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.

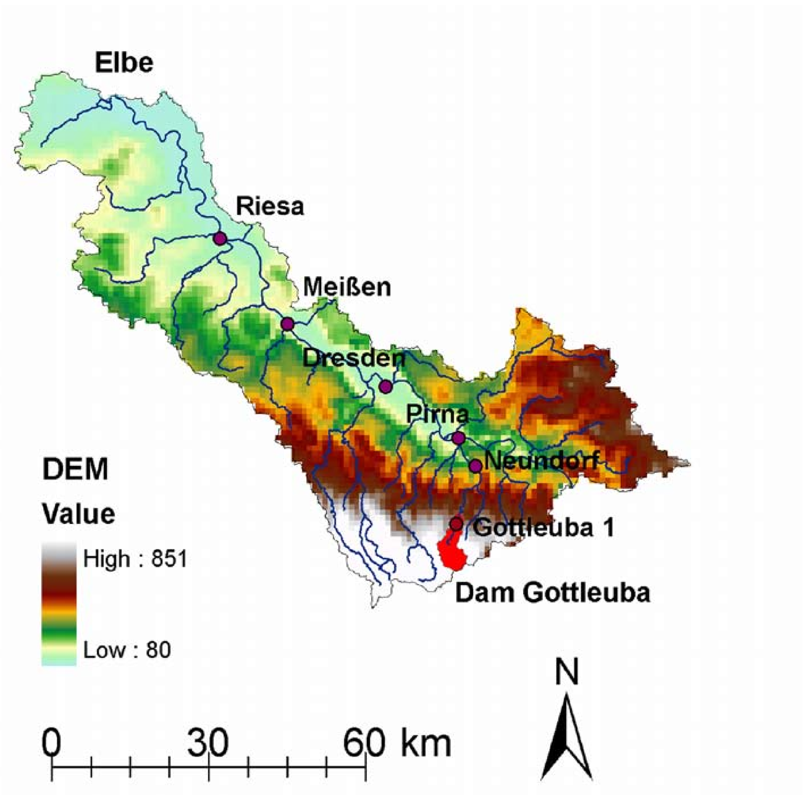

Figure 1: Location of the Dam Gottleuba

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 Figure 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.

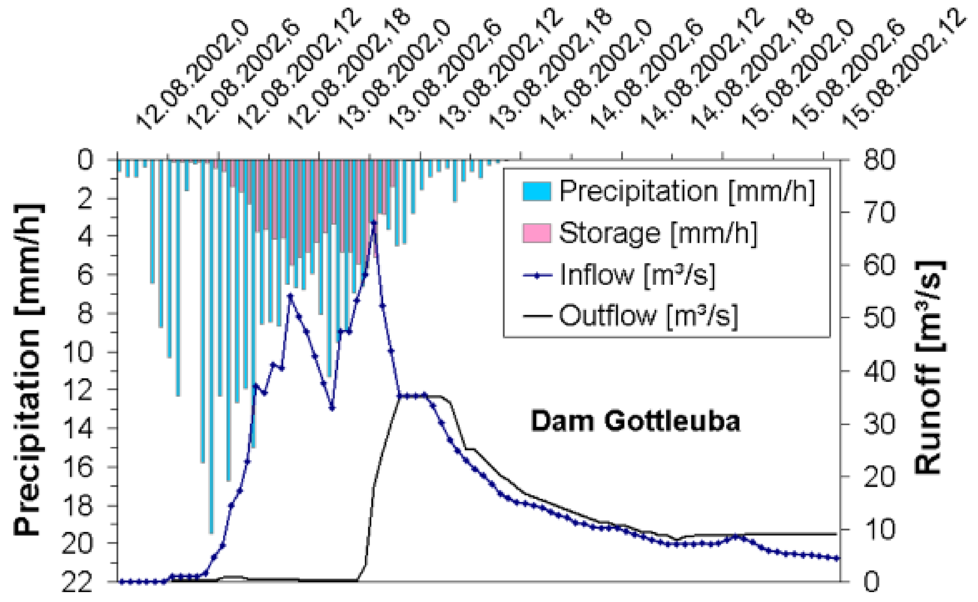

Figure 2: Flood 2002, Dam Gottleuba

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].

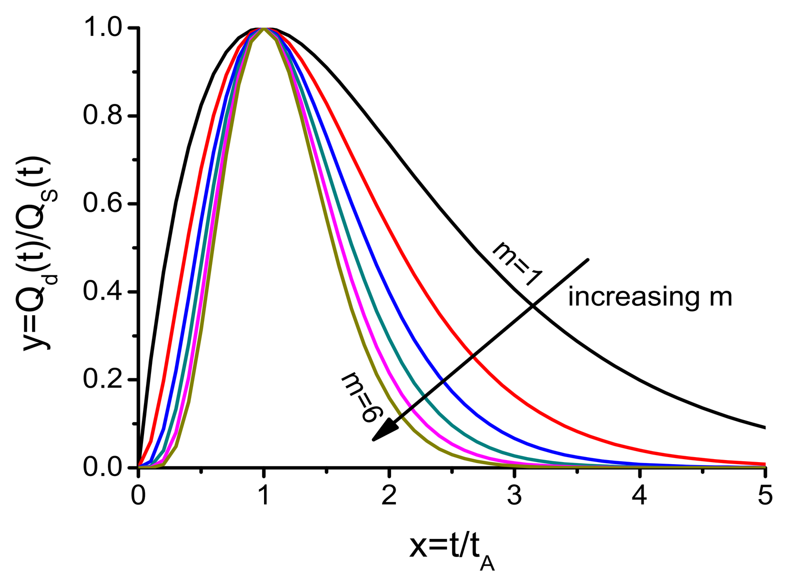

Figure 3: Change of the hydrograph shape with increasing parameter m

Hydrograph Function

Many functions can be found in the literature to describe the hydrograph analytically [2,3,4,5,6,7,8]. In most cases probability density functions like the Gamma-Distribution [2], Beta-Distribution [2,3], Pearson III-Distribution [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:

$$Q_d(t)=\frac{V}{k\cdot\Gamma(n)}\cdot\left(\frac{t}{k}\right)^{n-1}\cdot e^{-\frac{t}{k}} \qquad (1)$$

where k is a time scaling factor, n the shape factor and V the volume of the hydrograph.

The Gamma-Distribution obtains its maximum value at the time t_A = k(n-1) with a peak discharge of:

$$Q_{sd}=\frac{V}{k\cdot\Gamma(n)}\left(\frac{n-1}{e}\right)^{n-1} \qquad (2)$$

After the substitution of (n-1) with the shape factor m the discharge can be calculated [8]:

$$Q_d(t)=Q_{Sd}\cdot\left(\frac{t}{t_A}\right)^{m}\cdot e^{m\left(1-\frac{t}{t_A}\right)} \qquad (3)$$

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

By superposition of several Gamma-Distributions, complex multi-peak hydrographs can be generated. To reduce the number of parameter 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 $Q^I_d(t)$ and $Q^{II}_d(t)$ and the baseflow $Q_B(t)$, which is assumed as constant:

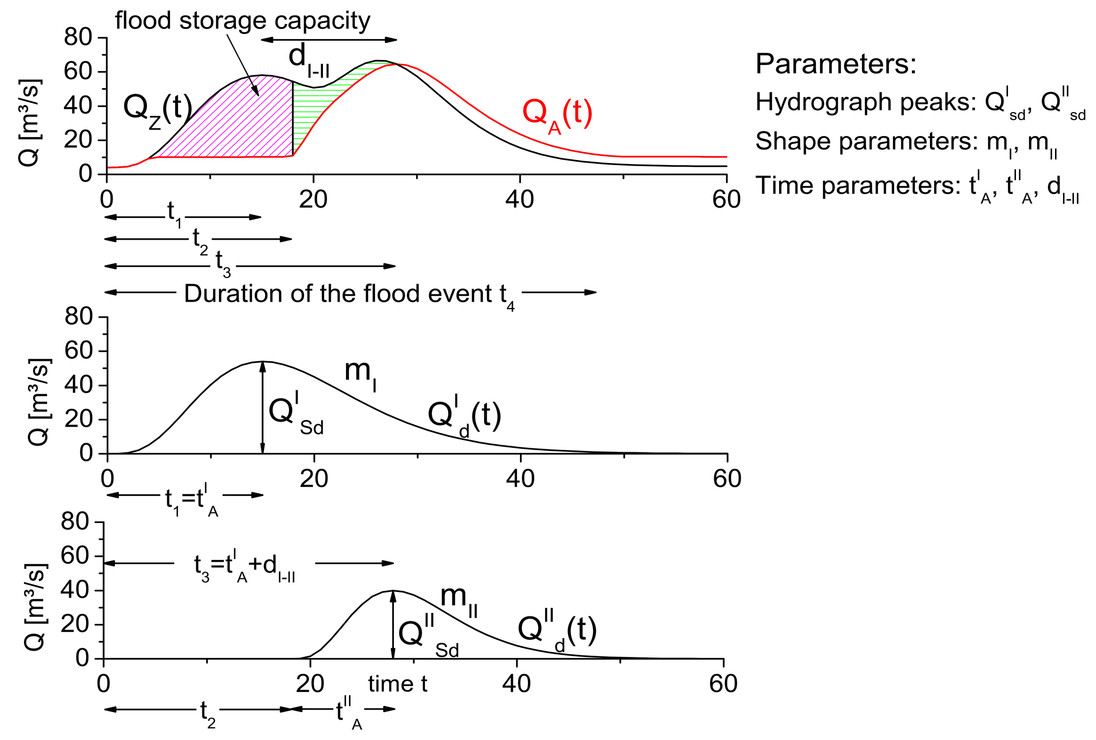

Figure 4: Description of a two-peak event with two Gamma-Distributions

$$Q_Z(t)=Q^I_d(t)+Q^{II}_d(t)+Q_B(t) \qquad (4)$$

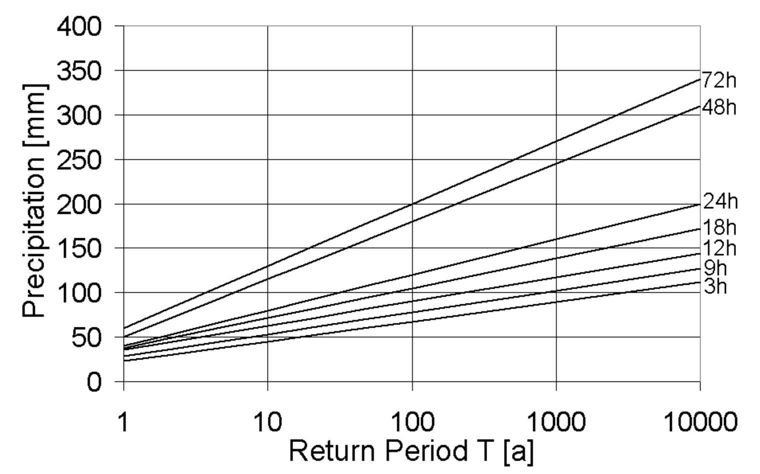

Figure 5: KOSTRA-Precipitation extrapolation (Dam Gottleuba)

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 100 years are provided in a grid which has 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.

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.

$$V=\int_0^{t_d}Q_Z(t)dt=h_N(D,T)\cdot A_{EZG}\cdot\psi+\int_0^{t_d}Q_B(t)dt \qquad (5)$$

This total precipitation amount is divided in two precipitation-parts which led to the 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 precipitation event:

$$T_I\cdot T_{II}\le T_{tot} \qquad (6)$$

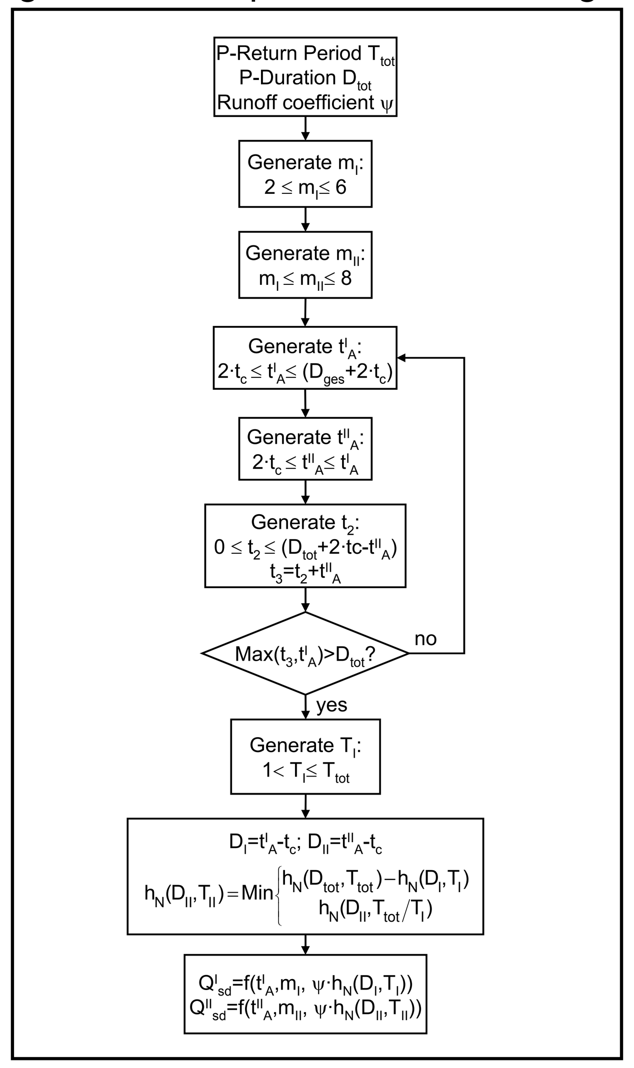

Figure 6: Generation scheme

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

$$h_N(D_I,T_I)+h_N(D_{II},T_{II})\le h_N(D_{tot},T_{tot}) \qquad (7)$$

Dependent 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.

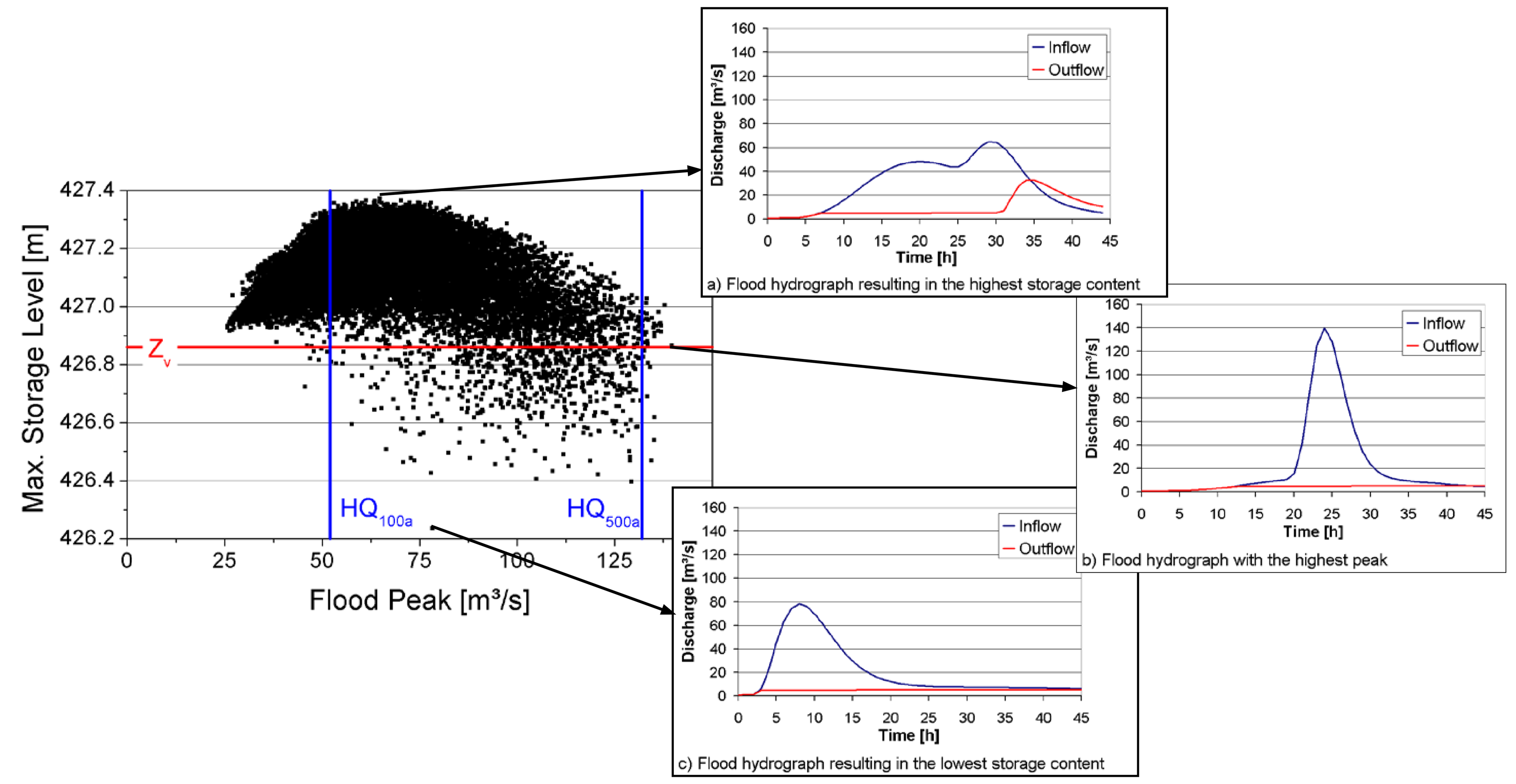

Figure 7: Monte-Carlo-Simulation of the hydrographs (Precipitation Duration = 24 h; Precipitation Return Period = 1000a)

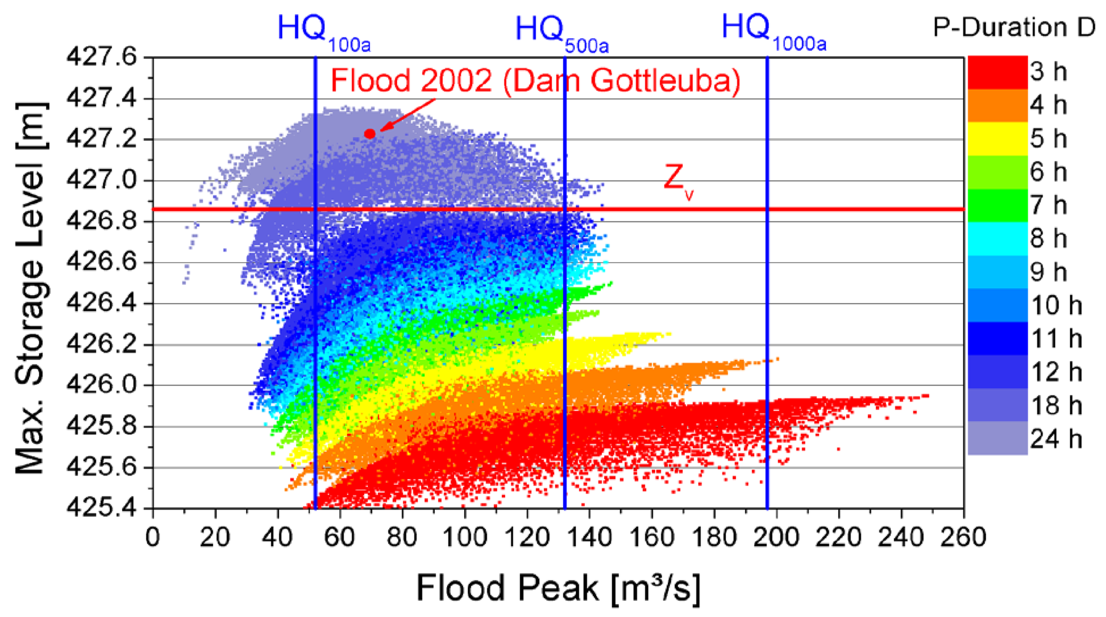

Figure 8: Monte-Carlo-Simulation of the hydrographs

In Fig. 7 the results of the hydrograph generation with a synthetic precipitation of 24 h and a return period of 1000 years is shown. It is obvious that the two-peak hydrograph (Fig. 7 (a)) and not the hydrograph with the highest peak (Fig. 7 (b)) led to the maximum storage level. This is also proved by the generation with precipitation duration from 3 h to 24 h (Return period 1000 years) in Fig. 8. The results shows that it is important to consider the shape of the hydrographs in the flood design of dams.

References

[1] Klein, B. & A. Schumann. Generierung von mehrgipfligen Bemessungsganglinien für die Hochwasserbemessung von Talsperren und Hochwasserrückhaltebecken. Tag der Hydrologie, München, 2006, 255-266
[2] Haktanir, T. & N. Sezen. Suitability of two-parameter gamma and three-parameter beta distributions as synthetic unit hydrographs in Anatolia. Hydrological Sciences - Journal - des Sciences Hydrologiques 35 (2), 1999, 167-184
[3] Yue, S., T. B. M. J. Ouarda, B. Bobée, P. Legendre & P. Bruneau. Approach for Describing Statistical Properties of Flood Hydrograph. Journal of Hydrologic Engineering 7 (2), 2002, 147-153
[4] Hiemstra, L. A. V. & D. M. Francis. Run hydrographs for prediction of flood hydrographs. Journal of the Hydraulics Division Vol. 107 (No. 6), 1981, 759-775
[5] Ahmed, N. Frechet Distribution and Natural Hydrograph. World Water and Environmental Resources Congress, Orlando, Florida, 2001
[6] Lohr, H. Generierung extremer Abflüsse für die Stauanlagenbemessung. Wasser und Abfall 7-8, 2003, 20-24
[7] Sackl, B. Ermittlung von Hochwasser-Bemessungsganglinien in beobachteten und unbeobachteten Einzugsgebieten. Schriftenreihe zur Wasserwirtschaft 13, Technische Universität Graz, 1994
[8] Dyck, S. & G. Peschke. Grundlagen der Hydrologie. Verlag für Bauwesen, Berlin, 1995
[9] DWD. KOSTRA-DWD-2000: Starkniederschlagshöhen für Deutschland (1951-2000), Grundlagenbericht. Offenbach, 2005

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