Continuous simulation for computing design hydrographs for water structures

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Abstract
The contribution discusses the problems with modelling design floods for water structures. The statistical extrapolations of observed flood series of, for example, 80 years "only" to the annual exceedance probability AEP = 0.01 is difficult due to the large variability in extreme values. For large dams, however, the AEP = 0.001 or 0.0001 is required. Most of the uncertainties in hydrological modelling are epistemic (uncertainties in model structure, model parameters, inputs, calibration data, and in measurements) and moreover some measurements can be disinformative. With powerful computers, it is now possible to produce very long series (100 to 100,000 years in hourly time step) using precipitation and temperatures computed with a weather model. Within the framework of the Generalised Likelihood Uncertainty Estimation (GLUE) many (thousands) of such continuous simulations are produced and compared to the observed historical data. According to Keith Beven’s Manifesto for the equifinality thesis the differences between modelled and observed values should not be larger than some limits of acceptability based on what is known about errors in the input and output observations used for model evaluation (e.g., for flow the current metering data are used). The unacceptable realisations are rejected. We have been working with the frequency version of TOPMODEL in various versions according to the unique characteristics of each catchment. Design hydrographs for water structures are then extracted from the acceptable realisations. The continuous simulation with uncertainty estimation seems nowadays the most promising method of computing design hydrographs for important water structures, even if issues associated with epistemic uncertainty of model assumptions remain.

KEYWORDS
acceptability limits, equifinality, frequency TOPMODEL, GLUE, hydrographs with very low AEP, safety of dams

1 INTRODUCTION

The actual frequency of a precipitation–runoff event with a high enough magnitude to threaten the safety of a dam is difficult to estimate due to the high sampling variability of large magnitude, low probability observed precipitation–runoff events, and the epistemic uncertainties in individual catchment responses under such extreme conditions (Beven, 2000, 2012b; Rougier & Beven, 2013, see also Taleb, 2007, 2010).

In spite of the required return period of the design flood being in the case of larger dams 10 or 100 times longer than the observed historical series, statistical extrapolations are still sometimes used. In the United States and other countries, Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF) are the most commonly employed procedures (Zielinski, 2011). Nowadays, however, several teams in Europe and elsewhere have been developing continuous simulation procedures (Arnaud & Lavabre, 2002; Bergström, Harlin, & Lindström, 1992; Beven, 1986a, 1986b, 1987; Blazkova & Beven, 1997, 2002, 2004, 2009a, 2009b; Calver, Stewart, & Goodsell, 2009; Lamb & Kay, 2004; Lawrence, Haddeland, & Langsholt, 2009; Loukas, Vasiliades, & Dalezios, 2000; Muller, Arnaud, Lang, & Lavabre, 2009; Willems, 2009) as an extension of the derived distribution approach of Eagleson (1972).

Using the frequency version of TOPMODEL, applied within an uncertainty framework with specified acceptability limits for model evaluation, it is possible to demonstrate in several steps the development of such a continuous simulation procedure suitable for design flood estimation (Beven, 1986a, 1986b, 1987; Blazkova & Beven, 1997, 2002, 2004, 2009a, 2009b; Cameron, Beven, Tawn, Blazkova,
& Naden, 1999). TOPMODEL is used here as a theoretical framework within which perceived hydrological processes, issues of scale and realism, and model procedures may be researched (Beven, 2012a). For a number of catchment applications in the Czech Republic on which we have carried out flood frequency research, TOPMODEL versions have been developed, starting with Blazkova and Beven (1997, 1994, 1995a, 1995b) and Beven and Blazkova (1999).

2 | NOVELTY OF THE PAPER

This paper follows the Blazkova and Beven (2009a, see also 2009b) paper in which we have introduced Generalised Likelihood Uncertainty Estimation (GLUE) with acceptability limits into the frequency modelling. The simulations, however, were only 10,000 years long, so that we presented the results only up to AEP = 0.001. In this paper, we have selected 19 series which fulfilled all criteria (see below) and modelled series of the length of 100,000 years. We have developed a partly automatic and partly manual procedure for finding hydrographs which might be dangerous for the dam. Another procedure that we have not published yet in connection with the design hydrographs is the routing the hydrograph through the reservoir and getting the water levels which are directly comparable to the safe water level from the operating rule.

3 | VARIABILITY OF OBSERVED DATA AND UNCERTAINTY IN MODELLED RESULTS

The consequences of a dam failure might be catastrophic (see the statistics of the International Commission on Large Dams, ICOLD [1995] and also the U.S. Department of Interior report [1999] on small dams). Therefore, it is essential to concentrate attention on being robust with respect to the sources of uncertainty. The sampling variability of high-magnitude extremes within the relatively short periods of historical data results in great uncertainty in estimated frequencies. We also do not know what form of distribution should be used to represent the extremes nor whether a single distribution is really appropriate (it is clearly not in many climate regions, e.g., Waylen & Woo, 1982), nor whether the distribution is really stationary (e.g., Clarke, 2007; Renard, Lang, & Bois, 2006). All of these issues are examples of epistemic uncertainties that will arise in the application of any statistical methodology for estimating frequencies.

There are a variety of sources of epistemic uncertainties (error) involved. The first is how to properly represent the joint effect of space–time patterns of rainfalls (and snowmelt if necessary), antecedent conditions and runoff generation processes on extreme events. This requires a model, either a statistical distribution or a stochastic process model, and models require assumptions about structures and parameters. In modelling extreme events that may be well outside the range of the historical observation period, there is little opportunity to test those assumptions as realistic hypotheses about the functioning of a catchment. We do not have the knowledge to do so. This does not mean that some models cannot be excluded as unrealistic under extreme conditions, only that there may be a number of potential models (or statistical distributions) that might be used. Certainly, such testing should be a part of the process, and models rejected when it is clear that they are not consistent with any available observations, including any internal observations in subcatchments (e.g., Beven, 2015). This can, however, only provide some confirmation within the range of the available data, it cannot protect against being wrong in extrapolating to more extreme events.

Any model (whether statistical or stochastic) needs to be calibrated, and whether a model structure survives a test depends on both the set of parameter values used and the uncertainty in the data used to calibrate it. In stochastic simulations, whether a model is acceptable or not might also depend upon the particular realisation of the input data (e.g., Blazkova & Beven, 2009a). Recent work suggests that uncertainty in the observations might have an important effect on model calibration (e.g., Blazkova and Beven, 2009a, 2009b; McMillan et al., 2010, 2011a, 2011b) and in some cases might even be disinformative in identifying a model that is right for the right reasons (Beven & Smith, 2015; Beven, Smith, & Wood, 2011; Beven & Westerberg, 2011). We also know, of course, that it can be rather difficult to specify parameter values a priori or extrapolate from gauged catchments to ungauged catchments or subcatchments. This also involves epistemic uncertainties, of not having enough knowledge about how model parameters might relate to the characteristics of a catchment, subcatchment, hydrological response unit or representative elementary watershed (e.g., Beven, 2005).

4 | METHODS

We can roughly say that there are three types of methods for estimating the frequencies of extreme floods: traditional methods using statistical distributions of extremes (also for ungauged sites); the use of PMP and PMF, which were designed on purpose for high and potentially dangerous dams; and finally, various variants of continuous simulation, which are making the fastest progress nowadays. The latter were originally intended primarily for research into hydrological processes (e.g., Beven, 1986a, 1986b, 1987) but their possibilities for routine use in frequency analysis are increasing with available computer power.

All these methods necessarily involve assumptions that are subject to epistemic uncertainties. In the statistical method, the choice of the distribution of extremes is hugely important, as is readily seen when applying several distributions fitted to the data with the extrapolation only up to 100 years. The largest one or two flood points usually lie on a highly uncertain plotting position, which becomes obvious when we work with a simulated series (Figure 1). A 100,000-year series (blue points) in Figure 1a is plotted here as a demonstration of the case when the points of individual floods lie on a reasonably correct plotting position up to the Gumbel reduced variate (see e.g. Kottegoda, 1980), y, for the 10,000-year flood ($y = 9.21$, AEP = 0.0001). There are 10 larger floods which are somewhat scattered. In Figure 1b, we are trying to find the 10,000-year flood by modelling “only” series 10,000 years long. The series are not so smooth—the scatter begins even before the 1,000-year flood. In Figure 1c, we try to model 1,000-year flood ($y = 6.91$) by modelling series 1,000 years long, and in Figure 1d, we are modelling 100 years flood ($y = 4.6$) using 100-year simulation. The series in plots b, c, and d were produced by splitting the series in the plot a. This visualisation method makes the high variability in floods with low probability obvious. When the 100-year series containing the
largest flood from the plot a is plotted into the other plots (red squares), it is possible to see the uncertainty (error) of the largest flood as to the plotting position in the plots a, b, and c. The largest flood can be plotted as a horizontal line (blue in Figure 1) instead of as a point. Obviously, the same caution must be employed when choosing a distribution in modelling rainfall series.

In the PMP/PMF approach (WMO, World Meteorological Organization, 1986; WMO-No. 1045, 2009) the assumptions concerning controls on the estimates of “probable maximum” values have also been contentious, most notably the role of advection of heat and moisture in the estimation of PMP, and the effects of antecedent conditions and spatial heterogeneities in the estimation of runoff coefficients in calculating PMF.

For the continuous simulation modelling, there are two main approaches: (a) creating various random combinations of observed extreme rainfall or rainfall on snowmelt events and wetness of the catchment computed with a model (e.g., Bergström et al., 1992) and (b) procedures using coupled precipitation and precipitation–runoff models (e.g., Beven, 1986a, 1986b, 1987 using the frequency version of TOPMODEL, which will be described in more detail in the following paragraphs.

5 | VERSIONS OF THE FREQUENCY TOPMODEL

A simple rainfall generator (based on the exponential functions originally suggested by Eagleson, 1972 for analytical computation) with a small number of parameters was used to generate hourly input series for the original frequency version of TOPMODEL (Beven, 1986a, 1986b, 1987). It has only three independent parameters: average intensity, average duration of an event, and average inter-arrival time.

In the Czech Republic, the flood frequency curve from TOPMODEL simulation (with rainfall parameters computed from data not containing any really very extreme rainfall events) was lower in low probabilities than the flood frequency curve of Czech Hydrometeorological Institute derived from the regionalisation. We have therefore introduced two types of rainfall distributions: one for lower intensity events and one for higher intensity events which occur on average once a year (Blazkova & Beven, 1997; Blazkova & Beven, 1995a). In the Wye study in the United Kingdom (Cameron et al., 1999), the two types of storms did not work and they had to introduce the dependence of mean storm intensity upon duration in seven duration classes and a generalised Pareto distribution for extrapolation. This model was then successfully used for two other U.K. sites Elmdon and Eskdalemuir (Cameron, Beven, & Tawn, 2000). At present, in applications in the Czech Republic, we are using not only ground rain gauges but also the radar information for the computation of the rainfall simulation parameters for the period without snow (Rezacova et al., 2013). As a result, at least on the Uhlska catchment, upstream of the Bedrichov reservoir in the Jizera Mountains, the original model with only one type of rainfall events (Beven, 1986a, 1986b, 1987) performs quite well because the average rainfall intensity computed using the radar record, which contained a flash flood rainfall event, was higher.

A further step that was needed in the Czech Republic was the generation of temperatures for modelling snow and evapotranspiration. This version was first used on the ungauged Ryzmburk catchment where a low dam was overtopped and seriously damaged, while the closest rainfall stations did not measure anything extraordinary. The resulting estimate was used in developing a flood management plan for the Ryzmburk water structure. The use of the frequency version of TOPMODEL within the GLUE uncertainty framework was also one of the first attempts to evaluate the impact of climate change on
floods (Beven & Blazkova, 1999). A similar version was then used on the Josefuv Dul catchment—a gauged catchment treated as ungauged (Blazkova & Beven, 2002) where TOPMODEL simulations are conditioned on regionalised flood frequency, maximum annual snow water equivalent, and flow duration curve information. Performance measures were combined using fuzzy inference (Blazkova & Beven, 2002). For the large Zelivka catchment (1.186 km²), the movement of the storm across the catchment was added (Blazkova & Beven, 2004, 2009b; Kjeldsen, Lamb, & Blazkova, 2014).

The paper of Blazkova and Beven (2009a) on the Skalka catchment was one of the first applications of limits of acceptability for model evaluation within the GLUE methodology. To be able to get the computed floods on approximately correct plotting positions in this paper, we have computed 19 series of the length 100,000 years using an hourly time step. These series were selected from 39 series which fulfilled a large number of limits of acceptability (see below). Some of the 39 series had parameter sets rather close to one another. To reduce the number of long series (for computational reasons), we selected 19 parameter sets markedly different in parameter values and also, of course, the annual probability of exceedence curves.

6 | FREQUENCY TOPMODEL WITHIN THE GLUE FRAMEWORK WITH THE ACCEPTABILITY LIMITS

In this study, calibration of the continuous simulation of flood frequency followed the approach outlined in Beven (2006). This is based on the expectation that there may be more (many) parameter sets and/or model structures to fit the observed data (the equifinality thesis). The Ohre catchment up to the Skalka dam in the Czech Republic has an area of 672 km² (most of which is in Germany) and range of altitudes from 460 to 1,041 m above sea level. It has been divided into six subcatchments/interbasins with flow gauges. A number of modifications of the continuous simulation with TOPMODEL had to be introduced in this study: particularly in the snow model (Figure 2), the amount of rainfall and on the recession curve (see Blazkova & Beven, 2009a for more details). In order to get the right results for the right reasons, we have used the experience from our long term studies of runoff generation (Blazkova & Beven, 1995b, Blazkova, Beven, & Kulasova, 2002a, Blazkova, Beven, Kjeldsen, & Blazkova, 2002b, Kjeldsen, Lamb, & Blazkova, 2014a, 2014b).

To define an ensemble of parameter sets for representing the catchment, limits of acceptability have been defined (see an example in Figure 3), prior to running the Monte Carlo model realisations (for detailed description, see Blazkova & Beven, 2009a).

The discharges within the catchment and the current metering data used to define rating curves were available at five sites within the catchment. The sixth site Cheb—the outlet of the catchment (observed before the dam was constructed)—was kept for validation purposes. For the computation of acceptability limits for flow, the data from current metering were used. For flood frequency, only quantiles of 1 to 10 years flood were selected; for the flow duration curve nine different quantiles have been used in model evaluation (from about 25% to 90% exceedence).

**FIGURE 2** Routing the winter flood through the catchment. (a) Precipitation in the individual subcatchments; (b) Snow cover in the individual subcatchments; (c) Flood waves from the individual subcatchments.
Since snowmelt is an important contributor to flood events in this catchment, limits of acceptability were defined for maximum annual snow water equivalents for different elevation bands. Snow water equivalent was evaluated in 13 snow zones (one to three zones in individual subcatchments), four of which have observed data. Following initial runs of the model, an additional criterion for the percentage of annual floods occurring in winter was constructed as a trapezoidal weighting function based on an estimate from observations (most floods in the Skalka catchment are from snowmelt).

 Altogether, there were 57 different evaluation criteria, each with defined upper and lower limits of acceptability, making 114 criteria in all. Then, 610,000 realisations of the same length as the observed flood series have been computed. Only 39 simulations were found that fulfilled all the 114 criteria. With the parameter space being rather large, however, it is possible that many more models might exist that would satisfy all the requirements, particularly because an examination of the realisation effect showed that the critical score for acceptance of a model was dependent on the particular input realisation. We allowed then the extension of the limits of acceptability in a way that, by normalising the limits of acceptability for different evaluation criteria to a common scale, allowed the 4,192 best models (in a Pareto sense over all criteria) to be identified with a minimal extension on each of 114 criteria.

 With the 4,192 parameter sets, we have computed series of 10,000 years long in order to be able to get prediction limits up to AEP = 0.001 that are not unduly affected by the length of the series considered. For each realisation, we have also checked if the 1- and 3-day rainfall totals causing flood on the AEP = 0.0001 quantile are not considerably larger than the PMPs computed in Rezacova, Pesice, and Sokol (2005). If the difference was smaller than 50%, the weight associated with that realisation in contributing to the prediction limits was reduced to one half. If it was larger than 50%, we have rejected the realisation. The resulting likelihood weighted flood frequency quantile estimates at the dam site were computed from the resulting set of 4,173 long model runs each of length 10,000 years (grey lines in Figure 4) and computed uncertainty bounds (thick dash green lines). In Figure 4, we have plotted one of the series of 100,000 years into the figure and got quite a reasonable agreement with the observed validation series at Cheb. The validation Cheb series has been observed before the construction of the dam and before measurement started at the other sites in the subcatchment (with one exception). Some nonstationarity in either the catchment characteristics or the climate

FIGURE 3 (a) Flood frequency curve at Lorenzreuth on Roslau; thick solid black lines are the initial acceptability limits; circles are the observed annual floods; gray lines are the 4,192 simulations; dashed lines are the 5% and 95% uncertainty bounds from the trapezoidal weighting; and thin solid black lines are the behavioural simulations with scores on all criteria <1. Points a–e correspond to Figure 2b; ev1 reduced variate is Gumbel reduced variate. (b; top) Trapezoidal weighting function. Full line trapezoid is the original limits of acceptability; dashed lines are the estimate and acceptability bounds; and dashed dotted are the lines of the expanded trapezoid. Points a–e correspond to Figure 2a. (bottom) Scores. Squares are points to which the bounds have to be expanded.

FIGURE 4 Ten thousand years simulations (grey) plotted up to 1,000-year flood, uncertainty bounds (dashed green); 100,000-year simulation (blue circles); observed annual maxima at the outlet Cheb from the period before the dam construction (white circles); ev1 reduced variate is Gumbel reduced variate.
Forcing is obvious in the differences between the lower annual maxima between the two observation periods.

Since these are continuous simulations at an hourly time step, they can be used to provide not only frequency information on flood magnitudes but also examples of extreme flood hydrographs. In an extension of the continuous frequency simulations for checking the safety of the Skalka dam in practice, we have extracted a number of flood hydrographs from the 19 series of 100,000-year simulations (Blazkova, 2011). Some examples are in Figure 5.

In principle, an assessment of reservoir safety should depend on the combined effect of hydrograph peak and discharge volumes that create conditions for failure. Regime of the individual water structure, however, depends on the particular conditions (i.e., the size of the controllable and uncontrollable retention storage relative to hydrograph volume, capacity of the spillways and outflow works relative to hydrograph peak and volume, and type of the dam) if it may be overtopped or not and operation rules of the dam.

7 | SELECTING FLOOD HYDROGRAPHS FOR THE SAFETY CHECK OF THE SKALKA DAM

Estimating flood hydrographs for extreme exceedance probabilities for use in dam safety evaluation is only possible using the continuous simulation method. There is, however, a problem that arises in doing so in that making multiple runs of 100,000 years with an hourly time step means that storage limitations constrain how many hydrographs can be stored for all the subcatchments. Yet it is not known beforehand which hydrograph peaks will occur near the AEP = 0.0001 (in this case, it is 400 to 550 m$^3$/s).

A practical solution to this problem was designed by computing each series as twenty 5,000-year series and saving the seasonal maxima in each simulated year of data. Then the whole 100,000-year series is plotted and events about AEP = 0.0001, selected. There are seasonal differences in the nature of the predicted hydrographs. For Figure 5, we have selected three spring events, three summer ones, one autumn one (in autumn, floods are very rare in this catchment both in reality and in the model), and three winter ones.

Then, we repeated the computation of those 5,000-year sections in which the floods occurred and saved the hydrographs of each event in question, the event before and after in all subcatchments, and also a number of model state variables. It is of interest that we have not come across a case of a winter flood peak anywhere near the estimated AEP = 0.0001 level. Winter floods can have practically any shape depending on the course of temperatures and precipitation. They can have a long duration over several modelled events. The procedure of identifying hydrographs of interest was therefore partly automatic and partly manual. For the winter floods, we have saved three events before and three after the event with the largest peak. After the visual inspection, it might be necessary to add a preceding or a following (fourth) event so that the whole process of melting and freezing again is available for computing. For the case in question, however, it does

FIGURE 5 Some flood waves extracted from 100,000-year series
not have much practical importance, because the outflow (spillway and outlet works capacity) is much larger than any winter peak in our simulations (i.e., outflow can be equal to inflow for the whole duration of several winter events without causing a problem. In cases of reservoirs where the volume of flood discharge plays the most important role, the considerations would be different.) We have found two simulated events with peak about 300 m$^3$/s and one event with peaks slightly over 400 m$^3$/s, while in the observed, the winter events had peaks up to only 250 m$^3$/s.

For the evaluation of the dam safety from the point of view of hydrology, we have selected four flood waves. Hydrograph 1 with plotting position almost exactly on AEP = 0.0001 with peak 549 m$^3$/s has been caused by 4 hours of intensive rainfall on the lower Roslau subcatchment in spring, that is, on a wet catchment (Figure 5).

Hydrograph 2 (summer; 584 m$^3$/s) moved during 1 day over the upper Eger in the direction to the Czech Ohre subcatchment. Hydrograph 3 had the rainfall totals in all subcatchments larger than the second one, and moreover, the catchment was wet after spring snowmelt (679 m$^3$/s). Hydrograph 4 was caused by snowmelt with rainfall (peak 411 m$^3$/s, Figures 2 and 5). The rainfall totals have not in any of those cases been near the PMP (Rezacova et al., 2005). It was the reason why we have recommended also the second and third events for evaluation, even if they have smaller AEP than 0.0001. A winter flood with a peak of 411 m$^3$/s was included because of the large volume of simulated inflow.

Most floods in the Skalka catchment (about 70%) happen in winter—the snow cover in the Czech Republic can be from November to April (depends of course on the elevation), but there are usually one or more snowmelt during this time. Floods, however, can happen in the Skalka catchment also in summer and rarely in the autumn. Hydrograph 3 is a summer flood.

When evaluating the safety of a dam, the maximum safe water level in the reservoir has to be determined. It is also necessary to take into account the geological composition of the dam foundations (bedrock or subsoil), the materials and building technology used, both from the point of view of expected deformation and the seepage regime. Exceeding this water level does not necessarily cause dam failure. It is necessary, however, to consider some possible damage depending on the duration of the stress hence the value of simulating a complete hydrograph forcing event.

In such evaluations the initial condition is always the level at the full storage volume, that is, the operational water level given by operating rule approved by the respective water management body (for the Skalka dam, the winter level is lower than the summer level). Operating rules are conservative. At the beginning of an event, the outflow is kept equal to inflow as long as the capacity of all spillways and low-level outlet works is not reached. Then during the event, an uncontrolled outflow occurs with a water level which is above the predetermined maximum operating level.

The outflow corresponds to the capacity of all spillways and outlet works (including possible spill over the dam). In each computational step the increase or decrease of the reservoir volume equals the difference between inflow and outflow. It is solved by iteration: The estimate of outflow determines a new reservoir volume, from which a new capacity of spillways and outflow works follows, that is, a new outflow. If the difference between the computed outflow and its estimate is larger than a given tolerance, the estimate is modified and the computation is repeated.

To find out if the dam will stand the flood, we can only from the water levels in the reservoir. Especially, earthfill dams should not be overtopped because this would cause erosion and a breach can form and cause a collapse of the dam. Usually, there is some freeboard to account for uncertainties, in this case, 1 m. In Figure 6, we show the routing of the flood hydrographs 2, 3, and 4 through the reservoir (hydrograph 1 has so small a volume that it cannot present any risk to the dam). The Skalka dam has recently been reconstructed—a
second spillway has been built (therefore, we show the outflow before the reconstruction and after it). The spring flood would have exceeded the safe water level before the reconstruction (1 m under the crest; Figure 7). The wind action is not accounted for in the safe water level.

We are of the opinion that a simple routing through the reservoir should already be a part of the continuous simulation. It would simplify greatly the above described selection procedure. Most hydrologists do not include the routing in the reservoir into their computations (but see, e.g., Bergström et al., 1992 with the continuous simulation and Blazek, 2014 with PMF). The design or the safety of dam engineer will, of course, compute many more variants of the task.

8 | CONCLUSIONS

The loss of life due to a dam failure can be quite large both for a large dam and for small dams (particularly domino failures in cascade during an unusually dangerous meteorological situation).

Hydrological modelling in general and modelling extremes in particular involve a number of epistemic uncertainties. With extreme events, there is little opportunity to test our assumptions and hypotheses in practice due to the huge sampling variability.

In the continuous simulation methodology, there exists, however, the possibility to work with a number of models (parameter sets), which allows a large number of realisations to be computed. The evidence from the "always short" historical series as used to specify limits of acceptability, allows many of those models to be rejected as unrealistic hypotheses about the functioning of the catchment. The GLUE uncertainty framework with acceptability limits also provides the possibility to keep the magnitude of the modelling uncertainty at a similar level to the magnitude of the measurement error for the historical flood events. If this is not achieved, it may be necessary to modify the model.

The process of continuous simulation also allows the realisations to be consistent in mass balance terms and does allow the non-linear effects of antecedent conditions on runoff generation to be represented. It also provides a selection of predicted hydrographs with which to test dam safety under extreme conditions. Moreover, this procedure provides evidence on which model improvements, reconsideration of observation uncertainties, or user assessments of fit for purpose of a particular model structure and its predictions, might be based. The disadvantage of the continuous simulation up to now has been the insufficient computer power, but it develops so quickly that nowadays in hydrology, the uncertainty in rainfall–runoff models can be computed without much problem. The time of the computation is dependent on the complexity of the model, the number of subcatchments, and the computer(s) used.

Routing the flood hydrograph through the reservoir based on the operating rule should be a part of the continuous simulation because it would greatly simplify the selection of design hydrographs.

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