# THE ESTIMATION OF PMP AND PMF ON ALPINE BASINS IN SWITZERLAND

***R. RECEANU,[1] J.-A. HERTIG[2], J.-M. FALLOT[3]***

**ABSTRACT. -** This paper presents a very fine grid hydrological model based on the spatiotemporal repartition of precipitation and on the topography. The goal is to estimate the flood on a catchment area, using a Probable Maximum Precipitation (PMP) leading to a Probable Maximum Flood (PMF). The spatiotemporal distribution of the precipitation was realized using six clouds modeled by the advection-diffusion equation. The equation shows the movement of the clouds over the terrain and also gives the evolution of the rain intensity in time. This hydrological modeling is followed by a hydraulic modeling of the surface and subterranean flows, done considering the factors that contribute to the hydrological cycle, such as the infiltration, the exfiltration and the snowmelt. This model was applied to several Swiss basins using measured rain, with results showing a good correlation between the simulated and observed flows. This good correlation proves that the model is valid and gives us the confidence that the results can be extrapolated to phenomena of extreme rainfall of PMP type. In this article we present some results obtained using a PMP rainfall and the developed model.

**Keywords:** Probable Maximum Flood (PMF), Probable Maximum Precipitation (PMP), hydrological model, alpine catchment.

## 1. INTRODUCTION

Protection against floods is a vital problem in the world and especially in Switzerland, a country of lakes and mountains. It is very important to be able to estimate the flow hydrographs to ensure safety against flooding. The design of spillways of major works, such as large dams, is made according to the degree of security desired and based on this type of estimation. The choice of this degree of protection depends on the risk of casualties and damage.

Several studies have shown that global warming could lead to an increase in the frequency of heavy precipitation and flooding in Switzerland and in many parts of the globe (Fallot, 2000). This makes the current research on modeling of rainfall and flooding on a fine scale even more important. The old methods of flow calculation are simple and use empirical equations and a uniform rain. These calculation methods have shown their limits in the case of natural disasters caused by extreme rainfall. For this, a new approach was proposed to estimate the

[1] "Institute of Geography", University of Lausanne, CH-1015 Lausanne, Switzerland, receanuramona@gmail.com

[2] Hertig & Lador SA, CH-1176, St Livres, hertig@hetl.ch

[3] "Institute of Geography", University of Lausanne, CH-1015 Lausanne, Switzerland, Jean-Michel.Fallot@unil.ch

reasonably probable maximum flood in a watershed, that is the PMP-PMF method (Probable Maximum Precipitation - Probable Maximum Flood).

The PMP is defined by Hansen and al. 1982: Theoretically, the greatest amount of precipitation for a given period, which is physically possible on a surface of a shower of given size in a particular geographic location at a certain time of year.

The PMF is proposed by the Bureau of Reclamation 1987:

The flood hydrograph of a PMF represents the peak flow conditions resulting from the most severe combination of meteorological and hydrological conditions considered reasonably possible for the studied watershed.

The PMP-PMF method was developed in the United States and was applied only in a few experimental studies in Britain by the Institute of Hydrology in 1975, and in Europe: Germany in 1983, Austria in 1990 and France 1983 (Bérod et al., 1992). More recently, Sweden has used the PMP-PMF method to estimate extreme precipitation at a resolution of 1000 $km^2$ for a period of 24 hours (Bergström et al., 2007).

In Switzerland, the PMP-PMF method has been the subject of two research projects applied to Alpine basins. The methodology used for mapping the PMP was developed in Switzerland in the second research project of extreme floods (CRUEX). This methodology is based on the use of numerical models for the evaluation of flood flows and is described in particular in Audouard et al. 2006 and Hertig and Fallot 2009.

The WMO recommends the application of this method in the whole world (WMO, 2007), however a misapplication of the PMP can overestimate the PMF.

To solve these problems and taking advantage of advances in information technology and GIS we have developed a distributed hydrological model at a local scale. In particular, better results are obtained if the PMP is distributed at a fine scale when calculating extreme floods with a hydrological model.

In the following sections, we present the development of our hydrological model and the results of the application of the PMP-PMF method.

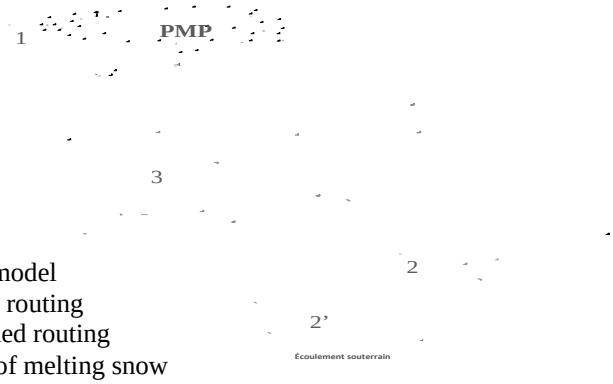
## 2. DESCRIPTION OF THE HYDROLOGICAL MODEL

The developed hydrological model includes three parts: the spatio-temporal modeling of rain, the water flow modeling and the modeling of snow melt. (Figure 1).

The first part of our model is the fine-scale spatio-temporal modeling of an extreme rain of PMP type (Hertig et al., 2005). The spatiotemporal distribution of the PMP was estimated using six clouds modeled by the advection-diffusion equation.

$$P(x,y,t) = \frac{I}{4\pi (D_x D_y)^{1/2}(t-t_o)} \exp\left\{ \frac{[x - x_o - v_{tx}(t-t_o)]^2}{4D_x(t-t_o)} - \frac{[y - y_o - v_{ty}(t-t_o)]^2}{4D_y(t-t_o)} - \lambda(t-t_o) \right\} \quad (1)$$

where I is the PMP [$m^3$/min], x, y are the coordinates [m], t is the time [min], Dx and Dy are the diffusion coefficients [$m^2$/min], v is the velocity [m/min], λ is the coefficient of development / dissipation of the intensity [$min^{-1}$].




Legend:

1. Cloud model
2. Surface routing

2'. Watershed routing

3. Model of melting snow

**Fig. 1.** ***Component of the model develop***

The temporal evolution of clouds follows a Gaussian distribution with a dissipation phase influenced by v, Dx, Dy and λ. The advection-diffusion equation models the temporal behavior of each cloud, that is to say, the temporal variation of the shape of the cloud and its temporal evolution. Early as the rain begins, every cloud is relatively small and the local intensity of rain is high, but concentrated on a small area around the centre of the cloud. As the cloud moves, pushed by the wind, it will grow at the same time, and the local intensity of rain is reduced, but the rain is distributed over a wider area.

The equation shows the movement of clouds (depending on wind direction) above the ground and also gives the evolution of rain intensity over time. In the model eight wind directions are analysed.

The rainfall for each point on the ground is structured to ensure consistency of the physical volume given by the PMP in time and space for the duration of the calculation. Therefore, with our algorithm we obtain a good spatial routing model.

The second part involves the modeling of water flows using the spatio-temporal distribution of rain and a digital elevation model (DEM). Surface water follows the slope to the outlet of the basin. Each terrain cell receives and gives a certain volume of water to neighboring cells, according to the slope and computed using Manning's equation.

The volume given by a cell at time t is given by equation (2):

$$V_{given}(x,y,t) = \left[ V_{accum}(x,y,t) + V_{rain}(x,y,t) \right] \cdot \frac{v \cdot \Delta t}{d} \qquad (2)$$

where: $V_{accum}$ is the volume of water present on the cell, $V_{rain}$ is the volume of rain falling on the cell and calculated through the PMP distribution, v is the

velocity for one of three types of flow, Δt the time step and d the distance between cells.

This volume is distributed to neighboring cells downstream depending on the slope, according to equation (3):

$$V_{received}(x \pm 1, y \pm 1, t) = V_{given}(x, y, t) \cdot \frac{slope}{\sum slopes} \tag{3}$$

This part also includes the infiltration of water into the ground. The flow velocity in the underground is calculated by Darcy's law (1856), assuming a uniform soil thickness. Similarly to the surface flow, each cell in the underground receives a volume of water from its upstream neighbors. This volume is added to the local infiltration, which has the same role in underground flow as precipitation has on the surface. When the terrain becomes completely saturated, the water flows out to the surface through the phenomenon of exfiltration.

The third part of our model includes modeling of snowmelt. We will limit ourselves to the worst case scenario that can happen in reality, the snowmelt caused by the arrival of an extreme rain of PMP type. This part is important because rain can increase the snowmelt and with it the extent of the flood.

This concept has been developed from a diagram made by Anctil (Anctil et al., 2005). This scheme provides for all heat sources that produce snowmelt, such as solar radiation, soil heat, air, rain and water runoff. In general, these factors act slowly, except for the rain and water runoff, which can have a major contribution to the melt. Therefore, only these latter factors were included in the model. Various assumptions have been made, especially in terms of the model parameters such as the thickness of the layer of snow, rainfall water temperature and snow temperature. All calculations are done using the equivalent volume of water in the snow, ie by multiplying the snow volume with the snow density.

## 3. THE STUDIED CATCHMENT

This studied catchment is located in the Bernese Alps and has an area of 28.8 $km^2$. According to the Hydrological Atlas of Switzerland this basin does not contain ice and is one of the most typical in Switzerland for torrential floods caused by violent summer thunderstorms.

For this basin data is available for several weather parameters, water flows and terrain structure, such as the 25 m DEM and simplified geotechnical map of 30 terrain types (Receanu et al., 2009). They were determined as follows. Altimetry data were obtained from the DEM (Digital Elevation Model) based on contour lines, made available to us by Swisstopo. Weather data was provided by the Federal Office of Meteorology and Climatology. The granularity of this data is ten minutes, measured by an automatic network (ANETZ). The flow data is used from the Federal Office of Environment (BAFU). With this data as input, the developed hydrological model is able to calculate flows on all points of the watershed.

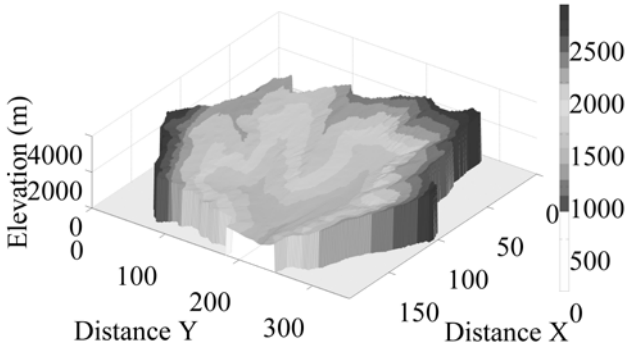



**Fig. 2.** ***Delimitation of the Allenbach basin***

## 4. RESULTS

The results obtained for several alpine basins, validated with the Nash equation, show a good correlation between the simulated and observed flows. This good correlation shows that the model is valid and gives us the confidence that the results can be extrapolated to phenomena of extreme rainfall of PMP type (Receanu et al., 2010).

In this paper we present the results obtained for the PMF using the developed hydrological model with a non-uniformly spatially and temporally distributed precipitation of PMP type.

The PMP is determined by a wind model for Alpine topography coupled with a rainfall model using the formulation of Caniaux. With this model the PMP maps for Switzerlad were computed for several rainfall periods (Hertig and Audouard, 2005).

The PMP has been estimated for the Allenbach basin using these maps. For this calculation we used a PMP with a period of 1 hour. The intensity of PMP for the Allenbach basin is 188 mm/h.

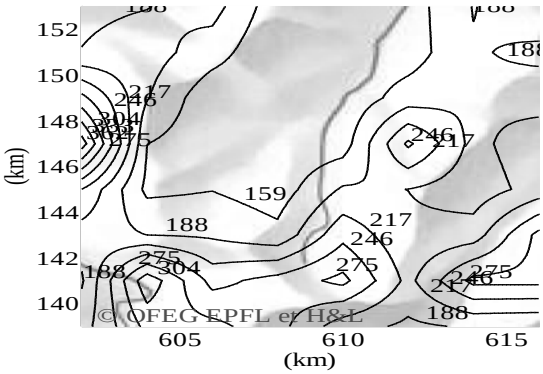



**Fig. 3.** ***Extreme precipitation (PMP): Allenbach basin in mm/h***

The spatiotemporal distribution of the PMP was obtained using the clouds developed in the first part of the model.

These are not real clouds, but precipitation zones reproduced by the model under the cloud. The volume of these rainfall areas is calculated to correspond to the respective values from the PMP map.

In the Figure 4 present the spatiotemporal distribution of the PMP for two wind directions.

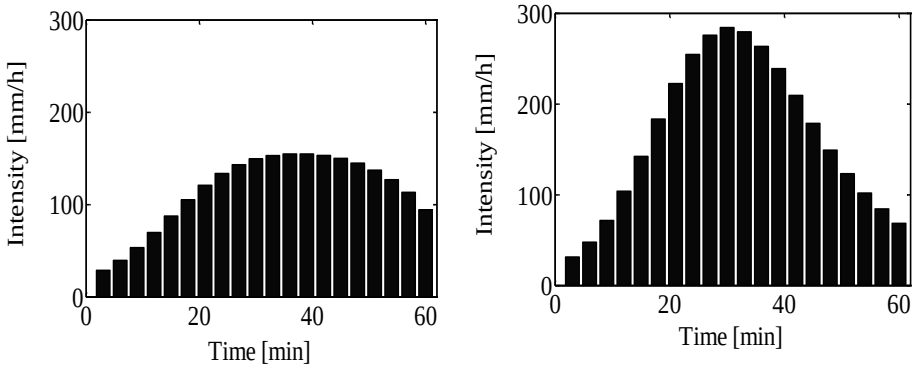



**Fig. 4.** ***PMP hyetograph, wind directions: west (left) and north (right)***

Flow modeling produced from a DEM gives a discrete representation of a continuous surface. The DEM has a resolution of 25x25 m. This modeling is done through an iterative procedure by calculating the volume of water that spreads from one cell to its neighbors across the field. In the end, the outlet is determined as the point of maximum flow.

Figure 5 shows the streams formed automatically based on the topography of the land without any manual processing of the water pathways.

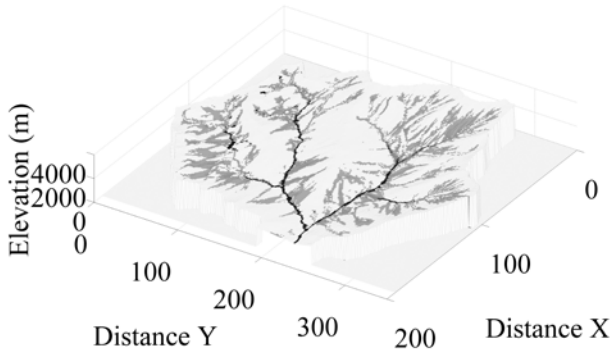



**Fig. 5.** ***River network – Allenbach*** **basin**

The same parameter values obtained from the model validation are now used to estimate the maximum probable flow (Receanu et al., 2010).

In Figure 6 and Figure 7 we present four different PMF hydrographs to show the influence of different wind directions. The results obtained show that the

wind has a great influence on the shape of the hydrograph and little influence on the volume of water coming into the outlet. As can be seen, the total volume of water (the area under the curve in the figures) does not vary with wind direction, a fact also confirmed by our calculations. On the other hand, the shape of the hydrograph, including the peak, varies, so that the severity of the flood may be different depending on the wind direction.

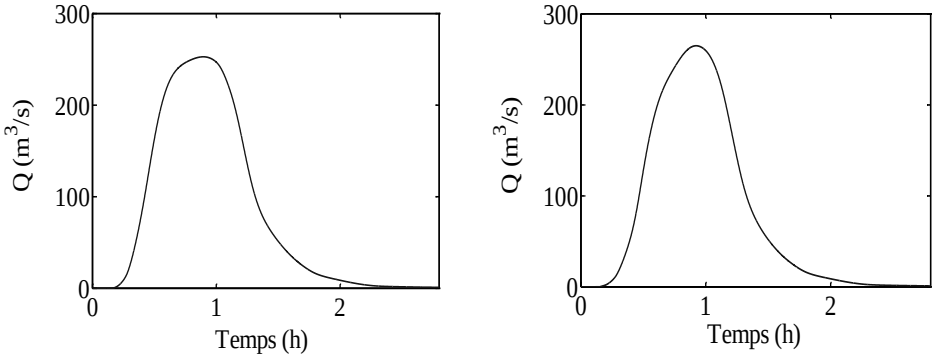



**Fig. 6.** ***PMF hydrograph for wind direction south in the left and west in the right***

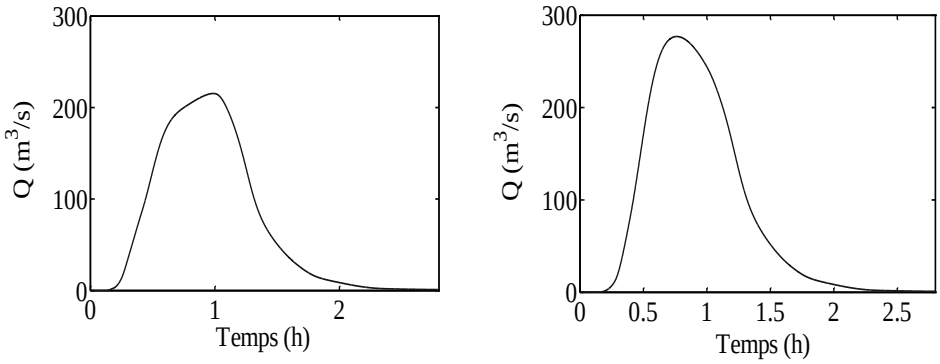



**Fig 7.** *PMF hydrograph for wind direction north in the left and east in the right*

The peak of the flood hydrograph (PMF) for the Allenbach basin is about 260 $m^3/s$ for south and north wind directions and 300 $m^3/s$ for east and west wind directions.

## 5. CONCLUSIONS

This paper presents new contributions to the estimation of the flood hydrograph (PMF), using a rain calculated from the map of PMP. Three main contributions have been made in the development of the hydrological model. The first is a method of spatio-temporal distribution of PMP using clouds, based on the

equation of advection-diffusion, including a temporal evolution depending on wind direction, which increases the nonlinearity of the PMF. The second is the flow model, which also includes groundwater flow, in addition to the surface flow. With this, the hydrograph at the outlet has a shape that is closer to reality. The third contribution consists in the development of a snowmelt model, which aims to highlight the influence of snowmelt on the flow. These parts are integrated into a single computation model.

The PMP-PMF method and the model in this project can be applied not only to spillways of large dams, but also to flood management and other less important works (shoreline development, temporary retention areas, flood zones, torrential floods...) for shorter return periods (10,100, 500 years).

## REFERENCES


1. Anctil F., Rousselle J. Lauzon N. (2005), *Hydrologie. Cheminements de l'eau*. Ecole Polytechnique Montreal.
2. Audouard A., Hertig J.-A. et Fallot J.-M. (2006), Modélisation des précipitations extrêmes en Suisse. Actes du 19ème colloque de l'Association Internationale de Climatologie (AIC), Epernay, 83-88.
3. Bergström S, Hellström S.S., Lindström G and Wern L. (2007), Follow-Up of the Swedish Guidelines for Design Flood Determination for Dams the Swedish Meteorological and Hydrological Institute.
4. Bérod D., Devred D, Laglaine V. (1992), La problématique PMP/PMF: une méthode déterministe pour l'estimation de la crue extrême; avantages, inconvénients et possibilités d'amélioration, Bern, Suisse.
5. Bureau of Reclamation (1987), *Design of small dams.* US Bureau of Reclamation, Washington.
6. Fallot J.M. (2000), Evolution du nombre de jours avec des précipitations abondantes en Suisse durant le 20ème siècle. AIC, 13, 100-109.
7. Hansen E.M., Schreiner L.C, Miller J.F. (1982), Application of probable maximum precipitation estimates., United States East of the 105th Meridian. NOAA Hydrometeorology, Report no. 52, Washington.
8. Hertig J.A. et Audouard A. (2005), Cartes des précipitations extrêmes pour la Suisse. Rapport final, EPFL, Lausanne, Switzerland, 43 + annexes.
9. Hertig J.A., Fallot J.M. (2009), Carte de précipitations extrêmes PMP pour la Suisse. Validation et utilisation des cartes de PMP pour l'obtention de la PMF, 47.
10. OFEN (Office fédéral de l'énergie) (2008), Sécurité des ouvrages d'accumulation - Documentation de base relative à la vérification de la sécurité en cas de crue http://www.bfe.admin.ch/.
11. Receanu R.G., Hertig J-A, Fallot J.M. (2009), Modélisation spatiale et temporelle des précipitations pour l'estimation des crues extrêmes dans les Alpes, AIC, Cluj, Roumanie, 383-389.
12. Receanu R.G., Hertig J-A, Fallot J.M. (2010), L'effet de la PMP et de la fonte des neiges sur la PMF dans un bassin versant Alpin Suisse, AIC, Rennes, France.
13. WMO (2007), Manual for estimation of probable maximum precipitation., World Meteorological Organization (WMO), Geneva, Switzerland, 2007.