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Application of a Bayesian hierarchical modeling for risk assessment of accidents at hydropower dams

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ABSTRACT

In this study, a dataset of worldwide hydropower dam accidents in the period 1896–2014 is used to analyze risks for different dam types, dam heights, stages of the dam life cycle, and accident causes in OECD and non-OECD w/o China countries. Evaluation of the risk for individual characteristics has proven to be meaningful in studies related to dam safety. Previous studies often suffered from the fact that the methods applied could not overcome limitations posed by scarce data. The proposed Bayesian hierarchical modeling presents all accidents as a multilevel system with modules reflecting specific characteristics. It samples from the entire system, and models probabilities even for modules with few data. Mean values of probabilities for both frequency and severity are combined to interpret the risk for a particular category. Embankment and gravity dams have a higher risk in non-OECD w/o China than OECD countries. For arch dams, frequencies are in the same range for both country groups, but consequences have large uncertainties; therefore, no statistical difference in risk was found. Risks in the dam life cycle depend on the dam type and region. Accidents due to natural causes have the highest risk both in non-OECD w/o China and OECD countries.

1. Introduction

Hydropower is the most used renewable electricity source all over the world. In 2010 the electricity generated by hydropower dams accounted for about 16% of the global electricity production, and this share is expected to increase in the future (IEA, 2017). Despite being beneficial to society, the use of large amounts of water in storage dams can lead to a disaster, for example, due to an overtopping of the dam. Accidents related to hydropower can occur during different stages of a dam life cycle and could lead to various consequences, including fatalities, economical losses, etc. (Burgherr and Hirschberg, 2014). Although dam accidents are generally considered rare events, their potential for severe consequences makes it important to analyze the risk posed by dams.

Generally, methods employed for risk assessment in the hydropower community can be divided into two broad categories, namely deterministic and probabilistic (Hartford, 1997). Characteristically, deterministic analyses examine one or few scenarios, e.g., a "worst case", and aim to demonstrate that the given structure (e.g., dam) is tolerant to these hazards, i.e., that the structure will remain safe in these scenarios. Probabilistic methods examine risk more comprehensively by treating loads and resistance of a given dam probabilistically (Kreuzer and Bury, 1983; Lafitte, 1993; Salmon and Hartford, 1995). Both deterministic and probabilistic analyses performed for a given dam account for the site, material, or type specific characteristics.

A different approach needs to be adopted for a comparative evaluation of the risk posed by classes of dams. This type of evaluation usually requires analysis at a regional or global scale. For example, the risk posed by different dam types is compared between countries that are members of the Organization for Economic Cooperation and Development (OECD) or not (non-OECD), reflecting also differences in regulation and safety culture (Burgherr and Hirschberg, 2008). Scaling up the analysis makes the model more general and, in contrast to the previously described probabilistic methods, ignores some details that are specific to each individual dam. In this case, historical observations of dam accidents can be used to probabilistically assess generic dam risk, depending on a given dam characteristic at a regional or global level.

Risk assessments for dams using historical dam accidents have been carried out by different authors in the past (e.g., Gruetter and Schnitter, 1982; Lafitte, 1993; Hirschberg et al., 1998). In these studies, risk is commonly interpreted as the product of the frequency and severity (Haimes, 2009), where the frequency is the number of accidents per time unit and the severity measures the extent of the consequences of an accident. Probabilities for frequency and severity are determined using datasets of dam failures and accidents that have been compiled by different organizations (ICOLD, 1995; NPDP, 2016). These sources can comprise accident data for a certain country, dams of different types, different accident causes, etc., enabling assessments at different scales (regional or worldwide), for different dams and different causes, etc., in a comparative framework.

In the above-mentioned studies, basic statistical methods, such as linear regression or ordinary least squares, have been commonly

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applied (Baecher et al., 1980; Johansen et al., 1997; Department for Environment Food & Rural Affairs DEFRA, 2002). These methods possess certain limitations, i.e., requiring strong complete data to achieve accurate results. Such studies usually have a focus on a specific category of accidents and prepare complete data for that category (e.g., only embankment dams or only dam failures), whereas other categories are not considered. Moreover, the calculated accident rates represent average rates over the considered time period and do not take into account developments in the design and construction.

It has been recognized that methods of advanced statistics, such as Bayesian analysis, can be used to partially overcome the above mentioned limitations (Hirschberg et al., 1998). The Bayesian approach quantifies the posterior of the parameter of interest as the product of the probability of a prior and the likelihood of the real data given this prior. This type of analysis has already been applied in risk assessment studies within the energy sector (Eckle and Burgherr, 2013; Khakzad et al., 2013; Spada et al., 2014; Bouejla et al., 2014; Burgherr et al., 2015). Although being a robust framework, the Bayesian analysis has some limitations. For example, when analyzing scarce data, the uncertainty of the modeled posterior distribution remains large. For this reason, applications of a standard Bayesian approach for the hydropower risk assessment are limited. The following example clarifies this challenge.

Dam accidents sharing certain characteristics show similar trends. For example, dam accidents at large arch dams in OECD countries are expected to occur with a different frequency than those at small embankment dams in non-OECD countries, since conditions (e.g., construction regulations or safety standards) are not the same. This dependency on a characteristic must be represented in the analysis for the correct inference to be drawn from the data. In particular, to determine the risk for a specific dam type in a specific region, it is not correct to sample from global data, but a subset of accidents for these characteristics should be created. However, if the data for the subset is too weak (few data points) the quantification of probabilities might lack robustness.

To overcome the above discussed issues a Bayesian hierarchical modeling framework has been implemented in this study. This allows analyzing the available hydropower dam accident data in the form of a multilevel system with subsets sharing specific characteristics. When the probabilities for a selected characteristic under interest are modeled, this approach samples from the entire dataset, borrowing the strength across datasets. Therefore, the Bayesian hierarchical approach helps to overcome the limitations of the classical statistical approaches (e.g. homogeneous data requirement), and to model distributions even for subsets with scarce data.

The aim of the current study is to demonstrate the advantages of the Bayesian hierarchical approach to model representative frequency and severity distributions for different dam characteristics. Specific characteristics were chosen to address different aspects of hydropower dams and related accidents, such as dam type, dam height, accident cause, and several others.

In the first phase of this study, the Energy-related Severe Accident Database (ENSAD) database was updated with new information about worldwide hydropower dam accidents (Section 2). Next, a Bayesian hierarchical framework was applied to construct a multilevel model, reflecting the complexity of the data (Section 3). Subsequently, accident frequencies and associated consequences were assessed for each characteristic and compared. Finally, the frequency and severity results were combined to evaluate the risk depending on individual characteristics (Section 4).

2. Dam accidents

2.1. Data collection

It is well known and acknowledged by experts dealing with safety of hydropower dams and related infrastructures that lessons learned from past accidents play a vital role in design, construction and operation of dams. Therefore, many attempts have been made to collect and assess information about dam incidents and accidents. A number of comprehensive databases, like the Database of Concrete and Masonry Dam Failures and Incidents CONGDATA (Douglas, 2002) or the National Performance of Dams Program Dam Incident Database (NPDP, 2016), have been created to comprehensively collect information about accidental dam events worldwide. Along with the data collection process, an evaluation and analysis of the data has also been performed in numerous studies and the results published. Some of the most important and influential publications about dam accidents have been made by the International Commission on Large Dams (ICOLD, 1974; ICOLD, 1995).

The current study relies upon historical accident data available from the Energy-related Severe Accident Database (ENSAD). This database was first developed in the 1990 s at the Paul Scherrer Institut (PSI), and it has been continuously updated and extended since then (e.g., Hirschberg et al., 1998; Burgherr et al., 2011; Burgherr and Hirschberg, 2014). ENSAD considers fossil, nuclear and renewable technologies, covers complete energy chains and more than four decades of accidents starting from 1970. The primary focus of ENSAD is on so-called severe accidents, i.e. an accident is considered severe if it fulfills at least one of seven consequence thresholds (e.g. 5 or more fatalities or 10 or more injured persons) (Burgherr and Hirschberg, 2008). Nevertheless, accidents with minor consequences (e.g., 1–4 fatalities) are also considered if feasible and necessary to meet a project's specific scope and goals (Burgherr and Hirschberg, 2005).

To ensure an up-to-date dataset, the hydropower section of ENSAD was first updated with new accidents, and new information was added to accidents that were already recorded in the database. For this purpose, more than 50 information sources were considered. The most important ones are listed in Table 1.

Due to its comprehensive structure and the integration of accident information from many sources, ENSAD allows storing detailed accident data, covering numerous aspects of an accident such as, for example, location of the dam, accidents causes, consequences and many

Table 1
Information sources used for the collection of hydropower accident data.

Source type	Source name
Databases	National Performance of Dams Program Dam Incident Database, Stanford University (NPDP, 2016); Bibliography of the History of Dam Failures (BHDF) by Vogel (1984); Lebreton (1985); Dartmouth Flood Observatory Database (University of Colorado, 2017); International Database for Civil and Structural Engineering (Structurae) (Janberg, 2006); Major Hazard Incident Data Service (MHIDAS) (Occupational Safety and Health on CD-ROM (OSH-ROM), 2006);
Reports	International Commission on Large Dams (ICOLD) data collections (ICOLD, 1974; ICOLD, 1995; ICOLD, 1997); US Department of the Interior, Bureau of Reclamation (Bureau of Reclamation, 2014); Sigma Insurance Research by Swiss Reinsurance Company Ltd (Swiss Re);
Case-study papers and articles	Anderson et al. (1998); Alcrudo and Mulet (2007); Ludlow Charles Dewsnup (2014); McCully (1996);
News portals, newspapers	The British Broadcasting Corporation (BBC) news; Neue Zürcher Zeitung (NZZ) news, etc.