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**Dam Safety : Selection of Critical Flood and Innovative Flood Estimation Method**

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* **Preamble**

Between the first steps of hydrology and the sophisticated techniques currently applied, a world of development found place over the centuries. Even after very long periods of improvements, this science is still subject to some subjectivity, as differences between countries on hydrological issues are sometimes not negligible. Despite these local divergences, the constantly refined techniques and more efficient technologies allow progressive quality progresses in the hydrology field. Automation of the collection of information, improvement of the dependability of data transmission and electronic processing of long series of numbers considerably lighten the tedious work of the hydrologist.

One should however refrain from considering that any performances progress in data processing is necessarily synonymous of a quality improvement of the calculations. The correctness, robustness or consistency of flood estimations is less due to "numericians" of extreme events than supported by experienced specialists, capable of carrying a balanced look, exerting insight and using of common sense while addressing these phenomena. An electronic calculator can handle hundreds of parameters and variables simultaneously... but how can all this information be collected in reality?

The sources of uncertainties are indeed so numerous in hydrology that the indefinite decomposition of the reality into ever and ever smaller elements does not necessarily bring convincing improvement to the final quality of a study. This quality is in essence more the outcome of a sound reasoning rather than the result of a myriad of calculations realised according to mechanical procedures, be they as optimised and sophisticated as can be.

Moreover, one should keep in mind that hydrology rests on bases different from those of many other sciences, the earth sciences for instance, where – theoretically at least – it is possible at any time to obtain complementary pieces of information. It suffices to carry out an additional measurement campaign to verify this or that aspect of bedrock, for instance. For his part, the hydrologist is oftentimes completely dependent on data collected decades before he started working on a watershed. He is bound to accept considering the recorded data as reasonably representing the past reality, without direct means of verifying or challenging their value. Broad checks (completeness, consistency, repeatability, for instance) allow nevertheless to assess up to a certain point the overall quality of the series.

But the data quality is primordial for the realisation of reliable analyses. It is of course out of question to wait a few decades to collect additional data in order to obtain confirmation of the rightness of measurements of the annual peak flow, for instance. One is therefore bound to live with the imprecision and possible errors of the past; this implies in turn to admit de facto a potential non-negligible (and non verifiable) historical uncertainty. The hydrologist is of course compelled to avoid committing additional errors on top of that!

**Design and check floods**

All the dams around the world must be designed to resist the sometimes extreme conditions set by their environment. One obvious dangerous solicitation is set by the earthquakes. Another is caused by the storms and the resulting floods in the river controlled by these dams. In this respect, two levels of intensity of the river discharge are usually considered: the design flood and the check flood. The former one must be successfully mastered in all cases with a reserve of safety. A check flood represents an extreme case that occurs extremely rarely; it pushes the dam and its appurtenant structures (spillway in particular) close to their limits. These floods have to be successfully mastered; some limited damages to the dams and their various structures are in general accepted.

Among all questions that may arise, two will be briefly discussed in this article :

- how shall the design, resp. the check floods be defined? Which criteria shall a flood satisfy to be considered as one of these two reference floods?

- how to estimate the most extreme flood?

**Floods and their significance**

The design of the flood evacuation system of a dam usually relies on two criteria:

- the dam must control a flood of a given return period (design flood) without damages

- it must also resist an extreme flood (check flood), with at most limited damages.

The classical approach for determining the magnitude of a flood concentrates on purely hydrological considerations. Flood frequency analysis (for the design flood) and deterministic analysis (for the extreme flood) are the most common applied methods. While attempting to characterise the design and check floods, two rapidly popping up questions are:

- which return period shall be selected as critical for a dam?

- how to consider the complexity of a flood to reach a decently acceptable order of magnitude for the most critical flood?

The most widely applied criteria for selecting adequate flood return periods in more than thirty countries around the world will first be presented. These criteria are in general based on one of two principles. They either consider :

- the risks linked to a failure of the structures (dam height, reservoir volume, etc.)

- or the potential damages downstream of the reservoir in case of a serious dam problem.

A new trend in flood hydrology will be sketched in the second part of the article. It consists in integrating reservoir operation and hydrology in the reflections aimed at determining the "right" magnitude of the extreme event. Unlike the classical methods addressing only the hydrological process, this new approach sets on a stochastic generation encompassing the causes and the effects of the flood. The result of the analysis is not an inflow hydrograph as usual, but the probability distribution function of a key design constraint (maximum water level, maximum released outflow, rapidity of the outflow variation, etc.).

These two issues are presented more in depth in the themes treated in an ICOLD Bulletin in preparation. This Bulletin addresses the issue of Flood Evaluation and Dam Safety. Its English version will be published within the next few months.

* **Determination of flood magnitude for dam projects**

**Introduction**

The dam safety Authority of any country is placed in front a simple problem, when it comes to setting criteria that the design of a dam must consider to guarantee its safety in case of a severe flood. As mentioned above, two levels of risk are usually defined: the "normally" large floods and the "really unusually" severe events. In general, two independent estimation methods are applied to determine the magnitude of these floods. This approach should reasonably guarantee that two independent looks at the flood issue come to estimating comparable and consistent orders of magnitude. This procedure limits the risk of making all the safety issue dependent on only one set of basic data, which may be biased or even flawed (oftentimes it is not possible to precisely check the quality of the records).

Usually the design flood rests on a estimate based on the statistics of observed river flow, and in particular of the time series of the annual maximum peak flow. A suitable extrapolation of these maxima with standard methods (Log Pearson III 1924, Gumbel 1958, others), allows to obtain a fair estimate of the flood intensity for large return periods. The procedure is fully statistical (Flood Frequency Analysis); it relies purely on one time series, the record of the annual peak flow at a given point of the river. The question the dam Authority must decide on is that of the frequency of occurrence to be considered for defining the critical flood.

The extreme flood estimation follows another path, based on deterministic reflections. This procedure is explained in the second part of this article and is totally independent from that applied for the design flood. The estimated flood having to correspond to the maximum probable event, its occurrence is even rarer than that of the design flood ; consequently its magnitude is also larger. Here too, the dam Authority is facing the question as to which criteria are to be set to consider this flood: how often (or rarely) is it allowed to occur? What assumptions must be made to reliably determine it?

In the study presently carried out by the Technical Committee in charge of hydrology at the International Commission on Large Dams (ICOLD), data from more than thirty countries have been collected, analysed and compared. Some families of thoughts can be drawn, regrouping countries having similar philosophy to address the issue of large floods. They are presented in a summarized form hereunder.

**Two dam hazard classification systems**

The Dam Hazard Classification System (DHCS) considers the potential consequences of a dam failure. This consideration can be implicit or explicit. Two main approaches are defined:

* System characteristics: dam height and type, reservoir volume, etc. This approach does not take into consideration other elements than those directly related to the dam itself. It implicit takes into account the consequences of the failure of the dam.
* Dam failure consequences: this approach considers explicitly the probable consequences of a dam failure. Important are primarily the third parties losses (TPL); the costs incurring to the dam owner are usually not considered as being relevant. The economical aspect of the consequences of a dam failure can be part of the classification; the loss of lives (LOL) too.

Some countries follow a hybrid way, combining the characteristics of the dam and the consequences of the dam failure.

**Evaluation based on system characteristics**

The system is understood as a the elements and structures constituting the origin of the flood and destruction risk for the downstream populations and goods. Three major characteristics are usually retained.

Dam height This is one the main retained characteristics. The risks are considered to grow in parallel to the height of the structure. This is only partially the case, as in general the higher the dam, the more intense are the design studies. Oftentimes small and very small dams are more prone to accident than large structures. But the consequence of their failing is fairly limited.

Dam type This is an important criterion too, since embankment dams are much more sensitive to overflow than concrete dams. Their flood evacuation system must be largely designed and be in a position to function under any circumstances. Any overtopping by a flood may end up in a catastrophe.

Reservoir volume This is directly related to the amount of energy that a dam failure would release. Even if brusquely released, the water coming from small and medium reservoirs would soon be absorbed by the river and present a limited risk to the people and goods located along its bank. The sudden burst of dam retaining a large or very large reservoir may trigger an immense wave extending over tens of kilometres with a very destructive behaviour.

Other, less crucial elements are sometime also considered; for instance, age of the dam, type of dam foundation, seismicity of the dam area, type of the flood evacuation system, etc. Various calculation have been set up to quantify the level of risk of these criteria with marks or ranks. These marks are then combined and weighed in a appropriately rational manner to come up to an indication of the overall level of risks set by the dam-reservoir system.

**Evaluation based on consequences of a dam failure**

This approach focuses on the river and areas located downstream of the reservoir. An evaluation of the damages resulting from a dam break is made. Among all criteria likely to be considered for such an evaluation, four elements can be considered as major.

Persons at risk This criterion considers the number of persons living on the area likely to be hit by the flood wave resulting from a dam failure. This area is determined by means of a dam break analysis, usually relying on a two-dimensional calculation model.

Loss of life This criterion is very important and has oftentimes a key position in the determination of the risks of a dam failure. Various methods estimate the number of persons possibly killed by flood wave. The preparedness for such situations (warning time, population evacuation concept) may be considered.

Economic damages The value of all goods present in the flooded area can be estimated and constitute also a criterion for quantifying the risk associated to a dam failure. Elements such as residential buildings, industries, traffic infrastructure (roads, railways, bridges, airports), public buildings (schools, hospitals, etc.), agriculture, etc. are preferably considered.

Environment The consequences of a dam break consider the loss of fish and wildlife, and the probable difficulties for regenerating their habitat. The contamination of soils due to the destruction of industrial sites or waste areas is an important element too. The destruction of cultural goods and historical heritage sites is also sometime considered.

**Example**

An example is sketched, to show the relatively large spread of the official requirements. A relatively modest embankment dam has been assumed, with â height of 20 metres; this dam retains a reservoir of 260 mio m3. The typical floods (100-year, 1'000-year, 10'000-year, PMF) have been estimated. The strict application of the rules set in the various standards shows that the Inflow Design Flood (IDF) may range from a 100-year flood to a PMF, most of the countries opting for a magnitude situated between the 1'000- and the 10'000-year floods.



*IDF according to 30 different standards around the world for an identical situation*

The figures illustrates clearly that there is no unified doctrine in the matter. Thirty countries on five continents follow different approaches. Some countries apply even different rules, depending on the location of the dam on the territory. One notices that the ratio between the least stringent standard and the most demanding is over one to three. Two-thirds of the standards base their IDF on either the 1'000-year, 10'000-year or probable maximum flood.

A simple indicator of the order of average magnitude of all these IDF comes to a value of 1'420 m3/s, corresponding to a return period of ca. 7'500 years (red dotted line on the graph). Other examples made on other situations would result in the same conclusion: important differences of the approaches are common and an important spread of the Inflow Design Flood usually results from these differences.

* **Stochastic generation of extreme flood**

**Introductory reflections**

The Probable Maximum Floods (PMF) are oftentimes used as reference for the verification of the resistance of a dam to the most extreme imaginable, but still realistic storm. The well-known PMP-PMF method has been developed for estimating the most extreme hydrological events likely to occur. The method estimates first the Probable Maximum Precipitation (PMP), considering the prevailing weather situation over a watershed, the worst storms ever recorded and extrapolating their key parameters (wind speed and water contents) to maximum thinkable (but still realistic) values. The precipitations are then routed through the watershed, the water concentrating along the river way to end up forming a very large wave at the point of interest (the dam site).

A further step may be made, allowing to include the response of the considered dam project to an extreme hydrological situation. The resulting indicator is no more the size, intensity or discharge of the extreme flood, but the probability distribution function of the selected indicator. This indicator may be the maximum water level reached during the extreme event, the maximum released flow, the maximum change of the spilled discharge or any other phenomenon of interest.

The traditional method to determine the PMF is subject to many uncertainties, which require simplifying assumptions. The imprecision and biases, and consequently the inaccuracy of the estimate, are summing up all along the hydrological chain. Usually, the resulting hydrograph is however considered representative of the most critical situation for the dam and its flood evacuation system.

To alleviate these drawbacks and damp the consequences of an oversimplification, integrated probabilistic approaches can been developed. All the uncertainties (precipitation intensity, snow melt, infiltration losses, timing, etc.) are considered as random events leading to a – random – response of the evacuation system. A series of simulations is carried out, which include not only the generation of possibly critical floods, but also numerically route these events through the reservoir and its evacuation system.

The method has been successfully applied to check the preliminary design of the spillway at Ostour dam (Iran). This case presents strong uncertainties shrouding the PMF determination. The hydrologists relied on the integrated approach through a Monte-Carlo analysis to statistically estimate the Probable Maximum Response of the reservoir for a given flood evacuation system.

**Description of the method**

It is possible to give this fact a particular attention by letting a large number of variables and parameters fluctuate within a given range around values considered as reasonably describing the precipitation, the watershed, the flood routing and their various characteristics. Each uncertain variable or parameter is consequently randomly generated. For each simulation, a set of basic data must be obtained and then run through an appropriate calculation model. This operation results in one flood hydrograph – inflow into the reservoir, a candidate to the title of PMF indeed – for each simulation.

This hydrograph is then immediately – numerically – run through the reservoir and its flood evacuation system. The appropriate resulting characteristic values (maximum water level, maximum discharge, e.g.) are retained as indicators of the reaction of the retention scheme to the selected random combination. The repetition of this procedure for a consequent number of times (several hundred at least) leads to a family of possible PMF and their derived indicators. The analysis of the resulting variability of one variable (the indicator) allows subsequently to retain the right level of risk as a function of the local situation or the official directives.

The number of possible combinations of the basic data is enormous. A classical Monte-Carlo procedure generates a set of random values for the independent variables. In a first approach, all the basic data can be considered as referring to events that are statistically independent from one another.

The figure below shows the typical duration curve of the selected indicator resulting from the repeated calculations. The zone that can be considered as critical is close to the maximum obtained value, yet a little less extreme. The very highest (and lowest) values of the graph are typically the result of numerical coincidences that have no link with the reality. Engineering judgement is required to position this critical zone. Another method may postulate that a given exceedance probability (10% for instance) represents the acceptable value of the indicator.



*Typical sorted curve of an indicator, with area of the most critical floods*

**Application**

In the example below, a water catchment of 42'000 km2 has been modelled; eight sub-basins have been defined. Some 3'000 simulations have been performed, all considering the following independent variables as random: starting time of the event, timing of the storm phases, intensity of rainfall, snow cover, initial loss, duration of river routing, as well as the characteristics of the individual hydrograph and the intensity of the base flow at the dam site.

In the case studied here, the water level was not allowed to raise beyond a certain value during a flood, due to the presence of dwellings close to the reservoir. Each flood has been numerically routed through the reservoir and its flood evacuation system, and the maximum level reached during the passage of the flood through the reservoir recorded.

The collection of 3'000 maximum water levels offers a sound ground for a statistical analysis. The series has been treated with classical statistical tools, in order to determine the probability distribution function of this variable. The figure below shows this discrete distribution function, almost exactly fitted by a normal distribution curve. The cumulative distribution function shows two extreme tails, which can be considered as numerical extreme values, as indicated above. The slope change has been retained as the maximal realistic point.



*Probability and cumulative distribution functions of the maximum water level;
comparison to a normal pdf (green curve); pink dot = selected probability*

Interesting is the representation of the simulation results on a discharge-volume graph. Each point represents the hydrological key characteristics of the generated flood at its entrance into the reservoir. The cloud of possible floods extends on a range ca. 5'500 m3/s in peak discharge and 650 mio m3 in volume. The tan ellipse indicates approximately the extent of the numerically acceptable solutions. Outside this area the dots correspond to rather unrealistic combinations. The blue dots concentrate around the 50% probability values in discharge and volume (14'300 m3/s, 4'700 mio m3). As the selected probability targets 90%, the critical flood must be larger in both volume and discharge to these average values.

 *Spread of the 3’000 simulations, with a 90% limit line*

**Volume (mio m3)**

**Peak (m3/s)**

The green dots represent all floods for which the maximum water level is just critical. One sees through the inclination of the line synthesising these dots that this variable (water level) is largely dependent on the peak flow of the flood; it almost does not depend from the flood volume. A possible flood is picked out of these green dots; represented with a red circle on the pink line. The red dots are not considered (either leading to an indicator probability beyond the retained 90% value of simply being numerical coincidences).

**Final words about PMF estimation**

The approach summarized above provides a useful complement to the classical PMP-PMF method. This tool frees the analyst from arbitrarily imposing simplifying hypotheses in the usual case of great uncertainties of extreme events. The method, relying on a probabilistic approach, integrates generation of extreme meteorological events, response of the watershed and characteristics of the flood evacuation system. Its outcome is the distribution curve of an indicator directly useful to the dam operator or the Authority in charge of dam safety.

It reveals very useful for controlling the adequacy of the preliminary design of a flood evacuation system. The work of the analyst abandons the multi-dimensional selection of the characteristics of the probably most extreme hydrological event. It focuses on assessing which one-dimensional response can statistically be considered as representatively resulting from the most extreme conditions.

The presentation of a real application illustrates the practicability of the method. The various phenomena coming into play do not need to be precisely defined. The important number of Monte-Carlo simulations carried out provides a reliable estimate of the variability range of the reservoir response. Simultaneously, it offers the opportunity of easily performing a sensitivity analysis.

* **Conclusion**

A few final reflections can be elaborated at this point of this short presentation. Both parts of the article have put forward the large uncertainties always present in hydrological processes. Be they inherent to the specificity of the natural process and its instantaneousness (if not its elusiveness), or mirrored in the important philosophical and technical differences institutionalised in the official standards implemented around the world.

A theme that is for instance only weakly used for flood determination is that of the base flow of a river at the onset of a flood. Two identical rainfalls on a given watershed however will not always lead to an identical peak flow, due to the initial filling state of the various aquifers of the water catchment and the different resulting discharges of the river.

Another bias frequently observed during the determination of the extreme floods is the very high weight attributed to the flood hydrograph (e.g. unit hydrograph) and the generally much smaller consideration attributed to the proper balance of precipitation and flood volumes. The simple check of the size of the estimated flood hydrograph with the volume of the precipitation at its origin is rarely performed. A re-balancing of these approaches can at any rate only be beneficial to the consistency of the hydrologist's work.

A last word on the mastering of uncertainties, which represents a major challenge of hydrology, as was seen above. In the realm of rare events, uncertainties are particularly marked. On one hand, there are "natural" uncertainties related to the observed floods. On the other, there are the additional uncertainties of extrapolation methods applied for estimating the magnitude of extreme events.

The random uncertainties related to the natural variability combine with the epistemic imprecision of the extrapolation; this leads to a very likely important uncertainty in the determination of the extreme events. The hydrologist faces then the delicate task of driving safely his boat on the oftentimes treacherous sea of uncertainties. Here, consistency and robustness of the approach must prevail over the illusion of precision.

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