Stochastic Generation of Hydrographs for the Flood Design of Dams

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Introduction

The hydrological design of dams and flood retention reservoirs requires design floods of an a priori defined probability which can be estimated with statistical and deterministic methods. International dam standards recommend return periods of up to 10000 years to ascertain dam structure security. Under consideration of retention and free storage capacities, critical flood loads for reservoirs result from flood waves with multiple peaks.

Extreme flood events in Germany during the last years, especially the big flood at the river Elbe in Saxony in 2002 (see subcatchment in Fig. 1), showed the importance of considering flood events with multiple peaks in the flood design of dams. In 2002 long-lasting, advective precipitation was further aggravated by precipitation caused by local storm events and orographic effects. These meteorological effects led to flood hydrographs with multiple peaks shown at the example of the Dam Gottleuba in Fig. 2. The multi-peak shape of the hydrographs leads to a reduced flood security of dams as the first wave fills the flood storage and the second wave causes critical flood load because of the filled flood storage.

Estimating design flood hydrographs with deterministic methods is problematic due to the required extrapolation of the model assumptions to forecast large floods. Though the model assumptions could be adequate for small and medium size floods, for which the model is calibrated, but may possibly not be applicable in the case of extreme floods.

Here design floods are determined by simulating the flood characteristics by means of Monte-Carlo Simulation to circumvent these uncertainties related to precipitation-runoff modeling [1].

Hydrograph Function

Many functions can be found in the literature to describe the hydrograph analytically [2,3,4,5,6,7]. In most cases probability density functions like the Gamma-Distribution [2], Beta-Distribution [3,4] or Frechet-Distribution [5] are used to represent the properties of the flood hydrograph. In this application a Gamma-Distribution is used as hydrograph function:

\[ Q(t) = \alpha \cdot \beta \cdot \gamma \cdot \left( \frac{t}{\beta} \right)^{\alpha-1} \exp \left( -\left( \frac{t}{\beta} \right)^{\alpha} \right) \]

where \( \alpha \) is a shape parameter, \( \beta \) the scale parameter and \( \gamma \) the location parameter.

Generation of Flood Hydrographs

To simulate these superposed hydrographs it is important to consider the flood synthesis in the generation of the parameters. The parameters are simulated dependent on design storms. A design storm of defined duration and return period and hydrograph parameters are linked via the flood volume according to Eq. 5 with the assumption of a runoff coefficient.

\[ Q(t) = \frac{\gamma}{\alpha \cdot \beta} \cdot \gamma \cdot \left( \frac{t}{\beta} \right)^{\alpha-1} \exp \left( -\left( \frac{t}{\beta} \right)^{\alpha} \right) \exp \left( -\gamma \right) \]

This total precipitation amount is divided in two precipitation parts which are linked to two superposed single-peak hydrographs. The two single events are dependent and so the product of the two return periods should be smaller than or equal the return period of the total event.

The Gamma-Distribution obtains its maximum value at the time \( t = \frac{\beta}{\alpha} \) with a peak discharge of:

\[ Q(t) = \frac{\gamma}{\alpha \cdot \beta^{\alpha}} \exp \left( -\frac{\gamma}{\beta} \right) \]

The influence of the shape parameter \( m \) is demonstrated in Fig. 3. With increasing \( m \) the shape of the hydrograph becomes steeper.

Multi-Peak Hydrographs

Superposition of several Gamma-Distributions, complex multi-peak hydrographs can be generated. To reduce the number of parameters in this application, only the generation of two-peak hydrographs is presented. The method is also adequate for hydrographs with more than two peaks. In Fig. 4 the superposition of two Gamma-Distributions is demonstrated. The flood hydrograph results from the sum of the direct runoff of the two single-peak waves \( Q_1(t) \) and \( Q_2(t) \) and the baseflow \( Q_0(t) \), which is assumed as constant.

\[ Q(t) = Q_1(t) + Q_2(t) + Q_0(t) \]

Design Storms

In Germany regionalized design storms are available in the KOSTRA-map [9] for the entire country. Design storms with a duration of up to 72 h and a return period of up to 1000 years are provided in a grid with a cell area of 71.5 km². Return periods over 100 years can be extrapolated. In Fig. 5 the extrapolation of the design storms is demonstrated for the grid cell of the Dam Gottleuba.

The sum of the precipitation amount of the two single events should also be smaller than or equal the total precipitation amount:

\[ Q_1(t) + Q_2(t) + Q_0(t) \leq \gamma \]

Depending on these two precipitation events, the parameters of the two superposed flood hydrographs are generated. The generation scheme is illustrated in detail in Fig. 6.

Application at the Dam Gottleuba

The Dam Gottleuba is situated in the Eastern Erzgebirge in Saxony, Germany (see Fig. 1). The catchment area is 35.25 km² and the mean annual discharge is 0.5 m³/s. After studies of the flood in 2002 the runoff coefficient for the flood volume calculation after Eq. 5 is assumed as 0.8.

References