. Notably, a few well-established alternatives such as event trees, fault trees, or failure modes and effects analysis can be highlighted [4]. Regardless of the chosen approach, fully depicting the risks associated with a large dam is an incredibly difficult mathematical problem and a practically impossible task. Commonly, probabilistic risk assessments focus on a limited number of triggering hazards, as the complexity of the systems tends to grow fast.

Over decades, experts have become very effective at modeling large dam systems' responses to single hazards and use them to increase security. Particularly in cases which have been designed, surveyed, and maintained according to recent recommended practices, dams can be remarkably resilient infrastructures [5]. Still, the dam industry continues the pursuit for ever-improving standards e.g. [6].

As dam design, maintenance, and surveillance evolve and address increasingly well single hazards, the main sources of risk may shift from low-probability high-intensity isolated events to low-probability combinations of lower intensity hazards or chains-of-events. Although this shift in the main sources of risk is to be expected, it can be argued that established tools, such as event trees, are of difficult application when the goal is to evaluate risks associated with low-probability combinations of hazards (e.g. earthquake followed by a series of floods leading to development of internal erosion). Furthermore, the vulnerability and losses associated to a given hazard may depend substantially on the water level in the reservoir at that time. The evolution of the reservoir levels – not easily captured, for example, in event or fault tree approaches – is therefore important to quantify overall risk. Due to these reasons, the investment in additional tools that are adapted to model large dams might be worthwhile.

The present work is part of the *Harmonized approach to stress tests for critical infrastructures against natural hazards* (STREST) project, which aims to develop standardized tools for hazard and risk assessment of low probability-high consequence events that can be systematically applied to whole classes of critical infrastructures.

Applying standardized tools to accomplish a comprehensive evaluation of risks associated with a large dam is challenging on many accounts: dams are essentially dynamic systems; they often pose risks to downstream areas where the potential losses are a function of numerous factors; and risk modeling tools must be both flexible and accurate in order to be on par with highly detailed deterministic safety assessments.

This paper aims to contribute to overcome the aforementioned challenges and explore the application of the Generic Multi-Risk (GenMR) framework [7] to large dams. In order to be applicable to large dams, an adaptation of the original GenMR is proposed and its results are analyzed and discussed for a conceptual large alpine earthfill dam. Focus is placed on the dam system itself, being losses deferred to a later study. In that light, the framework is employed as a means to preliminarily assess the relevance that the hazard interdependence might have in the system's vulnerability.

# Methodology

### The GenMR framework

The GenMR framework is based on a sequential Monte Carlo method and its principles are well described in [7]. It presents a powerful and flexible way to characterize the often broad range of risks associated with complex systems and is particularly well-suited to model hazard interdependencies and coincidences. In short, it conducts multiple simulations of a given system for a chosen period (usually one year), generating random events, evaluating the system's responses to them, computing damages, and assessing losses.

In order to frame the problem, events must be defined in terms of their probability of occurrence, intensity, and timing. The characterization of system elements requires the statement of vulnerability functions, recovery rates, and associated losses. Finally, event dependencies must be stated, notably in the form of an altered probability of occurrence, which constitutes a remarkably powerful approach.

As GenMR addresses low-probability events, it requires that a very high number of simulations is undertaken in order to quantify risks. For complex systems, the computation burden of a executing a full evaluation for each simulation can be overwhelming. Also, it can be wasteful

due to the fact that, in the large majority of the simulations, the low-probability events that may have an impact on the system will simply not occur.
The problem is elegantly solved by performing a two separate evaluations of the system The first focuses solely on the generation of primary hazards and is computationally cheap. The second evaluation, which requires that the full evolution of the system is performed, is only carried out for the simulations which registered at least one primary hazard. During this second evaluation – also referred to as resampling – the system is incrementally evaluated from one event to the next event. At each step, future events that are directly or indirectly dependent of those already observed are resampled. At the heart of the methodology are the matrices that define event dependencies and thus, control the process.

**Description of large dams within the GenMR**
The present work takes advantage of the GenMR framework's capability to cope with the difficulties underpinning the assessment of the risks associated with a large dam. It builds on a preliminary adaptation of GenMR to large dams [8].
Regarding dams as dynamic systems, there was a need to couple a reservoir routing model with GenMR. Resorting to it, the reservoir's volume and outflows are computed at each step of the resampling. As this is done, the functionality of each outflow element of the dam (such as hydropower system, bottom outlet, spillways, or crest), incoming flows (including floods), and operational orders (such as drawdown attempts) are taken into account.
All is coded in terms of events (actions or acknowledgement of an internal state) and elements (objects within the system). Events can be triggered spontaneously (if they have an associated return period), as the result of earlier events, due to specific element states (e.g. a threshold damage of the dam), or as a response to reservoir levels. A scheme of hazards, elements, system states, and interactions considered in the current application of the GenMR framework is presented in Fig. 1.

**Conceptual case study**
As a case-study, the adapted GenMR was applied to a conceptual large Alpine earthfill dam. The maximum supply level was assumed to be 93 $Mm^3$, and uncontrolled spillage starts when the reservoir holds 100 $Mm^3$. The crest is reached at 107 $Mm^3$ and average yearly inflows amount to 120 $Mm^3$. Over 10 000 000 simulations were conducted.
The elements, hazards, and system states considered are shown in Fig. 1. While a more detailed discussion of this conceptual system is presented in [8], some of its key features deserve being mentioned:

- Floods. Peak discharges are characterized by a Gumbel distribution conforming to the hydrology of the region (Fig. 2). As a strong correlation between flood duration and peak discharge was not evident following an initial assessment of catchments in the region, independence between both variables was assumed. The duration was modeled using a log-normal distribution (Fig. 3). The probability distribution of a flood during the year was assumed to be proportional to the expected inflows. A normalized hydrograph approach was used to shape the food (Fig. 4). Finally, it was assumed that the occurrence of rare floods increases the likelihood of smaller flood events taking place during the remainder of the year.
- Earthquakes. Have been quantified based on the Swiss dam safety regulations (OSOA, *Ordonnance sur la Sécurité des Ouvrages d'Accumulation*) [9] and maps of Medvedev-Sponheuer-Karnik (MSK) intensities of ground shaking covering the area. Damages to each element were defined qualitatively and made to comply with Swiss dam safety regulations. Fig. 5 depicts impacts on the dam and foundation (because in the case of earthfill dams the latter is only of particular relevance in specific cases such as alluvial

material, for simplicity the dam and the foundation were aggregated into a single element).

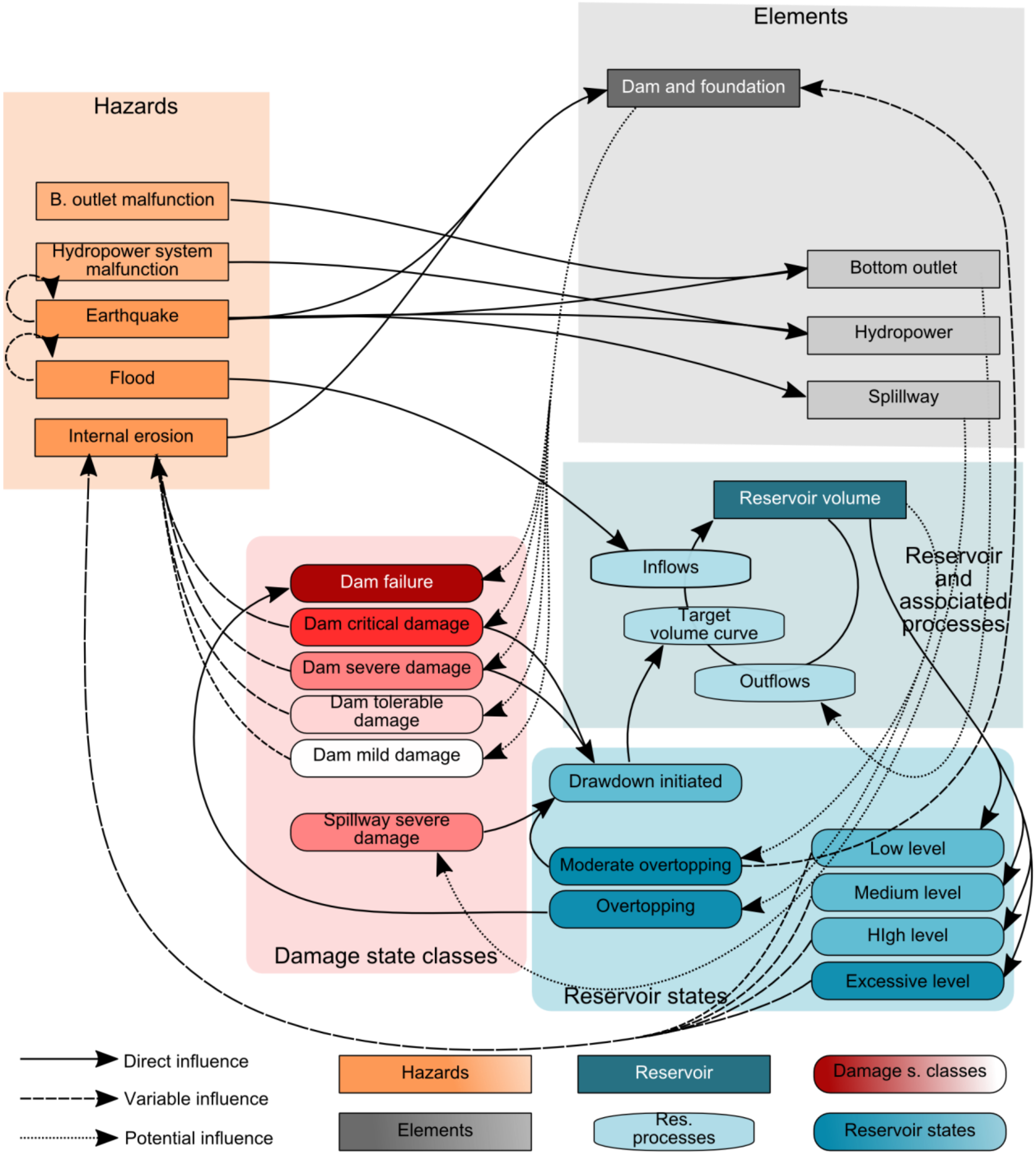


Fig. 1: Scheme of hazards, elements, system states, and interactions considered in the application of the GenMR framework to large dams. Adapted from [8].

- Internal erosion. Although approaches for the quantification of internal erosion in probabilistic risk assessments exist e.g. [10], in light of the multiple factors that affect this hazard and given the small historical record of internal erosion episodes in large dams, the damages to the dam and foundation element following internal erosion events were also defined qualitatively (see Fig. 6 depicting impacts on the dam and foundation). As indicated in Fig. 1, the return period of internal erosion events was made dependent on the damages endured by the dam and foundation and on the level of the reservoir.
- The bottom outlet and the hydropower plant system elements can also suffer damages due to random malfunctions or earthquakes.

- The functionality of outlet structures (maximum discharge) was assumed to be a linear function of their integrity and reservoir levels, but past a certain damage state they cannot be operated.
- The integrity of each element is steadily restored following damaging hazards. Recovery rates were estimated based solely on engineering judgment.
- The simulations start in March, when the reservoir is approximately at its lowest stage. This is done so that the impacts of deviations from target levels due to hazards that might occur throughout the simulated year have an impact on results.
- Hazard sampling in the GenMR framework is discrete. In the present case study primary hazards were sampled in 13 categories. These correspond to return periods from 316 to 1 260 000 years, with return periods roughly doubling at each step.

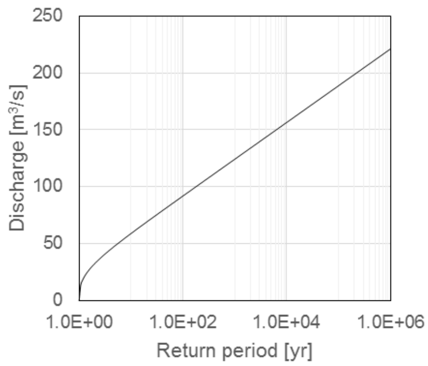


Fig. 2: Intensity vs. return period of the flood.

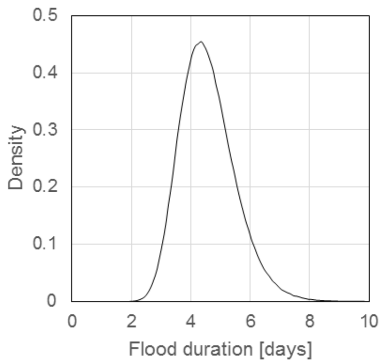


Fig. 3. Pdf of the flood duration.

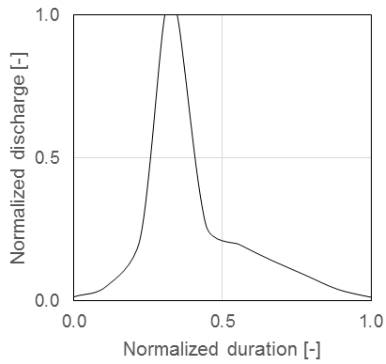


Fig. 4. Normalized hydrograph of the flood.

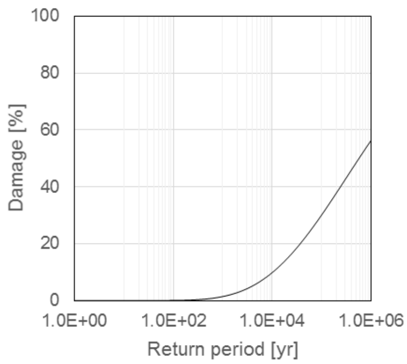


Fig. 5: Damage to the dam and foundation vs. return period of earthquake events.

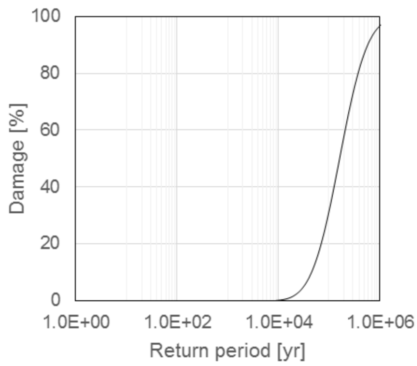


Fig. 6: Damage to the dam and foundation vs. return period of internal erosion events.

# Results and discussion

### Hazard sampling

The first step in the validation of the GenMR application should be to verify that hazards are being sampled as intended. For floods (whose timing changes seasonally) and internal erosion (whose occurrence is dependent on reservoir levels), this is particularly important. As can be seen in Fig. 7 floods tend to occur during the warm months, coinciding with summer storms and melting of the winter snow. Internal erosion episodes are, as intended, related to reservoir levels. The timings of earthquakes and other hazards are uniformly distributed.

Additionally, a check on the probabilities of occurrence of each hazard was made. In order to do so, assumed return periods are compared with the observed ones. Assumptions and observations matched well, the only exception being internal erosion events. The divergence was due to the fact that resampling substantially affects the occurrence rate of internal erosion as levels rise and the dam is damaged.

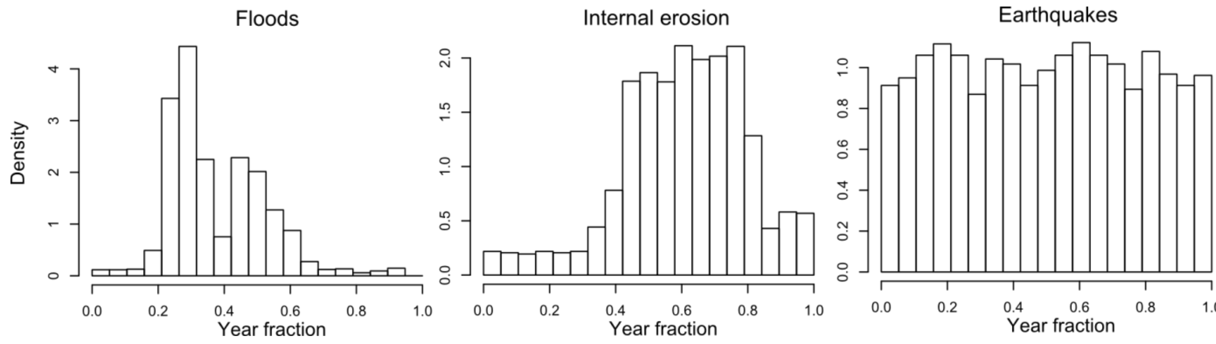


Fig. 7: Timing of flooding, internal erosion, and earthquakes from March to February of the following year.

**System responses**

As the overwhelming majority of the simulations are quite uninteresting, the system's response obtained during GenMR resampling is illustrated below for an artificial combination of two extreme events: a 10 000 years flood that occurs when the reservoir is full, followed by a 5 010 years earthquake (Fig. 8).

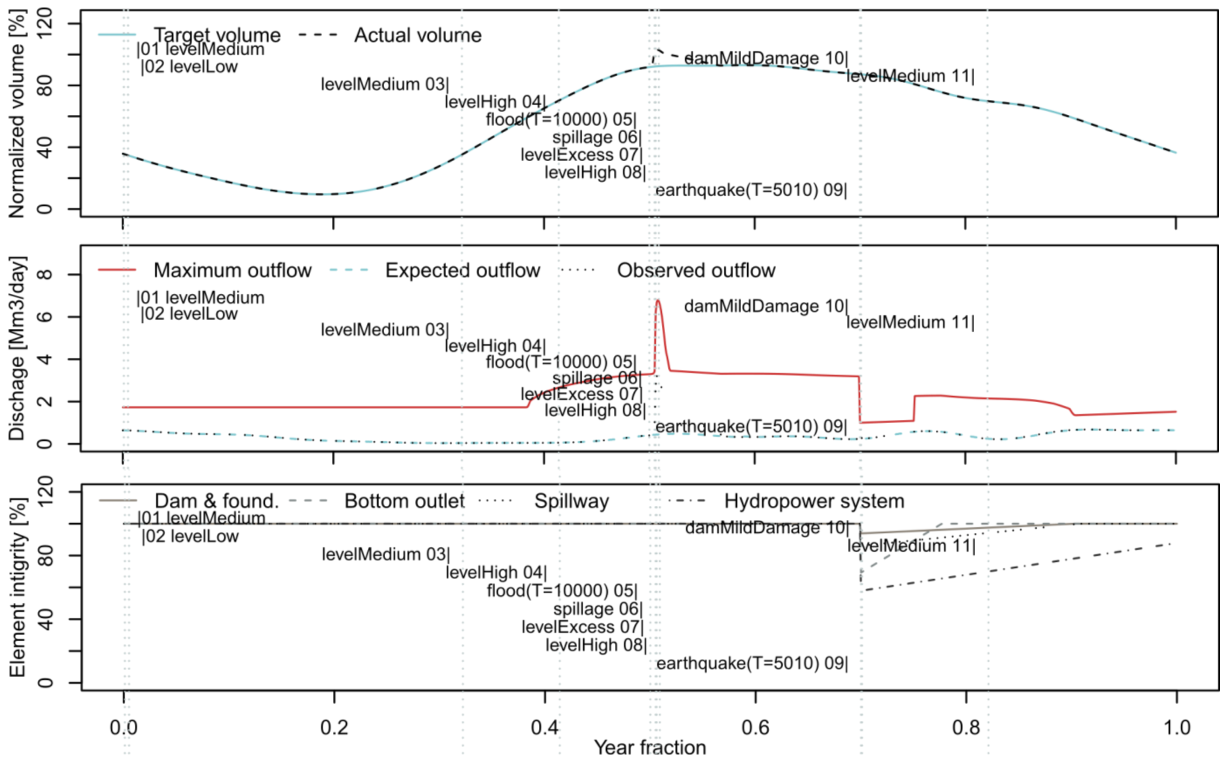


Fig. 8: Example of a system response to extreme events. Top: reservoir volumes (normalized by the initial spillage volume). Middle: outflows. Bottom: element integrities.

Even such an extreme flood, inflowing at the worst possible time, filled the reservoir only up to 103 $Mm^3$. Also, it is worth noting that the earthquake damages all elements, but impacts on the dam and spillway are very limited. Finally, one can observe that the maximum outflow drops abruptly after the earthquake as a result of the damaged bottom outlet and hydropower

system. Notwithstanding, if the water level were to rise above the spillway, the maximum outflow would increase accordingly.
Overall, 5 000 000 simulations of this conceptual system allowed to estimate that the dam is only critically damaged with a return period of about 65 000 years and failures would have a return period close to 100 000 years (well above deterministic design criteria). Due to a large freeboard and an adequate spillway, the return period of overtopping is even higher (over 200 000 years). It is apparent that the most dangerous situations are the result of internal erosion events whose likelihood is increased by earthquakes or excessive reservoir levels.

**Role of hazard interactions**

The role of hazard interactions and the dynamical nature of the system were taken into account. If, on the one hand, design floods and earthquakes can occur when the reservoir is not full, which translates into a system that is less vulnerable to them that what is assumed by traditional design criteria, on the other hand hazard interactions and potentially dangerous chains-of-events are evaluated. Overall, these effects seem to balance each other quite well, with estimated failure rates reasonably close to $1 \times 10^{-5}$.
Considering hazard interactions promotes also a migration of the risk. The phenomena is well described in [7]. For the case of the analyzed conceptual large dam system, the migration is illustrated in Fig. 9, not in terms of risk, but of vulnerability of the dam structure. Each simulation would constitute a point in the plane. Most of the simulations fall in the top left corner (higher frequencies and low damages), but the most interesting part of the plane is its right edge, where damages occur. What is shown in Fig. 9 is a difference between simulations with and without interactions. Through it one may infer that hazard interactions can lead to a raise in the damages produced by low probability events. This equates to hazard interactions motivating a shift in vulnerability and, consequently, in risk.

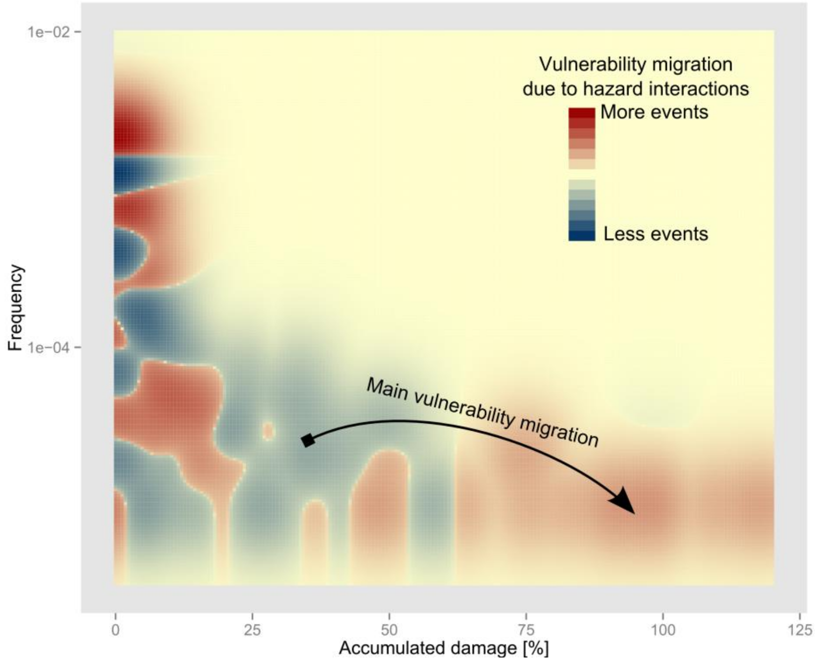


Fig. 9: Migration of vulnerability along the accumulated damage vs. frequency plane due to the consideration of hazard interactions. Adjusted scale evidences rare events.

# Conclusions and future work

The present work set out to apply the GenMR framework to large dams, test the effectiveness of the adaptations to the code, and evaluate the role of hazard interactions, along with the effect of the dynamic nature in the vulnerability of the system. The presented results include a great deal of uncertainty, and any conclusions drawn from them should account for that.

Regarding the GenMR adaptation, results suggest that it can be successfully adapted to large dams, perhaps even with worthwhile advantages over established methods. Though the evaluation of a conceptual case study, it has been shown that the resampling process returns reasonable results, fully agreeing with design criteria.

Though this work it can also be inferred that hazard interactions have the potential to shift the risks associated with large dams and, therefore, deserve further study.

Future efforts will be made on three fronts. Firstly, the retrieval and derivation of more precise hazard definitions and element vulnerability functions. Secondly, by making a transition towards loss and risk assessment (though the routing of floods and the consideration of potential losses downstream). Finally, by accounting for uncertainty.

# Acknowledgements

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