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A METHODOLOGY FOR THE ADAPTATION OF A PMP AT THE DETERMINATION OF A PMF

Ramona Georgeta Receanu[1], Jacques-André Hertig[2], Jean-Michel Fallot[3] Teodor Eugen Man[1]

Abstract - This paper presents a new type of very fine grid hydrological model based on the spatiotemporal repartition of a PMP (Probable Maximum Precipitation) and on the topography. The goal is to estimate the influence of this rain on a PMF (Probable Maximum Flood) on a catchment area in Switzerland. The spatiotemporal distribution of the PMP 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 flow, done considering the factors that contribute to the hydrological cycle, such as the infiltration, the resurgence and the snowmelt. These added factors make the developed model closer to reality and also offer flexibility in the initial condition that is added to the factors concerning the PMP, such as the duration of the rain, the speed and direction of the wind. All these initial conditions taken together offer a complete image of the PMF.

Keywords: extreme rainfall, floods, outlet, conceptual 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 [9]).

The greatest difficulty in estimating floods comes from the fact that they are the final manifestation of a complex chain of events such as: rainfall, characterized by their intensity, duration and location, the transfer to the catchment concerned, the hydraulic behavior of streams and rivers, draining, retention by the accumulation lake, manipulation of the hydraulic structure to control and flood discharge.

The section of the large dams of the Federal Office of Energy, (OFEN [17]) in Switzerland has issued a directive in 2008 requiring all agencies and offices to apply the method PMP/PMF (Probable Maximum Precipitation - Probable Maximum Flood) for sizing large dams in Switzerland (OFEN [17]).

The WMO also recommends the application of this method in the world (WMO, 1986 [22]).

2. THE PMP/PMF METHOD

The PMP-PMF method has emerged in the United States (Schreiner, 1978 [19]), and it applies primarily to the safety of large dams that may endanger a large population or cause damage downstream. This method is used to size the spillway so as to avoid the risk of an overflowing dam.

The PMP/PMF method assumes the existence of a physical limit to the amount of precipitation may fall on a given watershed. Under this assumption, the obtained flood also admits an upper limit. In this sense, the PMP/PMF method opposes the concept of unbounded statistical laws used to determine the flood return period of 10'000 years (Bérod et al. [5]). The PMP/PMF method is a deterministic tool for calculating maximum flood likely to occur on a watershed.

The concepts of PMP/PMF have evolved over time, together with its requirements and uses. We present here the latest definitions.

The PMP is defined by Hansen and al. 1982 [11]: 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 [7]:

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 depends on terrain features and limitations imposed by atmosphere physics on the extreme winds and precipitation. At the same time, these factors are a function of temperature, humidity, presence of air masses and cloud microphysics of clouds. All these factors are taken into account in the models developed, which makes them fairly complex.

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[1]Faculty of Hydrotechnical Engineering Timisoara, CHIF Department, George Enescu Str. No. 1/A, 300022 Timisoara, E-mail: receanuramona@gmail.com, [2] Faculty of Geosciences and Environment,University of Lausanne,Quartier Dorigny,Bâtiment Anthropole,CH - 1015 Lausanne,E-mail : Jean-Michel.Fallot@unil.ch, [3] Hertig & Lador SA, Grand'rue, CH 1176 St-Livres, hertig@hetl.ch

To obtain the PMF hydrograph, it is necessary to take into account the terrain, watersheds, water saturation, surface runoff and groundwater flow, as well as natural and artificial reservoirs.

This method is widely used in the United States and has been applied in experimental studies in Europe and in Britain by the Institute of Hydrology in 1975, Germany in 1983, Austria in 1990 and France 1983 (Bérod et al. 1992 [5]). More recently, Sweden has used the method PMP/MFP estimate extreme precipitation at a resolution of 1000 km^2 or a period of 24 hours (Bergström et al. 2007 [3]).

In Switzerland, the PMP/PMF method has been the subject of two research projects with the purpose of applying it to alpine basins. The methodology used for building extreme rainfall maps of PMP type was developed in Switzerland in the second research project, called CRUEX, on extreme floods. This methodology is based on the use of numerical models for the evaluation of flood flows and is described in Audouard et al. (2006, [2]) and Hertig et al. (2005 [12]).

In 2006 - 2007 new PMP maps were calculated with a meteorological model for the whole of Switzerland with a horizontal resolution of 2 km for periods of 1h, 3h, 6h, 9h, 12h, 18h and 24h (2006, [2])

In Figure 3, we present a map for PMP for Switzerland with a duration of 24 hours.

The PMPs calculated for a period of 24 hours have been compared with extreme daily rainfall estimated for a period of 500 years from Gumbel analysis on series of rainfall measurements at 425 locations in Switzerland for the period 1961-2008 (Fallot and Hertig, 2009 [13]). Gumbel analysis is one of the most used statistical methods in meteorology for finding the extreme values of winds and precipitation. This type of analysis can fit a regression curve according to the frequency of occurrence of events in the past and predict the likelihood of an event of greater magnitude with a return period longer than available time-series. This adjustment is made starting from a double exponential law using a method described in Gumbel (1958 [10]).

The PMP values calculated by the model were extracted at measure points of the 425 stations. Figure 2 shows that these PMP values extracted from the model are higher than the estimated daily extreme precipitation for a return period of 500 years computed from Gumbel analysis and in situ measurements. This gives an average ratio of 1.9 for all stations, a ratio slightly higher than that normally observed (1.5), between rainfall with a return period of more than 10,000 years (PMP) and precipitation for 500 years. The model tends to exaggerate the extreme rainfall in several parts of Switzerland, especially on the peaks of the Alps. But it also tends to underestimate precipitation extremes in other parts of the country, especially in the Southern Alps which is the most vulnerable region to heavy precipitation according to in situ measurement.

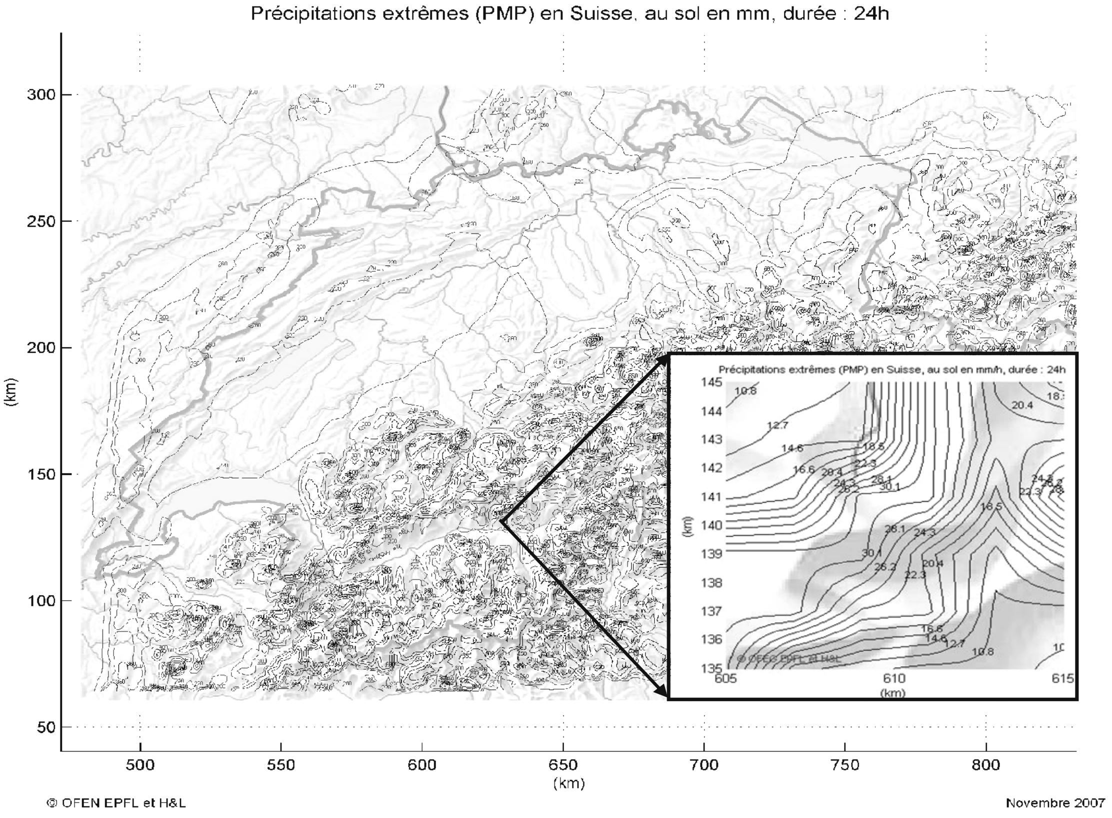

Figure 1. Extreme precipitation (PMP) in Switzerland, at ground level in mm/h, 24h duration, with detail

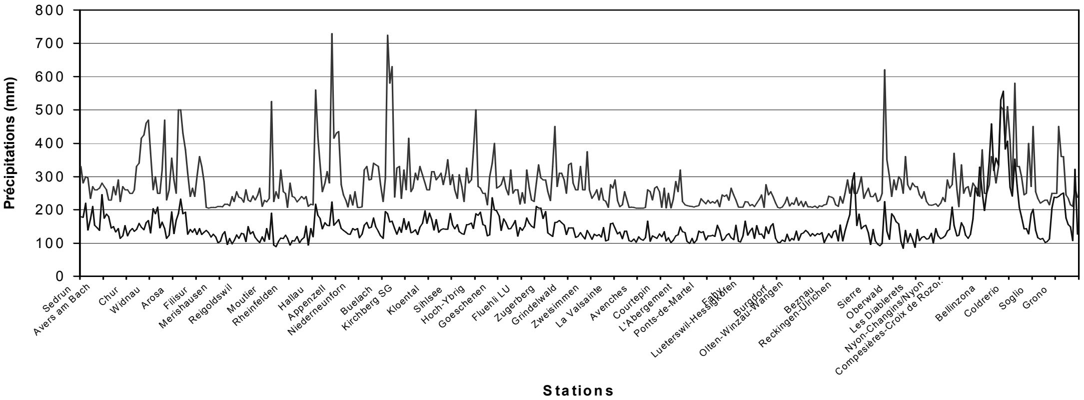

Figure 2. Comparison between PMP values calculated by the model (in red or up) and extreme precipitation with a return period of 500 years extrapolated from in situ measurements (in blue or down)

3. THE MICRO DISTRIBUTION OF THE RAIN

By the 1990s, the stochastic advection-diffusion equation was used to model the spatial and temporal distribution of rainfall volume (Jinno et al. 1993 [15]). Later, the structure of the extreme rainfall was analyzed using radar and rain gauge data (Smith et al. 1994 [21]). Zhang et al. (2001 [23]) have highlighted the influence of wind direction on the evolution of rainfall field shape in space and time by analyzing extreme rainfall events. Nunes et al. (2006 [16]) made a similar analysis, but considering only upstream-downstream and downstream-upstream wind directions.

Jinno et al. (1993 [15]) and Berntsson et al. (1994 [4]) have developed a forecasting model for the expansion and dissipation of precipitation events, giving their intensity, speed and direction. These values are obtained from a solution of the nonlinear advection-diffusion equation, supplemented by a stochastic analysis.

In our project, a model for advective-diffusive properties has been created to describe several clouds that will provide a volume of water equivalent to the point values of PMP. Our main contribution here is that, unlike for most other models that reflect a single rain structure without spatial and temporal variations, each domain point or pixel in our model has a different structure.

At the heart of the model is the advection-diffusion equation, which specifies the process of advection, essential for the formation of orographic clouds and precipitation type. The solution of this nonlinear equation is given by Brutsaert (1974 [6]):

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

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}]. The temporal evolution of clouds follows a Gaussian distribution with 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 following figures show the temporal behavior of clouds, given by the advection-diffusion equation.

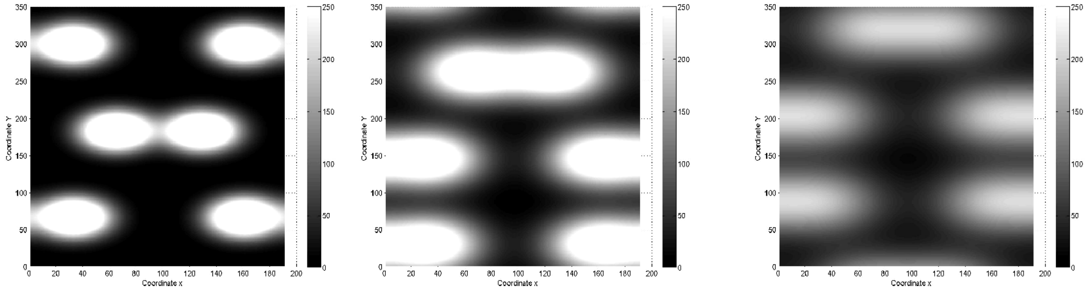

Figure 3. Spatial distribution of PMP in the field. (Time 3, 15 and 30 minutes)

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[1]Faculty of Hydrotechnical Engineering Timisoara, CHIF Department, George Enescu Str. No. 1/A, 300022 Timisoara, E-mail: receanuramona@gmail.com, [2] Faculty of Geosciences and Environment,University of Lausanne,Quartier Dorigny,Bâtiment Anthropole,CH - 1015 Lausanne,E-mail : Jean-Michel.Fallot@unil.ch, [3] Hertig & Lador SA, Grand'rue, CH 1176 St-Livres, hertig@hetl.ch

In Figure 3, we can observe the reduction of the peak of the cloud from 250 mm/h to 210 mm/h and finally to 160 mm/h, caused by diffusion. 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. So we have a good spatial routing model. In the following figures we present the distribution of rainfall in different parts of the field and in two different situations

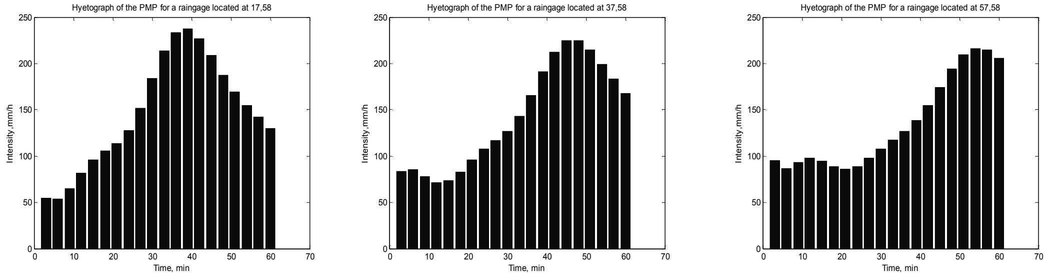

Figure 4. Hydrograph of PMP around a terrain point (1 km)

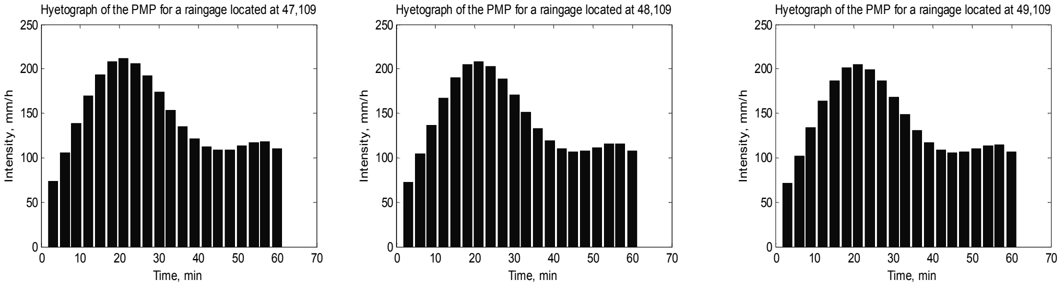

Figure 5. Hydrogramme de la PMP autour d'un point du terrain (distance de 25 m)

In a first situation, the points for which we present the hydrograph are placed at a high distance in order to show the spatial variation of rainfall over the total area.

In Figure 4 we show the hydrographs for three points placed at one kilometer of each other. On these hydrographs we can follow the movement of clouds from north to south. The centers of the clouds are represented by the peaks of the hydrographs. The peak arrives with a delay in the final image, showing that the cloud entering at the north of the field arrives after a while in the center of the field and even later in the south of the field. The maximum intensity is reduced from 240 mm/h to 230 mm/h and finally to 220 mm/h in 15 minutes.

Regarding the second situation, which is illustrated in Figure 5, the distance between points is small in order to show local variations between neighboring points, placed at a distance of 25 m. We can see here that local variations are very low.

After estimating the spatiotemporal distribution of the PMP, it is then introduced into a flow model for calculating the PMF hydrograph, as presented in the following section.

4. FLOW MODELING

The hydrological modeling of the flow follows the slope of the water on the surface and underground all the way to the watershed outlet. This model takes as input the spatial and temporal distribution of rainfall obtained after modeling the movement of clouds described in the previous section.

4.1. Surface flow

The flow modeling is done on an elevation map with a resolution of 25 m (DEM). This routing model takes into account the three types of surface runoff (Berndtsson et al. 1994 [4]) the watershed:

- sheet flow (laminar)
- shallow flow (concentrated)
- channel flow

With these three speeds, the slope between the terrain points and the distances between them, a temporal simulation is performed to determine flow rates at each terrain point with a temporal resolution of 10s. This simulation calculates the spread of water volumes from neighbor to neighbor, until the arrival of water at the basin outlet. Figure 6 illustrates as an example the flow of surface water to the outlet obtained by this method for one terrain cell.

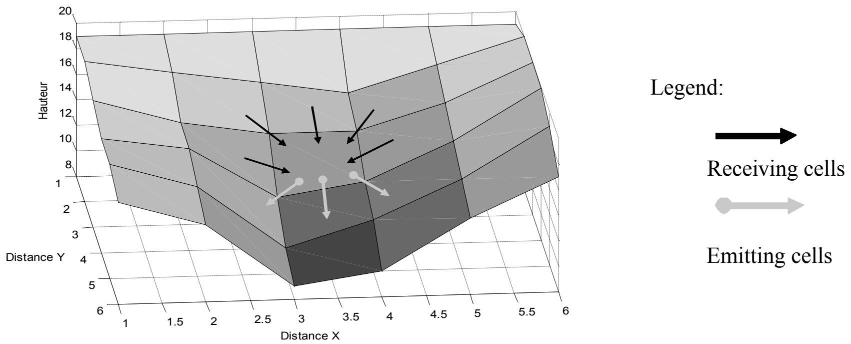

Figure 6. Water flow for one terrain cell

Each cell provides a certain amount of water to neighboring downstream cells and at the same time, receives a volume from its upstream neighbors, plus the volume of rain. 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, the velocity v 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:

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

Here the slope is normalized by the sum of the slopes between the cell and its neighbors downstream. Finally, this simulation allows the estimation of the flow in all parts of the field, including the outlet, at each time step.

4.2. Infiltration

Estimating the infiltration was done with the Horton equation (1933 [14]), one of the most widely used methods to estimate the temporal evolution of infiltration capacity for different terrain types.

The infiltration capacity of soil decreases rapidly at first and then gradually tends towards an asymptotic infiltration regimen called final infiltration. This trend is shown in Figure 7 for one particular soil type.

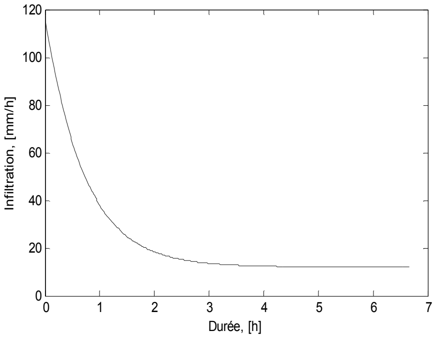

Figure 7. Time evolution of vertical infiltration.

Figure 7 shows the infiltration capacity for a type of rather permeable soil. In the case of PMP influence of infiltration is reduced, but visible, as we will show in the results section.

The geology of the soil has been interpreted starting from a simplified geotechnical map for 30 terrain types (Receanu et al. 2009 [18]). It is based on the geotechnical map of Switzerland (scale 1:200000) published by the "Commission Geotechnique Suisse".

In the following, the infiltration will be included in a model of groundwater flow. The infiltrated water moves under the ground until the moment when it meets a saturated ground and resurfaces by means of resurgence. In fact, there is a groundwater flow parallel to the surface, which influences the flow at the outlet.

4.3. Groundwater flow sub-module

The groundwater flow was calculated with Darcy's law (1856 [8]), assuming that the soil thickness is uniform throughout the basin and that the slope is identical to the case of surface runoff. Just as for the surface, in the underground each cell receives a volume of water from upstream neighbors which adds to the water already contained in the cell. In addition, local infiltration is also added to this volume, playing the same role for underground flow as precipitation does for surface runoff. Finally, a part of the total volume of water will be distributed to downstream cells based on the slopes and differences between the levels of water in each cell.

In the results section we present the influence of infiltration and groundwater flow on surface runoff

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[1]Faculty of Hydrotechnical Engineering Timisoara, CHIF Department, George Enescu Str. No. 1/A, 300022 Timisoara, E-mail: receanuramona@gmail.com, [2] Faculty of Geosciences and Environment,University of Lausanne,Quartier Dorigny,Bâtiment Anthropole,CH - 1015 Lausanne,E-mail : Jean-Michel.Fallot@unil.ch, [3] Hertig & Lador SA, Grand'rue, CH 1176 St-Livres, hertig@hetl.ch

and in particular the flow at the outlet. For this, we should know the geometry of subsurface layers and their fine-scale composition. Since this data is unavailable, it was assumed that the unsaturated zone's topography was identical and parallel to that of the surface.

This hypothesis is in fact valid for the flow that occurs in the area close to the surface, with a depth of up to 20-30 cm.

Each 25x25 m^2 soil cell is modeled through the use of 3 parameters: the soil permeability, the underground ratio volume and filling ratio. Darcy's Law manages the transfer of a cell to another.

5. SNOWMELT MODELING

Precipitation in the form of snow accumulates on the soil for periods ranging from hours to months. The snowfield is actually a water reserve that will be released during snowmelt. In several places, meltwater is the main source of surface water and contributes significantly to the recharge of aquifers and to spring floods.

This part of the study aims to show the contribution of meltwater on the flood hydrograph. This concept has been developed from a diagram made by Anctil and al. (2005 [1]). This scheme (Figure 8) provides for all heat sources that produce snowmelt, such as solar radiation, soil heat and air and 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.

The factors used to calculate snowmelt were selected based on available data and in addition to other assumptions that are presented below. Figure 8 shows the factors that make up our model - round elements are factors included in the existing model with its assumptions. Diamond-shaped elements represent factors that will be added later. Factors surrounded by a rectangle do not appear in our model and we do not intend to include them in the future.

Various assumptions have been made, especially in terms of the parameters such as the thickness of the layer of snow, rainfall, water temperature and snow temperature. The amount of meltwater (Q_{fonte}) is calculated using the following equation:

$$Q_{fonte} = \frac{E_{caleau}}{\rho \cdot C_{latneige} + (C_p * T_{neige})} \qquad (4)$$

where: Q_{fonte} is the amount of melt water expressed in m^3; $C_{latneige}$ is the latent heat of the snow expressed in kJ/kg; E_{caleau} calorie is the caloric energy of water expressed in kJ, ρ is the density of water expressed in kg/m^3, T_{neige} is the temperature of the snow expressed in ^oC and C_p is the specific heat expressed in kJ/(kg*K).

The amount of heat given by a volume of water is calculated:

$$E_{caleau} = \rho * V_{pluie} * C_p * (T_{pluie} - T_{neige}) \qquad (5)$$

where: T_{pluie} is the temperature of the rain expressed in ^oC.

These two equations describe the calorimetric process for melting snow.

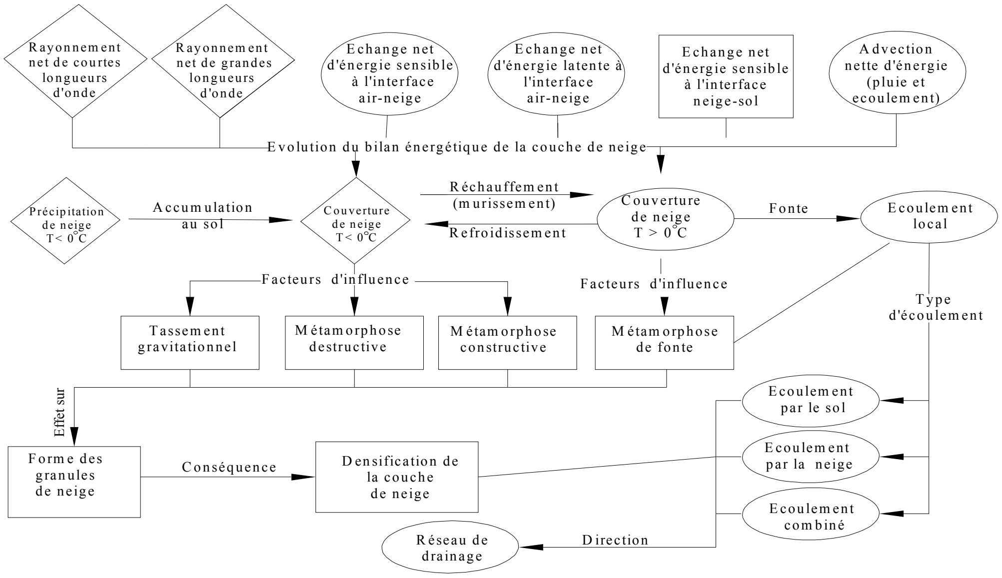

Figure 8. Factors included in the model of snowmelt

In the results section we first present the validation of our model for a summer storm, then the effect of snowmelt on the flood hydrograph to a test alpine basin: the Allenbach.

6. RESULTS

This part is divided in two sections, the first describing the validation of the developed hydrological model and the second showing the effect of snowmelt due to the influence of the PMP.

6.1. Model calibration

The model calibration was done for a small alpine watershed: Allenbach basin above Adelboden. It was chosen because it does not contain ice and is one of the most typical in Switzerland for floods caused by torrential storms in summer, as claims by the Hydrological Atlas of Switzerland. The surface of the Allenbach basin is 28.8 km^2. For this basin, there are continuous measurements of flow since 1960 and precipitation by an automatic weather station in Adelboden since 1980. For the validation of our model, we analyzed the data for violent summer thunderstorms.

In this paper, we present two episodes of severe floods used for model calibration. These events took place in August 2004 and they recorded a peak flow of about 60 m^3/s (7.08.2004), and then 21.22 m^3/s (24.08.2004). Rainfall is evenly distributed in space, while in time it has a varying distribution, as shown in Figure 9 and Figure 10. This distribution is then introduced into a flow model calculating the flood hydrograph.

The model calibration is focused on estimating the following parameters: the roughness coefficients and coefficients of river width for each type of flow used in the Manning equation (Receanu et al., 2009 [18]), the initial and final infiltration capacity for each soil type and the thickness of soil.

Figure 9 and Figure 10 show the results obtained after imposing the parameters of the model. We show with a dashed line the measured flow and with a continuous line the flow simulated by our model. The parameters are specific for each type of flow. In the case of transient flow, the river width ratio is 0.6 and the roughness of 0.05. Regarding the river flow, the river width ratio is 0.1 and the roughness 0.01.

The results show a good correlation between the measured flow evolution and the flow simulated by our model, which indicates not only that our model is able to follow the natural phenomenon, but also that the chosen parameters are close to reality. The differences between the simulated flow and the actual flow may be justified by the fact that rain was measured at a single point on the watershed and the simulation uses a uniform rain, while real rain has a structure given by dynamic cloud.

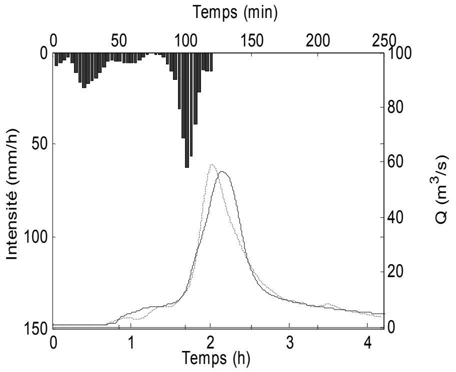

Figure 9. Histogram of the rain (top) and flood hydrograph (7.08.2004)

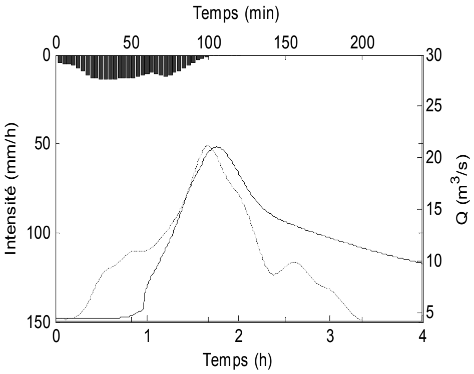

Figure 10. Histogram of the rain (top) and flood hydrograph (24.08.2004)

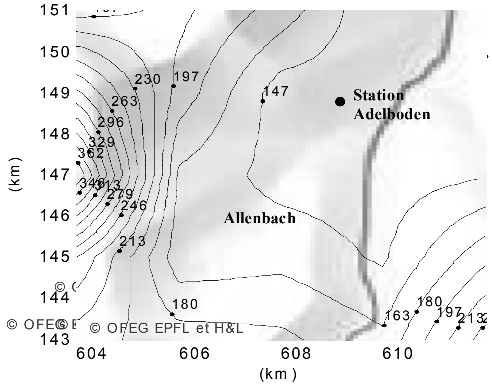

Figure 11. Extreme precipitation basin Allenbach ground in mm / h, 1h

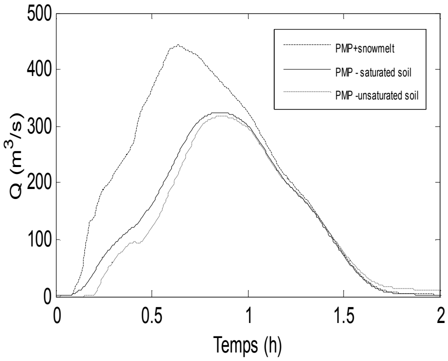

Figure 12. Flood hydrograph (PMF)

6.2. PMP and snowmelt

In this part we calculated the flood hydrograph (PMF), using the PMP. Figure 12 present three cases. The first case shows the flood hydrograph for saturated soil (continuous line), the second case shows the flood hydrograph for unsaturated soil (dashed line) and third case the effect of snowmelt on an extreme flood (discontinuous line).

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[1]Faculty of Hydrotechnical Engineering Timisoara, CHIF Department, George Enescu Str. No. 1/A, 300022 Timisoara, E-mail: receanuramona@gmail.com, [2] Faculty of Geosciences and Environment,University of Lausanne,Quartier Dorigny,Bâtiment Anthropole,CH - 1015 Lausanne,E-mail : Jean-Michel.Fallot@unil.ch, [3] Hertig & Lador SA, Grand'rue, CH 1176 St-Livres, hertig@hetl.ch

The PMP has been estimated for the Allenbach basin from the map of extreme precipitation (Figure 11) calculated for Switzerland (Hertig and Audouard, 2005 [12]) with a return period exceeding 10'000 years. The estimated average height of the PMP for 1 hour for the Allenbach basin is 188 mm/h.

The same values of parameters obtained in the calibration are now used in this calculation (in the model calibration section 6.1). The rainfall's spatiotemporal distribution was obtained using our model presented in section 3.

The peak of the flood hydrograph (PMF) for the Allenbach basin is obtained when the soil is saturated, at 324 m^3/s.

The influence of groundwater flow is to reduce extreme values as can seen in Figure 12, from the difference between saturated and un saturated soil. This influence remains quite low in comparison with the volume of the PMP. The difference introduced by the calculation of groundwater flow is close to 10% on the maximum value and this difference will be found towards the end of the period, after some time, because the flow speed underground is very small. Finally, this calculation is justified by the fact that its inclusion makes the evolution of the flow of water more realistic.

The effect of snowmelt on an extreme flood has been studied for the same 1 hour PMP. The thickness of the layer of snow was set at 10 cm for the entire basin. The temperature of the snow (T_{neige}) was set to 0°C and 5°C for the rain (T_{pluie}).

Figure 12 shows that the melting snow (dashed line in top) leads to a faster increase in water flow and a higher peak flow with the same extreme rainfall (PMP) compared to the case without snowmelt. Melting snow has a major influence on the maximum flow, but also on the total volume of water coming into the outlet. The wind direction also plays a very important role on the shape of the hydrograph. In this paper, we present only the flood hydrograph at the outlet and the critical wind directions for this watershed.

In conclusion, our modeling shows that an event (flood) which is already very dangerous with a PMP, may become even more extreme if it occurs when there is snow in the basin in spring. Even a relatively low rain temperature (5^oC) manages to cause significant melting of snow and a considerable supply of meltwater.

7. CONCLUSION

This paper presents new contributions to estimate the flood hydrograph (PMF), done using a measured rain or a rain calculated by using the map of extreme precipitation type PMP. Three main contributions have been made in the development of the hydrological model. The first is a method of spatial-temporal distribution of PMP in clouds, based on the equation of advection-diffusion, including a temporal evolution depending on wind direction, which increases the nonlinearity of 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 closer to reality. The third part consists in the development of a snow model, which aims to highlight the influence of snowmelt on the flow. These parts are integrated into a single model of computation. Each factor can be enabled or disabled individually depending on the desired conversion.

The PMP/PMF method and models in this project will be able to be applied not only to spillways of large dame, but also flood management and other less important works (shoreline development temporary retention area, flood zones, torrential floods...) for shorter return periods (10,100, 500 years).

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[1] Faculty of Hydrotechnical Engineering Timisoara, CHIF Department, George Enescu Str. No. 1/A, 300022 Timisoara, E-mail: receanuramona@gmail.com, [2] Faculty of Geosciences and Environment,University of Lausanne,Quartier Dorigny,Bâtiment Anthropole,CH - 1015 Lausanne,E-mail : Jean-Michel.Fallot@unil.ch, [3] Hertig & Lador SA, Grand'rue, CH 1176 St-Livres, hertig@hetl.ch