

# SAFE PASSAGE OF EXTREME FLOODS— A HYDROLOGIC PERSPECTIVE

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**Abstract**—This paper takes a fresh look at uncertainty in estimates of the inflow design floods (IDFs) used for spillway design for safe passage of extreme floods through dams, particularly dams with a height of 30 m or less. Development of IDFs currently involves statistical analysis; thus, IDFs incorporate uncertainties. The paper defines the extreme flood and suggests a means by which it can be estimated in order to incorporate uncertainty in the IDF. A clear understanding of the physical site conditions and the physical processes in question, as well as engineering judgment, are paramount in developing a safe design.

**Keywords**—ARI, bootstrap CI, dam, ELV, EMA, flood, hydraulics, ICOLD, IDF, PMF, PMP, spillway, WRC

## INTRODUCTION

Many developed countries use the probable maximum flood (PMF) as the design basis for establishing the inflow design flood (IDF) for dams that are classified as high hazard because of their high dam heights and large storage volumes. The failure of such dams would cause loss of life and result in major adverse economic consequences due to damage to properties downstream.

The PMF is defined as “the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible for the drainage basin in question.” In general, the PMF is considered to be statistically indeterminate.

When the PMF is not used as the basis of the IDF, it is at least used as a “check flood” to ensure that a dam will not fail catastrophically if overtopped. However, in some developed and many developing countries, the peaks of the IDF are estimated from probabilistic approaches, regardless of the hazards these dams may pose to downstream inhabitants. This is particularly true for small dams with heights of 30 m or less. In many cases, the available flood-flow data is barely sufficient for a probabilistic analysis; therefore, estimates of design-flood peak discharges that use probabilistic approaches are highly uncertain.

The International Commission on Large Dams (ICOLD) has charged the Technical Committee of

Hydraulics for Dams with developing a bulletin, entitled “Safe Passage of Extreme Floods,” to provide insight and approaches for determining design-flood peak discharges when probabilistic approaches are used. The bulletin was also developed to provide a better design of the outlet works that could safely pass extreme floods. The purpose of this paper is to capture the essence of Chapter 2 of that bulletin, “Confidence Level Assessment of Design Flood Estimates,” which suggests using the upper bound of the confidence limits to provide a margin of safety in defining IDFs for dams.

The precision of confidence-level determinations may also be improved by using recently developed algorithms in determining quantile estimators for some distributions that are commonly used in flood-flow frequency analysis. This paper provides additional discussion, not presented in the ICOLD bulletin, regarding the estimate of confidence levels in determining extreme floods for dam design.

## CURRENT PRACTICE AND UNCERTAINTY OF IDF ESTIMATES

The current practice in the design of dams is to first select the IDF appropriate for the hazard potential of a dam and reservoir and then to determine its peak flow rate and/or its entire hydrograph. Then the spillway and outlet works can be designed, or adequate storage can be allocated in the reservoir, to safely

Samuel L. Hui

shui@bechtel.com

André Lejeune, PhD

Université de Liège,  
Belgium

agh.lejeune@ulg.ac.be

Vefa Yucel

National Security  
Technologies, LLC

yucelv@nv.doe.gov

*Estimates for extreme events extrapolated from flood frequency analyses based on short records are highly uncertain.*

#### ABBREVIATIONS, ACRONYMS, AND TERMS

ARI	average recurrence interval
CI	confidence interval
ELV	estimated limiting value
EMA	Expected Moments Algorithm
ICOLD	International Commission on Large Dams
IDF	inflow design flood
LP3	Log Pearson Type III
PMF	probable maximum flood
PMP	probable maximum precipitation
WRC	Water Resources Council

accommodate the design flood without endangering the integrity of the dam and its appurtenant structures.

In many developed countries, dams are classified by their hazard potential, with regulations governing the selection of the IDF. For high-hazard dams, the PMF, or the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible, is commonly adopted as the IDF. When the PMF, which is considered to be statistically indeterminate, is not used as the basis of the IDF, it is used as a “check flood” to ensure that the dam does not fail catastrophically if overtopped.

The IDF is derived either deterministically with a precipitation-runoff model, using a design rainfall sequence and other basin hydrologic parameters appropriate for the design hydrometeorological conditions, or by means of a statistical analysis, using historical flood peaks observed at or near the proposed dam site. In the former case, the design precipitation values are generally determined using historical data. For example, in deriving the probable maximum precipitation (PMP) used in the development of the PMF, the 100-year or other frequency precipitation values form the basis of the PMP estimates. Therefore, regardless of the approach taken, determining the design-flood peak discharge involves statistical analysis of data. In many cases, the available data is insufficient (in terms of years of data collected), resulting in uncertainty in the estimate of the IDF.

Dam design professionals generally recognize that good engineering demands realistic or justified design, and that dams should be designed to accommodate the maximum flood computed based on approved hydrologic design

criteria (i.e., ranging from a 100- to a 10,000-year IDF). Therefore, an IDF estimate that exceeds the design-flood peak discharges (i.e., an extreme flood), as advocated by the ICOLD bulletin, should account for any uncertainty, usually defined by the confidence limits.

#### FLOOD FREQUENCY ANALYSIS

The IDF chosen from a flood frequency analysis is generally located in the “upper tail” of the cumulative distribution of the observed phenomena. This would correspond to an average recurrence interval (ARI) of 100 years to more than 10,000 years, depending on the potential hazard a dam poses to the downstream inhabitants and properties. Unfortunately, available sample data may include, at best, 100 years of observations, and often less than 50 or even 20 years. Without some assumptions about the population distribution of the data, we would theoretically need 3,000 years of observation to roughly define the 1,000-year event. In this case, the interval bounded by the highest and the 7th highest of the sample data would have approximately a 90 percent chance of containing the 1,000-year value. [1]

Therefore, when there is a limited amount of available historical data at a site, the use of regionalization techniques may be required to increase the database in deriving a reliable at-site frequency distribution. In any case, extrapolation beyond the database is required in estimating the design frequency event, usually in the range of a return period of 1,000 to 10,000 years.

The extrapolation to derive extremely rare peak flows could lead to uncertain estimates with the resulting flood quantile estimates highly dependent on the choice of theoretical distribution. Regardless of the appropriateness of the probability distribution used, the extrapolation of data to the 1,000- and 10,000-year range from even 100 years of available data is a stretch. However, sound design-flood estimates can be achieved by explicitly accounting for uncertainty in the estimates by means of confidence intervals (CI), relying on a clear understanding of the hydro-meteorological characteristics of the watershed, and using professional judgment.

In addition, the evaluation of the safe passage of a flood requires the routing of the design flood hydrograph through the reservoir. It also requires a determination of the corresponding flood volumes and distributions.

## CONFIDENCE INTERVALS

The precision of a design event estimate, in terms of a return period in years (described as T-years; i.e., T = 100 years or T = 1,000 years), that is derived from a probability distribution fitted to the sample data, can be quantified by computing a CI of a certain confidence level, e.g., 95 percent, for the T-year event. The CI is a range of estimated values within which the true value of the T-year event is expected to lie. If different CIs are derived using various methods, the CI giving the smaller range should be chosen.

The statistical distribution of the T-year event is usually unknown; therefore, it is not possible to derive an exact CI for the T-year event. However, analytical expressions (i.e., first-order approximations) have been developed that are acceptable for large sample sizes. Because hydrologic samples are typically small, these approximate CIs may lack accuracy. Methods for computing CIs are further summarized below.

## IMPACT OF RECORD LENGTH ON CONFIDENCE INTERVALS

The accuracy of estimates of the T-year events and the associated CIs are functions of the number of years of records available for the analysis, the assumed probability relationships (frequency distribution), and the way the sample statistics are estimated.

As the length of the record increases, the reliability of the estimate also increases. Approximate values of reliability (percent chance) can be calculated for different return periods. The approximate values for infrequent events are shown in **Table 1**, giving the approximate reliabilities as a function of confidence limit, ARI, and

record length. [2] For example, there is almost a certainty that with 25 years of historical database, the estimate for the 2-year ARI will fall within plus or minus 50 percent of the estimated value; but the chance of having the estimated value fall to within plus or minus 10 percent of the estimate is only about 68 percent. [3] The table also depicts the risk of having a flood with an ARI greater than T-years during the life of a project. It is important to note, however, that the lifetime of a dam, generally defined in economic terms, is different from the real lifetime of the structure, which is usually greater.

## ACCOMMODATING UNCERTAINTY IN THE IDF

On the basis of the method suggested in the U.S. Geological Survey's "Guidelines for Determining Flood Flow Frequency," Bulletin 17B [4], for a project involving a 1,000-year flood of 4,478 m<sup>3</sup>/s derived from a 39-year systematic record using the Log Pearson Type III (LP3) Distribution, the corresponding upper 95 percent confidence limit is estimated to be 7,632 m<sup>3</sup>/s. The extreme flood used for the design of such a project would include all floods up to 7,632 m<sup>3</sup>/s, an increase of about 72 percent of the expected value that is normally used as the IDF. In this example, the dam design professionals would have to find a way to accommodate the extra 3,154 m<sup>3</sup>/s, other than relying on the planned spillway, if they wish to have a 95 percent confidence that the dam could safely pass the IDF based on data accuracy alone.

Using the same database and the same LP3 distribution, the 10,000-year-flood peak discharge and the corresponding upper 95 percent confidence limit are estimated to be 11,768 m<sup>3</sup>/s and 19,039 m<sup>3</sup>/s, respectively. The dam designers

*The shorter the historic record, the larger the CIs and the associated errors.*

**Table 1. Approximate Reliabilities as a Function of Confidence Limit**

Average Recurrence Interval (ARI), years	Record Length, years	Confidence Limits, % error			Risk of Flood (ARI = T-years) Within Lifetime (N-years)	
		±10%	±25%	±50%	N = 30	N = 50
2	10	47	88	99	100%	100%
	25	68	99	100		
	100	96	100	100		
10	10	46	77	97	95%	99%
	25	50	93	99		
	100	85	100	100		
50	10	37	70	91	45%	63%
	25	46	91	97		
	100	73	99	100		
100	10	35	66	90	26%	39%
	25	45	89	98		
	100	64	99	100		

*The accuracy of  
CI estimates  
are very much  
method dependent.*

would have to find ways to accommodate the additional 7,271 m<sup>3</sup>/s in order to pass the extreme flood safely through the dam if the 10,000-year flood is adopted as the IDF.

It is possible that the extreme flood defined by the upper limit of the CI could exceed the PMF or the estimated limiting value (ELV) flood. The dam designers would need to perform sufficient analyses to ensure that this would not happen and to minimize any unnecessary over-design.

#### **METHODS TO DERIVE CONFIDENCE INTERVALS**

CIs based on asymptotic theory, along with CIs constructed using the non-central t-distribution, are commonly used in practice. Stedinger [5] discussed these methods in computing CIs for quantile estimates. He concluded that the use of the non-central t-distribution and the asymptotic distribution normally work well with observations and their logarithms if the data is normally distributed. For LP3 distribution with a known skew coefficient, a combination of the non-central t-distribution, with an adjustment based on asymptotic variance of the quantile estimator, is also generally performed satisfactorily. However, the approach suggested by Bulletin 17B did not perform as well as the other methods because a possible error in the specified population skewness coefficient was ignored.

Recent literature on CIs includes attempts to remedy some of the issues identified with the current commonly used CI estimating methods, particularly issues associated with procedures suggested in Bulletin 17B. These can be summarized as analytical methods and bootstrap methods.

One of the recent analytical methods is the Expected Moments Algorithm (EMA) method developed by Cohn et al. [6] The EMA is an attempt to remedy the shortcomings of the Bulletin 17B procedures, in which the parameters used to describe the distribution are derived independently of the distribution, without modifying or abandoning the use of the “method of moment,” a basic statistical structure in Bulletin 17B. EMA is an iterative method of moment procedure that computes the parameters of the LP3 distribution using systematic flood peak data as well as historic flood peaks, with analytical expressions for the asymptotic variance of EMA flood-quantile estimators and CIs for flood quantile estimates. Using the parametric bootstrap method (also known as Monte Carlo simulations), Cohn et al.

demonstrate that their expressions provide for useful estimates of the CIs even though they are not exact.

Bootstrap methods are among the many modern tools used by statisticians. There are nonparametric and parametric bootstrap methods. The idea behind the nonparametric bootstrap method is the use of the sample data at hand to generate many artificial samples of the same size using random sampling with replacement. For each artificial sample data, a quantile of interest can be computed based on the sample distribution. If there are N samples of data generated, then there will be N estimates of the quantile of interest. If a 95-percentile CI is sought, then the 2.5 and 97.5 percentiles of the N sample quantiles provide the needed upper and lower bounds of the 95-percentile CI. The major advantage of this method is that it can be applied to any estimating problem without the need to make assumptions about the uncertainty distribution around the estimate of the statistics of interest, which is often the problem with the analytical confidence expressions.

The parametric bootstrap method has four main steps: (1) use the observed data and compute the parameters based on a certain assumed parametric distribution, (2) generate a large number of samples from the assumed parametric distribution, (3) calculate the statistic of interest for each sample, and (4) sort these values and use the appropriate quantiles to define the CI.

The parametric bootstrap method of computing confidence levels is also found in the regional flood frequency analysis using L-moments developed by Hosking and Wallis. [7] Hosking and Wallis show that the method performs well even with the issues of heterogeneity and dependency among the gauging stations used in the regional analysis; the method also avoids the issue of making assumptions about the uncertainty distributions around the quantiles of interest.

#### **CONCLUSIONS**

We have defined the extreme flood in the context of the bulletin “Safe Passage of Extreme Floods” for the design of a dam. We have also suggested means by which the extreme flood can be estimated, while accounting for uncertainty. As in flood hydrology and in any predictive analysis that deals with nature, a clear understanding of the physical site conditions and the physical processes in

question, as well as engineering judgment, are paramount in the development of a safe design.

The question of how confident we are in our estimates of the confidence levels remains the real issue. The papers referenced here point out the inexact nature of the approaches used in deriving CIs, as well as the associated shortcomings of these procedures. Some methods perform better than others, depending on the sample data at hand.

In [8], six methods are evaluated, including both analytical approximate methods and the bootstrap method. The following is an excerpt from that paper, which also makes reference to a paper presented at the American Water Resources Association's 1997 conference. [9]

Nonparametric computer-intensive Bootstrap CIs are compared with parametric CIs for simulated samples, drawn from an LP3 distribution. Using this methodology, biased in favor of parametric CIs since the parent distribution is known, Bootstrap CIs are shown to be more accurate for small to moderate confidence level ( $\sim 80\%$ ), when parameters are estimated by the indirect method of moment (Bulletin 17B). However, the actual level of Bootstrap CIs is almost always lower than the target level. It is expected that, compared to parametric CIs, Bootstrap CIs perform even better when applied to actual series of maximum annual floods, since they need not come from an LP distribution.

It is recommended that several methods be used in defining confidence levels, and, based on performance criteria and professional judgment, the best method should be selected. Consultation with a professional statistician is always a prudent way for the hydrologist to build further confidence in his or her estimates. ■

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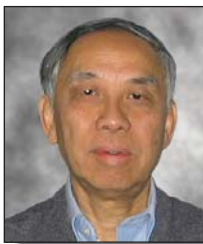
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This paper was presented at the International Conference on Dam Safety Management, held in Nanjing, China, in October 2008. The original version is slated for inclusion in the conference proceedings, which will be published at a future date.

Additionally, the original version of this paper is scheduled for publication in the January issue of *L' Houille Blanche*, the technical journal of the Société Hydraulique de France in Paris and one of the premier hydraulic engineering technical journals in France and the world. The paper was translated into French by Dr. Lejeune (who will be listed as lead author on the translation) and will be submitted under the title "Passage en sécurité des crues extrêmes."

## BIOGRAPHIES



**Samuel L. Hui** has 42 years of hydraulic engineering experience, including 35 years at Bechtel. His vast technical knowledge and skills have been applied to more than 40 projects in the United States and around the world, including such Bechtel megaprojects as the Jubail Industrial City, King Khalid International Airport, and King Fahd International Airport in Saudi Arabia;

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Sohar Aluminum Smelter in Oman; and Fjarðaál Aluminum Smelter in Iceland.

Currently, as the senior principal engineer with Bechtel Civil, Sam participates in hydraulic or hydrologic engineering tasks on multiple projects, and is the off-project design reviewer of hydraulic/hydrology tasks for the Guinea Alumina Project in West Africa, which ranks as one of the largest and most significant greenfield projects ever to be developed.

Sam was manager and global technical lead for Bechtel's Hydraulics and Hydrology Group, which performed technically challenging hydraulics and hydrologic studies worldwide, from 1995 to 2004.

Sam's many professional memberships include the U.S. Society on Dams (USSD), in which he serves on the Technical Committee on Hydraulics of Dams; and the International Commission on Large Dams (ICOLD), in which he serves on the subcommittee charged with the preparation of the ICOLD bulletin titled "Safe Passage of Extreme Floods." He was also a member of the American Society of Civil Engineers (ASCE), and formerly chaired the Surface Water Hydrology Technical Committee's control group and served on the subcommittee that oversaw revisions to the *ASCE Hydrology Handbook* (second edition).

Sam holds MS and BS degrees in Civil Engineering from Queen's University, Kingston, Ontario, Canada. He is a registered civil engineer in the province of Ontario, Canada, and in the state of California.



Professor **André Lejeune** teaches at the Université de Liège, Belgium, where he heads the Department of Hydraulics and Transport and the Laboratory of Applied Hydrodynamics and Hydraulic Construction. Dr. Lejeune has also taught at the International Institute for Infrastructural, Hydraulic and Environmental Engineering, Netherlands, and l'Ecole Polytechnique Fédérale de Lausanne, Switzerland, as a visiting professor.

Dr. Lejeune has lent his outstanding hydraulics expertise to projects in 70 countries, including China, Egypt, Ethiopia, Indonesia, Iran, Israel, Japan, Jordan, Kenya, Madagascar, Pakistan, Poland, Thailand, the former Soviet Republic, Venezuela, and Yemen. He currently participates in a feasibility study for the Red Sea-Dead Sea Canal, a potential joint Jordanian-Israeli initiative to bring water from the Red Sea to the Dead Sea, which is shrinking rapidly due to evaporation and upstream water diversion. Also, Dr. Lejeune recently served as an advisor for post-earthquake reconstruction of the Jian Rive irrigation dam near the city of Mianyang, in Sichuan, China.

Dr. Lejeune is a member of the Belgian Royal Academy of Science, and a past peer reviewer for ABET, Inc. (formerly the Accreditation Board for Engineering and Technology), which accredits educational programs in applied science, computing, engineering, and technology. He is also a member of the International Commission on Large Dams (ICOLD), and currently chairs the Technical Committee on Hydraulics for Dams.

In 1972, Dr. Lejeune received the Lorenz G. Straub Award, a prestigious international award presented annually by the University of Minnesota to the author of a particularly meritorious doctoral thesis on a topic related to hydraulic engineering. His paper was titled "The Operating Forces for the Opening and Closing of Miter Gates on Navigation Locks."

Dr. Lejeune holds a PhD in Hydraulics, and has received the US equivalent of master of science degrees in Oceanography and Civil Engineering, all with highest marks, from the Université de Liège, Belgium.



**Vefa Yucel** is a principal engineer with National Security Technologies, LLC (NSTec), which provides management and operations (M&O) services for the Nevada Test Site (NTS), a 1,350-square-mile area northwest of Las Vegas, Nevada. He leads GoldSim modeling (a contaminant transport and regulatory compliance model) development for low-level and transuranic (TRU) waste performance assessments and compliance evaluations of two disposal facilities, closure planning and cover design, and environmental monitoring of the site's waste management facilities. As engineering supervisor and principal hydrologist at NTS with Bechtel Nevada, he managed many of the same tasks he currently manages as one of NSTec's principal engineers.

Earlier, with Bechtel Environmental, Inc., in Oak Ridge, Tennessee, Vefa supervised Geotechnical and Hydraulic Engineering Services' hydraulics and hydrology group, which provided specialty services to environmental restoration and waste management projects in surface water and groundwater hydrology, and fate and transport modeling. He was originally a senior engineer in Bechtel's Hydraulics and Hydrology Group in San Francisco, where he was engaged in hydrologic studies for water resource and flood control projects.

Vefa is a member of the American Society of Civil Engineers (ASCE), and served on ASCE's Task Committee on Paleoflood Hydrology in 1999. He has authored numerous technical papers, most of which have been presented at professional conferences worldwide, including "Decision Support System for Management of Low-Level Radioactive Waste Disposal at the Nevada Test Site," "Hydrologic Simulation of the Rio Grande Basin, Bolivia," "Pollutant Loadings on the San Francisco Bay Estuary," "An Integrated Model for Surface-Subsurface Fate and Transport and Uncertainty Analyses (Part I: Theory, Part II: Application)," and "Development of Rainfall Intensity-Duration-Frequency Data for the Eastern Province of Saudi Arabia."

Vefa holds MS and BS degrees in Engineering from Iowa State University, Ames, Iowa, and has completed graduate courses in Civil Engineering at Stanford University, Palo Alto, California. He is a registered civil engineer in the state of California.