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A COMPARISON OF STATISTICAL AND DETERMINISTIC METHODS FOR PREDICTING EXTREME FLOODS IN AN ALPINE CATCHMENT

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Abstract

Flood protection is an important issue for a densely populated country like Switzerland due to the varied topography and the multitude of rivers and lakes. Because of the potential danger caused by extreme flood, structural and functional safety of large dams must be guaranteed. A comparison between statistical methods to estimate extreme flows and a more advanced methodology based on a combination of a deterministic meteorological model generating maximum precipitation and a semi-distributed conceptual hydrological model is presented here. A PMP-PMF simulation using the hydrological model is performed. The results show that the Swiss prescription of $1.5{\cdot}Q_{1000}$ used for the spillway design is 1.14 times smaller than the PMF calculated with a 24h-PMP and 1.43 times smaller than the highest estimated 9h-PMF.

Keywords: Probable maximum precipitation, Probable maximum flood, statistical extrapolation, Alpine catchment

1. Introduction

According to Swiss Committee on Dams (SwissCOD, 2011), 160 large dams (> 15m) have been constructed in Switzerland between 1836 and 2000. More than 130 dams have a reservoir capacity that is higher than 100 000 m^3. Still more than half of the Swiss dams have a reservoir capacity of more than 1 Mio. m^3. The highest capacity of 401 Mio. m^3 owns the Grande Dixence (SwissCOD, 2011). Therefore, the safety of dams, and thus the spillway design, is a major topic for engineers. In Switzerland, the design flood is defined as a 1000-years flood (Q_{1000}) which has to be evacuated below the maximum operation level even if one of the spillway gates with the largest capacity is out of operation. Furthermore the dam has to withstand without failure for the so-called safety flood which should be above $1.5{\cdot}Q_{1000}$ (FOWG/FOEN, 2002; Schleiss & Pougatsch, 2011; SFOE, 2008), if simply derived from the 1000-years flood. In general, according to Federal Office for Water and Geology (FOWG/FOEN, 2002), the safety-flood is corresponding to the probable maximum flood (PMF) that is deduced from the probable maximum precipitation (PMP).

In this paper, two different methods have been applied for one dam catchment, the statistical methods in order to extrapolate observed data to a flood corresponding to a return period of 1000 years and the deterministic rainfall-runoff method used to perform a PMP-PMF simulation considering the latest spatio-temporal rainfall distribution with the MPF (Modeling Precipitation Flood) hydrological model (Receanu, 2013). Finally, the ratio between the extrapolated flood discharge corresponding to a 1000 year event and the simulated PMF is calculated.

2. Catchment description and available data

The Mattmark dam catchment is situated in Canton of Wallis in the south of Switzerland. Its area is 37 km² with a lake surface of 1.76 km². This basin presents altitudes between 2174 and 4140 m a.s.l (Figure 1). About 27% of the catchment area is covered by a glacier (Figure 1 - gray in the upper part of the catchment) The main river is the Saaser Vispa, which flows through the Saas Valley. One of the problems of dam safety lies in the possibility of significant flooding in the Saas Valley. Furthermore, collectors, limited at a total discharge of 16 m³/s, are collecting the water from smaller surrounding catchments.

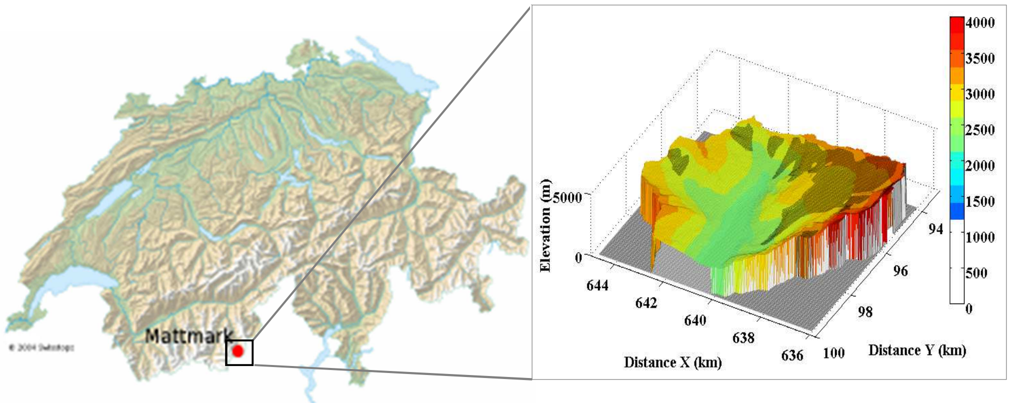

Figure 1. Position and topography of the main Mattmark watershed (gray area on the right = glacier zone).

For this basin, data is available for precipitation, temperature and discharge. The precipitation and temperature data have been provided by the Federal Office of Meteorology and Climatology from 12 meteorological stations in a radius of 50 km. The discharge data has been provided by the Mattmark dam owner. The available data series covers the period from 1982-2009. The largest floods recorded until 2009, have been observed in 2008, 1993, 1994 and 1987 with peak flows of respectively 64.05 m³/s, 63.84 m³/s, 62.77 m³/s, 56.45 m³/s.

In the next sections, these data series are used to estimate floods with high return periods on the Mattmark catchment using statistical and deterministic methods.

3. Statistical methods

In hydrology, statistical methods are frequently used to analyze observed data. The goal is to extrapolate observed data, in order to estimate floods with high return periods. According to (DWA, 2012) and (FOWG, 2003), an extrapolation higher than 2 to 3 time the length of the observed data series is not very reliable as the extrapolation are diverging for high return periods.

Nevertheless, the Swiss directives (FOWG/FOEN, 2002; SFOE, 2008) for extreme flood estimation for dam safety evaluation suggest to use $1.5 \cdot Q_{1000}$, if no detailed PMF calculation can be performed. Hence, an extrapolation up to a return period of 1000 years will be considered despite the fact, that the extrapolation may under- or overestimating the extreme flood.

3.1 Analysis of discharge data

The handbook for flood evaluation in Swiss catchments (FOWG, 2003) proposes several distributions for the extrapolation of observed flood data, i.e. Gumbel (GU), Frechet (F), generalized extreme value distribution (GEV), log-normal distribution with 3 parameters (LN3), Pearson type III (P3), log-Pearson type III (LP3), and Gamma (GA). These distributions have been applied to extrapolate the annual maxima of the observed floods for the Mattmark catchment. The plotting position was determined using the maximum likelihood method (ML). Figure 2 shows the results obtained for the Mattmark basin, taking into account a long series of data over 25 years.

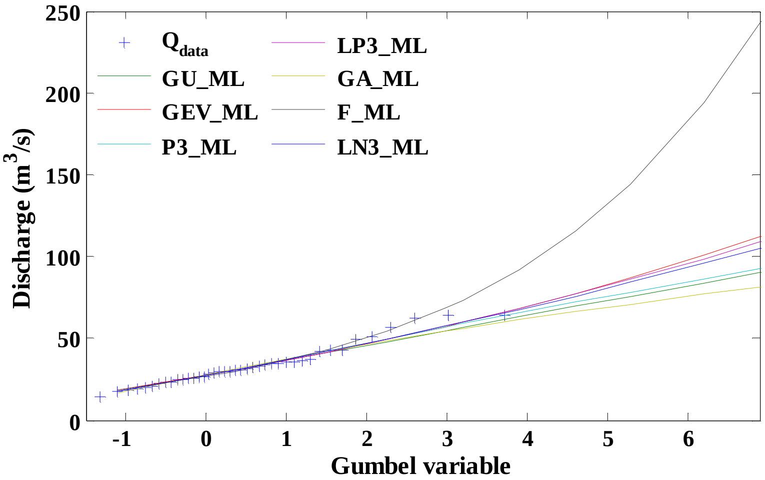

Figure 2. Annual daily maximum discharge extrapolation using 7 distributions (i.e. Gumbel, GEV, Pearson type III, Log-Pearson type III, Frechet and Log-Normal with 3 parameters) fitted with the maximum likelihood method.

The statistical tests used to evaluate the goodness of fit are the Kolmogorov-Smirnov test (Massey, 1951), the Cramér-von Mises ($n\omega^2$)-test (Laio, 2004), as well as the correlation coefficient R^2, the square of the Pearson correlation coefficient (Wang et al., 2011). Furthermore, the Akaike information criterion (AIC) and the Bayesian information criterion (BIC) (Laio et al., 2009) are considered. A visual verification of the goodness of fit is undertaken considering QQ-plot (Wilk & Gnanadesikan, 1968).

The values of the goodness of fit criteria for each distribution are presented in Table 1. The correlation coefficient R^2 is for all distributions higher than 0.95. Regarding Kolmogorov-Smirnov and Cramér-von-Mises the best fitting distribution seems to be GEV. Considering AIC and BIC, the Gumbel distribution should be chosen.

The statistical tests used for this study show different results (Table 1). Consequently those criteria are not sufficient to choose the best fitting distribution. The choice of the best statistical distribution for the Mattmark basin cannot be made on the only basis of these criteria.

Table 1. Performance criteria for the statistical distributions used to fit the observed distribution data using the maximum likelihood method.

	Gumbel	GEV	Pearson III	log-Pearson III	Gamma	Frechet	3 param. Log-norm
Kolmogrov-Smirnov	0.09	0.08	0.1	0.08	0.12	0.09	0.08
Cramer- von Mises	0.04	0.03	0.04	0.03	0.08	0.06	0.03
R2	0.98	0.99	0.99	0.99	0.98	0.97	0.99
AIC	316.45	317.88	317.68	317.8	318.42	318.56	317.73
BIC	319.88	323.02	322.82	322.94	321.85	321.99	322.87

The QQ-plots have been used for additional decision making information. These plots have been made for the two distributions Gumbel and GEV chosen according to the above criteria (Figure 3 and Figure 4). The QQ-plots show that the high quartiles are better estimated by GEV than by Gumbel. Therefore the choice of the distribution that is used for the following safety flood estimation is the GEV.

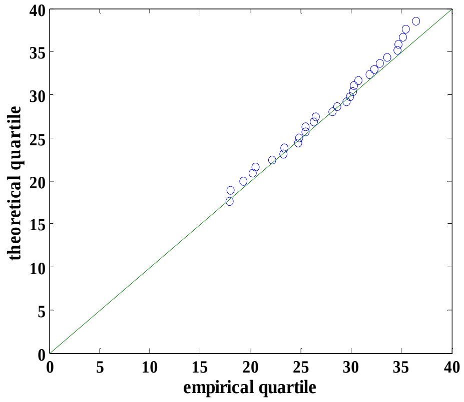

Figure 3. QQ-plot of the empirical quartiles and the quartiles estimated by a Gumbel distribution using the maximum likelihood method.

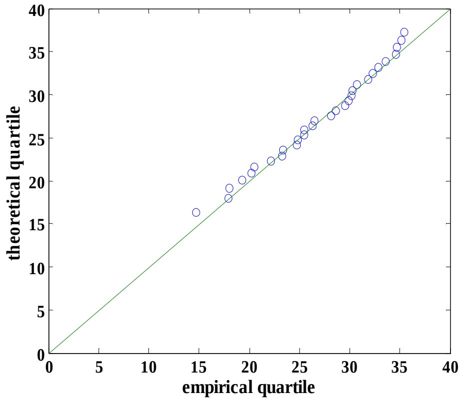

Figure 4. QQ-plot of the empirical quartiles and the quartiles estimated by a GEV distribution using the maximum likelihood method

Figure 5 shows the extrapolation using the GEV distribution. The upper and lower confidence intervals (95%) are also plotted. The estimation for the 1000 year flood is Q_{1000} =112 m^3/s. The confidence interval is quite large and goes from 70 m^3/s (lower interval limit) to 244 m^3/s (upper interval limit).

The discharge estimation based on the formula $1.5 \cdot Q_{1000}$ is thus 170 m^3/s. In chapter 4 this result is compared with the PMF obtained using a deterministic rainfall-runoff model.

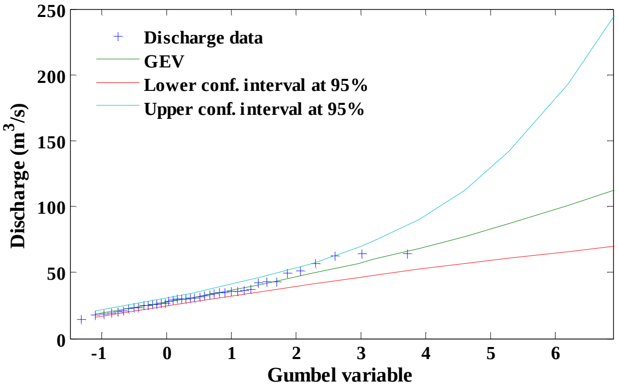

Figure 5. Extrapolation of the observed distribution data using a GEV distribution fitted considering the maximum likelihood method.

4. The deterministic method

To estimate the extreme flood in terms of PMF for the Mattmark watershed, a hydrological model using Routing System 3.0 is used to perform the rainfall-runoff simulations. The model is calibrated and validated on observed data. The PMP data used for the PMP-PMF simulation is extracted from Swiss PMP maps (Hertig & Fallot, 2009). This PMP data is then distributed spatio-temporally using the MPF hydrological model.

4.1 Hydrological model, RS 3.0

The semi-distributed conceptual hydrological model, built using the Routing System 3.0 (RS) software (Jordan et al., 2012), is composed of two models such as Figure 6.

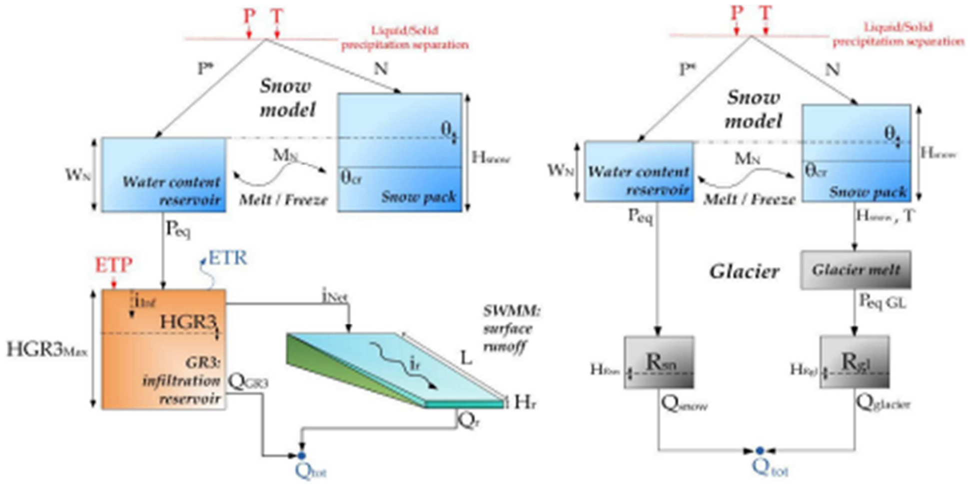

Figure 6. Sketch of the functions and parameters of the hydrological models SOCONT and GSM.

First model is SOCONT (Schaefli et al., 2005) is used for the non-glacier zones (Figure 6 – on the left). The second model is GSM model (Schaefli et al., 2005) is used for the catchment parts covered by a glacier (Figure 6 – on the right).

These models describe the hydrological functions corresponding to surface runoff, soil infiltration, subsurface flow, snow melt and glacier melt. These functions are applied over the entire catchment area which is sub-divided into altitude bands. Within an altitude band, the conditions are considered to be the same. The RS hydrological model needs 9 parameters to be calibrated. The rainfall intensity, the temperature and the evapotranspiration (ETP) can additionally be adjusted by a translation correction coefficient. In the next section, the calibration and the validation phases for the Mattmark catchment are presented.

4.2 Calibration and validation

To calibrate the RS hydrological model, the area of the Mattmark catchment has been modelled as 12 sub-catchments by glacier and non-glacier altitude bands. Subsequently, for all altitude bands, precipitation and temperature have been interpolated from 12 meteorological stations, available in a radius of 50 km.

Before the calibration can be performed, an analysis of the frequency duration curves was undertaken in order to choose an average hydrological year. Figure 7 shows, that the years 1996 and 1997 can be considered as average hydrological years.

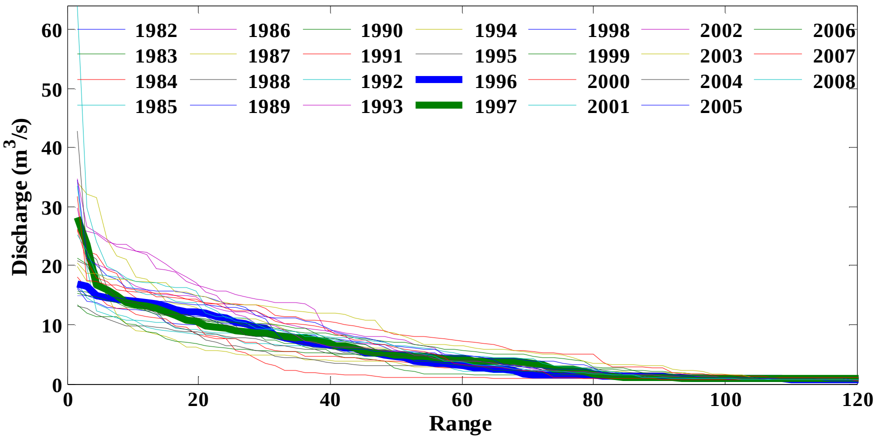

Figure 7. Frequency duration curves (zoom on the 120 days having the highest discharge).

The parameters of the RS hydrological model determined during the calibration could be validated over a 25 years period of observed floods. In the validation phase, the hydrological year 2000-2001 has been excluded due to erroneous rainfall data.

Figure 8 and Figure 9 show the simulated and observed hydrographs as well as the observed precipitation time series for the calibration period as well as an extract of the validation period.

The Nash-Sutcliffe coefficient and the water volume ratio ($=V_{sim}/V_{ref}$) have been calculated for the calibration and validation periods. The results are presented in Table 2. For this basin, the Nash coefficients are higher than 0.8, what can be characterized to be very good (Moriasi et al., 2007). The water volume ratio is close to 1, which also indicates a good correlation between the observed and simulated flows.

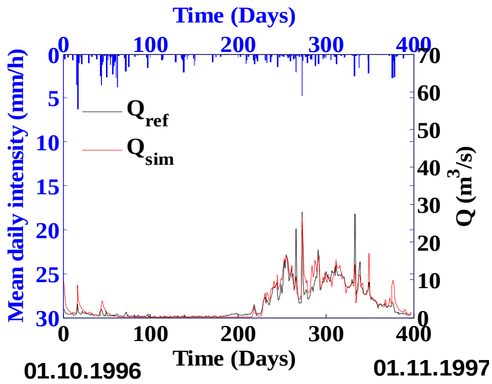

Figure 8. Rainfall hyetograph and flood hydrograph for the Mattmark watershed (calibration event 1996-1997)

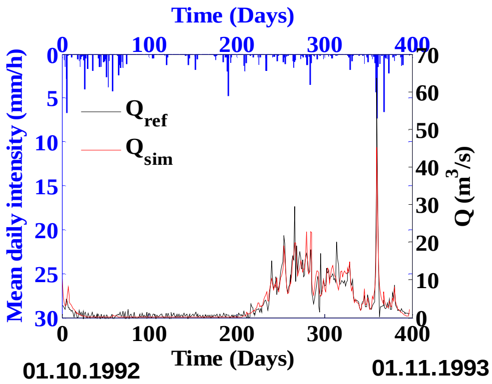

Figure 9. Rainfall hyetograph and flood hydrograph for the Mattmark watershed (validation event 1992-1993)

Table 2. Nash-Sutcliffe coefficient and volume ratio for the calibration and the validation of the hydrological model.

Criteria	Calibration (1996-1997)	Validation (1982-2000, 2001-2007)
Nash-Sutcliffe	0.84	0.83
Volume ratio	1.08	1.01

These good results confirm the assumption that the model can also be used for simulations of other event types such as the PMP-PMF.

4.3 PMP-PMF simulation

4.3.1 PMP input data

In Switzerland, PMP has been calculated using a meteorological model taking into account different wind directions and three main types of precipitation, i.e. convective, frontal and orographic. The resulting PMP maps have been elaborated indicating the isolines of probable maximum precipitation over the entire country with a horizontal resolution of 2 km (Hertig & Fallot, 2009). Additionally, for every wind direction, different maps exist for precipitation durations of 1h, 3h, 6h, 9h, 12h and 24h. Figure 10 shows an extract of the PMP map with the Mattmark catchment for a rainfall duration of 9h and a southern wind direction. The choice of the specific wind direction is based on a meteorological analysis of the weather conditions leading to the most significant floods. The corresponding PMP maps for different rainfall durations are thus considered in order to estimate the PMF.

To estimate a realistic PMF based on the PMP maps, it was necessary to define a spatio-temporal distribution to the flood event according to the PMP data. The goal is to obtain a distribution that is closer to reality than a simple uniform rain distribution. To obtain such a non-uniform distribution over the catchment, a cloud model is used, included in the MPF hydrological model (Receanu, 2013). This part of the model is based on an advection–diffusion equation (Jinno et al., 1993) which models the behavior of the cloud, both in terms of spatial displacement and of temporal evolution (Figure 11). It has been developed primarily to distribute precipitation for the short duration of the PMP episodes (1–6h). For long rainfall periods, the spatio-temporal distributions of the PMP over the basin, were obtained by combining several short structures of rainfall determined using the MPF hydrological model.

The final structures of the PMP for different rainfall durations used in the RS 3.0 model have a spatial resolution of 500 m and a temporal resolution of 10 minutes.

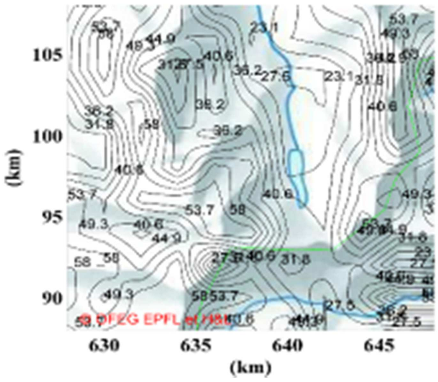

Figure 10. Extreme precipitation (PMP) in Switzerland, at ground level in mm/h, precipitation duration: 9h

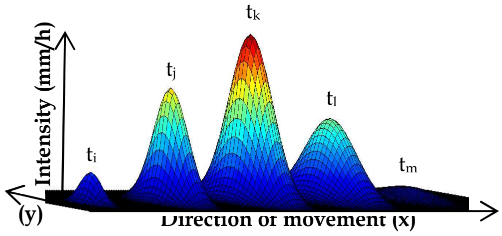

Figure 11. Spatio-temporal evolution of the cloud at different moments ($t_i < t_j < t_{k....}t_m$), the color gradient represents the rain intensity (mm/h)

4.3.2 PMF Mattmark

The PMF has been estimated using the hydrological model RS 3.0. (section 4.1) using spatio-temporally distributed PMP data (section 4.3.1). The PMF has been calculated under the assumption that the initial conditions for the simulation are the same as in the case of a major observed flood. In this case, the chosen initial conditions correspond to the conditions that occurred before the flood of 1993. The simulation with observed precipitation data allowed to estimate these conditions.

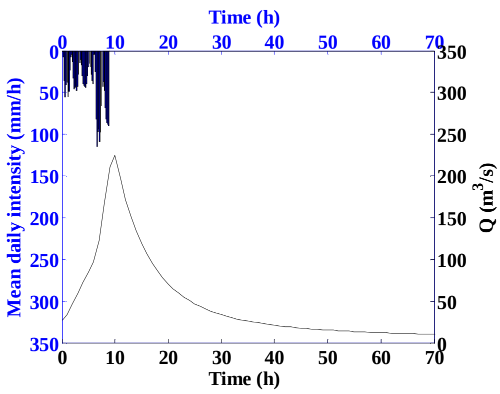

Figure 12. PMP 9h hyetograph at 640380/98438 and PMF hydrograph of the lake inflow

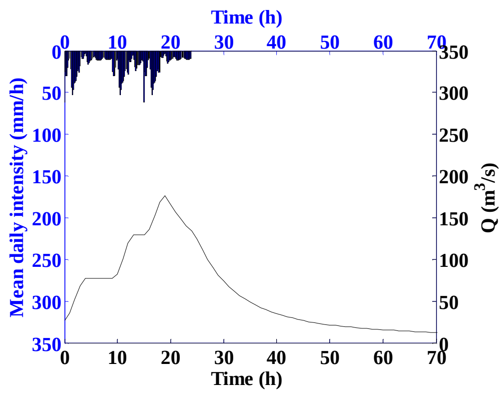

Figure 13. PMP 24h hyetograph at 640380/98438 and PMF hydrograph of the lake inflow

To estimate the critical precipitation duration leading to the highest PMF, different rainfall durations of PMP (3h, 6h, 9h, 12h and 24h) have been analyzed. In this paper only the PMF-results obtained for 9h (giving the highest peak discharge of $Q_{PMF,9h}$=225 m^3/s) and 24h (corresponding to the time resolution of the data series used for the extrapolation) are presented in Figure 12 and Figure 13, where the PMP hyetograph of the 9h-and 24h-rainfall (at 640380/98438) is also shown.

5. Analysis and comparison between the statistical and semi-distributed methods

The comparison is made between the extreme safety check flood ($1.5 \cdot Q_{1000}$) estimated using the result of the GEV distribution and the peak discharge calculated based on the rainfall – runoff simulation. The considered comparison ratio *R* is:

$$R = \frac{Q_{PMF}}{Q_{stat}} \quad [1]$$

were: Q_{PMF} is the probable maximum flood (m³/s); Q_{stat} is the discharge calculated by $1.5 \cdot Q_{1000}$ (m³/s) (Schleiss & Pougatsch, 2011) (Q_{1000} is estimated using the GEV distribution).

In order to compare the simulated data with the extrapolated data, the simulated PMF values have to be raised by the discharge from the collectors, since this is implicitly included in the statistical methods. Their upper discharge is limited at 16 m³/s.

It can be reasonably assumed that this limit is attended under PMF conditions. The ratios *R* between the estimated PMFs and the statistical estimation of Q_{stat} respectively $1.5 \cdot Q_{1000}$ are shown in Table 3.

Table 3. Ratio between simulated flow Q_{PMF} and statistical estimation Q_{stat} for 9h and 24h

R	Q_{stat} ($1.5 \cdot Q_{1000}$)=170 m³/s
$Q_{PMF,9h}$=241 m³/s	1.42
$Q_{PMF,24h}$=192 m³/s	1.12

The statistical estimation of Q_{stat} is 1.12 times smaller than $Q_{PMF,\,24h}$ and 1.43 times smaller than $Q_{PMF,9h}$. Concerning the comparison of the estimated PMF discharges with $1.5 \cdot Q_{1000}$, the ratio R shows that the 9h-PMF is 1.42 time higher than the statistical safety check flood. The 24h-PMF is only 1.14 time higher than $1.5 \cdot Q_{1000}$.

It can be observed that the statistical estimations of the safety check flood are closer to the 24h-PMF than the 9h-PMF. This may be due to the fact that the considered statistical extrapolations are based on daily values (24h). Another interesting point is that the values of $1.5 \cdot Q_{1000}$, $Q_{PMF,9h}$ and $Q_{PMF,24h}$ are still in the confidence interval (95%) of Q_{1000} estimated by a GEV distribution. This means that Q_{1000} can be much higher than Q_{1000}=112 m³/s. The large confidence interval of the GEV distribution confirms the high degree of uncertainties of the statistical methods.

6. Conclusion

The purpose of this paper is to argue that the extreme safety check flood ($1.5 \cdot Q_{1000}$) should be used in combination with a PMP-PMF analysis if possible. The PMP-PMF simulation on the Mattmark catchment leads to higher discharges than the statistical estimation of the safety flood, but stays in this case within the confidence interval of the GEV distribution estimated for Q_{1000}. The estimations of $1.5 \cdot Q_{1000}$ are close to a 24h-PMF when the extrapolations are performed using a data series with a time resolution of 24h.

This estimation is flattening the real peak discharge (in this case the peak is attended for a 9h-rainfall), which can, however, be critical for the design of spillways. The statistical methods to estimate an extreme flood can be used to get an order of magnitude of the peak discharge but should not be considered as a conclusive value for the design.

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