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EXTREME FLOOD ASSESSMENT IN SWISS ALPINE ENVIRONMENT [*]

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1. INTRODUCTION

In Switzerland, a lot of large dams (h>15 m according to the ICOLD definition of large dams) have been constructed. Of the total of 160 dams, 80 dams have a reservoir capacity higher than 10^6 m^3 [1]. As a matter of consequence, dam safety becomes a major issue, especially in the still not well understood domain of the estimation of extreme floods. Even if the return period of the safety flood specified by the directives are very large ($T >> 10^3$ years), their occurrence is not impossible and can cause huge damage on the dam and have catastrophic consequences for the population downstream. Therefore, it is important to reliably estimate extreme floods.

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[*] *Estimation des crues extrêmes dans les régions alpines suisses*

In Switzerland, two extreme floods have to be taken into account to verify the safety of large dams, the design flood Q_{1000} and the so called safety flood that is considered to be $1.5 \cdot Q_{1000}$ or the PMF (probable maximum flood) [25], [26].

Hydrologists use mathematical models and methods to estimate floods. Over the years, a lot of different approaches have been developed and are still being ameliorated. Research in this domain is under continuous development because of the high uncertainties of the involved phenomena responsible for the flood formation and its characteristics, such as peak discharge, volume, rising time, return period, etc. In addition, high uncertainties are induced by the deficiency of sufficient precipitation data and land cover as well as a sufficiently high resolution of the precipitation and discharge measurements. The state of the art of the existing flood estimation models and methods is presented hereafter.

2. STATE OF THE ART - MODELS AND METHODS FOR FLOOD ESTIMATION

A classification of the different existing models and methods has been elaborated (Fig. 1) according to the literature [2], [3], [4]. They can be subdivided in three main categories, i.e. the observation based methods, the simulation based methods (rainfall-runoff) and the mixed methods.

2.1. OBSERVATION BASED METHODS

The category of the observation based methods can be subdivided in empirical and statistical methods (Fig. 1).

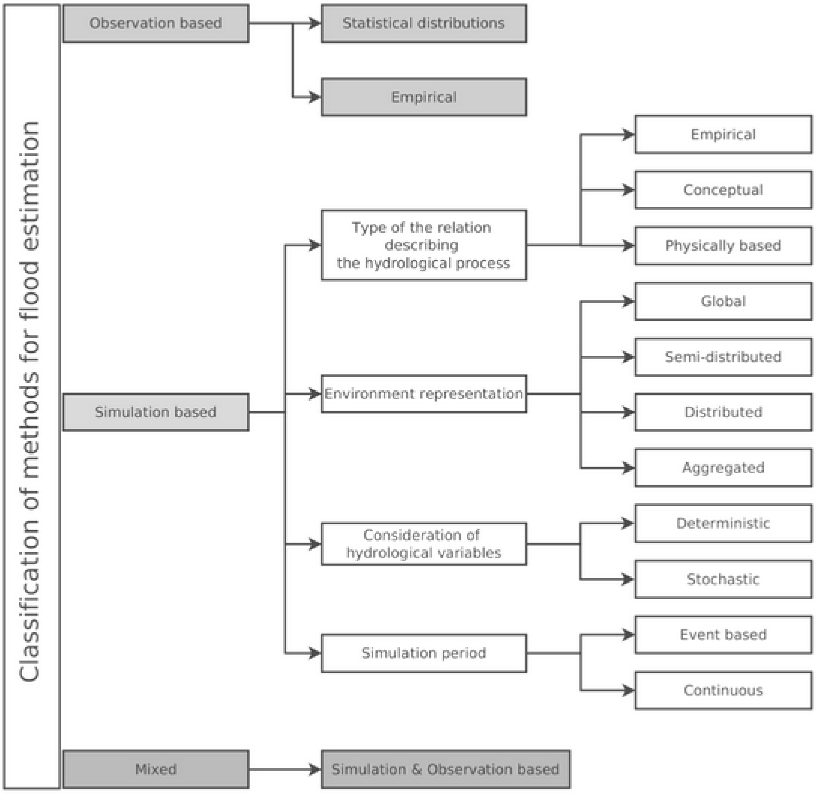

Fig. 1
Hydrological flood estimation model classification.
Classification des méthodes hydrologiques d'estimation de crues.

2.1.1. Empirical methods

Empirical methods are based on practical experiences or observations rather than on scientific proof. In hydrology, empirical methods are often used in ungauged catchments by using regionalization methods in order to extend the observed phenomena to the ungauged catchments. An empirical law can then be established to estimate hydrological variables, in this case the discharge. When empirical methods are "conceptualized", hydrologists speak of pseudo-empirical methods [2]. Those methods derive the discharge from precipitation variables [2]. The most frequently used pseudo-empirical method is the rational method. According to Hingray *et al.* [2], it has been developed during the middle of the

19th century by the Irish engineer Mulvanay. Further explanations are presented by Cleveland *et al*. [5].

Other methods can also be found in the literature. The method SCS [6] was developed in the 1960th by the Soil Conservation Service and is used in the United States. This method has then been improved and adapted by Cemagref to French catchments and is called SOCOSE [6].

According to the Federal Office for Water and Geology [7] and Schleiss [8], the empirical methods that are used in Switzerland are Kürsteiner [9], Hofbauer [10], Melli [11], GIUB '96 [12], [13], Method of moments [14], [15] and Müller-Zeller [16], [17].

The advantages of using empirical and pseudo-empirical methods are that not much data are needed, they can be used for ungauged catchments and the working time to get estimations is very short. However, the methods are very approximative and the determination of the coefficients is not always objective. Thus, the results can highly differ for different engineers achieving the same calculation. In addition, they are mostly applicable to small to medium catchments, and are adapted to the estimates of hundred year floods respectively to the estimates of floods based on the highest observed values. Consequently, they are not reliable for the estimation of extreme floods [7].

2.1.2. Statistical methods

Statistical methods can be used to estimate flood discharges when a large amount of discharge data is provided in order to fit a distribution function to observed discharge time series. The shorter the data series is, the less reliable the extrapolation is. The extrapolation should not go further than 2 to 3 times the length of the data series [7], [18].

According to the Swiss and German directives [7], [18], the most frequently used extreme value probability distribution functions in hydrology are Gumbel [19], Fréchet [20], Weibull [21], General Extreme Value Distribution (GEV) developed by Jenkinson [22] (cited in [23]), Generalized Pareto Distribution, Exponential, Pearson III and Log-Pearson III (from the Gamma distribution family). It is important to know the best fitting distribution function for a certain domain, i.e. discharge, precipitation, region, etc. . . . Unfortunately, there is no physico-mathematical justification why a certain distribution is more reliable for a certain domain ([24] cited in [18]). A more elaborated statistical method is the GRADEX [27]. To estimate floods, it does not only take into account discharge data but also measured rain data series for the extrapolation. It contains a breaking point between the ten to twenty year flood estimation, the so called pivot, due to the extrapolation of the discharge data using the rainfall data to derive the slope of the discharge extrapolation line from the pivot on. This induces a changing in slope at the pivot. This breaking point induces an overestimation of the floods with a return period between 10 and 1000 years when the GRADEX method is used. An improvement of the method was developed by Margoum *et al*. [28], leading to the model AGREGEE, conceived to extend the application domain of the GRADEX method by introducing a continuous smooth function in the transition zone containing the pivot in the GRADEX method. The introduced function is a mixed exponential function in order to fit ordinary and extreme values at the same time as described by Margoum *et al.* [28]. The basic assumptions of the AGREGEE method are the same than for the GRADEX method.

As already mentioned, a common problem with statistical methods is that data series are too short for good extrapolations to extreme floods. According to DWA [18], a better extrapolation can be obtained by using observed historical flood data. However, that information can contain big uncertainties. Therefore, the assistance of historians can be necessary [18]. Unfortunately, historical information are rarely available, especially in alpine catchments.

It can be stated that statistical methods are rather uncertain for high return period estimations, the extrapolations highly depend on the observed values and on the engineer’s choice of the distribution and the plotting position method. When no high floods have been observed in the past, statistical methods cannot be trusted for the estimation of high return period discharges.

2.2. SIMULATION BASED METHODS

The simulation based methods can be divided into four sub-categories, depending on the type of the relation describing the hydrological process (empirical, conceptual, physically based), the representation of the environment (global, semi-distributed, distributed, aggregated), the consideration of the hydrological variables (deterministic, stochastic) and the consideration of the simulation period (event based or continuous simulation) of the model (Fig. 1).

In the literature, the most discussed category is the one distinguishing the different environmental representations. Hence, this category deserves further explanations.

A distributed model takes into account the spatial distribution of the physical parameters describing the modeled environment. The catchments are represented by a grid of points, making possible to estimate the discharge at each grid point using physically based functions. Frequently used programs allowing a distributed modeling of the catchment can be found in the literature. TOPMODEL, developed by Beven and Kirkby. [29] (originally reported by Beven [30]), is an open source model. The latest version of TOPMODEL, called Dynamic TOPMODEL, is described by Beven and Freer [31]. Other models are MIKE SHE ([32] cited by Singh and Frevert [33]), LARSIM [34], WASIM [35], NASIM [36], MPF [37], [38], Modular Modeling System PRMS/MMS [39], TOPOG [40], SLURP Hydrological Model ([41] cited by Beven [30]).

Semi-distributed models also use physically based functions to estimate the discharge, but they do not take into account the spatial distribution of the physical parameters. They employ conceptual schemes, modeling the main characteristics of a catchment by gathering zones with similar physical characteristics and altitudes. Models entering this category are Mordor ([42], [43]), HEC-HMS [44], Integrated Hydrological Modeling System HBV ([45] cited by Krysanova *et al*. [46]), IHW [47], WMS [48], IHACRES [49], [50], CASC2D (described by Singh and Frevert [51] in [33]), SWMM (described by Gironás *et al*. [52]), SOCONT (described by Schaefli *et al*. [53]) and GSM-SOCONT [53] integrated in the modeling program Routing System 3.0 [54].

The so-called global or lumped models represent the catchment by only one model returning only the discharge at the outlet of the catchment. Thus they have the lowest level of information. Some can act as a black box.

Additionally, aggregated models can theoretically be imagined. It is a composition of the three types described above, leading to a mixed model. This type can be developed for huge catchments where sub-catchments are modeled using distributed, semi-distributed and global approaches and put together later.

Generally, the higher the resolution of a model is, the more preparation and computation time is needed. Thus the distributed models are the most time consuming and the fastest estimations are obtained from lumped models.

This section showed that the domain of simulation based models is very wide. Only a few models are open source or freely available. This domain offers a high potential for the flood estimation since the development of the simulation based models are continuously being improved. However, no information could be found about their applicability for extreme floods (HQ_{1000} and higher).

2.3. MIXED METHODS

The third category, the mixed methods, are a combination of the first two methods, using simulation based methods in order to generate input data for a statistical analysis.

In France, two mixed stochastic methods are used to estimate extreme floods: SHYPRE/SHYREG [55] and SCHADEX [56], [57].

In Switzerland, mixed methods have been developed during the projects CONSECRU 1 [58] and later CONSECRU 2 [59].The precipitation series are generated by a stochastic precipitation model (NRSPM, Neyman-Scott

Rectangular Pulses Model) ([60] originally reported by the Federal Office for Water and Geology [7]) and introduced in a rainfall-runoff model. The CONSECRU methodology leads to a large number of flood scenarios that are subjected to usual statistical analysis in order to conclude. It was conceived to estimate hundred year floods.

3. PMP-PMF METHOD

Hydrologists speak about the PMP-PMF method when the probable maximum precipitation (PMP) is transformed into the probable maximum flood (PMF) using a rainfall-runoff model [61]. Thus it is part of the category of simulation based methods, but due to its particular concept it deserves to be discussed separately.

This method has been developed in the United States of America in the middle of the last century since the empirical and statistical methods could not provide satisfactory results for the estimation of extreme floods.

It is frequently used in the USA [62], Australia [63], Canada [64], Spain [65] and Austria [66]. The main assumption of the method is that an upper limit of the intensity of the precipitation is existing [62].

The first time the PMP-PMF method was used in Switzerland was during the CERS project of the Laboratory of Hydrology and Facilities HYDRAM at EPFL [62]. The second project undertaken on this subject was the CRUEX project [62]. In the CRUEX project, PMP maps were developed for the entire surface of Switzerland [67], [68], [69], [70].

The methodology used for the mapping of extreme precipitation in Switzerland takes into account the mechanisms of orographic, frontal and convective precipitation. For orographic and frontal precipitation, a meteorological meso-scale model first calculates a wind field over the topography for given weather conditions specifying the initial conditions of wind, temperature and humidity. The wind field is then used to solve the equations of the rain model by Kessler [71] to obtain a spatial distribution of rainfall intensity, which is then associated to a precipitation duration. The convective precipitation is calculated using a meteorological model based on the method proposed by Haiden [72] and Haiden *et al*. [73].

In 2013, the distributed model MPF was developed for small non-glacier alpine basins by Receanu [37]. This model is divided into two modules. The first one is a model of clouds to distribute the precipitation data from the PMP maps. This model provides a dynamic evolution of the rain on a very fine scale over a watershed, or even across an entire region. The heart of the calculation model is an advection-diffusion equation, which models the behavior of the cloud, both spatially and temporally. The second module of the model is a flood routing model.

To sum up, the research concerning PMP has well progressed in the last years. However there is a great necessity of improvements in the domain of the PMF. The return periods for PMP and PMF are not easily evaluated neither the related risks. However, as the statistical methods cannot furnish a reliable estimation of floods with extreme return periods, to propose another reliable method to estimate extreme floods becomes indispensable.

4. CASE STUDY - MATTMARK

Statistical and simulation based methods (including the PMP-PMF method) have been applied to the Mattmark catchment are. Statistical distributions compared are Gumbel, Generelized Extreme Value, 3 Parameter Log-Normal, Pearson III, Log-Pearson III and the GRADEX. A PMP-PMF simulation combining MPF model (rainfall distribution module) and GSM-SOCONT [53] has been carried out. Since the empirical methods are not suitable for extreme flood estimations, they are not used in the presented study.

4.1. RESULTS AND DISCUSSION

The results obtained by the used methods are exposed (Fig. 2). The 1000 year flood estimated by statistical methods varies from 99 to 133 m^3/s depending on the distribution function used for the estimation. The 10’000 year flood estimates shows values from 122 to 183 m^3/s. It can be stated that the differences between the results are considerable. The Swiss guidelines for dam safety verification prescribe to use $1{,}5 \cdot Q_{1000}$ or the PMF as safety flood [25], [26]. These values have also been plotted on Fig. 2. The estimates of $1{,}5 \cdot Q_{1000}$ vary from 142 to 200 m^3/s. PMP structures corresponding to a rainfall duration of 1h, 3h, 6h, 9h, 12h and 24h have been used to simulate PMF hydrographs. Here, only the PMF simulation for 9h-PMP structures are shown as they induce the highest PMF ($Q = 241$ m^3/s). The lowest PMF estimation equals 201 m^3/s.

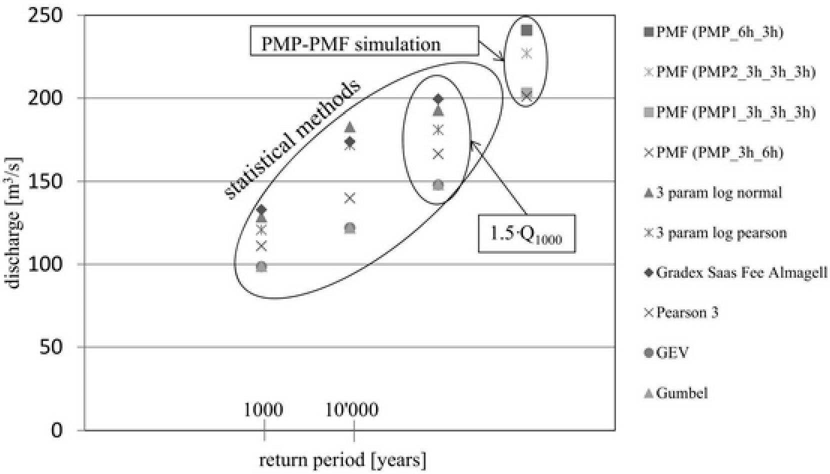

Fig. 2

Comparison of the flood estimates for different methods.

Comparaison des estimations de crues pour différentes méthodes.

The statistical methods can only return the discharge value. They provide no information about the hydrograph and thus the volume of the flood cannot be estimated. However, the hydrograph and the volume are necessary to estimate the retention effect of the reservoir and to verify the freeboard height. Furthermore, the choice of the distribution has a considerable influence on the extrapolated value, as shown on Fig. 2. In addition, the method selected for the determination of the plotting position (maximum likelihood, method of moments or L Moments) also has an influence on the extrapolation [18]. Moreover, the extrapolation period should not exceed 2 to 3 times the duration of the data series [7], [18]. Consequently, values extrapolated to high return periods can hardly be trusted. For reasons of comparison, flood estimates have been extrapolated to 10’000 year floods (Fig. 2) and it can be stated that the safety flood, that has to be larger than 1,5 · Q_{1000} [25], [7], has a return period higher than 10’000 years when estimated with statistical methods.

Regarding the simulation based methods, they provide entire hydrographs, but do not either lead to a satisfactory result, since the return period of the simulated flood is not clearly known.

Furthermore, the initial conditions (initial snow height, soil saturation) and the temperature during extreme precipitation events to set for the simulation have a high influence on the result, but it is not known how to fix these conditions for the simulation for event based simulations as it is the case for PMF estimates, for example.

In addition, the simulation with distributed precipitation data showed that the spatio-temporal distribution has a significant influence on the discharge. The used spatio.-temporal distribution module of the MPF model could be validated by Receanu [37] for precipitation durations up to 6 hours. For the Mattmark catchment, the critical precipitation duration could be estimated to be 9 hours. Therefore the considered precipitations for the simulation are composed by shorter PMP events (3h and 6h) and adjusted to the volume of a 9h-PMP according to the PMP maps of Hertig *et al*. [67]. Fig. 2 shows that the combination of a 6h-rainfall and then a 3h-rainfall returns the highest discharge value. By reversing the order of the rainfall events (3h-rainfall and then a 6h-rainfall), but keeping the same volume of precipitation, the smallest value for the PMF (based on a 9h-PMP) is reached. Another interesting result to retain is that the smallest PMF discharge is nearly equal to the highest value of $1{,}5 \cdot Q_{1000}$. This means that the discharge of the safety flood that the engineer in charge could choose according to the Swiss directives [25], [26] is within a very large interval (from 142 m^3/s to 241 m^3/s).

5. CONCLUSION

An overview of methods to calculate extreme floods in alpine catchments has been presented in this paper. Empirical, statistical and simulated based methods have been analyzed and first conclusions obtained.

Empirical methods are not suitable for the estimation of extreme floods. They are interesting for the quick estimation of 100 year floods in ungauged catchments. The estimation based on the maximum observed values has the inconvenient that the return period of the estimated value is not defined.

Statistical methods can only be used in gauged catchments. They allow attributing a return period to every discharge value. However, the results can highly differ when different distributions and plotting position estimation methods are used. Furthermore, the extrapolation period is limited by the length of the measured data series.

Simulation based rainfall-runoff methods can be applied to every catchment under the assumption that rainfall measurements are available in an acceptable radius for the calibration of the hydrological model, also needing measured discharge data. These methods allow the evaluation of different state variables like the soil moisture, the snow height, etc. Synthetic rainfall events or PMP data can be used for the estimation of floods. This method also provides additional information since the hydrograph is calculated. This information can be useful, even compulsory, for dam safety assessment. Regarding the return period, it is not directly provided by the method.

It has been shown that none of the known methods directly returns results ready to use for spillway design. Concerning the simulated based methods, an analysis of the return period calculation should be achieved, as well as a clearly defined utilization of initial conditions for event based simulations. Thus, the research in the domain of extreme flood estimation has not yet achieved and needs real improvements in order to provide a robust and reliable methodology providing clear flood estimates.

REFERENCES

[1] SwissCOD, *Dams in Switzerland: Source for Worldwide Swiss Dam Engineering*. Swiss Commitee on Dams, 2011.

[2] B. HINGRAY, C. PICOUET, and A. MUSY*, Hydrologie 2 - Une science pour l'ingénieur*. Lausanne: Presses polytechniques et universitaires romandes, 2009.

[3] P. MEYLAN, A.-C. FAVRE, and A. MUSY, *Hydrologie fréquentielle : une science prédictive*. Lausanne: Presses polytechniques et universitaires romandes, 2008.

[4] A. MUSY and C. HIGY, *Hydrologie: Une science de la nature*. Lausanne: Presses Polytechniques et Universitaires Romandes, 2004.

[5] T. CLEVELAND, D. THOMPSON, X. FANG, and W. ASQUITH, *Use of the Rational and Modified Rational Methods for Hydraulic Design*. Texas Tech University: Center for Multidisciplinary Research in Transportation, 2011.

[6] C. ANCEY, *Risques hydrologiques et aménagement du territoire*. Notes de cours. Laboratoire hydraulique environnementale (LHE): Ecole Polytechnique Fédérale de Lausanne EPFL, 2013.

[7] FOWG, *Evaluation des crues dans les bassins versants de Suisse. Guide pratique*. *Rapport de l'OFEG*, Série Eaux, No.4, Bern: Federal Office for Water and Geology, 2003.

[8] A. SCHLEISS, *Aménagements hydrauliques*. Cours EPFL, 2008.

[9] L. KÜRSTEINER, *Das neue Elektrizitätswerk der Stadt Chur an der Plessur bei Lüen*. Rascher, 1917.

[10] R. HOFBAUER, Eine neue Formel für die Ermittlung der grössten Hochwassermengen, *Österreichische Wochenschrift für den öffentlichen Baudienst*, pp. 38–40, 1916.

[11] E. MELLI, Die Dimensionierung städtischer Kanäle, *Schweizerische Bauzeitung*, Vol. 83/84, No. 12, pp. 137–141, 1924.

[12] C. KANN, *Die höchsten in der Schweiz beobachteten Abflussmengen bis 1990*. Diplomarbeit in der Gruppe für Hydrologie des Geographischen Instituts der Universität Bern. Publikation Gewässerkunde, Nr.169, 1995.

[13] R. WEINGARTNER, *Regionalhydrologische Analyse - Grundlagen und Anwendungen*, *Beiträge zur Hydrologie der Schweiz*, Nr. 37, Bern, 1999.

[14] H. DÜSTER, *Modellierung der räumlichen Variabilität seltener Hochwasser in der Schweiz*. Geographica Bernensia G44, 1994.

[15] M. BARBEN, *Beurteilung von Verfahren zur Abschätzung seltener Hochwasser in mesoskaligen Einzugsgebieten*. PhD thesis, 2001.

[16] R. MÜLLER, *Theoretische Grundlagen der Fluss- und Wildbachverbauung*., Mitteilung der Versuchsanstalt für Wasserbau der ETH Zürich, Nr. 4, 1943.

[17] J. ZELLER, *Berechnung der Abflusswassermenge*, Beilage zur Vorlesung Wildbach- und Hangverbau, Abteilung VI, ETH Zürich, 1975.

[18] DWA, *Merkblatt DWA-M 552. Ermittlung von Hochwasserwahrscheinlichkeiten DWA*, Dt. Vereinigung für Wasserwirtschaft Abwasser u. Abfall, 2012.

[19] E. GUMBEL, Statistics of extremes. New York: *Columbia Universit Press*, 1958.

[20] M. FRÉCHET, Sur la loi de probabilité de l'écart maximum, *Annales de la société polonaise de mathématique* (*Rocznik polskiego tow. matmatycznego*), Vol. 5, pp. 93–116, 1927.

[21] J. MAYNE AND N. COOK, *On Design Procedures for Wind Loading Garston*, Watford: Building Research Establishment, 1978.

[22] A. F. JENKINSON, The frequency distribution of the annual maximum (or minimum) values of meteorological elements, *Quarterly Journal of the Royal Meteorological Society*, Vol. 81, No. 348, pp. 158–171, 1955.

[23] P. ROCHE, J. MIQUEL, and E. GAUME, *Hydrologie quantitative: Processus, modèles et aide à la décision*. Springer, 2012.

[24] M. A. BENSON, Uniform flood-frequency estimating methods for federal agencies, *Water Resources Research*, Vol. 4, No. 5, pp. 891–908, 1968.

[25] FOWG, *Sécurité des ouvrages d'accumulation*, Directives de l'OFEG, Vol. Version 1.1, 01.11.2002, 2002.

[26] SFOE, *Sécurité des ouvrages d'accumulation. documentation de base relative à la vérification de la sécurité en cas de crue*, Directives de l'OFEN, Juin, 2008.

[27] P. GUILLOT and D. DUBAND, La méthode du Gradex pour le calcul de la probabilité des crues à partir des pluies, *International Association of Hydrological Sciences Publications,* Vol. 84/85, p. 10, 1967.

[28] M. MARGOUM, G. OBERLIN, M. LANG, and R. WEINGARTNER, Estimation des crues rares et extrêmes : principes du modèle agregee, *Hydrologie Continentale*, Vol. 9, No. 1, pp. 85–100, 1994.

[29] K. J. BEVEN and M. KIRKBY, A physically based, variable contributing area model of basin hydrology, *Logical Sciences Bulletin*, Vol. 24, No. 1, pp. 43–49, 1979. 9

[30] K. BEVEN, *Rainfall-Runoff Modelling: The Primer*, second Edition. Wiley Blackwell, 2012.

[31] K. BEVEN and J. FREER, *A dynamic TOPMODEL, Hydrological Processes*, Vol. 15, No. 10, pp. 1993–2011, 2001.

[32] DHI, MIKE SHE. Technical Reference Manual, Danish Hydraulic Institute, 1993.

[33] V. SINGH and D. FREVERT, Mathematical Models of Small Watershed Hydrology and Applications, *Water Resources Publications*, 2002.

[34] M. BREMICKER, Das Wasserhaushaltsmodell LARSIM, Modellgrundlagen und Anwendungsbeispiele, Freiburger Schriften zur Hydrologie, Vol. 11, 2000.

[35] J. SCHULLA, *Model description. WASIM (Water balance simulation model),* Hydrology Software Consulting J. Schulla, 2012.

[36] B. ROTHE and U.WOLF-SCHUMANN, Nasim 4.2, Speicherformeln, Stofftransport, Radar-Niederschlagsdaten, *Hydrothemen*, Vol. 24, p. 8, 2013.

[37] R. RECEANU, *Simulation fine des précipitations et des crues extrêmes. Application aux petits bassins versants alpins non glaciaires*, PhD thesis, Université de Lausanne UNIL: Faculté des géosciences et de l'environnement, 2013.

[38] R. RECEANU, J.-A. HERTIG, and J.-M. FALLOT, Modélisation hydrologique des précipitations et des crues extrêmes dans les bassins versants alpins, *Mémoires de la Société Vaudoise des Sciences Naturelles*, Vol. 25, pp. 35–54, 2013.

[39] K. SINGH and D. FREVERT, *Watershed Models*, Chapter 7. USGS Modular - Modeling System (MMS). Precipitation-Runoff Modeling System (PRMS) by Leavesley, G.H., Markstrom, S.L. and Viger, R. J., pp. 159–177. CRC Taylor & Francis Group, 2005.

[40] R. A. VERTESSY, T. J. HATTON, P. J. O'SHAUGHNESSY, and M. D. A. JAYASURIYA, Predicting water yield from a mountain ash forest catchment using a terrain analysis based catchment model, *Journal of Hydrology*, Vol. 150, No. 2–4, pp. 665–700, 1993.

[41] G. W. KITE, Scaling of input data for macroscale hydrologic modeling, *Water Resources Research*, Vol. 31, No. 11, pp. 2769–2781, 1995.

[42] R. GARÇON, Prévision opérationnelle des apports de la Durance à Serre-Ponçon à l'aide du modèle MORDOR. Bilan de l'année 1994-1995, *La Houille Blanche*, Nr. 5, pp. 71–76, 1996.

[43] E. PAQUET, Evolution du modèle hydrologique mordor: modélisation du stock nival à différentes altitudes, *La Houille Blanche*, Vol. 2, No.10, pp. 75–82, 2004.

[44] USACE, *Hydrological Modeling System HEC-HMS. Quick Start Guide, Version 3.5*, tech. rep., US Army Corps of Engineers, 2010.

[45] S. BERGSTRÖM, The HBV model - its structure and applications, *SMHI Report Hydrol.*, No. 4, 1992.

[46] V. KRYSANOVA, A. BRONSTERT, and D. I. MÜLLER-WOHLFEIL, Modelling river discharge for large drainage basins: from lumped to distributed approach, *Hydrological Sciences Journal*, Vol. 44, No. 2, pp. 313–331, 1999.

[47] E. PLATE, J. IHRINGER, and W. LUTZ, Operational models for flood calculations, *Journal of Hydrology*, Vol. 100, No. 1-3, pp. 489–506, 1988.

[48] EMRL, *Watershed Modeling System. WMS v7.1 Tutorials*, Brigham Young University-Environmental Modelling Research Labratory, 2004.

[49] A. J. JAKEMAN, I. G. LITTLEWOOD, and P. G. WHITEHEAD, Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments, *Journal of Hydrology*, Vol. 117, No. 1–4, pp. 275–300, 1990.

[50] B. F. W. CROKE and A. J. JAKEMAN, A catchment moisture deficit module for the IHACRES rainfall-runoff model, *Environmental Modelling & Software*, Vol. 19, No. 1, pp. 1–5, 2004.

[51] V. SINGH and D. FREVERT, *Mathematical Models of Small Watershed Hydrology and Applications*, Chapter 4, CASC2D: A two dimensional, physically based, hortonian hydrological model by Ogden, F. L. and Julien, P. Y. Water Resources Publications, LLC, 2002.

[52] J. GIRONÁS, L. A. ROESNER, L. A. ROSSMAN, and J. DAVIS, A new applications manual for the Storm Water Management Model (SWMM), *Environmental Modelling & Software*, Vol. 25, No. 6, pp. 813–814, 2010.

[53] B. SCHAEFLI, B. HINGRAY, M. NIGGLI, and A. MUSY, A conceptual glacio-hydrological model for high mountainous catchments, *Hydrolology and Earth System Sciences,* Vol. 9, No. 1/2, pp. 95–109, 2005. HESS.

[54] F. JORDAN, T. BRAUCHLI, J. GARCIA HERNANDEZ, M. BIERI, and J. L. BOILLAT, *RS 2012, Rainfall-Runoff Modelling. User guide*. Unpublished manual, Lausanne: e-dric.ch, 2012.

[55] F. CERNESSON, J. LAVABRE, and J.-M. MASSON, Stochastic model for generating hourly hyetographs, *Atmospheric Research*, Vol. 42, No. 1–4, pp. 149–161, 1996.

[56] E. PAQUET, J. GAILHARD, and R. GARÇON, Evolution de la méthode du Gradex: approche par type de temps et modélisation hydrologique, *La Houille Blanche*, No. 5, pp. 80–90, 2006.

[57] E. PAQUET, F. GARAVAGLIA, R. GARÇON, and J. GAILHARD, The SCHADEX method: A semi-continuous rainfall–runoff simulation for extreme flood estimation, *Journal of Hydrology*, Vol. 495, pp. 23–37, 2013.

[58] M. NIGGLI, D. CONSUEGRA, and D. BÉROD, *Etude CONSECRU. Modélisation des crues du Rhône en Valais.* Rapport final, IATE/HYDRAM-EPFL, 1997.

[59] B. HINGRAY, A. MEZGHANI, M. SCHAEFLI, M. NIGGLI, G. FAIVRE, F. GUEX, Y. HAMDI, and A. MUSY, *Rapport final réalisé dans le cadre du projet CONSECRU 2. Estimation des débits de crue du Rhône à Porte du Scex et autres points amont caractéristiques*, tech. rep., HYDRAM - EPFL, 2006.

[60] P. S. P. COWPERTWAIT, Further developments of the Neyman-Scott clustered point process for modeling rainfall, *Water Resources Research*, Vol. 27, No. 7, pp. 1431–1438, 1991.

[61] WMO, *Manual on Estimation of Probable Maximum Precipitation (PMP).* Geneva: World Meteorological Organization, 2009.

[62] D. BÉROD, D. DEVRED, and V. LAGLAINE, *La problématique PMP/PMF: une méthode déterministe pour l'estimation de la crue extrême, avantages, inconvénients et possibilités d'amélioration*, Internationales Symposium INTERPRAEVENT 1992 - Bern, Tagungspublikation, Vol. 4, 1992.

[63] R. NATHAN, P. HILL, and H. GRIFFITH, Risk Implications of the PMF and the PMP Design Flood, *NZSOLD / ANCOLD Conference on Dams*, 2001.

[64] J. BEAUCHAMP, R. LECONTE, M. TRUDEL, and F. BRISSETTE, Estimation of the summer-fall PMP and PMF of a northern watershed under a changed climate, *Water Resources Research*, Vol. 49, No. 6, pp. 3852– 3862, 2013.

[65] M. C. CASAS, R. RODRÍGUEZ, M. PROHOM, A. GÁZQUEZ, and A. REDAÑO, Estimation of the probable maximum precipitation in Barcelona (Spain), *International Journal of Climatology*, Vol. 31, No. 9, pp. 1322–1327, 2011.

[66] F. NOBILIS, T. HAIDEN, and M. KERSCHBAUM, Statistical Considerations Concerning Probable maximum Precipitation (PMP) in the Alpine Country of Austria, *Theoretical and Applied Climatology*, Vol. 44, pp. 89–94, 1991.

[67] J.-A. HERTIG, A. AUDOUARD, and A. PLANCHEREL, *Cartes des précipitations extrêmes pour la Suisse (PMP 2005)*, 2005.

[68] A. AUDOUARD, J.-A. HERTIG, and J.-M. FALLOT, Modélisation des précipitations extrêmes en suisse, *Actes du 19e colloque de l’Association Internationale de Climatologie*, pp. 83–88, 2006.

[69] J.-A. HERTIG, J.-M. FALLOT, and A. BREÑA, *Projet CRUEX. Directive Crues de l’OFEN. Etablissement des cartes des précipitations extrêmes pour la Suisse. Méthode d’utilisation des cartes PMP pour l’obtention de la PMF.*, Report destined to SFOE, 2008.

[70] J.-A. HERTIG and J.-M. FALLOT, *Validation et utilisation des cartes de PMP pour l’obtention de la PMF. Projet CRUEX: Directives Crues de l’OFEN*, Report destined to Dr. Georges Darbre, 2009.

[71] E. KESSLER, On the distribution and continuity of water substance in atmospheric circulation, *American Meteorological Society*, Vol. 10, No. 32, p. 84, 1969.

[72] T. HAIDEN, *A deterministic approach to the determination of orographic PMP*, Institute of Meteoroloy and Geophysics, University of Vienna, Austria, 1991.

[73] T. HAIDEN, M. KERSCHBAUM, P. KAHLIG, and F. NOBILIS, A refined model of the influence of orography on the mesoscale distribution of extreme precipitation, *Hydrology Sciences Journal*, Vol. 37, No. 5, pp. 417–427, 1992.

SUMMARY

Territories within the influence zone of the rivers are not only subject to the vagaries of the weather but also depend on anthropogenic interventions that alter the behavior of their watershed. Thus, reservoirs of large dams introduce an attenuation effect that reduces the size and frequency of floods downstream. To fully master this beneficial effect, the structural and functional safety of these structures must be guaranteed, resisting the passage of the extreme flood. Therefore the reliable estimation of extreme floods is primary. The current paper presents an overview about the available estimation methods existing in the literature, from the statistical ones to the hydrological model approach. The focus is given to the methods that are most frequently used in Switzerland. Those are applied to the Mattmark catchment in the Canton of Valais for extreme flood estimations. The results are assessed and discussed.

RÉSUMÉ

Les territoires se trouvant dans les zones d'influence des cours d'eau ne sont pas seulement sujets aux intempéries mais également aux activités anthropiques qui altèrent le comportement hydrologique du bassin versant. Les retenues des grands barrages, par exemple, atténuent les pointes des crues et leur fréquence d'occurrence en aval. Afin de maîtriser cet effet bénéfique des réservoirs en cas de crues extrêmes, leur sécurité structurelle et fonctionnelle doit être garantie dans ces conditions particulières. Pour cette raison, une estimation fiable des crues extrêmes est primordiale. Cet article présente une vue d'ensemble des méthodes existantes dans la littérature, allant des méthodes statistiques aux méthodes de simulation hydrologique. L'accent est mis sur les méthodes fréquemment utilisées en Suisse. Ces dernières sont appliquées au bassin versant de Mattmark, situé dans le canton du Valais, dans le but d'estimations de crues extrêmes. Les résultats sont évalués et discutés par la suite.