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AN INTEGRATED PROBABILISTIC APPROACH FOR DETERMINING THE EFFECTS OF EXTREME HYDROLOGICAL EVENTS ON A FLOOD EVACUATION SYSTEM

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ABSTRACT

The well-known PMP-PMF method has been developed for estimating the most extreme hydrological events likely to occur. It is however subject to many uncertainties, which require as many simplifying assumptions. The imprecision and biases, and consequently the inaccuracy of the estimate, are summing up all along the hydrological chain. The resulting hydrograph however is considered representative of the most critical situation for the dam and its flood evacuation system.

To alleviate these drawbacks and damp the consequences of oversimplifications, an integrated probabilistic approach has been developed. All the uncertainties (precipitation, snow melt, infiltration, 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 route these events through the reservoir and its evacuation system.

All the independent variables are randomly generated within their respective estimated variation range. The statistical analysis of the response distribution focuses on an indicator of interest (max. water level, max. outflow discharge, e.g.). This allows to determine – among others – the extent of its probable variation range. On the basis of this response, the design engineer can decide whether the occurrence probability of the indicator is compatible with the safety rules in force.

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.

***Keywords*:** PMP-PMF, Spillway design, Probabilistic approach, Monte-carlo, Integrated routing

INTRODUCTION

The PMP-PMF method for determining the critical floods aims at describing phenomena whose effects must be analysed for extreme conditions. A single event, characterized by a hydrograph, results from the study and is considered as the Probable Maximum Flood a reservoir will ever experience. The water evacuation system is then designed on the basis of this synthesized flood.

The PMP estimation is however subject to many uncertainties, concerning its magnitude as well as its general pattern. The response characteristics of the sub-catchments hit by the precipitations are also only partially known, especially for extreme events. The quantification of the uncertain sub-catchments response to that little known PMP, magnified by the imprecise combination of these individual runoff contributions, cannot result in a reliably accurate estimate of the critical flood!

An integrated approach – of probabilistic character – allows to alleviate the consequences of the inevitable simplifying assumptions and a priori. The uncertainties contributing to the vagueness of the PMF hydrograph are considered to be linked to random events. Any combination of these events leads to a possible PMF, which can be run through the reservoir and the spillway, resulting in a set of possible maximum responses (water level, outflow, etc.). The response distribution for a number of simulations can then be analysed to determine the statistically critical event.

1. PRINCIPLES AND LIMITS OF THE PMP-PMF METHOD

1.1. Estimation of the Weather Impulse (PMP)

1.1.1. Background

PMP is the probable maximum depth of precipitation in a given area and during a given duration, fallen in a very appropriate dynamic and thermodynamic condition. In reality, the important factor of precipitation depends on the synoptic patterns. If they benefit from appropriate parameters such as temperature, humidity and wind, and simultaneously from appropriate dynamic and thermodynamic conditions, they can produce the most severe precipitation in a specific given duration.

The obtained parameters are considerably related to our knowledge of the physical synoptic methods. The PMP values are dependent on the long-term synoptic parameters such as the solar radiation energy and other effective dynamic factors. There is hardly any specific way to exactly determine the precision of the PMP values. The judgment of meteorologists is based on dynamics, extension of storms and the physical capacity of accepting water vapor.

1.1.2. Selection of Model

There are various models used for estimation of probable maximum precipitation, one of which to be selected based on the situation of the catchment area, restrictions and precision of the data, length of the record period, and some other factors.

The statistical methods shall inevitably be used where there are no synoptic or higher stations. There are two other synoptic models: the mountainous and the convergence models. The latter has been used in PMP calculation of the Ostour basin. This model is mostly applicable when suitable data for relatively long periods are available. It is usually used for non-mountainous (flat) regions; the effects of mountainous areas are considered later in the computations.

In order to estimate the PMP values, the applied methods in the maximized storm precipitation require the area of humidity and the humidity convergence through the storm and its expansion. Generally speaking, each storm has the following features:

- Convective activity of the hot, humid air towards the storm center
- Advection of the hot, humid air.

1.2. Characteristics of the Ground Response

1.2.1. Background

The PMF is a hypothetical flood representing an upper limit to what has a reasonable likelihood of occurrence for the basin in question. The PMP plus associated temperatures and snow pack are the inputs to the development of the PMF for the basin.

1.2.2. Methodology

Transformation of PMP into PMF is usually carried out following the rainfall-runoff approach. In this regard, it is required to determine basic rainfall-runoff elements of the studied watershed and taking in consideration the basic data accessibility. First of all, during a hydro-meteorological analysis, major historical floods and relevant storms are determined and then for each storm, the rainfall-runoff parameters are simulated.

A calibrated numerical model is required to determine the resulting runoff from the meteorological parameters. In general, due to lack of basic data, normal approaches of using standard flood hydrograph packages, do not lead in sound rainfall-runoff correlations, as is the case of Ostour project. Results of calibration processes highly depend on basic data. Thus, a robust process has to be set up to collect all available data in different authorities.

These characteristics lead to adopt a simplified calculation procedure, in line with the overall quality of the available data. This method, based on a probabilistic approach, allows to easily take the simplifications and uncertainties into account and proceed further in a balanced way.

1.3. Limits of the PMP-PMF Method

The classical PMP-PMF approach attempts to describe and quantify the possibly most critical flood hydrograph (PMF) at a given location. The procedure is straightforward and the resulting hydrograph serves as a reference for further engineering and design reflections. However the method bears some intrinsic limitations:

- there is a risk of systematically considering the worst situation for all the independent variables (weather pattern, precipitation, soil saturation, routing time, etc.), thus overestimating the PMF;
- another risk is to consider an apparently critical hydrograph, which turns out not to be the most critical for the dam, thus basing the design of the flood evacuation system on an inadequate PMF;
- in addition, coarse simplifying hypotheses must often be advanced to start a calculation, without much control on their individual influence on the resulting hydrograph.

The multidimensional nature of the problem makes it difficult to keep an overview on the biases introduced at all stages of the study. At least, it results in a plausible estimate of the most critical event a dam and its appurtenant structures are likely to ever experience. In this sense, this approach is appropriate at the preliminary design stage. In the authors' views however, it comes a bit short for the final design check.

2. INTEGRATED PROBABILISTIC APPROACH

2.1. Principle of the Method

As seen above, the various unknowns and uncertainties are abundant and present sometime a large magnitude for extreme hydrological events. A parameter combination only considering the most critical contribution of all variables may result in an overestimated PMF – in peak discharge or total volume, or both. On the other hand, the respective influences of the single factors may offset each other. As no one has ever observed a PMF, nobody can tell with certainty the combination which will cause the most critical flood at the outlet of the watershed, but without overestimating it.

It is possible to give this fact a particular attention by letting a large number of variables and parameters fluctuate. These variations should be allowed to occur freely within a given range around values considered as reasonably describing the precipitation, the watershed, the flood routing and their various characteristics. Instead of defining a limited number of scenarios and then selecting the most critical reaction of the watershed, the method proposed here follows a simpler and yet more flexible way. 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 hundreds at least) leads to a family of possible PMF and their derived indicators. The ranking of these indicators according to a logical criterion is finally performed. As a by-product, the selection of the hydrograph that makes most sense for the design of a safe operation of the reservoir can easily be done.

2.2. Illustration of the Calculation Process

The estimation of the uncertainties requires some flair, since their nature is sometimes very elusive (most critical weather pattern, for instance, or losses incurred by the catchments). The imposition of very small uncertainties may confer a feeling of security – the results all lay within a narrow range –; they may also miss the point, if some parameters have been wrongly determined at first. On the other hand, very large variation ranges – a more realistic position, considering the numerous unknowns – would lead to such a strong results spread that the calculations would not be of much use.

The number of possible combinations of the basic data is enormous. Most of them would not lead to hydrographs close to the PMF; some would generate data combinations so extreme that their outcome could not be considered as realistic, since referring to all too rare events. The results of a few however would allow to consider them as stemming from a critical data combination. The most critical PMF for the reservoir and its appurtenant structures is tightly linked to these cases.

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 combination of their respective influence can thus be analysed without particular restriction (e.g. conditional probabilities). Figure 1 illustrates what the outcome of such a simulation might resemble, for a sorted indicator.

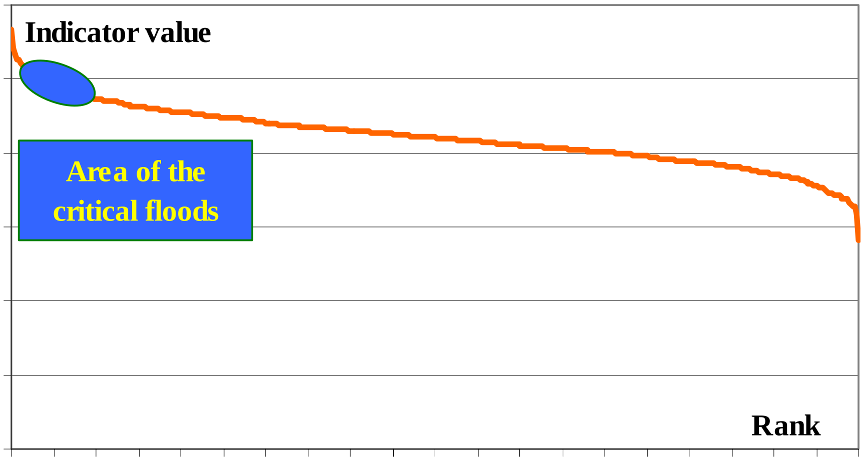

Figure 1. Typical sorted curve of an indicator, with area of the most critical floods

The input data being considered as random variables, the resulting indicators will as well be random, each referring to a particular distribution function. The general slope of the cumulative distribution function is a indication of the overall uncertainty of the estimate. A greater slope is the sign of a greater uncertainty, and vice versa.

The very extreme results would have to be disregarded, being more the result of numeric combinations than illustrating realistic physical conditions. The extreme values excluded, the central part of the distribution could be considered as representative of the reasonably possible PMF's. The PMF leading to the most critical values of the indicator (within the acceptable range) can be considered as the critical floods. No rules pre-determine the magnitude of the extreme fringes. Their setting is a matter of appreciation and engineering judgement.

2.3. Discussion of the Method

The conventional PMP-PMF method is rather straightforward: once the Probable Maximum Precipitation is determined and the watershed reaction estimated, the Probable Maximum Flood can readily be derived. The first design of the evacuation system is based on this PMF.

The new approach offers a way to check this preliminary design before finalization by putting it in a broader context. In a sense, it enables to complement the engineering work with a sensitivity analysis. In particular, the great number of simulated situations reveal the respective influence of the flood characteristics (total volume, peak flow, e.g.) on the evolution of the selected indicators.

In addition, the method frees the analyst of the cumbersome task of precisely selecting the values of the numerous variables stepping into the problem. The uncertainties of a variable are simply taken care of by means of its randomization. At any rate, the selection of a variation range is easier than the choice of a single value. It also prevents from artificially introducing biases into the analysis by systematically considering the worst case for each variable, or by assuming that some arbitrarily selected variables do not reach their critical value for some reason.

Actually, there is no need with this approach to even know precisely the characteristics of the PMF. The method directly leads to the probability distribution function of the selected indicator. The more simulations, the more precise this function. The comparison of the acceptable limit for that indicator with its variation range immediately reveals any possible problem in the design of the evacuation system and allows to rapidly take corrective measures if necessary.

The exact shape of the critical PMF can be considered as a by-product of the method. As will be shown in the example below, not only one single set of flood characteristics may result in a critical indicator value, but a number of possible extreme events. In this sense, the critical PMF should rather be seen as a possible collection of critical floods.

3. APPLICATION TO OSTOUR RESERVOIR

3.1. PMP – Sub-catchments

3.1.1. Hydrological Characteristics of the Study Area

Ghezel Owzan basin, in the central parts of the northwest of Iran, is located in between 35^{o} to $38^{o}20$’ North latitude and $46^{o}30$’ to 51^{o} East longitude. It is one of the greatest and most important rivers in the country. The confluence of Ghezel Owzan with the Shahrud River constitutes the Sefidrud River, from which almost 85% of the basin size belongs to Ghezel Owzan River. The great Sefidrud River reaches the Sefidrud reservoir dam around the town of Rudbar. The northwards outflow of the river from the dam pours into the Caspian Sea.

The Ghezel Owzan Basin, with a basin area of 42075 km2, is limited by the Alborz Mountains from the North and by the northern Zagross Mountains from the West and South. This chain of mountains is extended to the East of the basin and reaches the Central Plateau of Iran, in the eastern and south-eastern parts. Ghezel Owzan River is almost 600 km long while the prevailing altitude in all the sub-basins is 1950m.

The middle and upper sections of this river is constituted of 7 large basins, whose outflow runoffs are measured at hydrometric stations. Figure 2 illustrates the contribution of the catchments upstream to major hydrometric stations during selected storms.

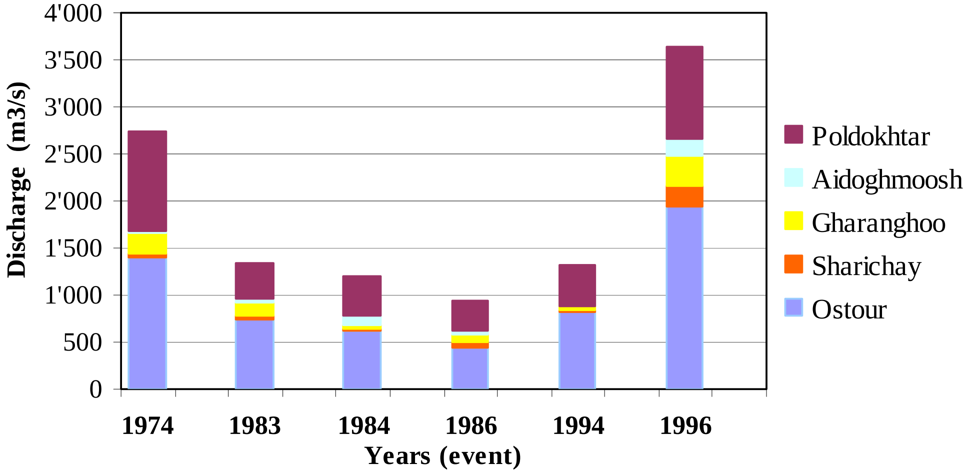

Figure 2. Contribution of sub-basins in flood production during selected storms

3.1.2. Assessment of the Climate in the Area

There is a low-pressure system on the North of Sudan and South of Egypt, called as *Sudan Seasonal Low-Pressure System*. This is a thermal low-pressure with a southwest–northeast motion, but no dynamic activity. However it may change to a dynamic system, under some specific conditions.

Also there is a *Low-Pressure center* on the *East of Mediterranean*, which is dynamic and may conduct the atmospheric currents into this low-pressure system, from two directions. These two low-pressure systems are very active and effective and provide the actual rainfalls in Iran.

The combination of Sudan and East Mediterranean low-pressure systems have effective role. The Sudan system, either independently or if combined with the low-pressure East Mediterranean system and fed with the humidity of the Oman Sea, can cause intensive precipitations on the Ostour basin. This is due to the existence of the high-pressure hot system on the Caspian Sea and convection of humidity and cold air from Alborz northern slopes towards East, North and northeastern areas.

The PMP studies have been carried out through synoptic approach. Based on order of magnitude and basic available data, also according to the relevant produced historic floods, basic storms for PMP have been finalized, on the basis of relevant synoptic maps during selected storms.

The duration of the global event has been considered relatively short, corresponding to the most severe storm as yet observed (55 hours). This concentration of the precipitation has an adverse effect on the reservoir operation and leads to conservative results. To concretize this fact, the storm has been sliced into five sequences of eleven hours each. Two typical shapes of the storm are presented in Figure 3; they are randomly selected and independently applied to all sub-catchments at each simulation. These regionally generated time patterns care hence for both differentiated starting times and the search of the most critical combination of regional events.

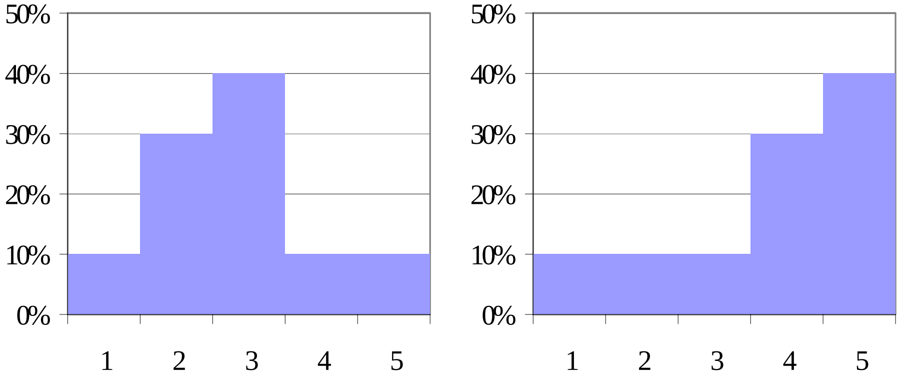

Figure 3. Two possible precipitation patterns (five sequences, total = 100% precipitation)

3.1.3. Watershed Characteristics

The PMP-PMF study for the Ostour reservoir relies on a modest basis, in terms of basic data availability. The most important are the discharge measurements in Ostour – even though there are some doubts about the quality of this basis material – and precipitation statistics. The snow data are not numerous, and give more an indication than a real statistical picture. The data related to the losses are very poor. One has to rely on comparisons and own best guess type of estimations.

The PMF part of the work involved two steps. The first dealt with the determination of the various physical and hydrological characteristics of the Ostour watershed and its sub-catchments. The second integrated all the elements previously determined (PMP patterns and hydro-physical characteristics) into a procedure that could take the most out of these data, without artificially introducing new uncertainties or bold assumptions.

3.1.4. Subdivision of Watershed and Analysis of Observed Flood Hydrographs

For the sake of the simulations, the Ostour watershed has been first subdivided into 3 sub-basins, then into 11. It has been noticed that both approaches influence somewhat the results, what they should not. The optimal number of sub-basins for the Ostour watershed and the methodology chosen is estimated to be seven to nine. The final choice has been settled on eight. Only the results obtained with this division pattern are presented here.

Analysis of rainfall-runoff components carried out according to the data collected in 10 major hydrometric stations. Results of these analyses include the following parameters. By this, the main parameters required for transformation of rainfall to runoff are defined :

- Duration (instantaneous/daily hydrograph)
- Total precipitation
- Runoff coefficient
- Total hydrograph volume
- Net runoff
- Curve Number (CN) and losses

3.1.5. The Reference Values and Assumptions

The generated values of all the uncertain parameters are centered on most probable values, which will serve as references. These values result from the previous studies. They are the following :

Total precipitation over sub-catchments	130 mm
Total snowmelt of sub-catchments	25 mm
Total I+O losses of sub-catchments	45 %
Routing time (between sub-catchments and Ostour)	individual
Base duration of the individual unit hydrographs	individual
Time to peak of the individual unit hydrographs	individual
Base flow in Ostour (initial discharge)	800 m^3/s

It has been assumed that the uncertainties lie in the range +/- 10 to 20%, depending on the parameter considered. The variables are allowed to randomly vary within this range.

3.2. Flood Routing Through the Reservoir

The Ostour Dam project, as it was planned in 2003, is equipped with a surface crest spillway, a gated spillway on an abutment and safety orifice spillways. The total capacity of the spillways under design conditions is around 10’000 m^3/s. The determinant criterion for checking the safety in case of a PMF event is the maximum outflow discharge of the spilling devices.

This is directly linked to the maximum level reached by the water in the reservoir. This last statement implies that the routing effect through the reservoir is to be integrated in the process of determining the most critical hydrograph corresponding to PMF conditions. This routing effect is governed by the head-discharge function of each spilling device and the flood management rules of the dam, as well as by the volume-elevation relation of the reservoir.

The probabilistic approach for determining PMF conditions generates a set of hydrographs. As appears on Figure 4, these hydrographs may assume quite different shapes. Two parameters were particularly relevant in the Ostour case: the peak discharge value and the total volume.

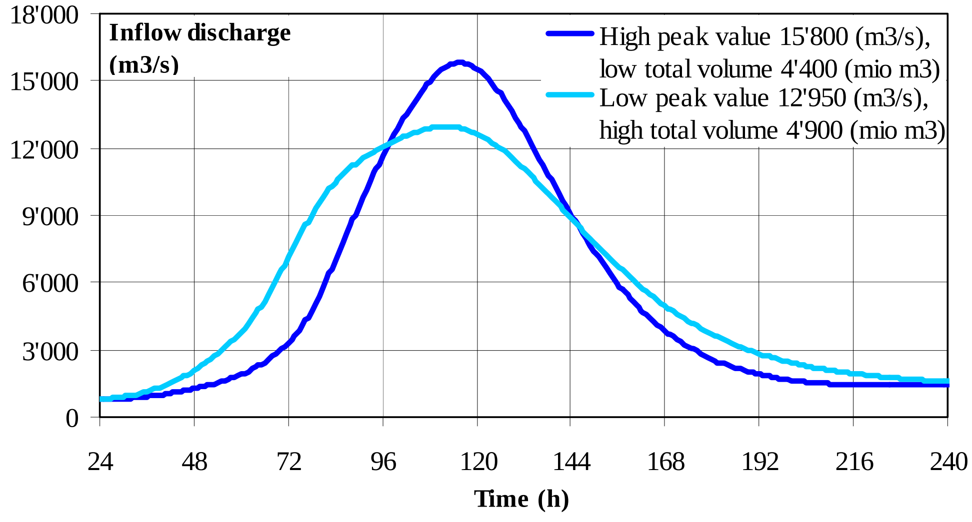

Figure 4. Example of possibly critical hydrographs

By coupling the stochastic tool for generating possible PMF hydrographs and the routing process through the reservoir – considering the head-discharge function of the spilling devices and the flood management rules –, it becomes possible, for each run of the Monte-Carlo process, to determine the maximum water level in the reservoir. The statistic analysis of the set of values obtained using the coupled PMF generation – Flood routing process allows the designer to select the most appropriate value for a credible PMF flood.

Figure 5 shows the routing through the reservoir effect for two representative possible PMF hydrographs. Inflow and outflow discharges, as well as the reservoir level are plotted versus time.

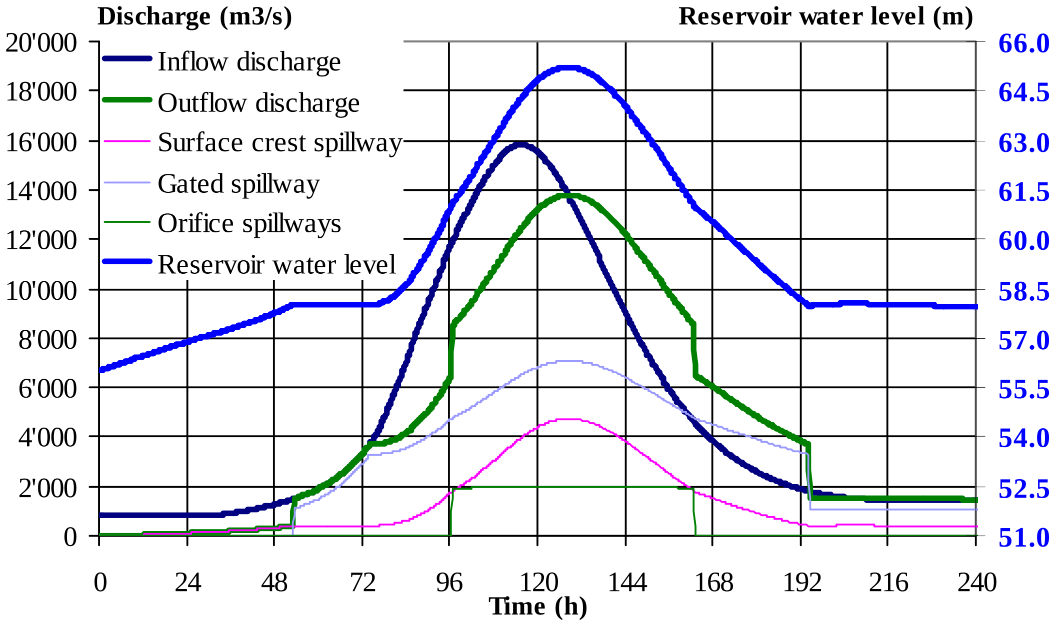

Figure 5. Routing process for a possible PMF hydrograph

A set of 3000 hydrographs have been generated by the Monte-Carlo type stochastic tool and routed through the reservoir. These calculations included each the determination of the hydrograph in Ostour as well as the routing through the reservoir, to end up with the maximum water level reached during that particular event.

As Safety Check conditions for the spillways, it is not reasonable to consider the statistically most critical value of all possible PMF-hydrographs generated. As stated above, the most unfavourable probabilistic combination of all governing parameters renders this particular configuration unrealistic. Critical PMF conditions should however correspond to a reasonable probability of reaching a maximum outflow discharge. The deterministic approach, which corresponds to a classical PMP-PMF approach, would give a mean value, leading to a ca. 50% probability of overrun.

To illustrate the present example, a probability of 10% of overrun has been considered, leading to a maximum water level of 65.20 m over the reference level for PMF conditions.

Each dot shown in Figure 6 refers to a generated hydrograph, characterized by a set of values peak inflow discharge – total volume. The green dots indicate all the hydrographs leading to the defined accepted maximum water level (65.20 +/- 0.02 m a.s.l.). Any of these hydrographs could be selected as the PMF hydrograph, all having the same consequences for the maximum outflow discharge. The selection of one hydrograph as representative of the PMF conditions doesn't really have a physical sense, but is commonly done for simplification of the further design steps.

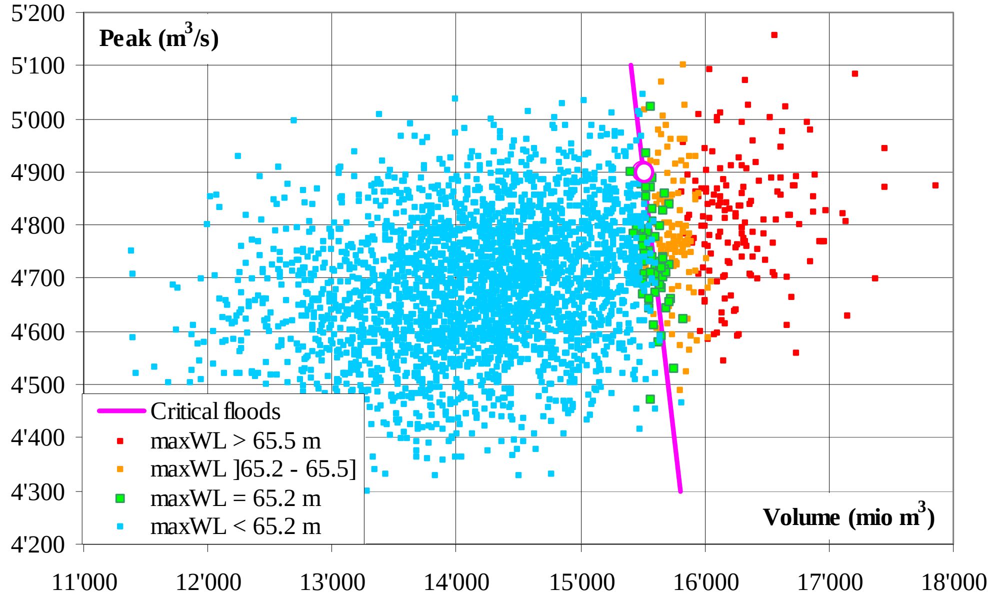

Figure 6. Spread of the 3’000 simulations, with a 90% limit line

3.3. Statistical Analysis of the Response

Table 1 shows the statistical analysis of the results obtained by the coupled Generation-Routing tool. The main statistics of the key variables (characteristics of hydrgraph, response of Ostour dam and spillway) have been presented.

Table 1. Statistical analysis of the results

	Peak discharge [m^3/s]	Total volume [mio m^3]	Maximum water level [m]	Maximum outflow [m^3/s]
Mean value	14'332	4'692	64.51	12'706
Standard deviation	973	135	0.54	726
Maximum value	17'551	5'160	66.93	15'012
Minimum value	10'962	4'249	62.68	10'191
Probability of overrun				
5%	15'913	4'914	65.39	13'898
10%	15'573	4'872	65.20	13'619
90%	13'065	4'516	63.82	11'758
95%	12'746	4'472	63.61	11'513

The figures presenting the main results of the simulation have been drawn from the standpoint of the dam operator, who is concerned with the global consequence of an extreme event. The maximum water level in the reservoir reached during the flood has been selected as the indicator.

The distribution curve is presented on the Figure 7 below. One observes that its variation spreads slightly over 4.0 meters. The shape of the curve is very close to a normal distribution (pink curve). For this example, the cumulative value of 90% has been considered as representative of the probable critical physical process, the 10 upper per cent being disregarded (orange area). This leads to a Probable Maximum Response of 65.2 m above the reference level, in terms of water level. This value has then to be compared to the maximum allowed water level, to ascertain the adequacy of the flood evacuation system and procedures.

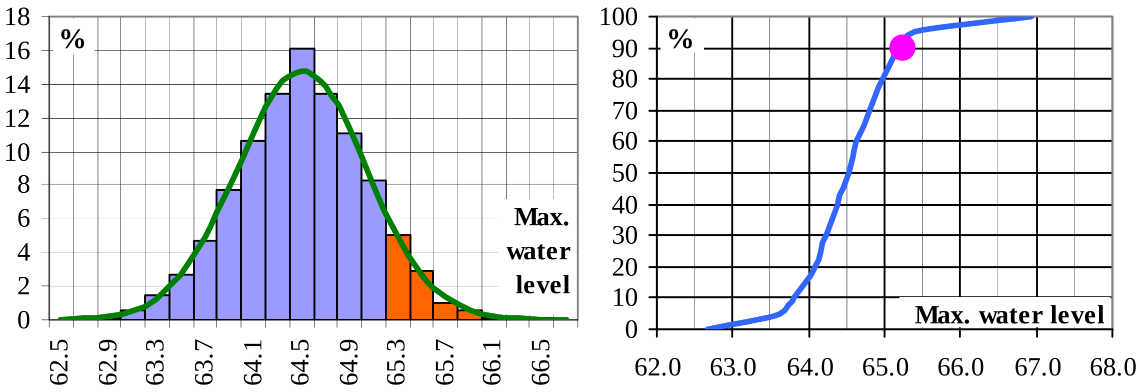

Figure 7. Probability and cumulative distribution functions of the maximum water level; comparison to a normal pdf (green curve); pink dot = selected probability

The cumulative distribution function shown on Figure 8 below illustrates the dispersion of the extreme values. At that point, the experience of the hydrologist and of the design engineer are required to assess the nature of the curve extremities. In the example, the kink of the curve above the 90% mark and its queue are considered to be rather due to numerical unfavourable combinations than to probable physical phenomena.

4. CONCLUSION

A useful complement to the classical PMP-PMF method has been developed. This approach provides a tool that frees the analyst from arbitrarily imposing simplifying hypotheses in case of great uncertainties of extreme events (which is usually the case). The method, relying on a probabilistic approach, integrates the generation of extreme meteorological events, the response of the watershed and the characteristics of the flood evacuation system (design, evacuation procedure). The outcome of the approach is the distribution curve of an indicator directly useful to the dam operator (max. water level in a reservoir, maximum outflow discharge through a spillway, etc.).

By properly formalizing the fuzzy and fairly elusive nature of an hydrological event that is by definition not observable, it reveals very useful for controlling the adequacy of the preliminary design of a flood evacuation system. The work of the analyst shifts from selecting the characteristics of the probably most extreme hydrological event (a multi-dimensional task) to assessing which response can statistically be considered as representative of the most extreme conditions (a one-dimensional issue). In this context, it is possible to introduce the notion of a Probable Maximum Response.

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 (an impossible task indeed). The important number of Monte-Carlo simulations carried out (3’000 in the example presented) provide a reliable estimate of the variability range of the reservoir response. Simultaneously, it offers the opportunity of easily performing a sensitivity analysis.

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