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D6: Examples of maps showing the risk zoning of a few selected sites

SURVEY AND PREVENTION OF EXTREME GLACIOLOGICAL HAZARDS

IN EUROPEAN MOUNTAINOUS REGIONS

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The deliverables related to numerical simulations initially planned were:

(D5) *numerical simulation of the potentially affected areas*
(D6) *some examples of maps showing the risk zoning of a few selected sites, as an experimentation to see whether risk zoning is realistic for glacial hazards.*

It was planned to use existing models like snow avalanche models applied to ice avalanches or dam breakage models applied to flood outbursts. Knowing the involved volumes of ice or water and the topography of the environment of the glacier or lake stay nevertheless necessary in order to realise numerical simulations giving some approximations of the area which might be covered by the avalanche or the flood.

The first investigations have shown that many questions and difficulties remained, related to the knowledge and the modelisation of the processes specific to the ice material and the glacier dynamics. Furthermore, it seemed that the global uncertainties in determining areas affected by glacier hazards, depend at least as much from the knowledge and the comprehension of the glacial processes, as from the use of existing models of avalanches or floods propagation. The most important factor limiting the practical use of these tools seems to be the knowledge on the triggering factors, related to glacial processes. For instance in the case of GLOF, the process of triggering very strongly influences the input discharge, upstream the zone of propagation and consequently also all the propagation itself and subsequently the level of risk for settlements located downstream.

Therefore we took the option to concentrate the efforts on the glacier behavior, and to focuse the ***D5*** *deliverable on numerical simulations of these processes. We kept of course the principle, for the validation, to test these models on existing cases which are well accurately known.*

Concerning the natural variations of glaciers which leads to some problems in the modern utilisation of the mountainous environment (ski resorts on the glaciers, intake of glacial waters, cable cars located close to the edges of the ice, etc.) we have continued the developpement of models of prediction of ice extension in length and altitude.

We have nevertheless tested, for the ***D6*** *deliverable, in the case of breaking of a glacial lake, the possibility to use models tested and validated in many domains such as dam-break problems, floods, snow avalanche and debris-flow propagation. In that context, the aim was to illustrate a possible methodology that would make it possible to consider the hazard resulting from the breaking of a glacial lake and to map the corresponding risk.*

Study of the propagation of the water wave induced by the breaking of a glacial lake Application to the Rochemelon lake (Bessans, Savoie, France)

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1. Introduction: position of the problem

The rupture of a glacial lake is often a complex phenomenon which can give birth to a large number of scenarios of triggering ranging from limited flows to catastrophic events. The common feature of glacial lake breaking events is the fact that a huge quantity of water can be released in a limited time and result in the propagation a some unsteady free surface flow that can be regarded as the propagation of a water wave. The common feature with dam-break problems is relatively evident at least from a qualitative point of view. In fact, and schematically, dam-breaks can be of two types: a sudden dam-break that can be considered more or less as instantaneous and a limited dam-break which is the result of some complex interaction between the structure of the dam and the flow of water. Once again, for glacial lakes, this process of flow triggering is still not well known, at least from a quantitative point of view that would make it possible the precise modelling of all natural phenomena. In these conditions, specialists of free surface flows are obliged to adopt possible scenarios of triggering on the basis of glaciologists expertise. Furthermore, adopting only one scenario of triggering is not realistic. This is why, in the framework of the present study, we preferred to adopt several possible scenarios to illustrate possible subsequent flows but keeping in mind that each of these scenarios is probably unrealistic. This problem of flow triggering can be regarded as the most important issue, or in other words as the most important source of uncertainty, once some flow modelling is sought. In fact, there are other sources of uncertainty like the precision of the topographical survey for example, but none of them, on the basis of the present knowledge, are as critical as this “determination” of input data of the models of propagation.
Once input data are, or can be supposed well-known, the parallel with flow propagation resulting from dam-breaks is clear. Furthermore, tools that can be used to compute the flow propagation are similar. For this reason, we adopted here numerical models dedicated to the computation of unsteady free-surface flows of water. These models or similar versions have been used, tested and validated in many domains such as dam-break problems, floods, snow avalanche and debris-flow propagation. In the present context, they are used to illustrate a possible methodology that would make it possible to consider the hazard resulting from the breaking of a glacial lake. Thus, considering in one hand the flow propagation in a relatively narrow valley from the glacier to the main valley floor and in the other hand, the propagation of the flow on a flood-plain where it is likely to spread laterally. From these models, flow characteristics can be deduced at any time and any point of the zone of interest. Maps of danger can be deduced from these computations, leading to some information of primarily importance for local authorities and people in charge of protection.
At present, only the propagation of water can be considered by these models. One has to keep in mind that with huge water discharge, some bed-load transport occurs and even debris-flows can be triggered and propagate. These phenomena have not been considered so far. However, suggestions on further developments that would make it possible to take them into account are proposed.
In the present paper, both models are briefly presented and the capacities of this methodology are illustrated on the Rochemelon lake. In that case, scenarios of triggering are adopted (the present knowledge on flow triggering being not completely satisfactory, some of these scenarios may appear not perfectly realistic), the propagation of the water wave is computed in the Ribon valley, downstream the Rochemelon glacier, using a 1D model and finally the spreading of the flow is computed on the main valley floor in the Bessans (Savoie, France) vicinity.

2. Presentation of the models

The models we use here deal with transitory free-surface flows of water. The general set of equations (steep slope shallow water equations) is constituted of one continuity equation (conservation of mass) and one (in 1D) or two (in 2D) momentum equations (conservation of momentum) including a dissipation term depending upon material characteristics: for water, the classical Manning-Strickler formula is adopted. The equations of motion of unsteady flows generally do not have an analytical solution. A numerical model is therefore necessary to solve the set of equations. Both models require topographical data and input hydrograph. Numerical codes are written in Fortran and use finite volume techniques with a Godunov-type numerical scheme. Characteristics of the flow are computed at any time and any point of the domain of interest.

2.1. The 1D model

The 1D model deals with the propagation of channel flows. Required topographical data are constituted of a longitudinal profile and cross-section profiles. Required input data is a hydrograph. This model can also deal with instantaneous dam-break problems considering initial data representing water initially present within the reservoir.

2.1.1. Equations of motion

The 1D set of equations results from the integration of general 3D Navier-Stokes equations over a flow cross-section and from the bed level to the free surface level.

$$\frac{\partial A}{\partial t}+\frac{\partial\left(A\overline{u}\right)}{\partial x}=0$$

$$\frac{\partial\left(A\overline{u}\right)}{\partial t}+\frac{\partial\left(A\overline{u^2}\right)}{\partial x}+gA\cos(\theta)\frac{\partial h}{\partial x}=g\sin(\theta)A-\frac{1}{\rho}P_e\tau_p$$

$$\tau_p=\rho g\,K^{-2}\,\overline{u}^2\,R_H^{-1/3}\quad \textit{with}\qquad R_H=A/P_e$$

A: flow cross-section area (m^2)
t: time (s)
x: abscissa (m)
h: flow depth (m)
Pe: wetted perimeter (m)
R_H: hydraulic radius (m)
K: roughness coefficient (-)
θ: bed slope angle (°)
$\overline{u}$: mean velocity in the flow cross-section ($m.s^{-1}$)
τ_p: bed shear-stress (Pa)
ρ: density of flowing material ($kg.m^{-3}$)
g: gravity ($m.s^{-2}$)

2.1.2. Input and output data of the 1D model

The 1D model requires two main types of input data: the input hydrograph and the topographical data. The hydrograph consists of a file giving the input discharge versus time. In that case, the model can deal with a slow release of water from the reservoir. Another possibility consists of the instantaneous dam-break problem which does not require some input hydrograph. In this latter case, the topography of the reservoir has to be considered explicitly and initial hydraulic conditions consist of a given quantity of water at rest inside the reservoir with a horizontal free-surface. At the beginning of the computation, water propagates downstream as if the dam closing the reservoir completely vanished at time t=0 s. Topographical data consist of a file giving the topography of the channel by a longitudinal profile and of cross section profiles. In more details, this file gives for a number of points: the abscissa along the profile, the elevation and the shape of the cross section. This representation of each cross-section is parameterised using the following formula where K and α are two parameters: $A=Kh^{\alpha}$ where A is the cross section area and h is the flow depth.

2.2. The 2D model

The 2D set of equations results from the integration of general 3D Navier-Stokes equations along a direction perpendicular to the bed and from the bed level to the free surface level. This model requires some input hydrograph and topographical data covering the entire zone of interest that is to say: the zone of possible spreading of the flow. This model deals with flows not limited laterally by the presence of banks as it is the case with the 1D model. Equations of motion are solved using finite-volume techniques which require a computation mesh integrating topographical data.

2.2.1. Equations of Motion

$$\frac{\partial h}{\partial t}+\frac{\partial h\bar{u}}{\partial x}+\frac{\partial h\bar{v}}{\partial y}=0$$

$$\frac{\partial\left(h\bar{u}\right)}{\partial t}+\frac{\partial\left(h\,\delta\bar{u}^{2}+\frac{g\beta h^{2}}{2}\right)}{\partial x}+\frac{\partial\left(h\,\delta\bar{u}\,\bar{v}\right)}{\partial y}=g\sin\left(\theta_{x}\right)h-\frac{\bar{u}}{\sqrt{\bar{u}^{2}+\bar{v}^{2}}}\frac{\tau_{p}}{\rho}$$

$$\frac{\partial\left(h\bar{v}\right)}{\partial t}+\frac{\partial\left(h\,\delta\bar{u}\,\bar{v}\right)}{\partial x}+\frac{\partial\left(h\,\delta\bar{v}^{2}+\frac{g\beta h^{2}}{2}\right)}{\partial y}=g\sin\left(\theta_{y}\right)h-\frac{\bar{v}}{\sqrt{\bar{u}^{2}+\bar{v}^{2}}}\frac{\tau_{p}}{\rho}$$

$$\tau_{p}=\rho g\,K^{-2}\sqrt{\bar{u}^{2}+\bar{v}^{2}}\,h^{-1/3}$$

$$\beta=\cos(\arctan(\sqrt{\tan^{2}\theta_{x}+\tan^{2}\theta_{y}}))$$

t: time (s)
x: abscissa (m)
h: flow depth (m)
K: roughness coefficient (-)
θ: bed slope angle (°)
$\bar{u}$ and $\bar{v}$: mean velocities in the x and y directions respectively ($m.s^{-1}$)
τ_p: bed shear-stress (Pa)
ρ: density of flowing material ($kg.m^{-3}$)
g: gravity ($m.s^{-2}$)
δ: quadratic correcting coefficient

2.2.2. Input and output data of the 2D model

Topographical data of the model are constituted of a DTM with regular cell size that can be generated by the GIS Arcview. This DTM is also used to generate the computation mesh which is required by the use of finite-volume techniques. Input data are also constituted of a file giving the surface roughness of each cell, a file giving data necessary to the computation scheme and a file giving boundary conditions. This latter is constituted of data giving for a limited number of cells located at the boundary of the domain of interest: the input discharge and, when necessary, the associated flow depth for each time of the computation.

3. Application to the Rochemelon lake

The application of the models previously presented to the Rochemelon lake, must be considered as an illustration of the models capacity to deal with this kind of phenomenon. Used assumptions on the triggering of the phenomenon are very schematic, so that at this stage, it is hardly possible to deduce results accurate enough for practical purpose. In practice, the 1D model was used to compute the propagation in the Ribon valley, from the lake to the bridge which delineates the arrival in the Bessans plain (main valley floor). The 2D model was tentatively used to compute the spreading of water on the Bessans plain, downstream the bridge.

3.1. Computation of the propagation in the Ribon valley

3.1.1. Input data and scenarios

The longitudinal profile of the Ribon valley (Fig. 1) was determined using aerial pictures for the downstream part and the available topographic map (scale 1:25000) for the upstream part. The shape of cross-sections was determined the same way and somewhat corrected on the basis of direct surveys when necessary. The roughness coefficient of the torrent bed was determined on the basis of some measurement of the grain size distribution at several points and using the following formula: $K=15/d_{90}^{0,29}$ (Meunier, 1991).

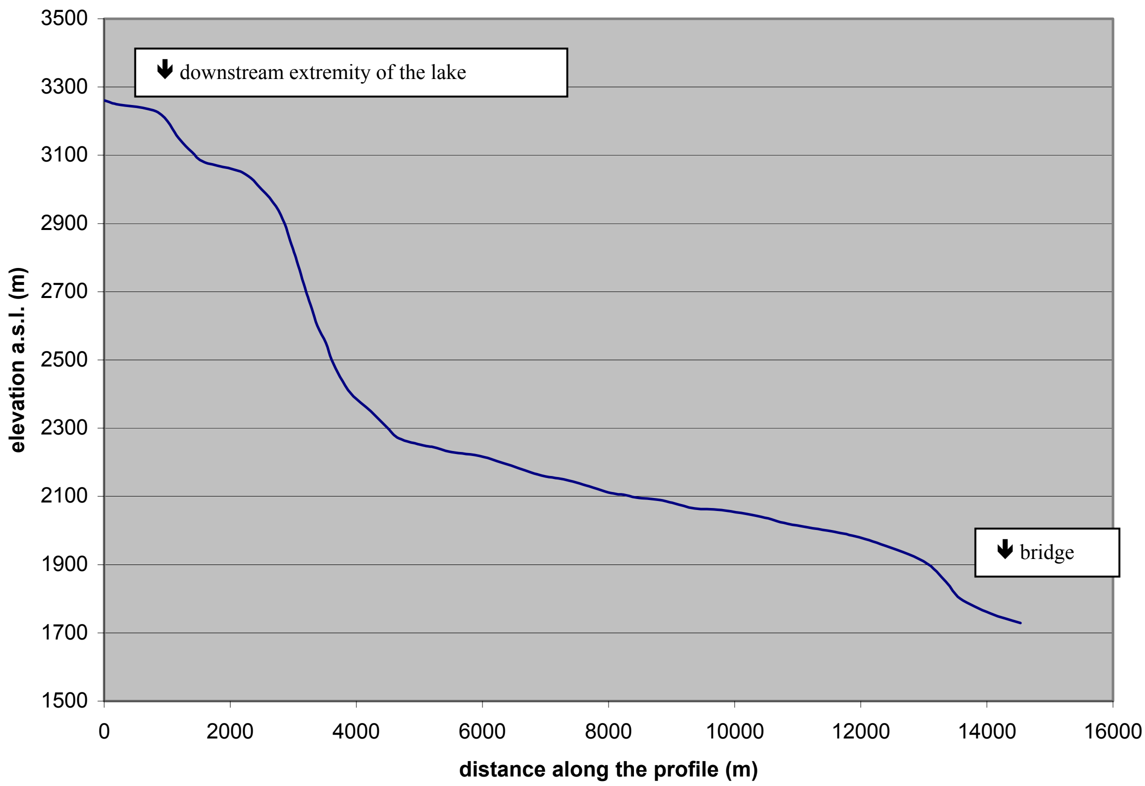

Figure 1: longitudinal profile of the Ribon valley

Schematically, two main types of scenarios were considered: the case of some prescribed input hydrograph and the case of instantaneous dam-break. In the first case (input hydrograph) only the zone from the downstream extremity of the lake and the bridge was considered. Having no precise information on the possible process of breaching of the natural dam, we arbitrarily adopted a very simple hydrograph with some triangular shape. The discharge value is equal to zero at time t=0 s, the peak discharge equal to 200 m^3/s occurs at time t=20 s and the discharge comes back to zero at a time corresponding to the release of the total volume initially stored in the reservoir (200000 m^3 or 500000 m^3 for considered assumptions). In the second case (instantaneous dam-break), the zone between the upstream extremity of the lake and the bridge is considered. Consequently, the topography of the reservoir is considered while no input hydrograph is prescribed. In fact, the topography of the reservoir was not known precisely so that we considered it arbitrarily as a rectangular cross-section channel with a longitudinal profile coherent with field observations. In this portion of channel, we imposed simple initial conditions with a water depth of 20 m (according to field observations) at the dam and some horizontal free surface upstream (length of the lake coherent with field observations: approximately 600 m). The channel width was arbitrarily adjusted so that the volume stored was coherent with both assumptions adopted (volume equal to 200000 m^3 and 500000 m^3 respectively).

3.1.2. Results

Table 1 gives a synthetic overview of the results of the computations which were carried out. Figures 2 and 3 present respectively the evolution of the discharge and flow depth versus time, under the bridge, for the computation of the instantaneous dam-break with a volume of 500000 m^3.

	Maximum discharge value upstream: 200 m^3/s Volume: 200000 m^3	Maximum discharge value upstream: 200 m^3/s Volume: 500000 m^3	Instantaneous dam-break Volume: 200000 m^3	Instantaneous dam-break Volume: 500000 m^3
time of propagation (s)	1830	1790	1180	1000
maximum discharge value at the bridge (m^3/s)	153	180	465	964
maximum velocity at the bridge (m/s)	8,70	9,18	12,31	14,63
maximum flow depth at the bridge (m)	1,76	1,97	3,82	6,58

Table 1: overview of computation results

Another test was carried out with a constant value of the input discharge of 200 m^3/s for 1000 s (total volume 200000 m^3) and for 2500 s (total volume: 500000 m^3). In both cases, the computed propagation between the lake and the bridge lasts 1760 s and the maximum flow depth (associated to the maximum discharge value: 200 m^3/s) at the bridge is about 2.1 m.

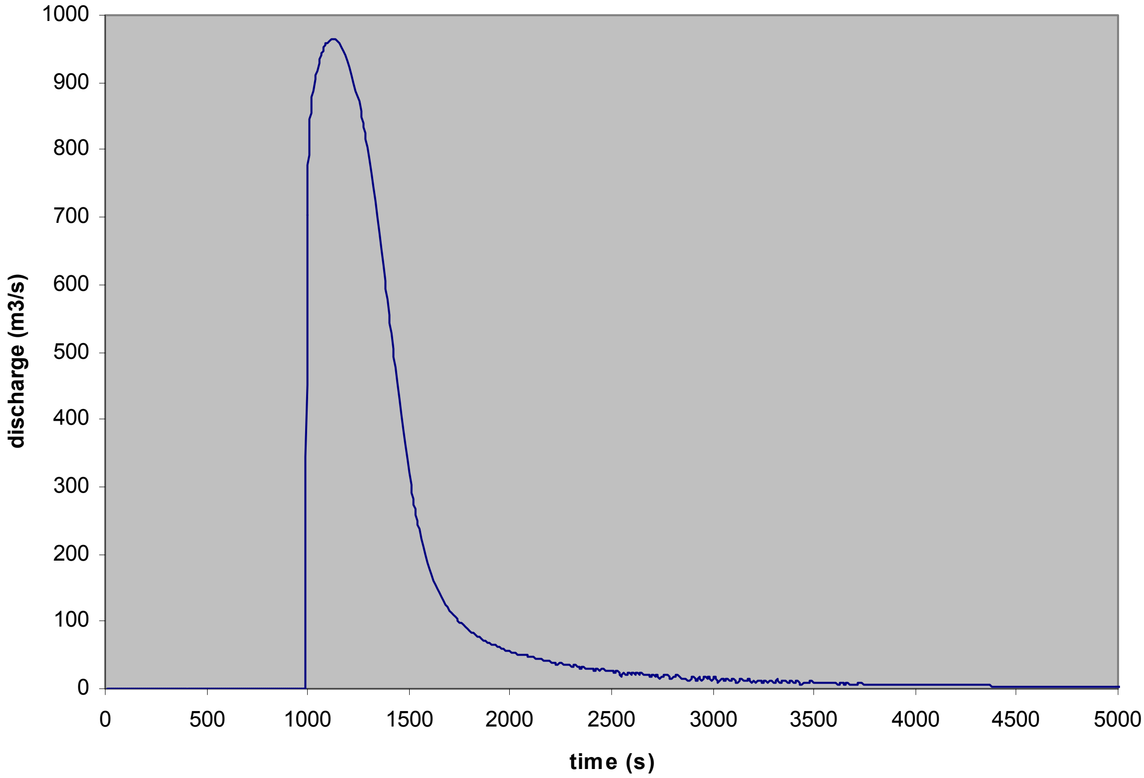

Figure 2: discharge versus time under the bridge, time t=0 s corresponds to some instantaneous dam-break with volume = 500000 m^3

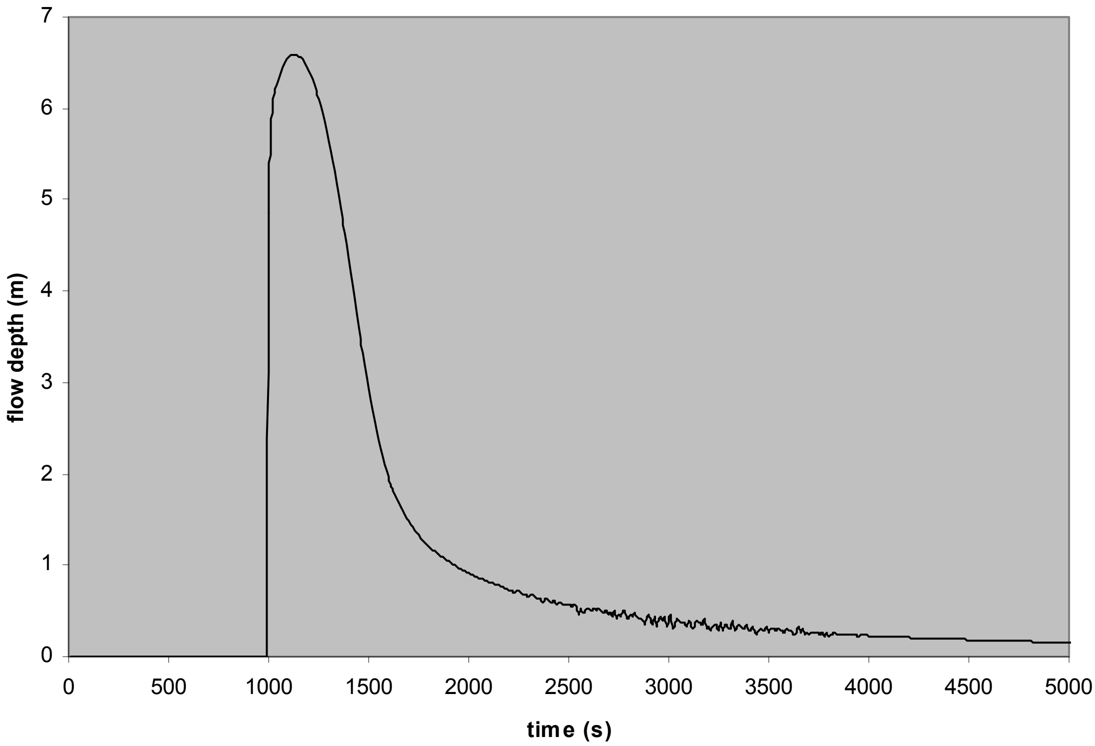

Figure 3: flow depth versus time under the bridge, time t=0 s corresponds to some instantaneous dam-break with volume =500000 m^3

3.1.3. Discussion

Even though results presented here must be regarded with substantial care, they nevertheless provide interesting information on the phenomenon that can possibly occur. One can consider that the instantaneous dam-break is unlikely to occur. However, for a given volume and a given initial water depth (at the dam) this schematic case most probably corresponds to the most violent propagation that can be envisaged. The case of some input hydrograph is probably closer to the natural phenomenon. However, a better definition of the triggering mechanism would be required so that practical information can hardly be deduced from present results. Considering all uncertainties, one can however deduce that the propagation on that site will last at least 1000 s and this result in itself is interesting for alert purpose. Considering now that the instantaneous dam-break is unlikely to occur, one can deduce from the simulations that the discharge value at the bridge is very closely related to the discharge coming out of the lake. So once again, we exhibit there the strong necessity to know more precisely the triggering process.

One has also to keep in mind that all these results were obtained without considering the solid transport (erosion and deposition) which is likely to occur and consequently modify the propagation of the phenomenon.

3.2. computation of the spreading on the main valley floor

This computation is carried out with the 2D model presented here-above which requires some precise topographic data. These data were obtained after some photogrametric investigations. This model also requires data related to the input hydrograph. The input hydrograph in the example presented here was deduced from a simulation carried out with the 1D model. The entrance point of the flow on the Bessans plain is the bridge which constituted the downstream extremity of the channel considered by the 1D model.

3.2.1. Input data: scenarios

Apart from the topography of the site, constituted in practice of a matrix of elevation (a.s.l.) coming from GIS Arcview and covering the zone of interest, other data are a matrix (same size as the matrix of elevation) of roughness coefficient (arbitrarily imposed uniform in the present example) and data concerning the input hydrograph. The input hydrograph was built up on the basis of one of the output hydrographs of the 1D model. The simplified hydrograph which was used in practice is triangular and exhibits a discharge equal to zero at time t=0 s, a peak discharge of 243 m^3/s at time t=550 s and once again a discharge equal to zero at time t=4115 s so that the total volume of water entering the domain is 500000 m^3.

3.2.2. Results

Obtained results consist of a several maps representing the extension of the flow and the flow depth at several times.

4. Further possible developments: consideration of the bed-load transport

In the previous developments and for the sake of simplicity, we have considered only the propagation of water and not the solid transport which is most likely to occur in such conditions. As mentioned previously, for very high values of the liquid discharge and on steep slopes, some debris-flow could possibly trigger. However, for a large part of the Ribon valley, slopes are relatively gentle, so that possible debris-flows are not likely to propagate at a long distance from the initiation point. Consequently, this phenomenon has been neglected. However, solid transport, and particularly bed-load transport and possibly hyper-concentrated flows are most likely to occur because the liquid discharge inevitably generates some erosion of the bed which depends upon the local slope. The resulting flow can be considered as a two-phase or non-homogeneous system. In that case the continuity and momentum conservation equations are expressed for both clear water and solid fraction. In practice, the technique very often consists in treating completely the mass conservation which after a few simplifications can express as follows:

$$(1-p)\frac{\partial z_s}{\partial t}+\frac{\partial q_s}{\partial x}=0$$

with: p the porosity of the solid material

z_s the level of the bed

q_s: solid discharge per unit width

This expression deals with phenomena of erosion and deposition and induces variations of the bed slope angle that must be also considered when computing the propagation of water. On the contrary, considering all forces applying to granulars inside the flow of water is often very complicated and a classical treatment consists deducing the solid discharge from the liquid discharge by using an equation of transport capacity established experimentally as it is the case for the classical Rickenmann's (1990) expression presented below and which is valid for bed-load transport. One considers first a critical liquid discharge under which no transport occurs:

$$q_{cr}=0{,}065\cdot(s-1)^{1,67}\cdot\sqrt{g}\cdot d_{50}{}^{1,5}\cdot I^{-1,12}$$

Once this threshold is overcome, the solid discharge is computed, using the following expression:

$$q_s=12{,}6\cdot\left(\frac{d_{90}}{d_{30}}\right)^{0,2}\cdot\frac{I^2}{(s-1)^{1,6}}\cdot(q_l-q_{cr})$$

q_l: liquid discharge per unit width of the channel
q_s: solid discharge per unit width of the channel
q_{cr}: critical liquid discharge
d_x: parameters of the grain size distribution
s: density of the sediment ($s=\rho_s/\rho_l$)
I: slope (m/m)

A complete approach of the phenomenon would require to consider bed-load transport simulation as a part of the model but such equations have not been coded for now inside the model. Another possible approach, simpler and more case specific, consists in considering bed-load transport only in some reaches of the Ribon valley. If one considers only bed load transport arriving at the bridge, it is possible to consider it is closely related to the water hydrograph by the use of a formula of maximum capacity of transport (formula above considering erosion threshold is overcome). For the Ribon valley, the canyon reach directly upstream the bridge is hardly erodible. Consequently the solid transport at the bridge corresponds approximately to the solid transport just upstream the canyon. It would be then possible to translate the water hydrograph into a solid hydrograph, using the formula above and possibly deduce approximately the quantity of material which is likely to deposit at the bridge. Of course, this approach is very simple and not as precise as a "complete" simulation. Nevertheless, it could give useful results in practice.

5. Conclusion

We have presented two numerical models whose aim is to compute the unsteady free surface propagation of water on steep slopes. These models have been applied to the study of glacial lakes breaking, considering this phenomenon essentially results in the propagation of water in valleys or plains located downstream the glacier. In that sense, these models constitute the core of a methodology of determination of the risk that can result from glacial lake breaking. To illustrate this possible use, we applied the models to the Rochemelon lake (Bessans, Savoie, France) and the Ribon valley and Bessans plain downstream. From this tentative use, we deduced that the models can give interesting practical results on the propagation itself, like for example orders of magnitude of the peak discharge and propagation time. But of course, the precision of the simulations depends strongly upon several factors which are: the precision of topographical surveys, the estimate of roughness coefficients, the consideration of bed-load transport (erosion and deposition). But the most important factor limiting the practical use of these tools seems to be the knowledge on the triggering factors. In fact, the process of triggering very strongly influences the input discharge, upstream the zone of propagation and consequently also all the propagation itself and subsequently the level of risk for settlements located downstream.

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