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The CRUEX++ methodology

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LABORATOIRE DE CONSTRUCTIONS HYDRAULIQUES

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1.1 Introductory description

The final outcome of the CRUEX++ methodology is a safety flood hydrograph whose peak flow return period can be estimated by a maximum annual peak discharge extrapolation causally expanded by an upper bound derived from the PMP-PMF approach. The safety flood hydrograph is derived using hydrological simulations based on a design storm. For the PMP-PMF simulation, the Swiss PMP maps can be used to determine the PMP depth. Due to the application limits of these maps, the catchment of interest should be smaller than 230 km^2. Caution should be taken when areas are between 75-230 km^2, as this range corresponds to the transition zone from valid to invalid results. This is due to the overestimation of spatial coverage of the PMP event as derived from the Swiss PMP maps.

The methodology is separated into two different approaches: one deterministic (Figure 1.1) and the other stochastic (Figure 1.2). The main difference between the two approaches is the way in which initial conditions are considered.

1.2 Model construction

The first step is the construction of a hydrological model of the catchment of interest. The model should be able to reproduce the hydrological processes as well as the hydraulic characteristics of the basin and the dam, in order to simulate the flood attenuation effect of the lake. In mountainous catchments, the hydrological model should account for snow fall and snow melt at different altitudes of the basin. These requirements can be easily achieved by using a semi-distributed conceptual hydrological model. For the development of the present methodology, the GSM-SOCONT model (Schaefli et al., 2005; Schaefli and Zehe, 2009; Jordan et al., 2012; Garcia Hernandez et al., 2016) has been applied. Other semi-distributed conceptual models, for example HBV (Bergström, 1992) , SAC (Burnash, 1995), GR4J (Perrin et al., 2003), could also be used. The main steps of the construction of a semi-distributed conceptual model, i.e.

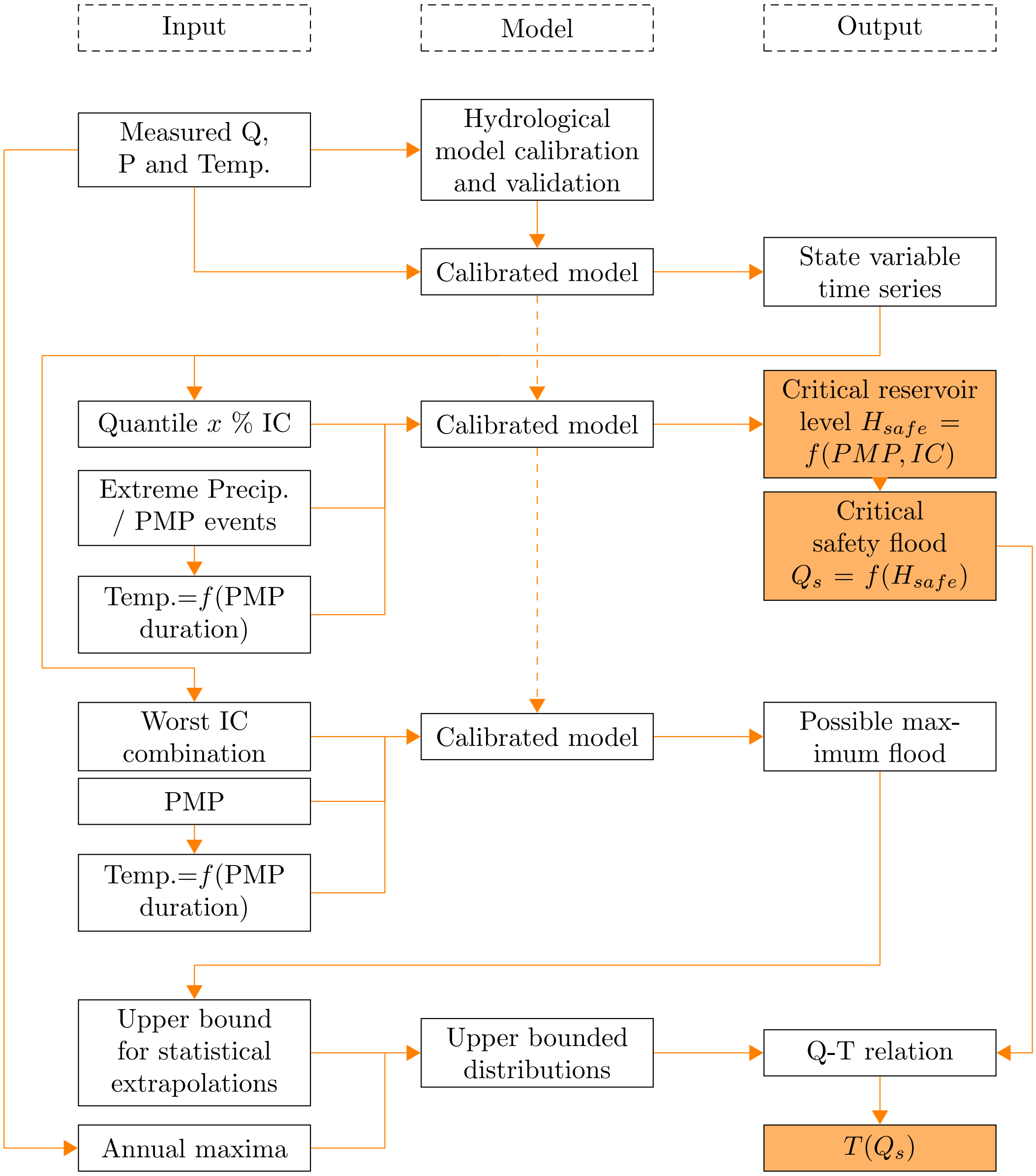

Figure 1.1: Flowchart of the methodology proposed for the deterministic estimation of extreme floods. IC = initial conditions, PMP = probable maximum precipitation, Q = discharge, T= return period, Temp. = temperature, Precip.=precipitation., H_{safe} = safety level, Q_s = safety discharge.

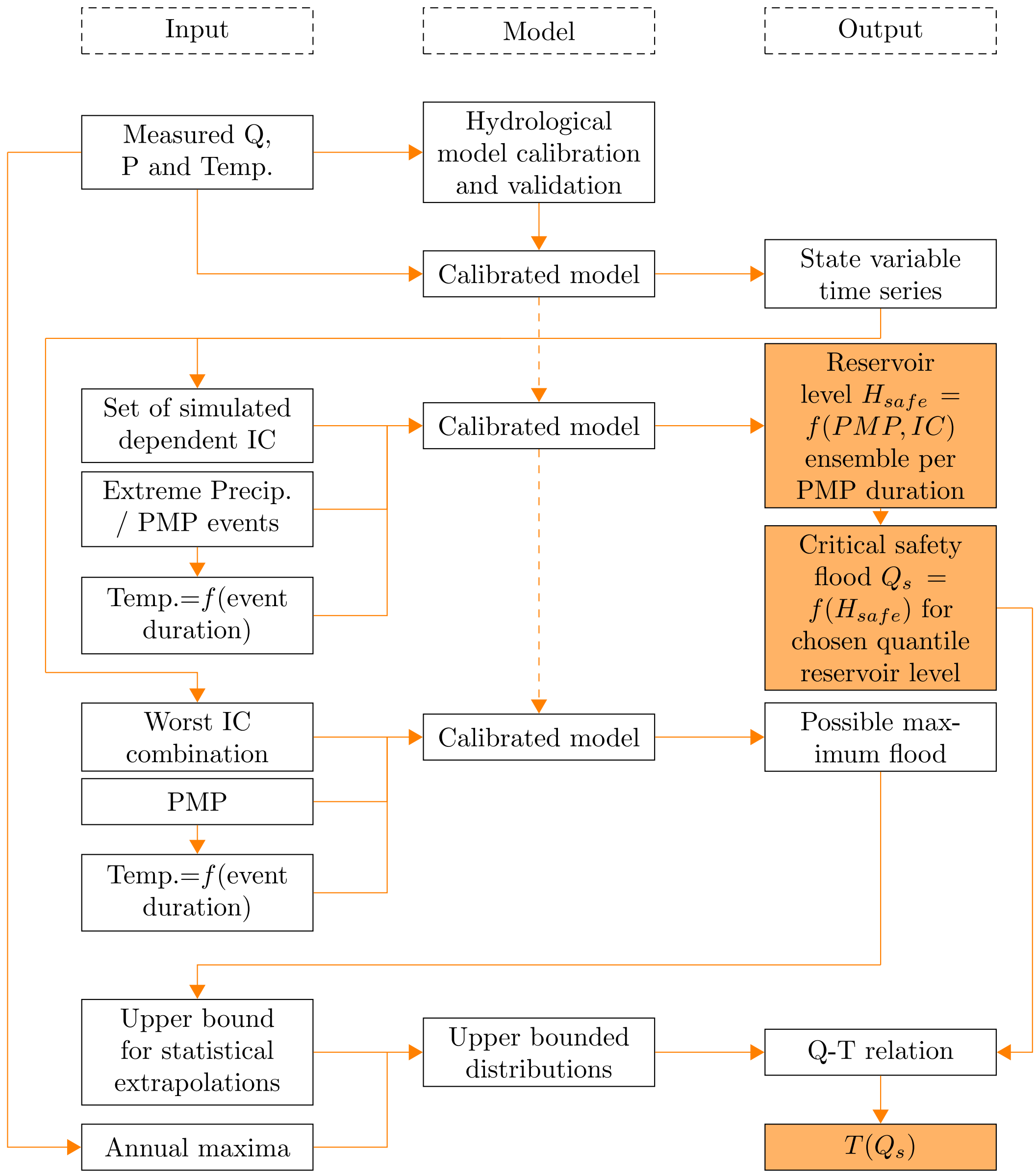

Figure 1.2: Flowchart of the methodology proposed for the stochastic estimation of extreme floods. IC = initial conditions, PMP = probable maximum precipitation, Q = discharge, T= return period, Temp. = temperature, Precip.=precipitation., H_{safe} = safety level, Q_s = safety discharge.

the delimitation of the basin, the determination of altitude bands and the attribution of model elements to the altitude bands, are illustrated in Figure 1.3. The model should be calibrated and validated based on measured discharge data that are compared to the simulated discharges derived from measured precipitation and temperature data.

1.3 Determination of the precipitation for synthetic extreme meteorological events

Two possibilities for the determination of the precipitation depth are worth considering: the Swiss PMP maps and intensity duration frequency curves (IDF). The choice depends on the aimed result, i.e. the safety flood ($T(Q_s) >> 1000$ years) or the maximum employed in the extrapolation with upper bounded statistical distributions.

In fact, for the determination of the maximum considered for the bounded statistical distributions, the probable maximum precipitation (PMP) has to be used. In Switzerland, this information can be extracted from the Swiss PMP maps (Pérez and Hertig, 1998; Hertig et al., 2005; Audouard et al., 2006; Hertig et al., 2008; Hertig and Fallot, 2009). In the case of extreme precipitations, for example PMPs, it has been shown in the CRUEX++ project that high precipitation depths are likely to occur concurrently with high temperatures. The summer season is therefore the most coherent with the PMP data. Seasonality plays an important role for the temperature determination and the assumptions concerning the initialisation of the hydrological model. As such, summer conditions have been assumed for the elaboration of the Swiss PMP maps (Hertig and Fallot, 2009). Furthermore, the development of the Swiss PMP maps accounted for three different wind sectors (North, South and West-North-West). The critical sector depends on the region of application and can be determined by hydrological simulation in order to determine which sectors leads to the highest discharges. Moving towards flows, a PMP event has to be combined with severe initial model conditions in order for the upper bound for the statistical extrapolation to be prepared. Some may call this upper bound the **possible maximum flood (PoMF)**.

For the determination of the **safety flood** (not suitable for the upper bound estimation considered for the bounded statistical extrapolations), the precipitation depth may correspond directly to the PMP or alternatively be derived from intensity duration frequency (IDF) curves. The latter option can be chosen if the flood generation from extreme precipitation, less intense than the PMP, is aimed for (e.g. for the determination of P_{1000}). Combined with less severe initial conditions, the routing of the PMP translates to a flood that is less severe than the PoMF and may be considered as safety flood. The routing of a design storm derived from IDF curves follows the same steps as for the PMP. The spatial distribution of the PMP is provided by mapped PMP data (Pérez and Hertig, 1998; Hertig et al., 2005; Audouard et al., 2006; Hertig and Fallot, 2009);. A stationary event is assumed. On the contrast, the spatial distribution is not necessarily known in the case of IDF curves. To determine it, observed events can be considered. Once chosen, an observed event can then be scaled to equal the precipitation intensity derived from the IDF curves. An advantage

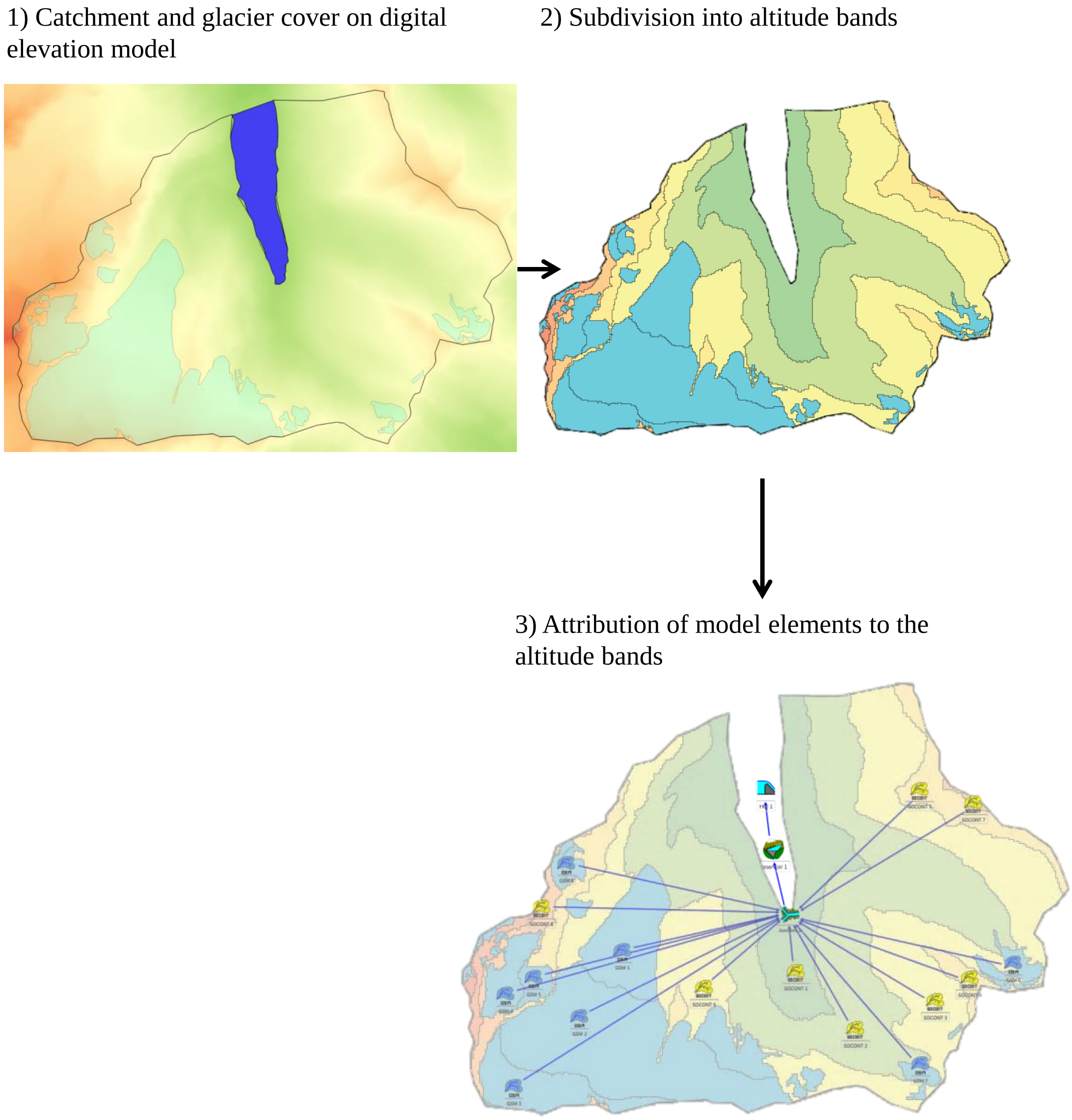

Figure 1.3: Three main steps of the semi-distributed hydrological model construction: 1)Delimitation of the catchment and glacier cover, 2) subdivision into altitude bands, 3)Attribution of model elements to the altitude bands.

of the IDF curves is that a return period is associated to the precipitation depth.

Concerning the Swiss PMP maps, they have been elaborated for precipitation durations of 1h, 3h, 6h, 9h, 12h and 24h as well as for different wind directions, i.e. north, south and west-north-west winds. For the determination of PMP-durations in between the duration for which the PMP maps have been developed, the findings of Bérod et al. (1992) can be considered. Bérod et al. (1992) showed that the PMP data displayed on a IDF plot in a log-log space, produce a line that is parallel to IDF curves (Figure 1.4). The PMP durations not originally mapped can thus be easily deduced by interpolation for every map pixel.

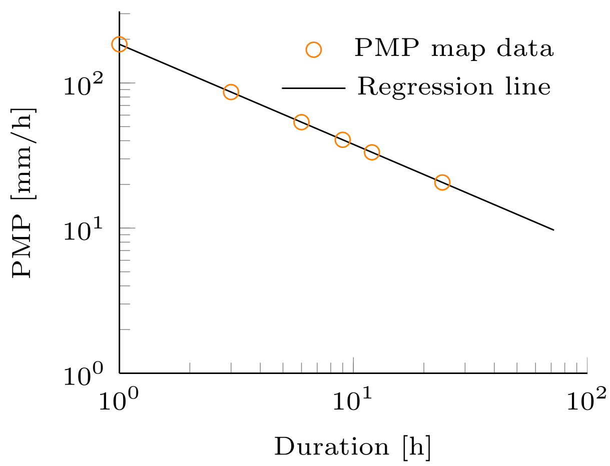

Figure 1.4: Example of PMP data plotted on an IDF like plot.

The temporal structure of the precipitation event is deduced from a rainfall mass curve. Rainfall mass curves reduce the precipitation events to a dimensionless curve by adimensionalizing the total duration of the event and the cumulative rainfall depth. They allow the derivation of a hyetograph from any given precipitation height and duration. Figure 1.5 schematically shows the procedure of temporal structuring. According to Bonta and Rao (1992) and Bonta (2004), it can be assumed that the temporal structure is independent of the precipitation duration. The rainfall mass curve considered for the CRUEX++ methodology has been derived from precipitation events observed in Switzerland. Following the superposition of the curves of several thousand events, the 5% quantile curve has been deduced. It is represented in Figure 1.6, whose plotted values are provided in Table 1.1. The 5% quantile curve is more conservative than the rainfall mass curve proposed by the World Meteorological Organization (WMO, 2009) for a PMP distribution. Their curve is comparable to the Swiss median rainfall mass curve.

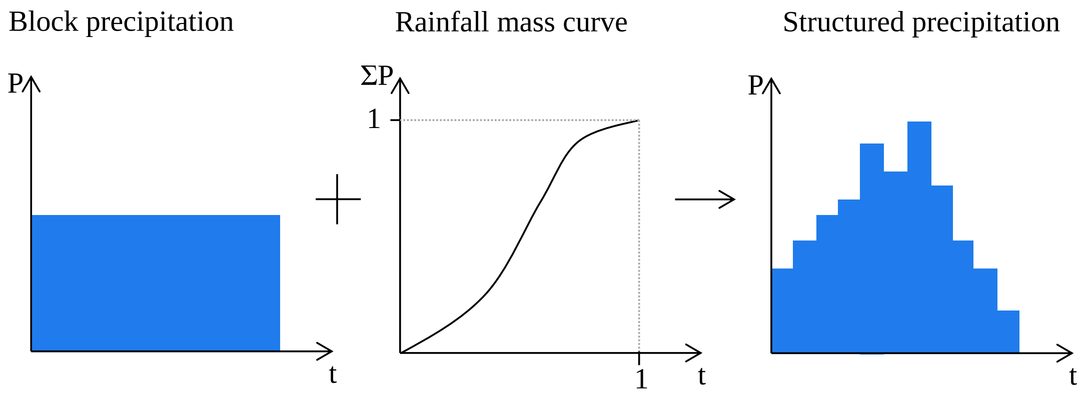

Figure 1.5: A block precipitation (left) and a rainfall mass curve (middle) allow to derive the temporally structured hyetograph (right).

1.4 Determination of the temperature for synthetic extreme meteorological events

The temperature that can be considered in combination with extreme precipitations has been shown to be related to the duration of the precipitation event during the CRUEX++ research project. The methodology uses the 0°C isothermal altitude as a means to define the temperature. The relations between the precipitation duration and the isothermal altitude to be combined with extreme precipitations are depicted in Figure 1.8. The two relations have been derived under summer conditions, distinguishing between regions north and south of the Alps. The geographical separation is shown in Figure 1.7.

These relations allow to introduce into the model a single value, i.e. the 0°C isothermal altitude, that is assumed to be valid for the entire catchment. This implies that the used model adopts a temperature-altitude gradient to derive the temperature at the surface from the 0°C isothermal altitude. The temperature gradient to adapt should be part of the calibration procedure of the hydrological model. According to Rolland (2003) and Damm and Felderer (2013), gradients from -0.4 to -0.7 °C/100 m are common in the Alps. During summer a gradient between -0.55 and 0.7 °C/100 m is likely to occur (Rolland, 2003).

Table 1.1: Detailed values of the 5% quantile rainfall mass curve.

Duration [%]	0	4	8	13	17	21	25	29	33	38	42	46	50
Precipitation [%]	0	1	2	4	6	8	11	13	17	20	24	28	33
Duration [%]	54	58	63	67	71	75	79	83	88	92	96	100	-
Precipitation [%]	37	42	48	53	58	65	71	77	84	90	96	100	-

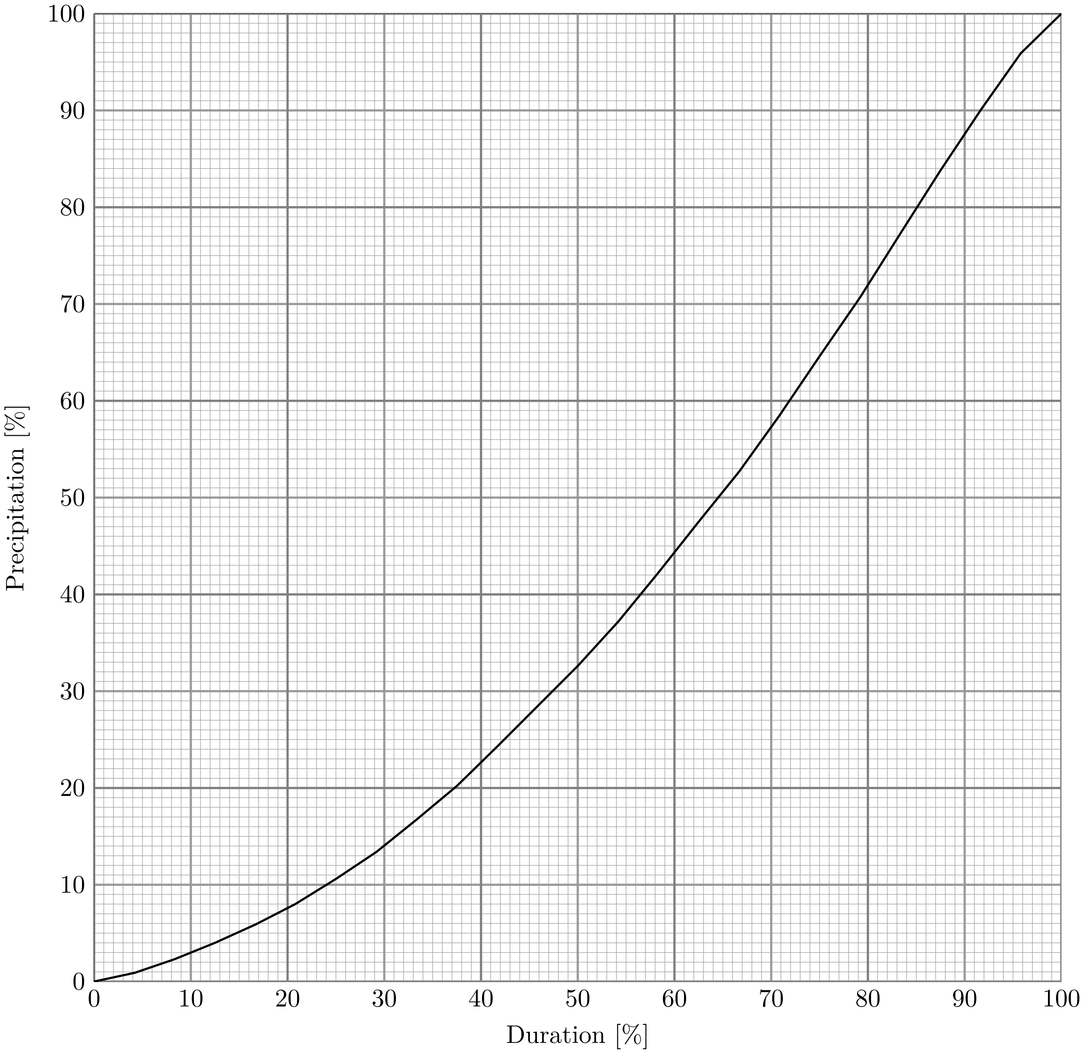

Figure 1.6: Swiss 5% quantile rainfall mass curve for the temporal distribution of extreme precipitation data determined during the CRUEX++ project.

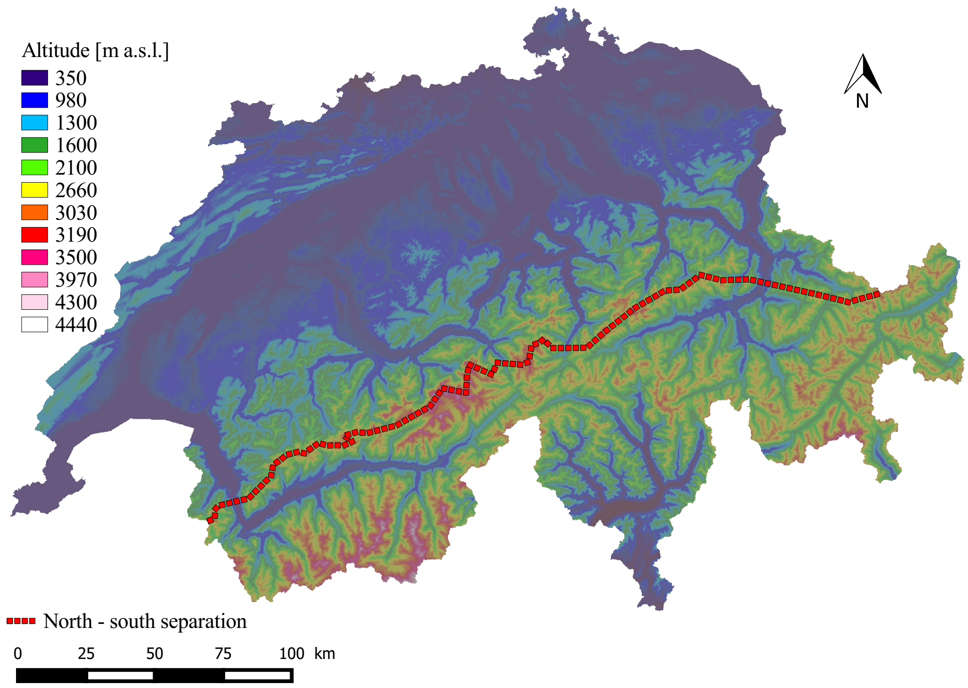

Figure 1.7: Separation line between north and south as considered for the determination of the relations between the precipitation duration and the 0°C isothermal altitude.

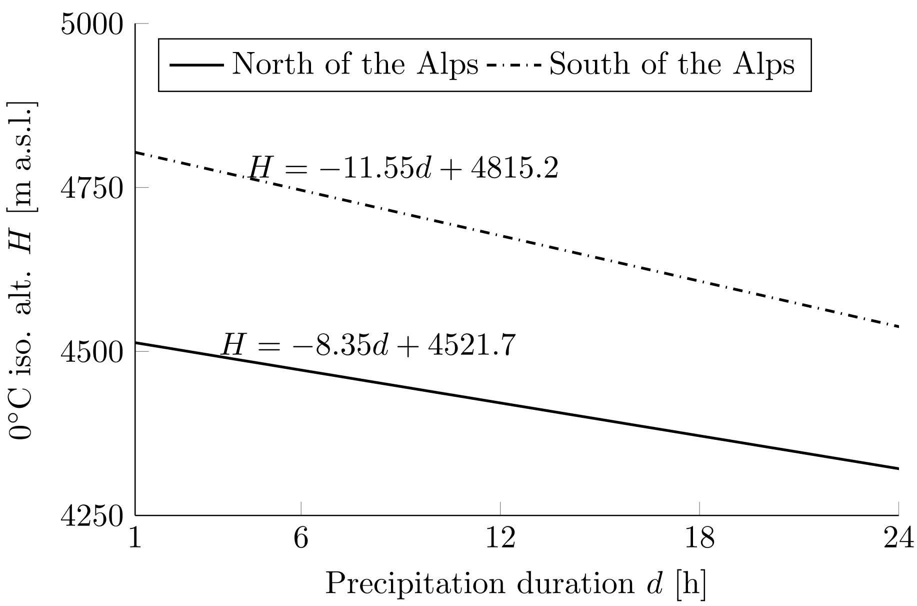

Figure 1.8: Relations between the precipitation duration and the 0°C isothermal altitude for the summer season distinguishing between north and south of the Alps.

1.5 Determination of the initial conditions for deterministic event based flood simulations

The event based simulations can be highly influenced by initial conditions. The number and values of the initial conditions depend on the hydrological model that is adopted. In general, the state variables of a hydrological model need to be fixed at the beginning of the event based simulation in order to describe the initial state of the model. Consequently, in order to promote the use of coherent initial conditions, the initial values of the state variables should be derived from a continuous simulation. Accordingly, they can be drawn from the generated state variable time series considering the period after the warming period of the model. As the retained initial conditions should be coherent with the meteorological event, it is well advised to take seasonality into account when the initial conditions are determined.

For the determination of the initial conditions, a deterministic and a stochastic approach have been elaborated. The stochastic approach uses an initial condition set generator, illustrated on Figure 1.9. This generator chooses random instants in the time interval corresponding to the period of the simulated state variable time series. The values of the state variables at that precise moment correspond to one possible initial condition set. The advantage of this approach is that the dependence of the initial conditions is respected. If the number of initial conditions sets is large enough, the generated hydrograph ensemble can be used to derive quantile hydrographs. The quantiles are a useful tool to describe the prediction interval of the discharges derived from a certain design storm. The disadvantage of this approach lies in its computational cost; it may demand substantial computation capacity and the simulations take several hours (much longer than the computational time of the deterministic approach).

Regarding the deterministic approach, the initial values are chosen independently in the range of possible values determined for the season of interest. In the context of the CRUEX++ project, the initial state variable values were determined according to a certain probability of non-exceedance from the cumulative distribution of each state variable, as illustrated in Figure 1.10. The quantile is proposed to be the same for all state variables. When the main influence on the variation of the peak discharge stems from one single state variable, the quantile of the estimated discharge corresponds to the quantile of the initial condition. In the context of the GSM-Socont model, used for this research project, this would be typically the case if, for the considered season, there is no snow or ice present being soil saturation the main driver. The advantage of this approach, if applicable, is that the computational effort is small. The disadvantage is that the detection of the main driving state variable may not always be straightforward. Sensitivity analyses can be used to determine the main driving state variable. If the dependency between the state variables was mistakenly neglected, the simulated flood can be under or overestimated. The degree of under or overestimation varies from case to case.

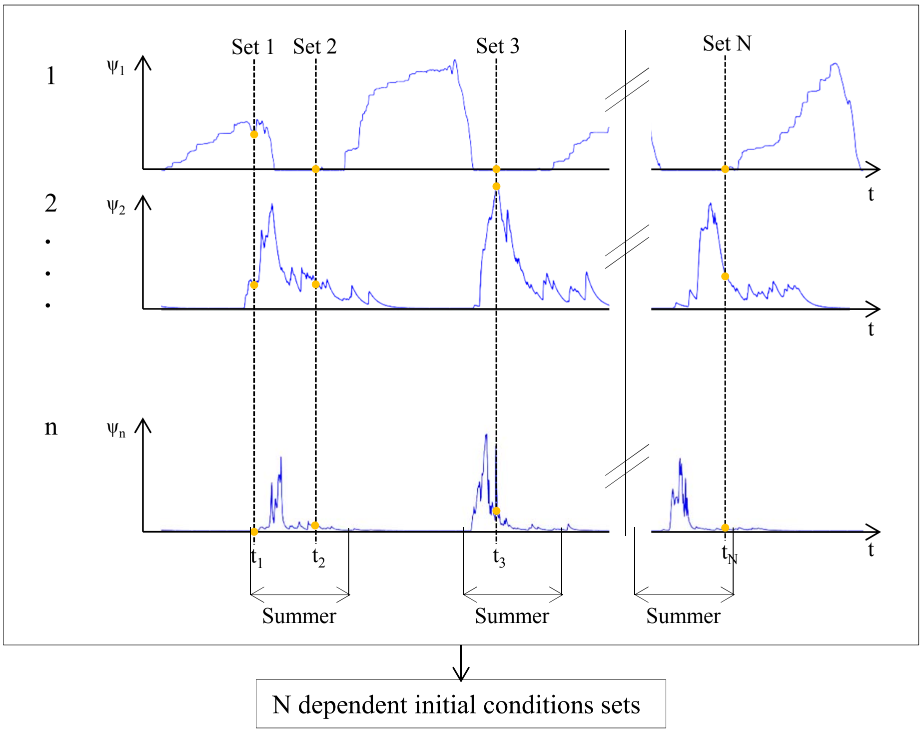

Figure 1.9: Schema of the stochastic initial conditions generator. Randomly, N moments in time in the season of interest, here the summer, are chosen to derive dependent initial state variable values from the state variable time series. The state variable are denoted ψ_i, where i goes from 1 to n, n being the number of different state variables.

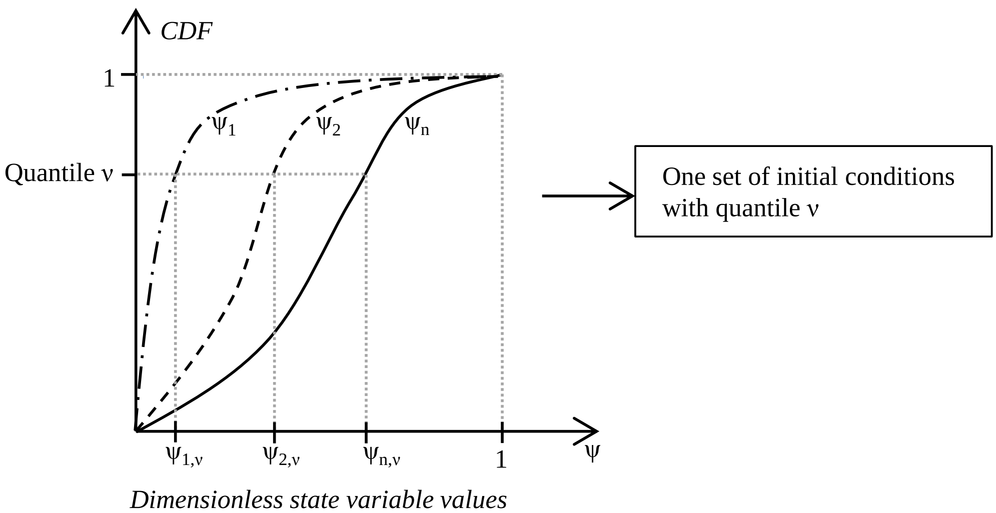

Figure 1.10: Schema of the determination of the initial conditions from the cumulative distribution functions (CDF) of the different state variables ψ_i, where i goes from 1 to n, n being the number of different state variables.

1.6 Simulation of the safety flood and the possible maximum flood

Once the initial conditions have been determined, the synthetic meteorological event can be transformed into a runoff hydrograph. The simulation of the safety flood and the possible maximum flood (PoMF) only differ due to the chosen inputs. An extreme precipitation smaller than a PMP (for example P_{1000}) in combination with the chosen initial conditions leads to a safety flood. The PMP in combination with initial conditions less severe than the worst initial condition combination also leads to a safety flood, which one could name as probable maximum flood (PMF). The appropriate way of generating the PoMF (to be considered as upper bound for the bounded statistical extrapolations) is to consider the worst possible initial conditions in combination with a PMP.

The number of simulations required to estimate the critical safety flood and the PoMF depends on the approach chosen to determine the initial conditions. The decision criterion for a flood to be considered as a critical safety flood is the maximum reservoir level it induces. For the determination of the PoMF, the decision criterion is the maximum discharge. This is because it is used to extend the data set of annual maximum inflow observations for the upper bounded statistical extrapolation. Consequently, the critical safety flood and the possible maximum flood may be generated by a precipitation event with a different duration.

The deterministic approach, for which the quantile of the initial conditions has already been chosen, the number of simulations per PMP duration corresponds to the number of initial condition sets that are explored. The procedure of the stochastic approach is illustrated in Figure 1.11. The critical lake level is derived by routing PMP events with different durations under the assumed non-exceedance probability of the initial conditions through the basin and the reservoir. The safety flood is derived from the most critical PMP event. The PoMF is derived by considering the initial conditions to be the 99% quantile values of the state variables. Theoretically it should be the 100% quantile, but assuming the absolute maximum can coincide for all variables simultaneously is not realistic from a physical point of view. For instances, the maximum snow height cannot concur with the maximum saturation.

For the stochastic approach, the simulation of reservoir level ensembles for each PMP duration combined with each set of initial conditions allows the derivation critical lake level under the assumption of a certain residual risk that is linked to the chosen conditional probability of non-exceedance of the lake level under the considered precipitation event. For the chosen probability (for example 50%), the corresponding quantiles are estimated from the simulated ensembles for each PMP duration. The PMP duration leading to the highest lake level (under the assumed conditional probability of non-exceedance) is considered to be the critical PMP event. The safety flood corresponds to the flood event generated by the critical PMP event. The procedure of the stochastic approach to determine the critical safety flood is illustrated in Figure 1.12. The PoMF corresponds simply to the highest simulated discharge (without quantile estimation). For the stochastic approach, the number of simulated hydrographs should be large enough in order not to miss rare combinations of state variable values used to initialize the model.

Once the critical PMP event has been determined, the hydrological model, incorporating the hydraulic characteristics of the reservoir (level-volume relation) and the spillway (level-outflow relation), allow simulating the attenuation effect of the safety flood due to the reservoir, as shown on Figures 1.12 and 1.11. After the determination of the possible maximum flood and the safety flood, the return period of the safety flood can be determined resorting to the aforementioned upper bounded statistical distributions.

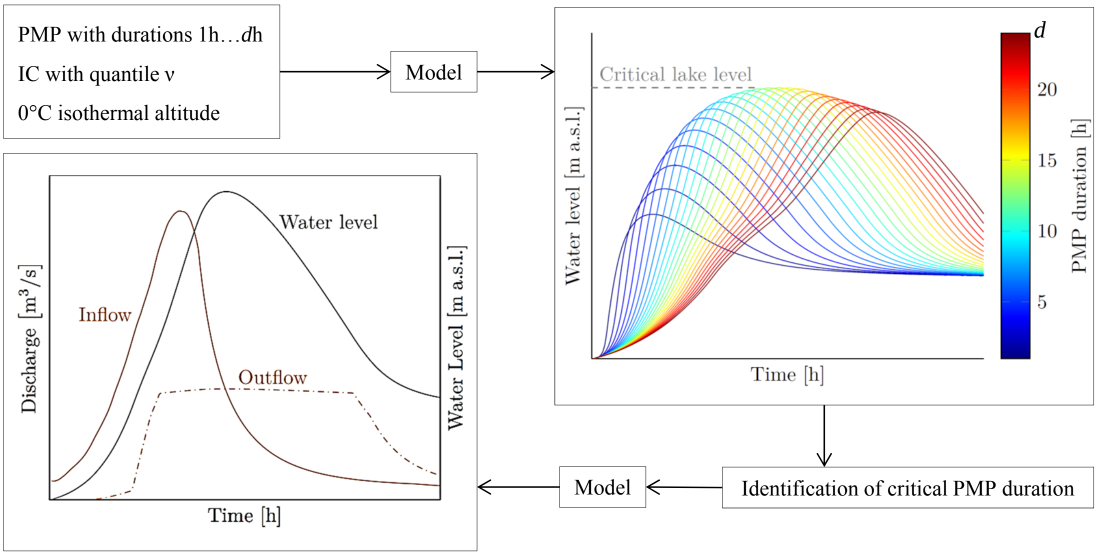

Figure 1.11: Procedure of the deterministic approach to determine the critical safety flood, the reservoir level and the outflow discharge, for a single quantile v chosen for the determination of the initial conditions (IC).

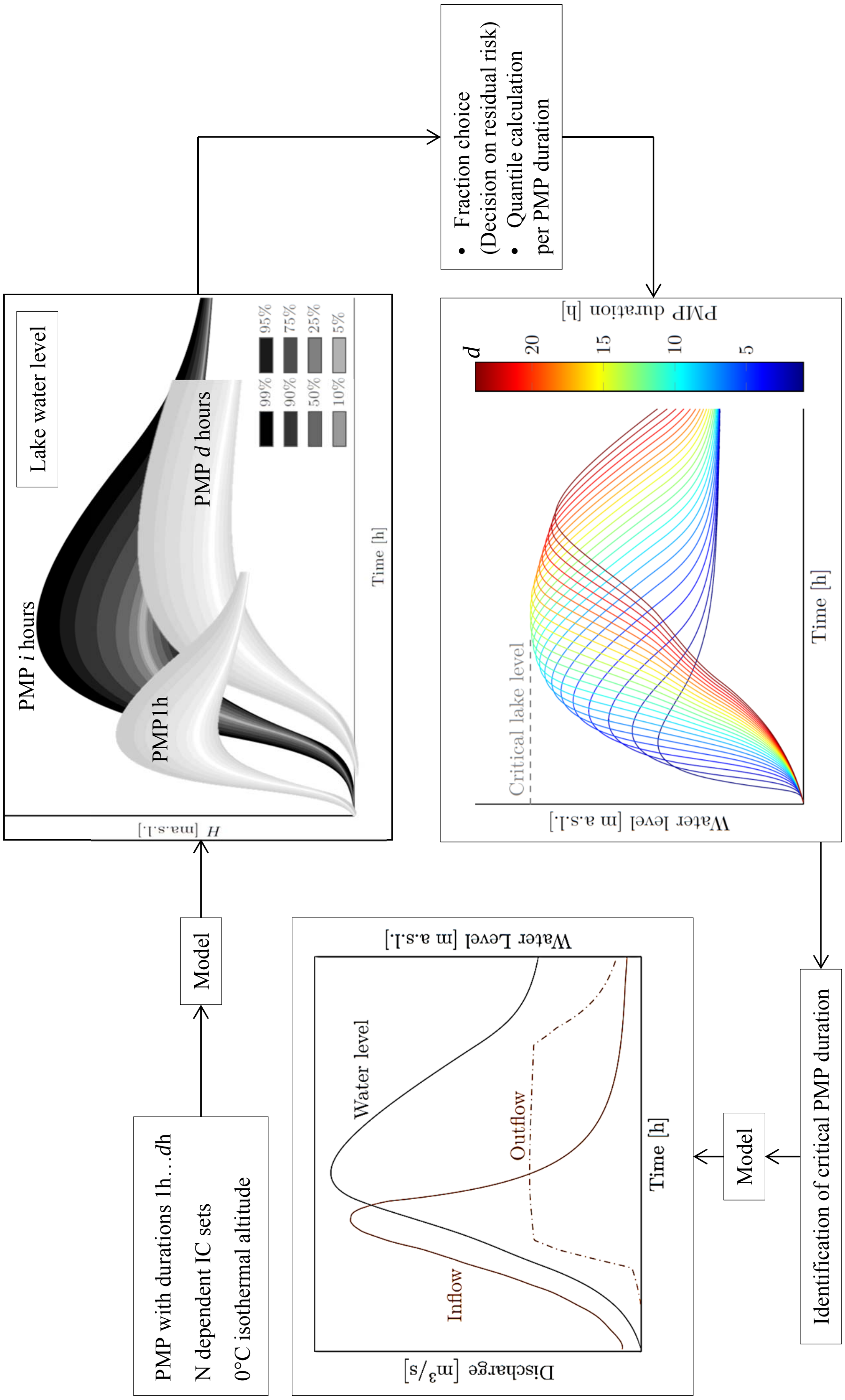

Figure 1.12: Procedure of the stochastic approach to determine the critical safety flood, the reservoir level and the outflow discharge based on N randomly sampled dependent initial conditions (IC) sets.

1.7 Estimation of the return period of the safety flood

The upper bounded distributions (EV4, LN4) allow taking into account an upper limit for the discharge value determined a priori . The PoMF is considered as the upper limit for the extrapolations using these distributions. In order to fit the distributions, annual maximum discharge data are needed. For coherence, the temporal resolutions (daily, hourly...) of the annual maximum data and the possible maximum flood should be the same. Once an adapted distribution has been determined it can be used to derive the return period of the peak discharge of the critical safety flood. Figure 1.13 illustrates the determination of the return period of a safety flood discharge from a fitted upper bounded distribution.

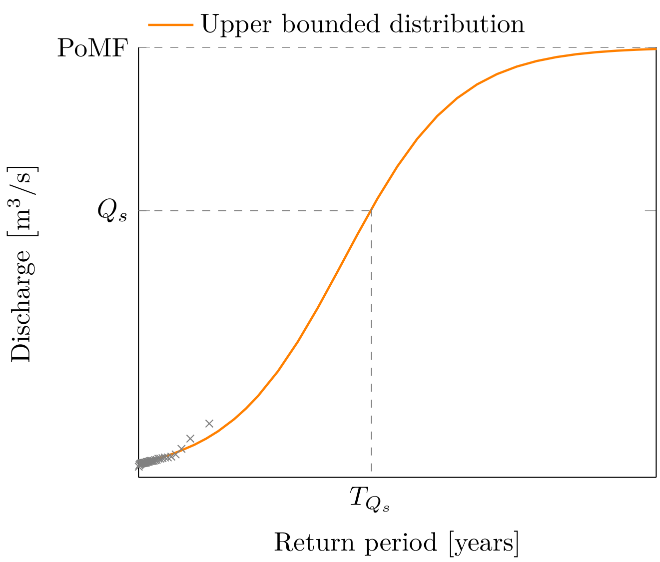

Figure 1.13: Schema of an upper bounded distribution fitted to annual maximum discharge data. The PoMF (possible maximum flood) is taken as the upper bound. The return period T_{Q_s} of the safety flood discharge Q_s can be derived from the fitted distribution.

2 Application limits of the methodology

The presented methodology has been developed based on different analyses focussing on temporal rainfall distribution, the correlation between temperature and precipitation, initial conditions for extreme flood simulations and on the application limits of the Swiss PMP maps. Each part of the analysis has been undertaken for current climatic conditions. Climate change has not been accounted for because at the current state of the art, the effect of climate change is smaller than other methodological uncertainties. The methodology's main objective is assumed to be the verification of the spillway capacities of existing and new dams. Due to the constant evolution of technology and to climate change, the methodology should evolve in the future. Besides this general consideration, different parts of the methodology can be discussed as follows.

Analysing the correlation between the precipitation and the temperature, it has been found that it was reasonable to consider the maximum 0°C isothermal altitude observed before a rainfall event. The precipitation could be shown to increase with increasing isothermal altitude. Some cases have been observed, however, where the maximum temperature did not concur with the maximum observed precipitation. This means that the consideration of the temperature for PMP-PMF simulations as it is proposed in this work can lead to an overestimation of the 0°C isothermal altitude. Consequently, snowfall in high altitudes could be underestimated, snow melt overestimated and, therefore, the estimated PMF could also be overestimated. This shortcoming is hard to address as precipitation temperature scalings cannot be extrapolated beyond the measured values. Eventually, the assumption to consider such a high 0°C isothermal altitude may be confirmed in the future when further observations in the range of high temperatures are available due to observations in a warming climate.

It is also assumed that the isothermal altitude is constant during a precipitation event. This is not the case in reality where the isothermal altitude usually decreases during an event. Unfortunately, the meteorological soundings that have been used for the analysis that derived the relation between the precipitation duration and the 0°C isothermal altitude are only performed every 12h. This temporal resolution is not sufficient for a reliable characterisation of the evolution of the isothermal altitude during a rainfall event. Fortunately, the assumption of a constant 0°C isothermal altitude during a precipitation event is safe because snowfall tends to be underestimated.

Regarding initial conditions, the determination of the initial model state for PMP-PMF simulations is based on simulated values derived from the longest possible simulation over a period where meteorological observations are available. In case the observed meteorological data set does not contain any major event, the initial conditions derived from the simulations may not be severe enough. Therefore, attention should be paid on the presence of major events in the data set used for the derivation of the initial conditions. The presence of a major observed event is indeed important, not only for the initial conditions but also for the calibration of the model itself. In fact the calibration should contain those, so that the model can reproduce rare flood events.

The choice of the initial conditions according to the 99% quantile for the deterministic approach to estimate the PoMF can be discussed. The argument not to take the 100% quantile because maximizing all the state variables for the initialization of the model may be correct, but the choice of a 99% quantile is not easily justifiable. In qualitative terms, the dependence of the state variables is neglected in this approach. If dependence does play a role in some catchments, it could be dangerous to opt for using lower quantiles. Also, the case of one variable to be dominating the flood's characteristics is common, which provides a further argument for the choice of a high quantile such as 99%.

About the application limits of the Swiss PMP maps, regarding the size of the catchments, it can be stated that the analysis was carried out on a limited number of basins. More basins would have increased the power of the determined upper spatial coverage of PMP events from the Swiss PMP maps, especially if it would have been possible to simulate a large number of glacial and non-glacial basins. This distinction could be of interest since the glacial regime differs from the non-glacial one. However, it can be assumed that the upper surface limit derived from only glacial catchments would have been less severe because the glacier acts as a discharge buffer: Ice starts melting only once the snow cover on the glacier has gone. Thus an attenuation of the peak discharge can be induced by the glacier. This effect may have led to an overestimation of the application limit (maximum catchment surface) for non-glacial catchments. At the same time, an underestimation of the application limit for glacial catchments can be imagined.

In regard to the PMP-PMF simulations, it can be underlined that the hydrological model has to be assumed valid for the simulations of meteorological events that are rarer than those the model has been calibrated on. There is unfortunately no possibility to verify this assumed validity because events that would be comparable to a PMP event have seldom been observed. Furthermore, the methodology assumes that the hydrological processes do not change during a PMP event. Nevertheless, it may be concluded that the application is reasonable as it can be assumed that a sufficiently long time series for the calibration and validation of the hydrological model allows mobilising almost all hydrological processes in the model. For example, Hortonian overland flow is not taken into account by the used model. It occurs when rainfall and snowmelt rates exceed the infiltration rate (Kirkby, 1988), what can occur in extreme cases. The model should thus be well trained for all situations including large floods. It follows that the simulation of floods generated by unobserved meteorological events can be assumed trustful, given the assumption that the hydrological processes do not change during the simulations.

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