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INTERNSHIP REPORT

ANALYSIS OF DEBRIS FLOW CHARACTERISTICS WITH NUMERICAL MODELLING – APPLICATION TO TWO ALPINE TORRENTS AND TO THE SEMERU VOLCANO

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FOREWORD

Global Context of the internship

The internship has been conducted within the **European 'Mountain Risks' project**, as part of the 'Marie Curie' Actions. This project is financed by the European Union and consists of a research and training network between eighteen institutes. The purpose of the project is to develop the understanding of hydro-geomorphological processes in mountains, in order to apply this knowledge to **natural hazards management**. The occurrence of disastrous events over the last decades is constantly increasing and concerns more and more inhabitants of mountainous areas, although there is still a lack of efficient measures, which are socially and environmentally accepted. Engineering, environmental, social, information and economic sciences are tools to improve hazard analysis, as well as collaboration between several research groups with various backgrounds.

The internship took place in two different institutes.
Half of it was made at the **'Institut de Physique du Globe' in Strasbourg, France**. The research fields are oriented towards earth sciences, ranging from seismology to magnetism or tectonic for example. The institute is part of the Louis Pasteur University, and is associated with the School and Observatory of Earth Sciences of Strasbourg.

The other part of the period took place at the **Department of Physical Geography at the faculty of Geosciences of Utrecht University, the Netherlands**. The institute studies earth surface morphodynamic. The purpose of those three months abroad was to understand how the model works and to learn how to handle correctly the model's software. The main modelling work has been done there.

INTRODUCTION

During the two first weeks of December 1999, in the middle of the wet season, the watersheds of the north coast of Venezuela and especially the Cerro Grande river, have been saturated by intermittent rainfalls (Bello et al., 2003). Then followed a three-day period (December 14-16th) of heavy rainfalls which triggered debris flows, mud flows and flood waves in the Cerro Grande river bed which started to flow downstream and reached the town of Tanaguarana, located on the alluvial fan of the river, partly destroying the city. Over 15,000 people died during those three days because of a natural phenomenon.

This is only one particularly murderous example of the impact **natural hazards** can have on people and goods. Floodings in Germany in 2006 and Great Britain in 2007, regular landslides and avalanches during the winter season in the European alpine countries show that western countries are not spared: natural hazards are present everywhere on the globe.
Some hazards, such as sismology, are studied for decades now and their working has almost no secrets for researchers anymore. Others are currently less known, and most studies aiming to a better understanding and prediction are still in progress. It is the case about **debris flow modelling**. Debris flow modelling tools can not systematically be used as prediction mean, as they are currently not enough calibrated on real field events (Remaître, 2006). Precise field observations of this very complex process are very rare. Moreover, no model is able to model the whole progress of a debris flow for the moment.

The topic of the internship is to **analyse debris flow characteristics by numerical modelling**. This analysis only concerns the spreading phase of **muddy** debris flows. Triggering or propagation phases are not taken into account in this report. The final purpose of such work is an estimation of the risk, with a determination of the speed, of the thickness and of the speading distance of possible debris flows.

The study is lead on three different cases: the Wartschenbach torrent in Austria, the Faucon torrent in France and the Semeru volcano in Indonesia.
The objective of the training period is to make a **back analysis** of those three events, in order to **calibrate the MassMov2D model**. Back analysis is made with simulation runs of the model on the study cases. Calibrating the model means obtaining the best possible comparison between the simulation results and the field datas. Different flow behaviours can be implemented in the model, for a better matching with the event characteristics.

A state of the art about debris flows general knowledge will be made in the first part of the report. Then the model will be presented, as well as the methodology used during the internship. On the third part, the results of the simulations will be analysed and compared to previous studies on the same events. A sensitivity analysis of the model is finally made.

1. CURRENT KNOWLEDGE ABOUT DEBRIS FLOWS DYNAMICS

1.1. Characteristics of debris flows

1.1.1. General characteristics

Debris flows are natural, highly concentrated **mixture between water and solid particles** flowing in a mountain **torrent channel** (Remaître, 2006). The solid fraction volume in a debris flow is usually superior to 50 %, and the density is varying from 1900 to 2600 kg.m^{-3}. According to the Meunier Classification (figure 1), debris flows can be situated between hyperconcentrated flows (more fluid) and rock falls or landslides (more solid).

Debris flow run-outs are not uniform, but involve **several surges** during the flow. A hundred surges can be seen at some event (Malet, 2003), even if in the Alps this number is greatly reduced (around 6 for the most numerous). The different surges can be separated by more fluid waves. The time between the surges is very variable, depending on the size of the water catchment or from the channel morphology for example.

Enormous amounts of material can be transported during an event and large boulders (of a volume of several cubic meters) can be carried, floating at the surface of the flow.

There is no granulometric sorting within a wave, the particles are randomly flowing (Major, 1997).

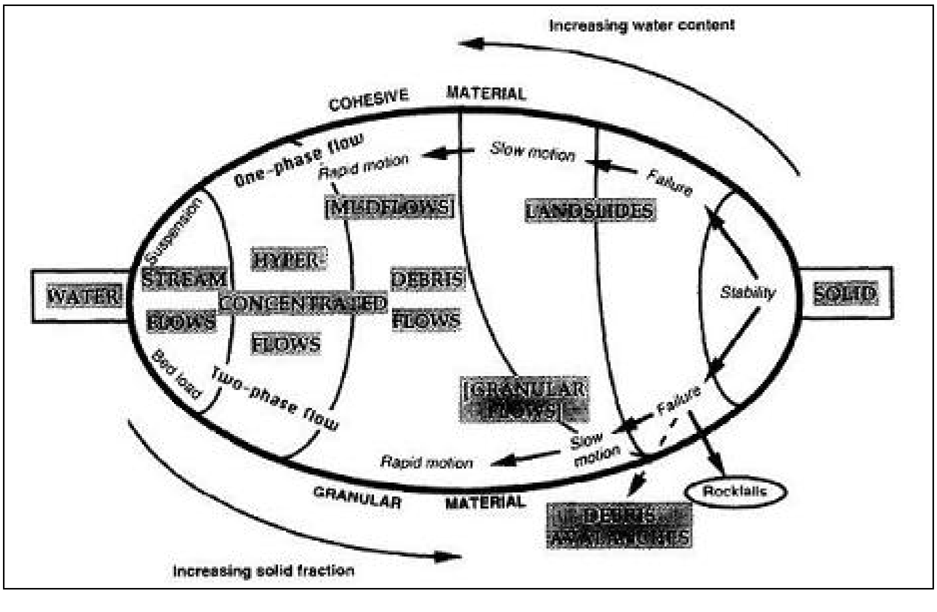


Figure 1: Meunier classification (1991) of mass movements on steep slopes (Coussot, 1995)

There are two types of debris flows: the **granular debris flows** composed by coarse particles like sands, gravels and rocks, and the **muddy debris flows** composed by finer particles like loams and clays. The type is determined by the percentage of loam and clay: if it is > 20 %, the debris flow will be considered as being muddy, if it is < 20 %, the debris flow will be considered as being granular.
The granular debris flows flow in two separated phases, liquid and solid, whereas the muddy debris flows look like one-phase flows.

Debris-flows are separated into different parts (figure 1):

- The **front** is composed by the largest boulders and rocks; which are slided or rolled by the flow. It is the widest flowing section. A small hyperconcentrated flow generally preceeds the front, with a mud cloud resulting from the shocks between the boulders provocated by the run-out.
- The **body** is the main part of the flow and represents the main volume which is running. The size of the particles is low and relatively homogeneous. The material flowing in the body is completely saturated with water.
- The **queue** is composed by the finest particles and is more fluid than the main part of the flow. It is pretty similar to a hyperconcentrated flow. It erodes the last deposits let by the body and rolls the boulders on the bottom of the channel.

Lateral levees form during the run-out, which are coming from the smallest material transported within the front. They are deposited when the particles from the body flow faster than the front and push the lightest pebbles towards the banks, or when the flow is unconfined.

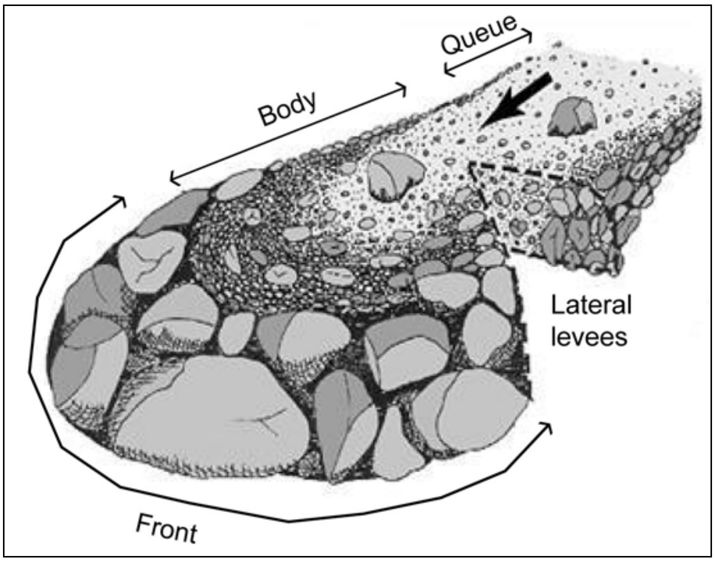


Figure 2: granulometric structure of a debris flow (Bardou, 2002)

1.1.2. The triggering phase

Debris flows are exclusively triggered by **water**. They are usually associated to extreme meteorological events, like storms, massive rains or even fast snow meltings. However, water only is not sufficient, **available material** is needed too (May, 2003). Water flows will depend on the initial state of the water catchment: if the soil is already wet, a debris flow will be triggered more easily. Available material will depend on the bedrock and on the geomorphologic state of the channel. Several processes are involved: rocks can be directly lead by the water to the torrent, but they also can stay on a slope without reaching the watershed, creating an accumulation which would be mobilized during the next rainy event. Moreover, **contribution zones** add some material during the flow. Landslides can be transformed into debris flows or give some material to the torrent, natural dams in the channel can be broken and swept downstream with the rest of the flow. There are also other factors involved into a debris flow triggering (slope value, presence of vegetation, etc).

1.1.3. The propagation phase

During the propagation, debris flows will lose materials along the torrent but also incorporate some others which can be stored in the channel or due to the **bulking process**, rocks or boulders can be pulled out from the banks as the wave flows downstream.

Five different phases have been considered for the propagation of debris flows (Bardou, 2002):

- *'the pre-event phase'* (figure 2.a.): pore water of the soil is pushed forward before the arrival of the front of the wave.
- *'the front phase'* (figure 2.b.): the front is the widest part of the flow. It is preceded by a hyperconcentrated flow, and always followed by the body and lateral levees, but not necessarily seperated by a queue from the following surge.
- *'the main phase'* (figure 2.c.): the main volume of the event flows during this phase. It is composed by a mixture between water and small particles, lateral levees will form if the channel topography allows it.
- *'the ending phase'* (figure 2.d. and 2.e.): the queue is following the body. The flow gets weaker and fluider and the channel begins to get filled with deposits. Boulders are rolled on the channel bed.
- *'the post-event phase'* (figure 2.f.): the channel is cleared. The material, coming from bank erosion or deposits, is brought downstream by water.

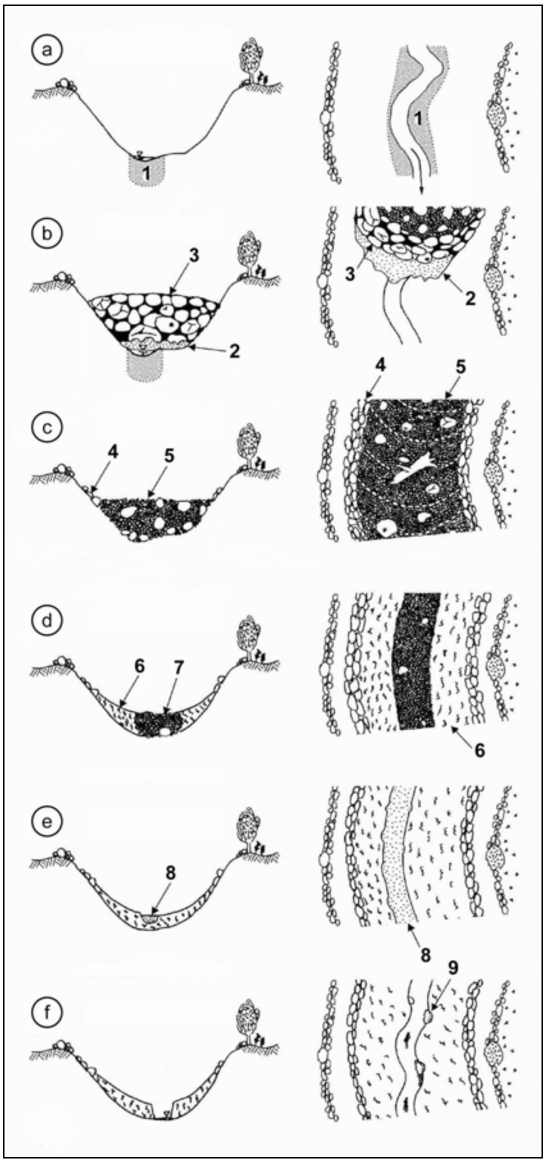


Figure 3: the different phases of a debris flow (Bardou, 2002)

1.1.4. The spreading phase

Most debris flow spread on **alluvial fans**. The deposits are either lateral levees, or lobes when the flow overflows the channel. Debris flows stop when:

- the slope decreases
- the channel gets wider and the flow then spreads
- there is an overflow on the banks, followed by a spreading
- there is a dam in the channel
- there is a brutal change in the channel direction, causing a run-up on the other side

1.1.5. Influence of rheology on debris flows behaviour

Rheology is concerned with the description of the flow behaviour of all types of matter (Doraiswamy, 2002). A well-accepted definition of rheology is to define it as the **study of the flow and the deformation of matter under the influence of an applied stress**.

Rheology considers debris flows as **unvarying one phase flows** even if it not really true in reality, in order to describe the behaviour of the flow. The body can be considered as a mass of a single viscous material (Coussot, 1998). The front and the queue are neglected. The behaviour of debris flows has been divided in two groups: debris flows with muddy behaviour law and debris flows with granular behaviour law, according to the granulometric classification.

Different rheological models have been developed for **muddy** or **granular** debris flows.
The **Bingham** or **Herschel Bulkley** model apply for muddy flows and consider the fluid as viscoplastic, i.e. the matter needs a stress to begin to flow and it has finite yield stress and viscosity. The **Coulomb-viscous** model is also applied in case of muddy debris flows. In this case, the yield stress is considered as a combination of cohesive and frictionnal strenghts (Begeria et al., in press). The flow is assumed to be laminar in those models.
If a turbulent flow behaviour is dominating, the **Voellmy** model can be used. It is usually applied to granular flow cases.
The study of granular debris flows is based on the the mixture theory, where interstitial pressure inside the fluid rules the spreading. **Collisional** and **frictional** models are applied in case of granular run-outs, the fluid is then considered as a two phase flow (Malet, 2003).

1.2. Contribution of previous debris flows numerical simulations to the study

1.2.1. Critical points of previous studies

According to many research papers, the main problem of debris flow modelling concerns the **accuracy of event data**. Uncertainties in peak discharge, flow velocities, hydrograph shape, total event volume or also in the best rheology to use can lead to significant errors in the modelling. Debris flow events are sudden and short, and observation or measurements of their flow behaviour is very difficult (Sosio et al., 2006). Studies often refer to eyewitness statements of inhabitants instead.
Estimation of rheological paramaters by laboratory analysis afterwards seem to be a great problem. The results of those laboratory measurements are sometimes very different from those obtained with back analysis from field observations (Van Asch et al., 2004). Theoretical measures are sometimes only made on the fine grain fraction, which is not representing the real flow behaviour.

Accurate representation of **the topography is particurlarly critical**. The flow is usually very thin compared to the topography changes, so a small error in the roughness height of the ground can result in an important change in the flow spreading or deposition (Rickenmann et al., 2006). In many cases, a detailed representation of the topography strongly improves the simulations results. Nevertheless, geometric terrain details can hardly be identified on the usual maps and field survey is needed to precisely evaluate the real topography (Ghilardi et al., 2001).
In cases of smoothed Digital Elevation Models (DEM), oversimplified representation of the topography may modify the forces acting on the flow (Chen, Lee, 1999), as the topography plays a great role on the surface, the speed and the height of the flow.

Of course, apart from the event available datas, **numerical computation** is also a critical point. The model itself obviously has a great influence on the simulation results. Several different models have already been used for previous debris flow numerical modelling. Some can only be applied to the propagation phase, some to the spreading phase, some to both. Every model has its own characteristics, sometimes several different rheologies can be implemented.

1.2.2. Presentation of the main models for debris flow simulations

Name of the model	Rheology implemented	Main characteristics	Used in
FLO-2D	Bingham	- good combination with a GIS application - most widely applied model to debris flows only one rheology implemented	Rickenmann et al., 2006 Bello et al., 2003 Hübl & Steinwendtner, 2000 Sosio et al., 2006
HB	Herschel Bulkley	- boundary conditions can be specified with an hydrograph - only valid for materials where the fine fraction is large enough to lubricate the contacts between the grains	Rickenmann et al., 2006
DFEM	Voellmy Bingham dilatant turbulent Coulomb	- 1D and 2D versions - several rheologies implemented	Rickenmann et al., 2006
ALCO_2D	frictional	- erosion/deposition process taken into account - no viscous rheologies implemented	Ghilardi et al., 2001
J-DFM 1-D	Herschel Bulkley	- 1D propagation model - contribution process taken into account	Remaître, 2006
BING	Bingham	- propagation model - built in an easy-to-use interface	Malet, 2003 Remaître, 2006
CEMAGREF	Herschel Bulkley	- 1D version for the propagation phase - 2D version for the spreading phase - initially developed for avanlanche modelling	Malet, 2003 Remaître, 2006

Figure 4: presentation of the main models for debris flow simulations

Although they have been used for many studies, the presented models still have **several disadvantages**. Some of them which take the contribution process into account are not able to compute different rheologies. Only one rheology can usually be simulated, and propagation and spreading phases are sometimes separated. Moreover, calculation time is very long (a dozen hours for a simulation with the CEMAGREF code for example) and programming skills are needed to modify the input data. Those models are very complicated to use and to understand.

On the contrary, the MassMov2D model has been created in order to be **as easy as possible to understand and handle**. The results are displayed on maps with a GIS application. Changes on the script, the input data or the sedigraphs are extremely fast. The calculation time is very short compared to other models (see also 2.1.).

1.3. From the state of the art to the purpose of the study

General characteristics of debris flows, the propagation and spreading phases, the importance of the rheology as well as the main debris flow models have been detailed in the state of the art. All those informations open prospects for this study.

For every field event, it is necessary to determinate the characteristics of the flow, in order to deduce the rheology and the rheological parameters. Data about the debris flows must be gathered, with as many as details as possible on deposition extent and on scenarios. The model calibration has to provide a comparison to other existing models in order to, as a final aim, show its validity.

2. PRESENTATION OF THE MASSMOV2D MODEL

2.1. MassMov2D presentation

2.1.1. A model for debris flows and landslides

The MassMov model is a **two dimensions model**, available to be applied on cases such as spreadings on alluvial fans (Begueria et al., in press). The flow is considered as a **one phase homogeneous material**, whose behaviour is controlled by a rheology. Several flow resistance relations have been implemented which allow the user to simulate a flow using different rheologies. Different initial and boundary conditions can be simulated.

Governing equations

The model uses a depth-integrated form, based on the shallow water assumption which applies when the horizontal length scale is much greater than the vertical length scale. Vertical velocity variations can be then neglected. The governing equations are referenced in a 2D space with Cartesian coordinates (x, y).

The **mass conservation equation** is developed as:

$$\frac{\partial h}{\partial t} + c_x \frac{\partial (hu)}{\partial x} + c_y \frac{\partial (hv)}{\partial y} = 0 \, ,$$

where h is the flow thickness in the normal direction to the ground and $(u\ ,v)$ are the x and y components of the velocity vector along the bed (m.s^{-1}). The coefficients $c_x = \cos \alpha_x$ and $c_y = \cos \alpha_y$ are geometry factors to correct from local to global reference system, α_x and α_y are the values of the angle between the bed and the horizontal plane in the x and y directions. The first term on the left represents the change of thickness in time, while the second and third terms represent the thickness and the speed in the x and y directions respectively.

The **velocity conservation equation** is developed as:

$$\frac{\partial u}{\partial t} + c_x\, u \frac{\partial u}{\partial x} + c_y\, v \frac{\partial u}{\partial y} + c_x\, k \frac{\partial (g c_x h)}{\partial x} = -g \sin \alpha_x + c_x\, S_f \frac{-u}{|\vec{u}|}$$

$$\frac{\partial v}{\partial t} + c_y\, v \frac{\partial v}{\partial x} + c_x\, u \frac{\partial v}{\partial y} + c_y\, k \frac{\partial (g c_y h)}{\partial y} = -g \sin \alpha_y + c_y\, S_f \frac{-v}{|\vec{u}|}$$

where g is the acceleration due to gravity, $|\vec{u}| = \sqrt{u^2 + v^2}$ is the modulus of the velocity vector, k is the earth pressure coefficient, i.e. the ratio between the tangential and normal stresses. It ranges between extreme values corresponding to the active (when the flow is expanding) and passive (when the flow is compressed) state of the Rankine theory, $k_{\text{act}} \leq 1 \leq k_{\text{pas}}$. Sf is the depth integrated value of the shear stress. It is the variable which describes the rehological properties of the flow, thus controlling its behaviour.

The first term on the left hand side represent the real acceleration of the flow. The spatial derivatives (second and third term) represent the convective acceleration, i.e. the change of acceleration in space caused by the topography. The last term on the left hand side is the pressure acceleration, i.e. the acceleration due to pore pressure differences within the flow. The right hand side of the equation is the local or time acceleration, which is, at each point, the force that speeds up the flow. The first term on the right hand side of the equation represents the gravity force, and the last term is the flow resistance.

Rheological equations

The **Herschel-Bulkley** model is applied to the flow when there is a large fine grain fraction. The fluid is considered as viscoplastic with constant yield stress and viscosity. This rheology can be described by the following relation:

$$\tau = \tau_Y + \eta \left(\frac{\partial v}{\partial z} \right)^{\beta},$$

in which the shear stress τ (Pa) depends on two factors: a constant yield stress due to cohesion τ_y, and a second factor depending on the shear rate, $\partial v / \partial z$, times a viscosity coefficient η (Pa.s). The exponent β is an empirical parameter which equals one in the **Bingham** model.

The **Coulomb-viscous** model is applied for a wider range of fluids, and the constant yield stress is replaced in the model equation by a cohesive-frictional component:

$$\tau = \tau c + (\sigma - u) \tan \varphi + \eta \left(\frac{\partial v}{\partial z} \right)^{\beta}$$

where τc is a cohesive yield stress, $\sigma = \rho g h$ is the bed normal stress, u is the internal pore pressure, φ is the friction angle of the flowing material.

Pure cohesional or frictional models can be easily implemented by setting the appropriate parameters to zero. The **Voellmy** model can also be implemented, but as it is not used for simulating the field cases (which are exclusively **muddy flows**), it is not described here.

2.1.2. PCRaster: a simple environmental modelling langage

The MassMov2D is linked to the **PcRaster** software, which is used for any operations on the model: simulation runs, creation of the input maps or visualization of the simulation results.

PcRaster is an **environmental modelling langage** developped in Utrecht University, the Netherlands (Karssenberg, 2002). On the contrary to some models that need computer or programming skills, PCraster is a general modelling tool based on the knowledge of an environmental specialist, who is often not able to program a tricky numerical model on their own. Complex environmental models usually gather scientists and programmers together in

the same research team. Programmers may completely understand how the model works, but others see them as a “black box”.
In other words, the PcRaster modelling language matches the level of thinking of a researcher or geoscientist who thinks before all in terms of **environmental processes**. He is allowed to build a model in a short period without any real programming experience. He can understand and act on the model script by changing quickly and easily the characteristics as well, avoiding a complete re-writing of the numerical code. The created model is then easily adjustable to the study case. Moreover, models in numerous scientific fields can be run on PCRaster. An unlimited number of environmental models can be built with the functions developed in PCRaster and new specific functions can even be developed. It is possible to implement simulations on very different cases whereas other modelling langages are usually more restrictive.

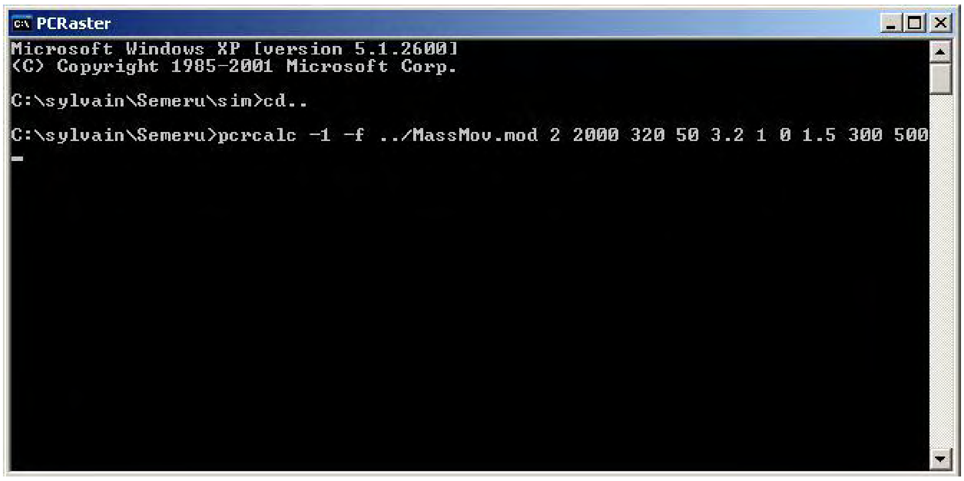
Another strong point of the software is the computer load. Simulation time is much shorter than for other models: it takes usually around one hour on a normal computer, whereas other complex codes can need very powerful computer for simulations longing several hours.

A **GIS visualization software** is integrated in PCRaster, which allows the user to easily handle and display the datas (only under a raster format) and thus avoid too many data exchange between the model and a classical GIS software.

2.2. Methodology of the model calibration on field events

The first part of the internship consisted in an intense bibliographic work, in order to become familiar with the general debris flow characteristics, to understand the basic knowledge of rheology and to get an overview on previous modelling studies. Much information, especially about rheological datas, has been picked up in publications or reports on Semeru, Wartschenbach and Faucon case studies.

The main work of the trainee consisted in **implementing simulations** and then **comparing the results to available deposit maps**.
To be able to run simulations, base maps are needed. The most important map is the DEM, but others are necessary too. Depending on the cases, buildings, debris flow inlet zone (Wartschenbach and Faucon) or debris flow source area (Semeru) must be represented. The model modifications have been done by Santiago Begueria. A model run is controlled by a PcRaster command line:



```
Microsoft Windows XP [version 5.1.2600]
(C) Copyright 1985-2001 Microsoft Corp.

C:\sylvain\Semeru\sim>cd..

C:\sylvain\Semeru>pcrcalc -1 -f ../MassMov.mod 2 2000 320 50 3.2 1 0 1.5 300 500
_
```

Figure 5: PcRaster command window

where:

- `pcrcalc -1 -f` are PcRaster applications in order to run the computation
- `MassMov.mod` is the script file of the model
- `2` indicates the rheology which is used (in this case, the rheology is viscous, 1 is for frictional behaviour)
- `2000` is the density of the flow (kg.m^{-3})
- `320` is the yield stress (Pa)
- `50` is the viscosity (Pa.s)
- `3.2` is the internal friction angle (°)
- `1` is the surge thickness at the inlet (m)
- `0` is the velocity along the x direction (m.s^{-1})
- `1.5` is the velocity along the y direction (m.s^{-1})
- `300` is the surge duration (timesteps)
- `500` is the number of timesteps of the simulation

The methodology of the internship is summarized in the figure 6.

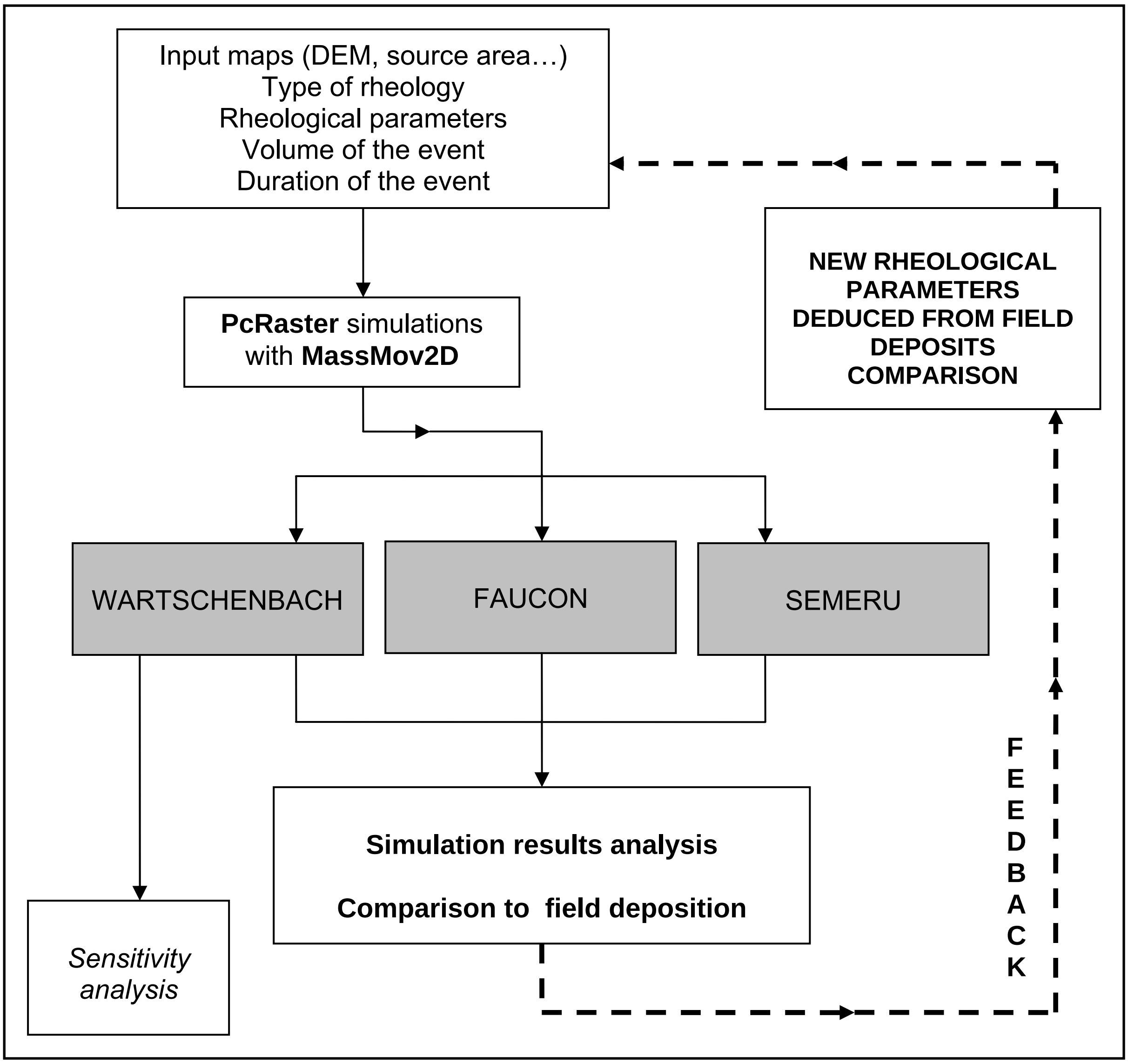


Figure 6: methodological figure

3. CALIBRATION OF THE MODEL ON REAL DEBRIS FLOW EVENTS

3.1. Semeru (Indonesia)

3.1.1. Description of the study site and definition of lahar

The Semeru Volcano, 3676 meters high, is situated on the Java Island in the Indonesian archipelago (figure 7). The volcano is in constant activity since 1967, regularly provoking ash clouds and lahars. Rainfalls cause lahars very frequently (up to a dozen a day). The climate of this region is very wet with an intense rainy period from October to April. The annual pluviometry is around 2000 mm per year (Durand, 2006). The slopes of the volcano are covered by ashes which are very easy to mobilize in case of heavy rainfalls.

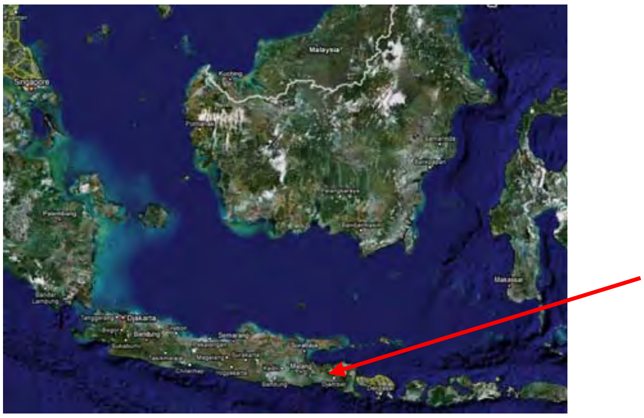


Figure 7: location of the Semeru volcano, marked by the red arrow (Google maps)

Lahars are debris flows that originate on volcanoes and surge towards adjacent lowlands, potentially jeopardizing people and property downstream (Iverson, 1998). They are separated into two types depending on their sediment concentration (Carine):
- debris flows with a sediment concentration higher than 60 % of the volume
- hyperconcentrated flows with a sediment concentration from 20 % to 60 % of the volume.

3.1.2. Available dataset

On May 14th 1981, 300 mm rain felt on the Semeru, triggering a **landslide** of 685,000 m^3 on the upper part of the volcano, between 1600 and 2000 meters high, which carried away sediments until an altitude of 1300 meters, then transforming into a flow of around 850 000 m^3. The peak discharge would have reached 2200 m^3.s^{-1} and the deposition volume was constatntly increasing as long as the lahar flowed down to the see. The increase of the volume during the event is due to the **bulking process**, i.e. bank erosion as well as previous lahar deposits sweeping. The total deposition volume was estimated around 6,250,000 m^3 and the total flow volume was estimated between 15,000,000 (with a sediment concentration of 40 %) and 20,000,000 m^3 (with a sediment concentration of 30 %). This lahar is the largest, the longest (25 kilometers long), and the **most devastating event which ever happened on the Semeru volcano**. It killed 252 people, 152 persons were injured, 120 disappeared, 626 hectares of rice fields were destroyed and 16 villages flooded (Durand, 2006).

Figure 8: path of the lahar (Durand, 2006)

3.1.3 Characteristics of the event

The Semeru is case is different from both other cases as the flow is triggered by a landslide. This situation can be implemented in the model. An important characteristic is the **size of the area** (more than 4000 km^2) and the **length of the lahar** which do not allow to simulate precisely neither the path of the flow, nor the deposition.

3.1.4. Main Difficulties encountered

It was not possible to pick up the DEM on which Durand's modelling study has been made. A new DEM has thus been created. Unfortunately, waves appear on the plains of the new map which could be the cause of wrong flow directions. The grid resolution of the DEM is 25 meters.

It was tricky to adapt the model to this case, as the characteristics are completely different from other studied events.

A try to implement the bulking process has been made, by a flow contribution at some points were material would be added to the flow. Unfortunately, it had no real success. It was not satisfying as the flow did stop anyway a few timesteps after the material was added.

3.1.5. Results

A **frictional** rheology and a **viscous** rheology have been tested, with a simulation time of 5000 seconds. The volume of the source area of the landslide is 2,770,000 m^3 and the density of the flow was fixed at ρ = 1100 kg.m^{-3}.

The viscous rheology was the Bingham rheology, with parameters of τ_y = 10 Pa and v = 200 Pa.s (figure 9.a.), according to Durand's best results.

The frictionnal rheology was actually the Coulomb-viscous rheology with setting the yield stress and the viscosity to 0, with a angle of frition φ' = 7° (figure 9.b.), according again to Durand's best results.

For both rheologies, the flow stops very early after the triggering, running out only during a few kilometers. Nevertheless the Bingham rehology seems to provide a better respect of the lahar path, whereas the flow with the Coulomb-viscous rheology divides into several arms.

Even with significantly increasing the source area volume, the amount of material is still very far from the real value, due to the contribution of the bulking process during the event.

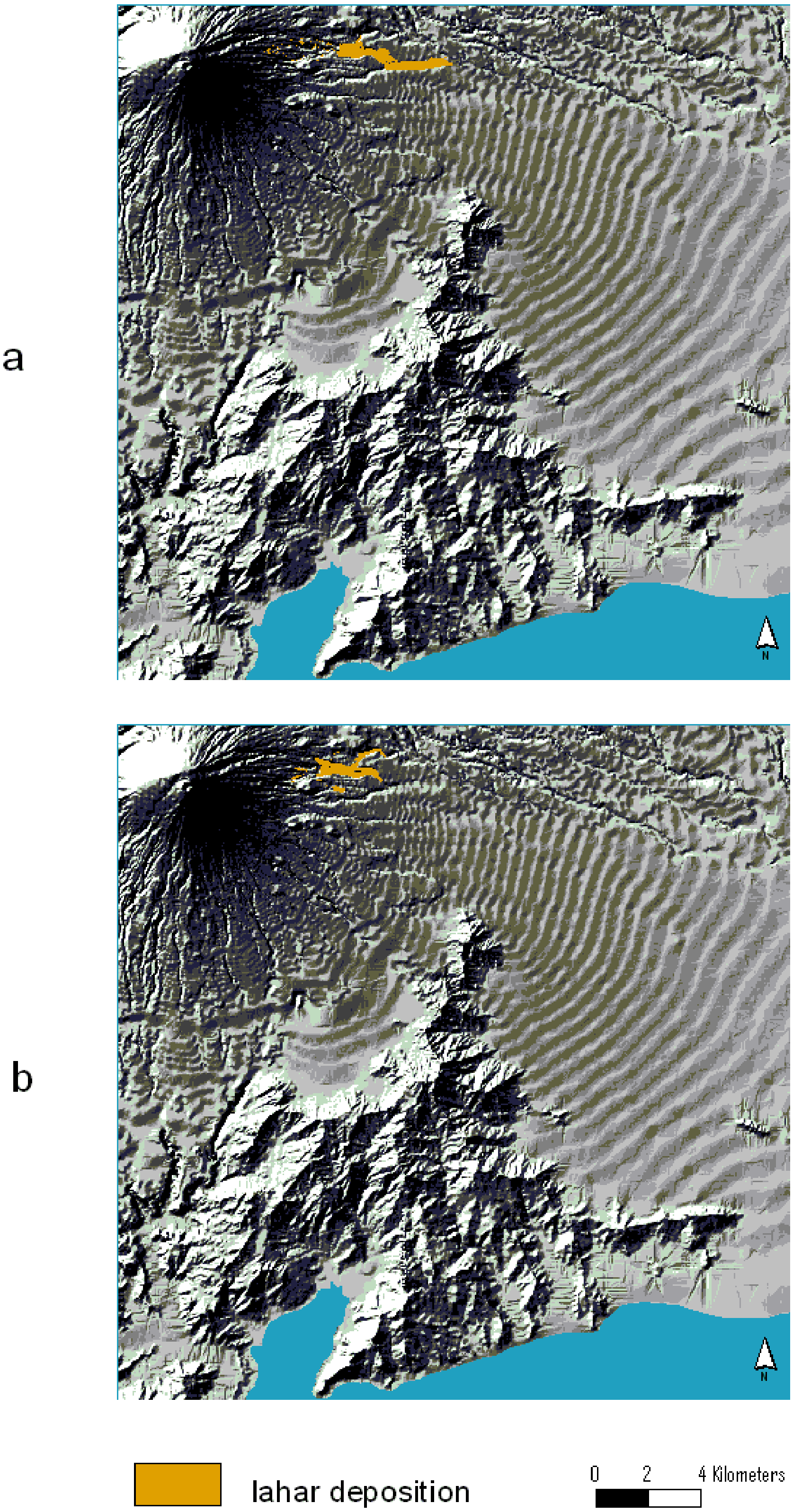


Figure 9: best simulations

a. Bingham rheology, ρ = 1100 kg.m^{-3}, τ_y = 10 Pa, v = 200 Pa.s

b. frictional rheology, ρ = 1100 kg.m^{-3}, τ_y = 0 Pa, v = 0 Pa.s, φ' = 7°

3.1.6. Discussion – Comparison with the work of Durand (2006)

Durand used four different rheologies to model the event: frictional, constant frictionnal, collisional and viscous (see appendix 1 for the collisional and constant frictional results).

The frictionnal rheology provided the best results for a friction angle of 7° (figure 10). The simulated deposition did not match the real deposition, and the flow stops in the middle of the DEM, although material is added with a bulking process simulation.

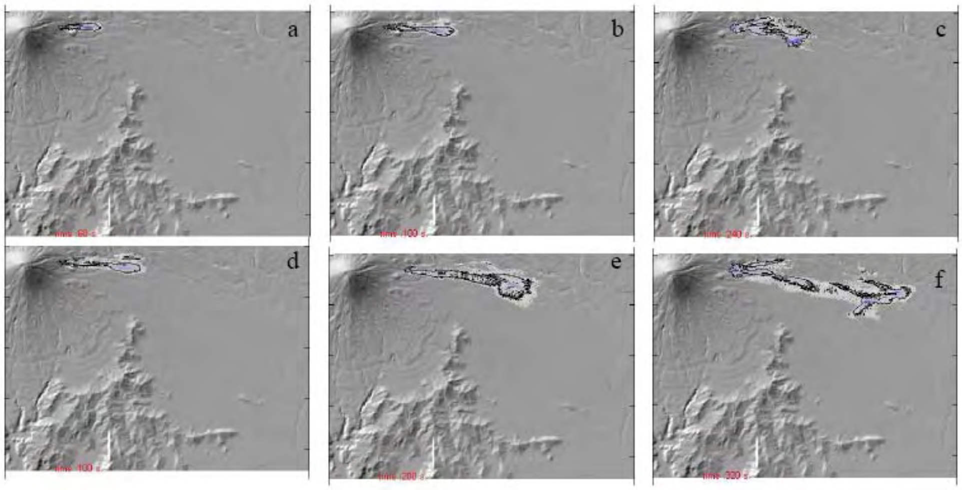


Figure 10: results obtained with the frictional rheology (Durand, 2006)

The viscous rheology provided the best results for a viscosity of 200 Pa.s (figure 11). The flow follows the righ path until the coast, but spread too much in the plains. It never stop and flows out of the calculation zone.

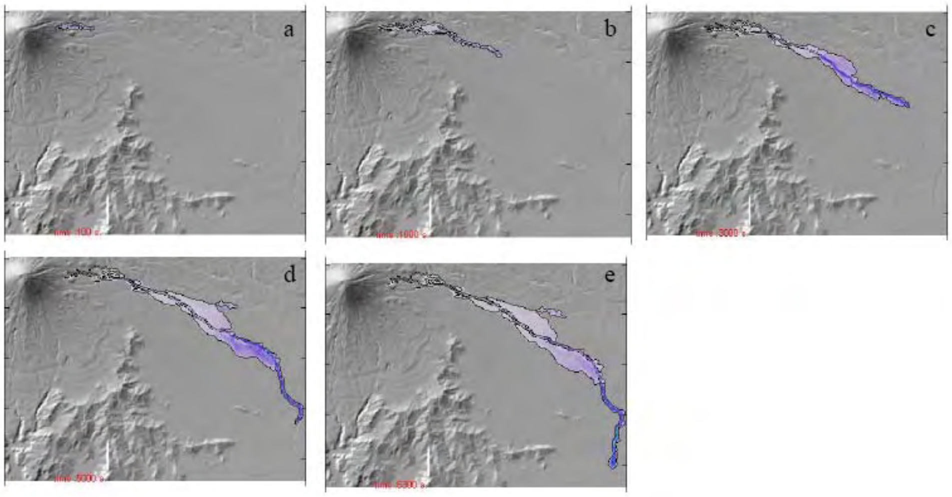


Figure 11: results obtained with the viscous rheology (Durand, 2006)

The Semeru case is not the main aim of the topic, but is more a **first step towards further detailed studies**. Studying this case was an opportunity to study another phenomenon, an occasion to see if the model would work in another case than a debris flow spreading. The complete event is here concerned, from the landslide triggering to the flow deposition, and its scale is too large to provide a precise work. This case was the last to be studied during the internship, and the lack of time explains the poor modelling results.

3.2. Wartschenbach (Austria)

3.2.1. Description of the study site

The Wartschenbach torrent is located near the town of Lienz, in the eastern part of the Tyrol, in Austria (figure 12). The catchment area is 2.5 km² with altitudes ranging from 600 to 2500 meters. The torrent forms an alluvial fan at the bottom (mean slope of the fan: ~9°), crossing an inhabited area.

Figure 12: location of the Wartschenbach torrent, marked by the red ‘A’ (Google maps)

3.2.2. Available dataset

The debris-flow event occurred on August 16th 1997 after an intense rainfall with hail (40 mm within 20 min). It created an enormous erosion process which mobilized 45,000 m³ of water and sediments. Between 20,000 and 25,000 m³ finally reached the fan, **damaging 15 buildings** (Hübl & Steinwendtner, 2000) (appendix 2). The peak discharge is estimated to 16 $m^3.s^{-1}$. Analysis of the deposits showed that the behaviour of the debris-flow was clearly viscoplastic (Rickenmann & al., 2006) therefore it has been modelled using **viscous rheologies**.

A DEM with a grid resolution of two meters was used for the simulations. Buildings were treated as obstacles, which mean the area taken by the houses on the DEM has no value (the mud can not flow in).

3.2.3. Characteristics of the event

The Wartschenbach case concerns only a fan spreading. No channel is involved in the simulation (even though there is one on the field, but its influence on the debris-flow spreading is negligible), and there are no interactions between the flow and the DEM borders. The distance between the inlet area and the end of the spreading is also very short (~150 m). This makes the modelling easier.

3.2.4. Main difficulties encountered

At first, parameters of the simulations have been set according to the laboratory experiments made on the field deposits. Those experiments were giving values for the yield stress and the viscosity, deduced from tests made only on the fine fraction of the deposits. Used to model the whole debris-flow, those values were inappropriate to get correct results for the whole grain fraction.

An overflow in the upper part of the fan occurred before the dense forested areas were treated as obstacles. The overflow was due to the slow velocity of the flow at the inlet (~1m.s^{-1}). It resulted in creating dikes, decision taken while analysing photos of the event. Those forested areas were actually acting as a fence, preventing the mud to flow towards the east and west directions. This was not taken into account in the original DEM.

3.2.5. Results

A triangular hydrograph has been used to model the input parameters. The total duration of the discharge was approximately 54 minutes (3246 timesteps of one second), increasing from 0 to 15.9 m³.s^{-1}, maximum value, after 18 minutes (timestep 1087) then decreasing until the end of the input time. The total volume of the surge represents 23,129 m³.
The speed of the flow at the inlet was regularly increasing from 0 to 1.25 m.s^{-1} at timestep 1080 then decreasing to reach 0 m.s^{-1} again at the end time of the input discharge.
The density of the flow was fixed at ρ = 2000 kg.m^{-3}.

Both **Bingham** and **Coulomb-viscous** rheologies were tested. The results (extension and thickness) of the simulations were compared to the deposits measured on the field after the event. The shape of the extension of the deposits was reasonably well predicted with both rheologies.

The best parameters were τ_y = 2500 Pa and v = 525 Pa.s for the Bingham rheology (figures 14.a. and 15), τ_y = 2500 Pa, v = 1300 Pa.s and φ' = 4.8° for the Coulomb-viscous rheology (figure 14.b.). Different sets of parameters can obtain very good results, but those ones were the best.

The thickness of the Coulomb-viscous simulation is the most similar to the field deposits. The simulated deposits are thicker with the thickest area situated in the upper part of the fan, inside the debris-flow coarsest deposits boudary, alike the real event. The thickness differences are more pronounced with the Coulomb-viscous rheology. The Bingham rheology allows the flow to spread as a regular layer, yet keeping the thickest deposits at the right place, just a bit southern compared to the Coulomb-viscous simulation.
On the other hand, the Bingham rheology simulates better the general shape of the event. The simulated deposits mostly stayed into the debris-flow deposits boundaries (which corresponds to the non-fluvial deposition) and never spread more than the fine deposits. However, there is still some spreading into the fine fraction zone.
For both simulations, the problematic zones are situated on the upper part of the fan. On the northeastern part, the flow expanded on the side is a bit too thick compared to the field datas: this can be explained again by the presence of trees that could have acted as a protection against the flow during the event. The northwestern part is also concerned by this overflowing, but this time with no possible explanation.There is also a bit too much spreading on the southeastern lobe, but according to the event photographs where you can see fine mud deposits further than the road, **the predictions seem realistic**.

Figure 13: aerial photograph of the debris flow deposition

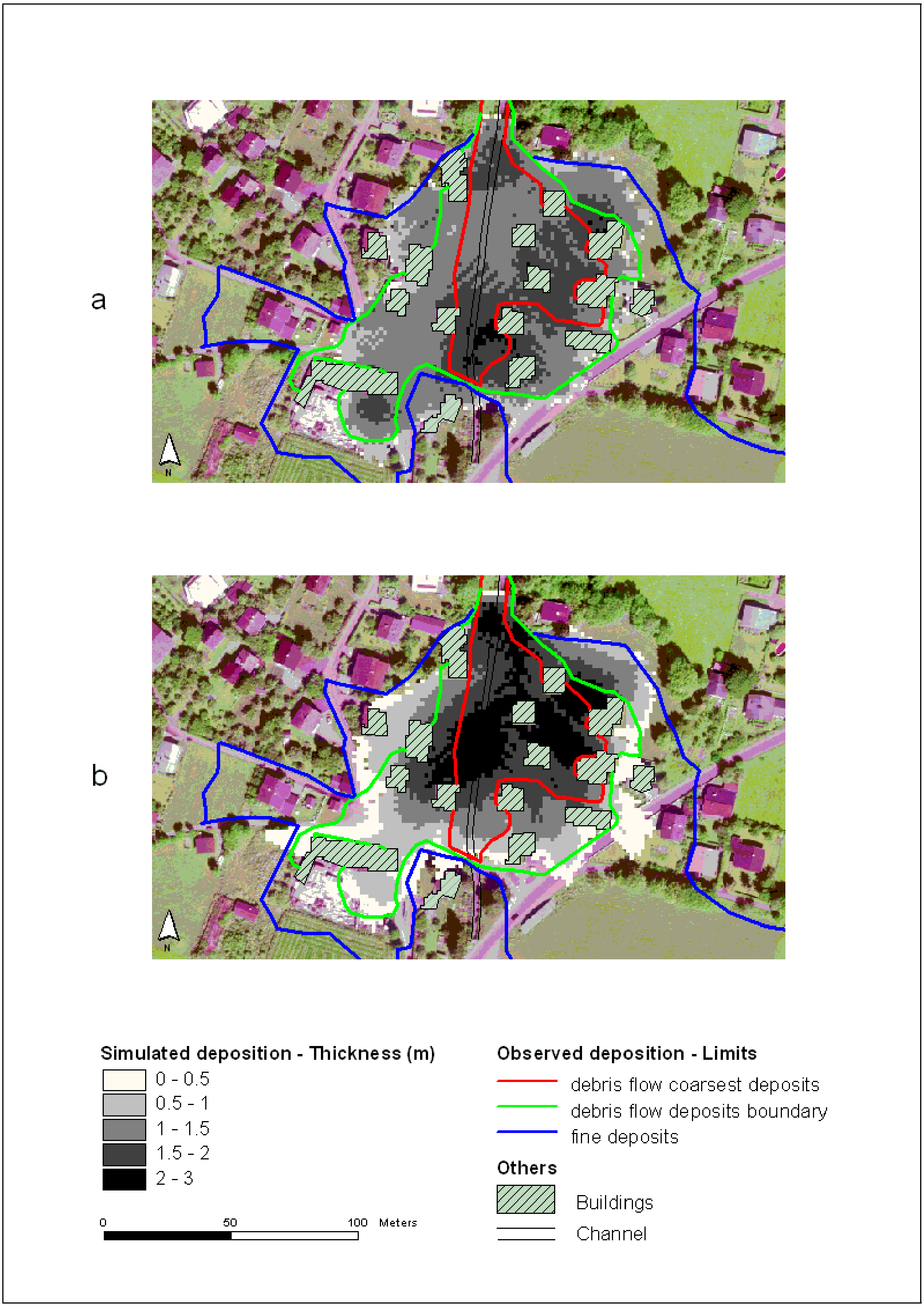


Figure 14: best simulations

a. Bingham rheology, ρ = 2000 kg.m^{-3}, τ_y = 2500 Pa, ν = 525 Pa.s

b. Coulomb-viscous rheology, ρ = 2000 kg.m^{-3}, τ_y = 2500 Pa, ν = 1300 Pa.s, φ' = 4.8°

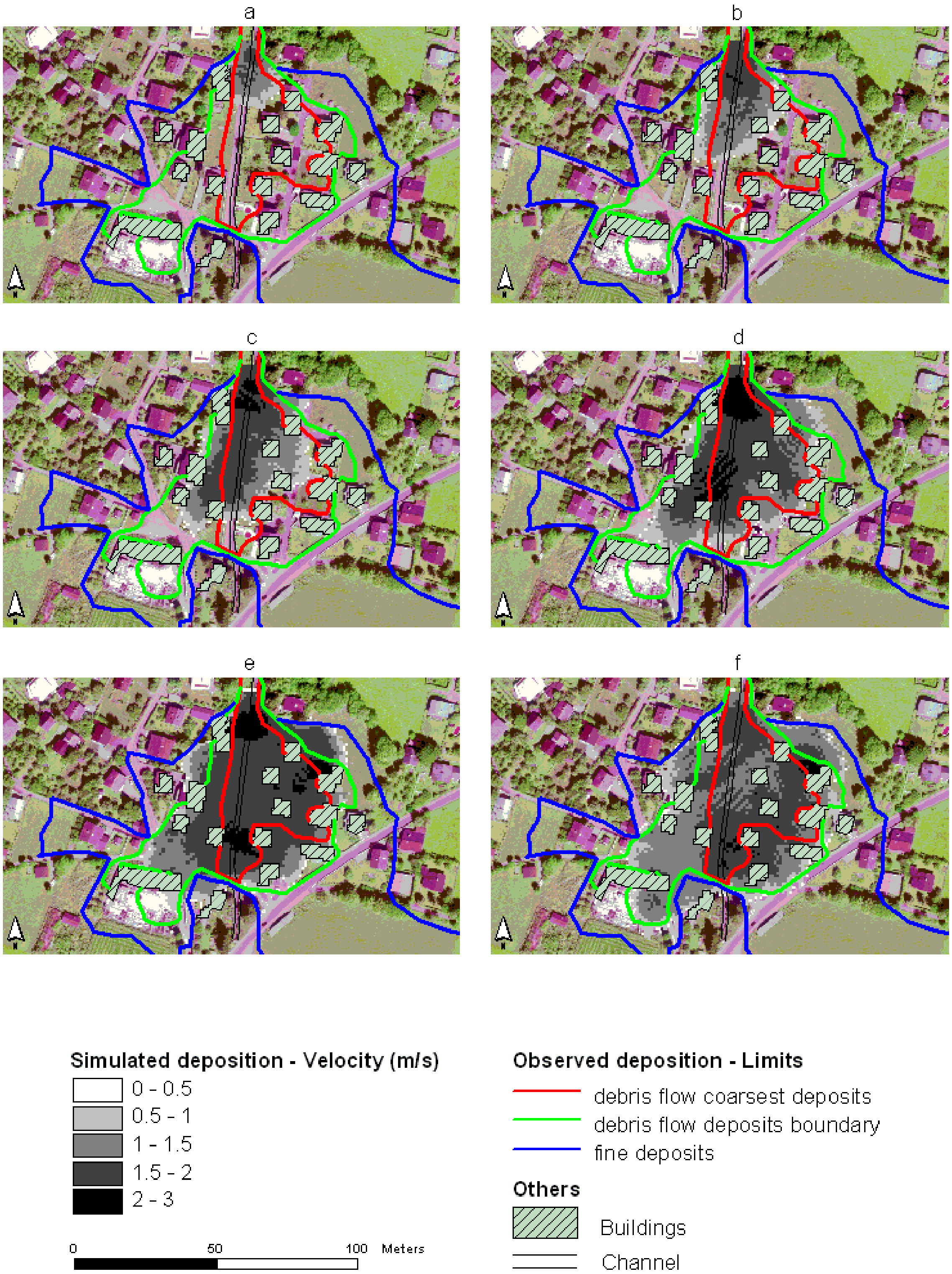


Figure 15: bingham best simulation at timesteps a = 500 b = 800 c = 100 d = 1500 e = 2500 f = 4000

3.2.6. Comparison to the work of Rickenmann et al. (2006)

Rickenmann & al. have already treated the Wartschenbach case (figure 16), simulating the event respectively with the HB model (**Bingham rheology**) and the DFEM-2D model (**Voellmy rheology**) (appendix 3).
They were using the **τ_y/ρ** and the **v/τ_y** ratios to define the characteristics of the flow. For their experiments, those ratios were $0.8 < \tau_y/\rho < 1.35\ m^2.s^{-2}$ and $v/\tau_y = 0.3\ s^{1/3}$.

The values of τ_y/ρ, calculated from the input parameters of the best simulations, were this time ranging from 1.075 to 1.25 $m^2.s^{-2}$, which is very similar, but the mean ratio v/τ_y equals 0.22 $s^{1/3}$, slightly lower than the value of 1/3 proposed by Rickenmann, and before that, by Coussot et al. (1998).
Based on simulated datas at local points (the five same points where the sensitivity analysis has been made, see 3.4.1.), values of τ_y/ρ are calculated using the relationship $\tau_y/\rho = g.h_0.(\sin i)$ where g = gravity, h_0 = thickness of the deposit, and i = slope. The result is $0.6 < \tau_y/\rho < 1.22\ m^2.s^{-2}$

The fine fraction of the deposits was analysed in previous publications dealing with the Wartschenbach case (Rickenmann et al., 2006, Hübl and Steinwendtner, 2000). The yield stress values after laboratory experiments were respectively estimated at 53-79 Pa and 36-79 Pa, whereas the viscosity values were estimated at 4-6.3 Pa.s and 2.5-6.3 Pa.s.
The huge difference of the values used as input parameters can be surprising, but it is worth precising they are relevant for the whole debris flow and not only the finest grains. The values used by Rickenmann et al. for the modelling are not given in the article.

Nevertheless, the results presented above **seem to be better than those of Rickenmann**. The thickest area is situated further upstream, the shape is also fitting better the real deposition.

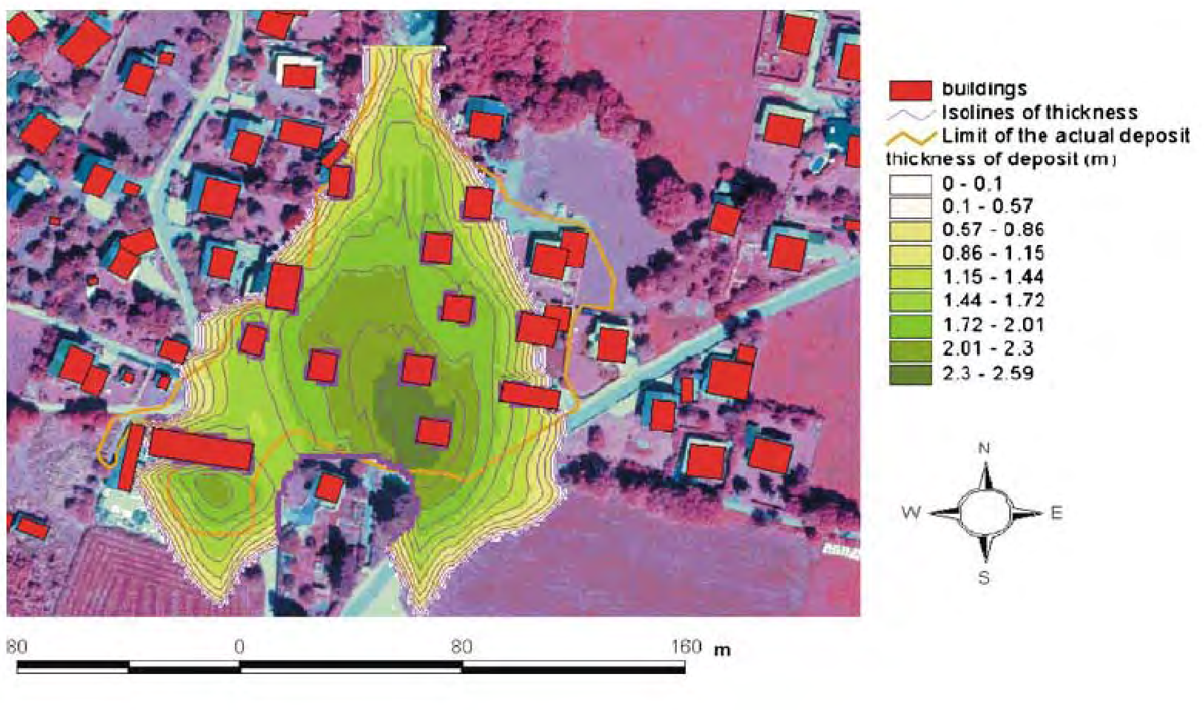


Figure 16: simulated deposition of Rickenmann et al. (2006) with the HB model

3.3. Faucon (France)

3.3.1. Description of the study site

The Faucon torrent is located in the Barcelonnette basin in the south of the French Alps, in the Alpes de Haute Provence department (figure 17). The climate type is continental with Mediterranean and mountainous influences, with strong rainfall differences during the year (733 ± 412 mm over the period 1928-2002) and strong storm intensities (over 50 $mm.h^{-1}$).
The size of the catchment area is 8.2 km^2. The torrent takes his source at 2550 meters, flows down during 6 km with a mean slope of 17° to join the Ubaye river at the altitude of 1130 meters (Remaître, 2006).

Figure 17: location of the Faucon torrent, marked by the red 'A' (Google maps)

Debris-flows recently occurred in the Faucon torrent, in 1996 and 2003. The modelling focus on the event of the August 5th 2003, which caused a **significant overflowing** (figure 18) and **damaged the houses nearby the torrent** (figure 19) (appendix 4).

3.3.2. Available dataset

A DEM with a grid resolution of one meter was used for simulating the event. Various numerical maps were used as a basis of the simulations, to define the channel depth or the inlet zone just to name a few. The location of the houses was determined from aerial photographs. They are considered as obstacles.

The event consisted in **four equal surges**, referring to eyewitness statements. Each wave was estimated around 15,000 m^3 with a total volume of the event of 60,000 m^3. It lasted approximately twenty minutes with a lapse of one or two minutes between the waves, which were more or less three minutes long. The maximum discharge of the surges reached 100 $m^3.s^{-1}$, whereas the maximum speed, according again to eyewitness testimony, was around 10 $m.s^{-1}$. The thickness of the flow at the inlet of the simulation varied between 0.5 and 2 meters. The channel of the torrent was 6 meters wide and 2 meters deep.

A laboratory analysis has been made after the event, it estimated the rheological parameters as τ_y = 195 Pa and v = 72 Pa.s (Remaître, 2006).

3.3.3. Characteristics of the event

The Faucon case is very different from the Semeru and Wartschenbach cases. It is the the only case where **the flow crosses the whole DEM**. A channel is involved and a special attention must be paid to the boundaries which are always critical spots.

3.3.4. Main Difficulties encountered

The first problem was about the nature itself of the study case. **Channelized flows** are much more complicated to implement than fan spreading as in Wartschenbach. The **link of the flow between the channel and the banks** is very complicated to model.

At first, the entire part of the material flowing in the channel was giving some momentum to the material which was overflowing on the banks, and thus greatly increasing the overflow. Basically, only the material which is over the two meters depth of the channel (i.e. only the part of the surge that overflows) should give the momentum to the material on the banks. The overflowing effect is then much reduced. It was necessary to modify the original model code in order to correctly describe the overflow from the channel. After the modification, exchange of mass and momentum between the channel and the banks only occurs when there is a physical connection between both flows, i.e. when the flow thickness exceeds the height of the channel walls.

Other problems were situated at the **boundaries** of the DEM, at the inlet and the outlet. The numerical smoothing implemented in the model correlates the amount of material of the cells that are situated next to each other. It averages the thickness and velocity of the cells in order to avoid numerical instability in the time propagation of the solution. Based on the thickness at the inlet, the cells located right next to the inlet cells were thus acting as if they were giving material. But those cells were situated outside of the channel and therefore not allowed to release some flow into the DEM, therefore creating an overflow immediately at the border of the DEM, at the inlet. This bug was only discovered when modelling a channel flow and did not have an effect on previous simulations. Another problem was located at the outlet of the DEM. Although the outlet cells were planned to let the flow through, they were reflecting some of the material into the DEM due to the central differences scheme used for calculating the spatial derivatives, creating a big overflow at the end of the channel. Both problems have been solved by modifying the original script of the model.

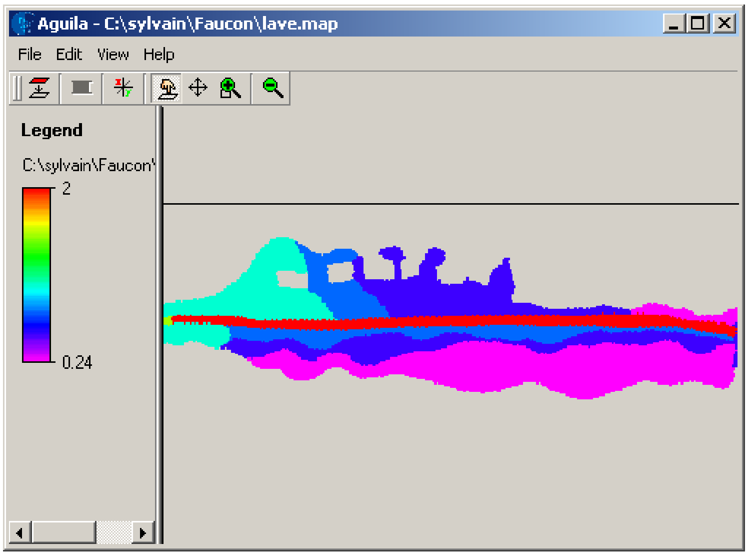


Figure 18: deposition thickness of the debris flow within a PcRaster view

The DEM was also problematic. It was impossible to have a DEM that was exactly the same as the field topography. The original DEM was really imprecise along the channel area and some zones were inexplicably flat, then steeper, the whole area finally looking like a stair way. This was probably an artefact resulting from the interpolation algorithm of the DEM from the original topographical information in the form of contour lines. Considering the channel, overflowing always occurred at the exact spot of the first curve in the channel. Consequently, the DEM has been modified and smoothed to get better results, and as the results were still unsuccessful, the channel was straightened, obtaining almost the same case as an artificial flume (this explains the difference between both real and numerical channels on the maps). This was a better way to calibrate to model and get the optimum rheological parameters, which were the main purpose of the study.

Figure 19: damaged house nearby the torrent

Then it was difficult to decide how the **scenario** of the event should be interpretated. The first two surges were similar to a hyperconcentrated flows, whereas the two following waves were real muddy flows. The hyperconcentrated surges just flowed under the bridge in the torrent with no overflow on the banks, whereas the first muddy surge was mostly blocked by the bridge, creating a stopper. When the fourth surge arrived, it swept the bridge away, generating most of the overflow downstream the location of the bridge. Thus, the fourth surge was responsible for the main extension of the deposits.

That is why it has been decided to model only the **fourth surge**, with a total volume of 15,000 m³ corresponding more or less to the amount of the observed deposits on the field (approx. 12,000 m³).

Modelling the four surges ended either in a huge overflow or in very fluid waves, since it was impossible to find a balance between parameters that would let the surges flow in the channel, and parameters that would cause overflowing. Considering the total volume of the four waves (60.000 m³) and the volume really spread on the banks, getting a correct match with the field deposits was impossible.

To match the field conditions, an **obstacle** has been numerically built in the DEM, representing the stopper created by the third surge. This obstacle is located in the channel at the place of the first bridge, with a height of 1 meter.

A trench has been created too, once again to get as close as possible to the real characteristics of the event. It is situated just before the last building of the DEM, acting as a protection since the mud accumulated in without flooding the house.

Moreover, to represent the forest which prevented the mud to widespread far from the channel, an area where the **viscosity is multiplied by two** has been settled in the DEM, right next to the channel on the right bank.

3.3.5. Results

The density of the flow was fixed at ρ = 1850 kg.m^{-3}. A constant discharge of 100 m³ was used during 150 timesteps of 1 second. The thickness of the surge was 1.67 meters high, with a constant velocity of 10 m.s^{-1} at the inlet.

As for the Wartschenbach case, both **Bingham** and **Coulomb-viscous** have been used to model the event. The best simulations have been modelled with parameters of τ_y = 400 Pa and v = 65 Pa.s for the Bingham rheology (figure 20.a.), and τ_y = 200 Pa and v = 10 Pa.s and φ' = 3.8° for the Coulomb-viscous rheology (figure 20.b.). Again, other sets of parameters obtained very good results.

Concerning the shape, the Bingham rheology is underpredicting the size of the flooded are, whereas the Coulomb-viscous rheology is overpredicting it.
Concerning the Bingham simulation, the influence of the area where the viscosity is doubled is clearly visible on the right side of the torrent. The overflow is a bit underestimated, meaning that most of the material is flowing in the channel across the DEM. On the left side of the channel, the spreading is well matching the real deposition, except before the second bridge where there is no overflow at all.
The main overflow happens exactly at the spot of the first bridge, where the obstacle has been located. After approximately 2 minutes, the overflow moves back and flows further up on the banks, explaining the final shape. Both rheologies are concerned by this phenomenon.
The Coulomb-viscous rheology simulates more spreading than in reality. There is a bigger overflow on the left bank around the houses, then slowly decreasing along the torrent. The overflow on the right bank is also too important with this time no obvious effect of the high viscosity area.

Nevertheless, the Coulomb-viscous rheology globally provides a better thickness distribution. The deposits are thicker and match the event thickness pretty good. The simulation with the Bingham rheology resulted in thinner and more homogenous deposits, as if only a small mud wave would have ran on the banks.

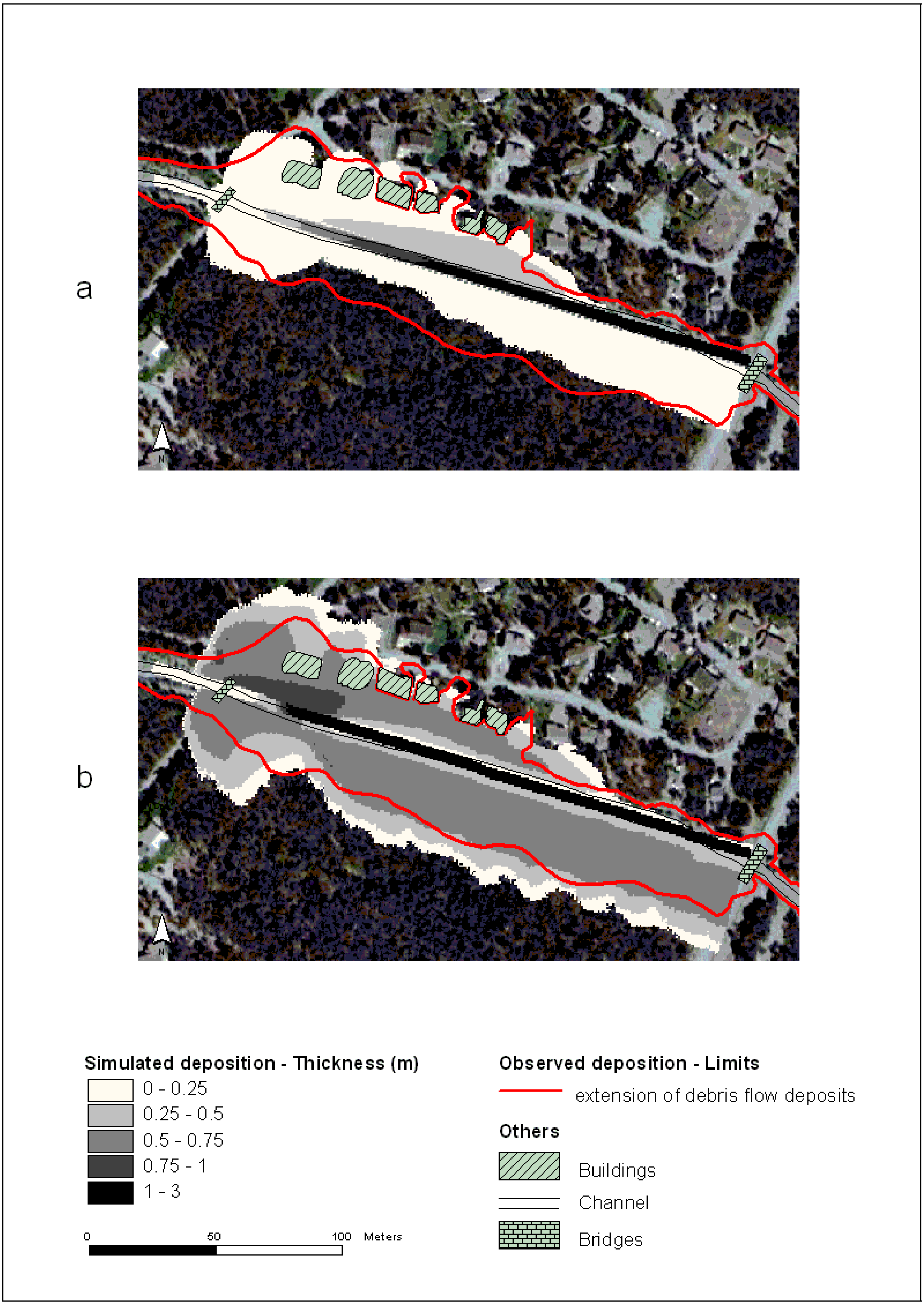


Figure 20: best simulations

a. Bingham rheology, ρ = 1850 kg.m^{-3}, τ_y = 400 Pa, v = 65 Pa.s

b. Coulomb-viscous rheology, ρ = 1850 kg.m^{-3}, τ_y = 200 Pa, v = 10 Pa.s, φ' = 3.8°

3.3.6. Discussion – Comparison to the work of Remaître (2006)

The Faucon case, which is one of the pilot study site of the Mountain Risks project was very tricky to model. Considering all the modifications described before which were necessary to obtain a good result, the **model code had to be modified several times**. Those difficulties were mainly caused by the fact that a channel flow is involved in the simulation, and the biggest difficulty is to represent the link between this channel and the banks.

There are only a **few examples** of study cases with channel modelling in the literature yet, but the Faucon debris flow of 2003 has already been modelled by Remaître (2006) with a Herschel-Bulkley rheology. His parameters for the best simulation (figure 21) were τ_y = 404 Pa and v = 122 Pa.s, values very close from the best Bingham parameters of this study.

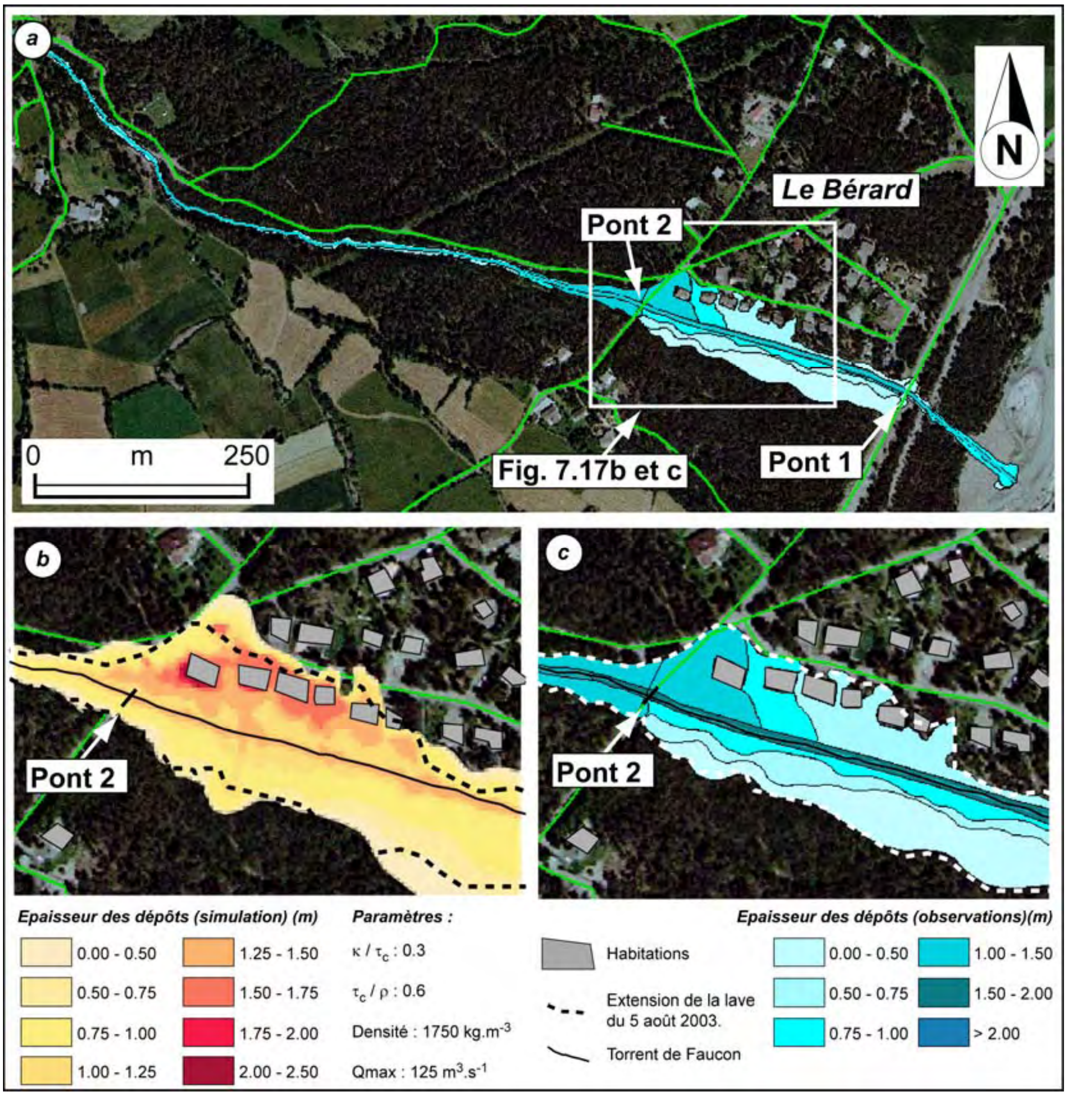


Figure 21: simulated deposition of Remaître (2006)

3.4. Sensitivity analysis of the MassMov2D model

3.4.1. Methodology of the sensitivity analysis

The sensitivity analysis has been made on the **Wartschenbach** case.

Thickness and velocity have been compared at **five different points** on the map (figure 22) for both Bingham and Coulomb-viscous rheologies. Three of them have placed in the channel, and two others into the thickest part of the deposits.

Rheological parameters have been modified to reach **± 10, 25, 50, 75 and 90 %** of the density, yield stress, viscosity and friction angle (for the Coulomb-viscous rheology) of the best simulations. The thickness of the flow has been surveyed at the final timestep of the simulation, whereas the velocity has been surveyed at timestep 1800, before the end of the input time. **New input sedigraphs** have also been used while keeping the parameters of the best fit, allowing to compare the influence of different thickness or velocity at the input zone on the spreading.

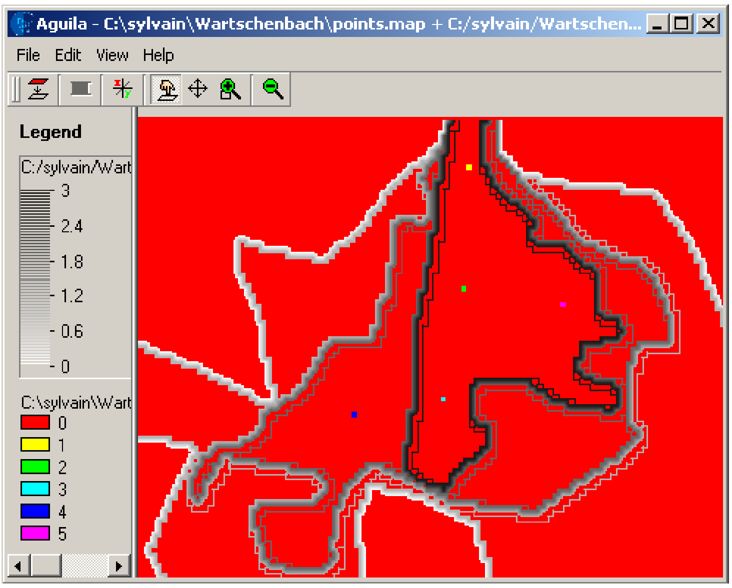


Figure 22 : location of the five points on which the sensitivity analysis has been made

3.4.2. Influence of the rheological parameters on the thickness

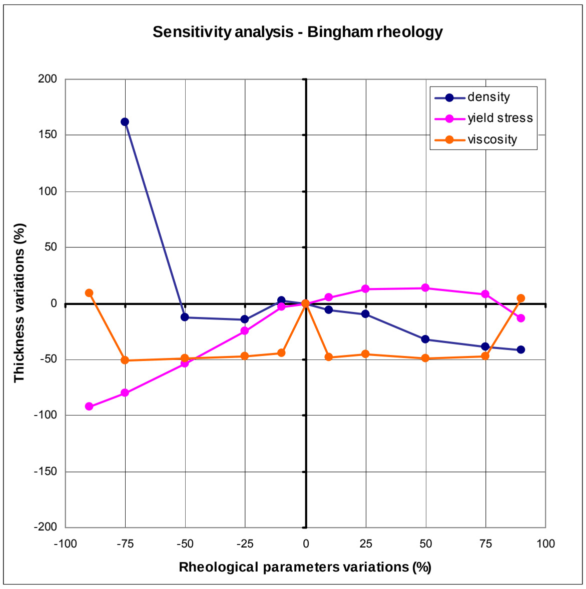


Figure 23: results of the sensitivity analysis on the thickness (Bingham rheology)

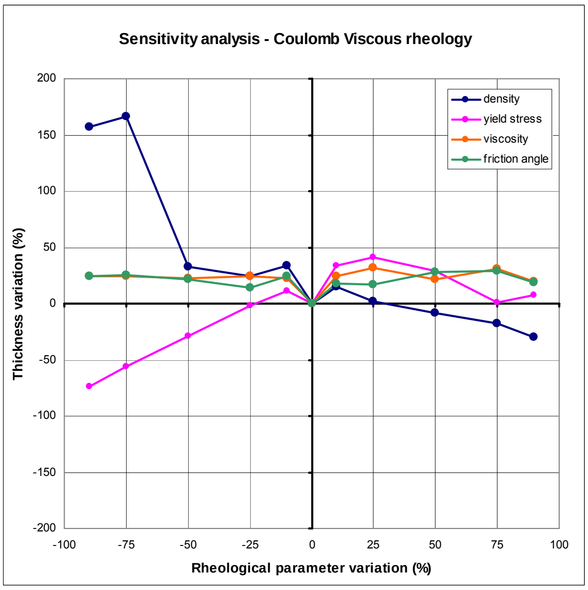


Figure 24: results of the sensitivity analysis on the thickness (Coulomb-viscous rheology)

For both rheologies (figures 23 and 24), the thickness of the deposits is highly increased (+160 %) when the density of the flow is inferior to - 50 %. There is a slight decrease of the thickness as the density is increasing.

The yield stress curve is also similar on both graphics, providing a thickness decrease when the yield stress is the lowest, increasing as the parameter value is increasing too, with a slight decrease when the value is the highest.

The viscosity has a different influence depending on the rheologies. The curve of the Bingham rheology is symetrical, increasing the thickness only at the extreme parameters values, whereas it keeps along - 50 % for the others. The curve of the Coulomb-viscous rheology stays almost constantly at a value close to + 25 %.

The angle of friction tends to thicken the deposits, no matter of the variation of the parameter.

3.4.3. Influence of the rheological parameters on the velocity

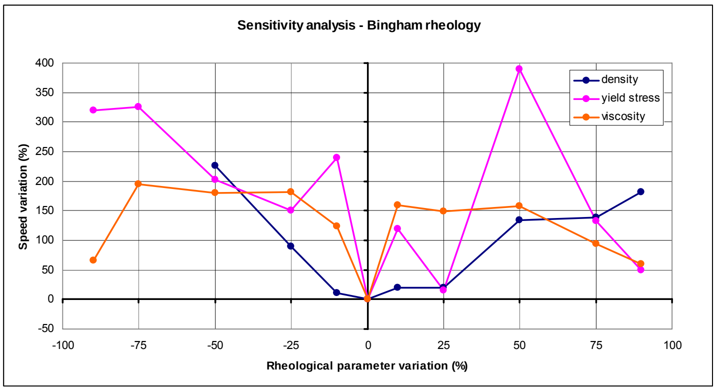


Figure 25:results of the sensitivity analysis on the velocity (Bingham rheology)

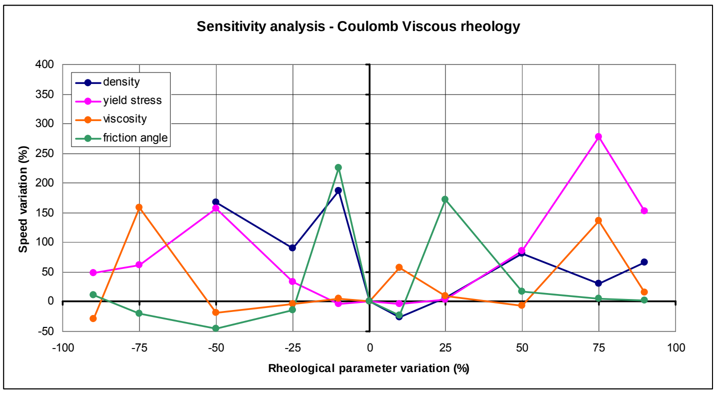


Figure 26:results of the sensitivity analysis on the velocity (Coulomb-viscous rheology)

The velocity variation **does not seem to be a useful indicator** (figures 25 and 26). The velocity of the flow in one pixel during a simulation is very random, and greatly varies during the computation time (figure 27). It is depending on the material situated on the pixel upstream, and as the material stops and starts again to flow many times during a simulation, the velocity value at the timestep 1800 can equals 0 although the material will re-start to flow at timestep 1801. Velocity values are then greatly random and thus don't have a real meaning.

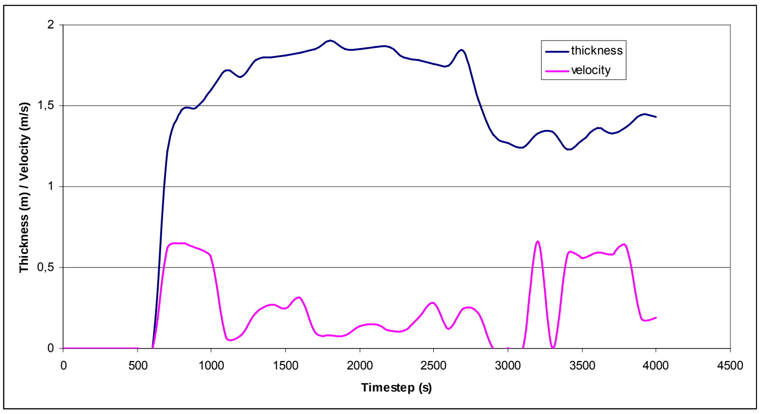


Figure 27: Velocity and thickness variations during a simulation (Bingham reference simulation)

3.4.3. Influence of the input sedigraphs on the spreading

For testing the influence of the input parameters on the field deposition, the original input sedigraph (figure 28) have been changed for both rheologies. **Keeping the total volume event and the rheological parameters of the best simulations for both rheologies**, simulations have been run using new input sedigraphs, with 2 equal surges (figure 29) and 3 different surges (a big wave followed by two smaller) (figure 30). Those scenarios could correspond to real debris flow event.

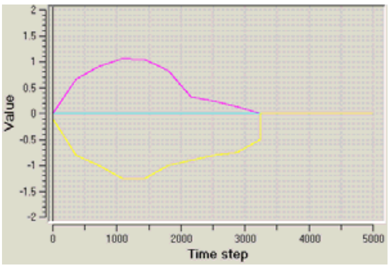


Figure 28: reference sedigraph

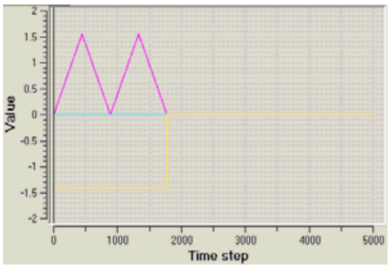


Figure 29: 2-surges sedigraph

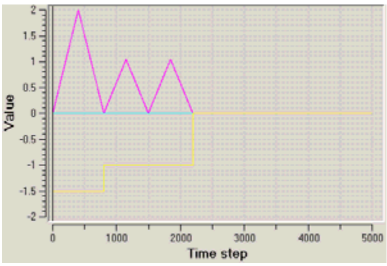


Figure 30: 3-surges sedigraph

Concerning the Bingham rheology (figure 31), the results with the 2-surges sedigraph are very similar to the original input sedigraph: the overflow is only a little bit more pronounced on the western corner but the thickness distribution is the same. There are no real differences with the 3-surges sedigraph simulation.

About the Coulomb-viscous rheology (figure 32), both 2-surges and 3-surges sedigraph provide thinner deposits than the original sedigraph, the thickness layer is more regular. **The sedigraphs do not seem to have any important influence on the deposits shape.**

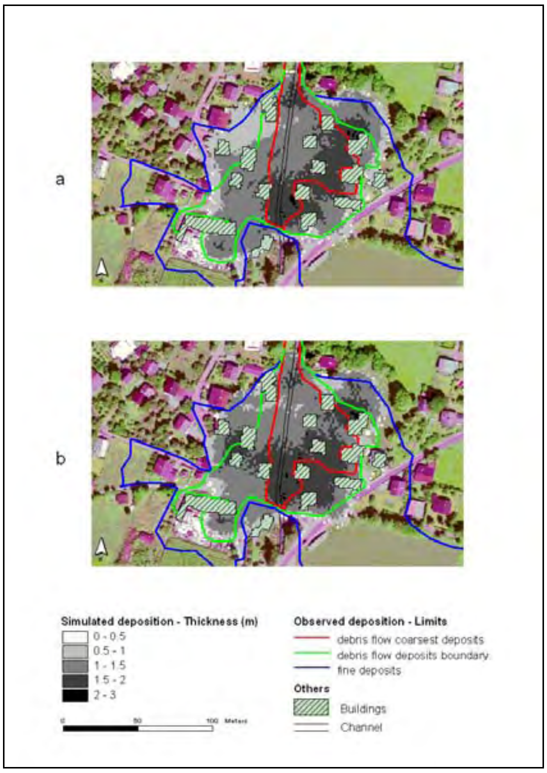


Figure 31: Bingham rheology deposition

a. two-surges input sedigraph
b. three-surges input sedigraph

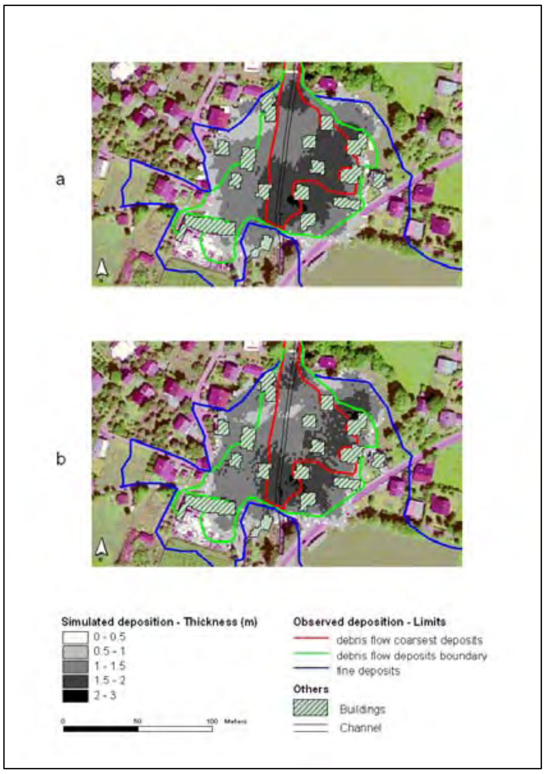


Figure 32: Coulomb-viscous rheology deposition

a. two-surges input sedigraph
b. the three-surges input sedigraph

CONCLUSION

MassMov2D is a **numerical simulation model** of the run-out and deposition phases of debris flows. It can be adapted to material with different characteristics, therefore several rheologies can be implemented. The model is integrated into a GIS environment, resulting in a friendly interface and easy handling.

The purpose of this study is the **calibration** of the MassMov2D model with a **back analysis** on debris flow events.
The Semeru case is the least documented event, and the modelling results are rather an opening towards further work.
On the contrary, Wartschenbach and Faucon cases are well documented events and precise field observations have been made. Simulated depositions are very close to the real deposition in both cases, using Bingham and Coulomb-viscous rheologies. **The determination of the extent and thickness of the deposits supports the validity of the model**. The comparison with previous studies on the same field events is also a good reference to rely on and proves the correct calibration of the model.

The results maps of Wartschenbach and Faucon cases will be used for a research paper which is going to be submitted within the next months. Then, the MassMov2D will be recognized as a tool for **natural hazards evaluation and mitigation**, allowing to predict mass movements behaviours and to estimate flow characteristics such as the depth or the impact force. A Monte Carlo analysis would be the next step in order to result in a hazard map of the zone. Even if models are always a simplification of the reality, their application finally concerns real life.

The future tools for debris flow modelling will have to be able to use different rheologies during the same run and to allow the model to switch from one phase to two phase flows. Those improvements would be a step forward towards a finest modelling precision.

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APPENDIXES

Appendix 1: collisional and constant frictional results of the Semeru event modelling (Durand, 2006)

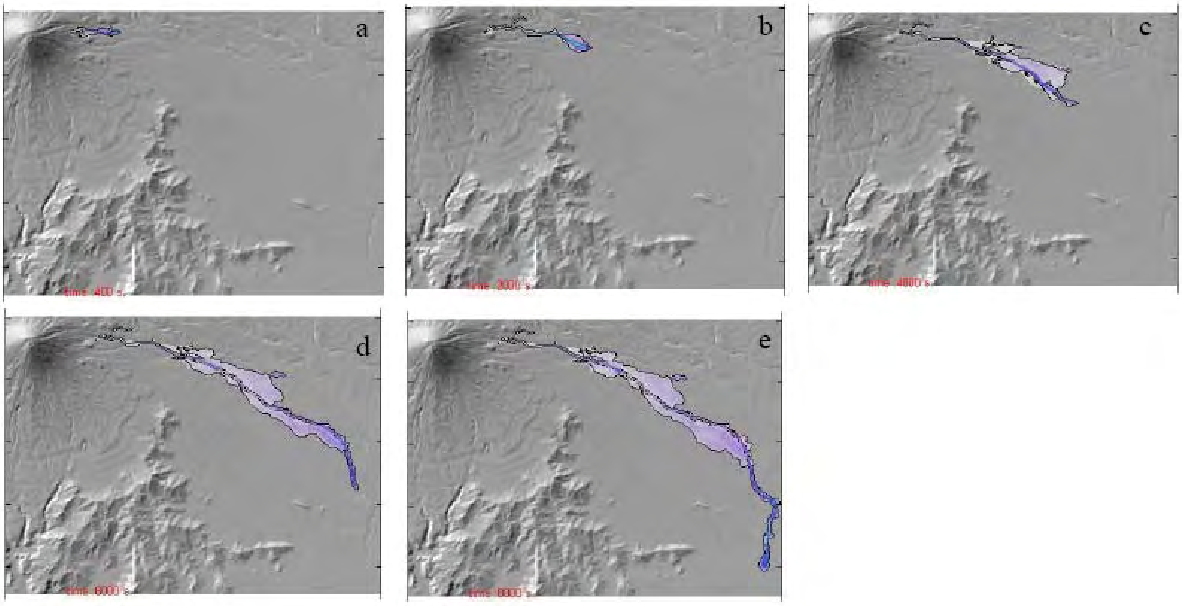

Figure A.1: collisional results

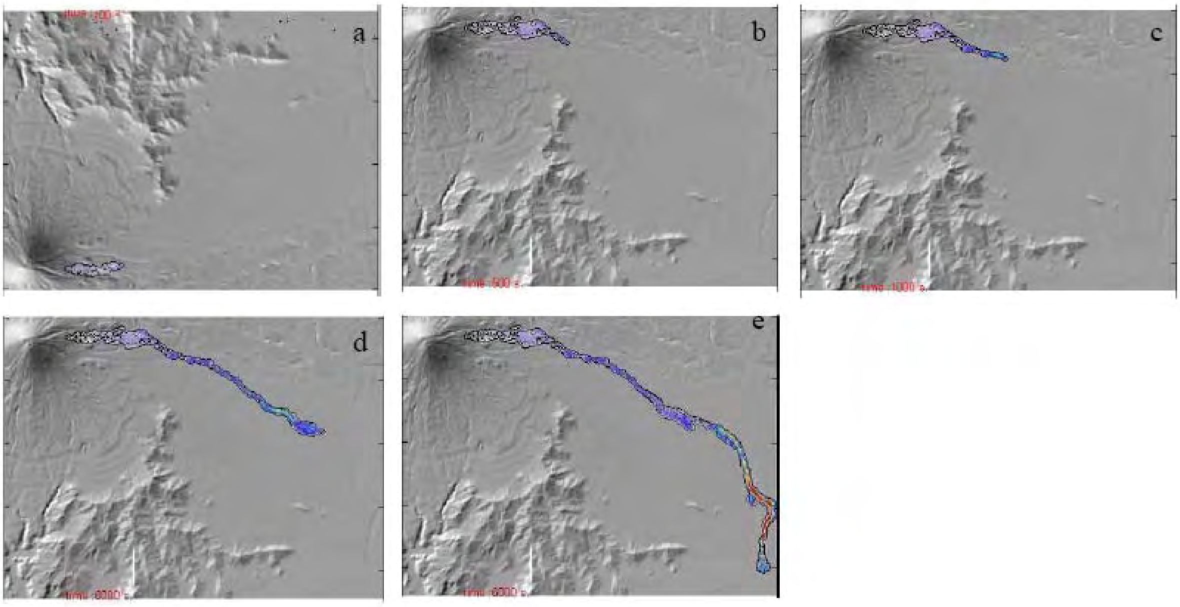

Figure A.2: constant frictional results

Appendix 2: photographs of the Wartschenbach event

Appendix 3: Voellmy rheology results of the Wartschenbach event modelling (Rickenmann et al., 2006)

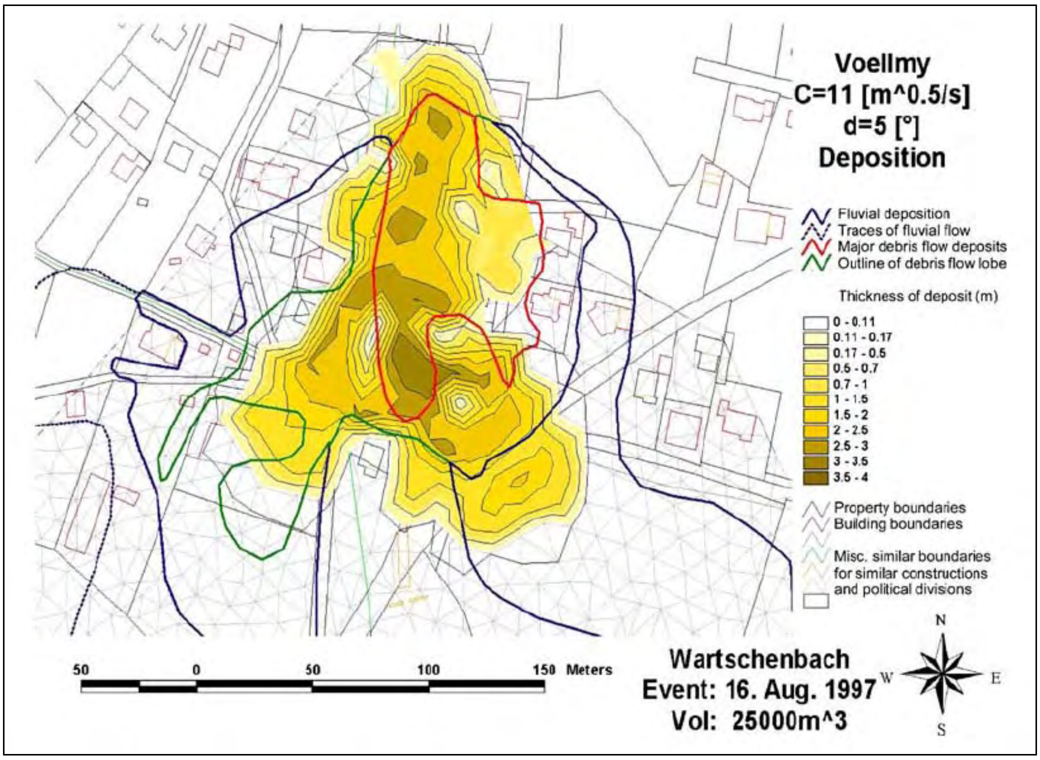

Figure A.3: Voellmy rheology results with an angle of friction = 5°

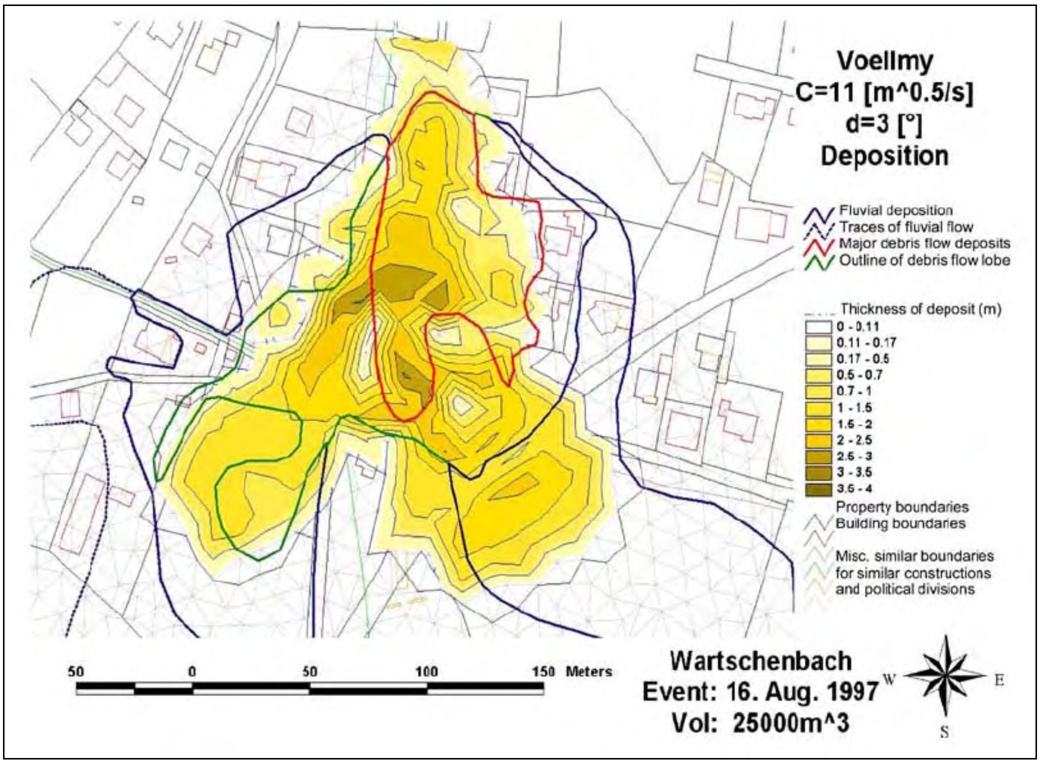

Figure A.4: Voellmy rheology results with an angle of friction = 3°

Appendix 4: photographs of the Faucon event

ABSTRACT

Debris flows are a major risk in mountaineous areas. They are highly concentrated mixture of soil, rock, debris and water flowing into a torrent channel. Most studies about modelling debris flows are still in progress. The purpose of this work is to calibrate a debris flow and landlside model on three well-documented field events. The model is an easy-to-use tool, highly linked with a GIS software. Several rheologies can be implemented for a precise description of the flow behaviour. The events are back analysed with numerical simulations, deducing the rheological parameters of the flows. A sensitivity analysis of the model is also made.

RESUME

Les laves torrentielles constituent un risque majeur dans les régions montagneuses. Ce sont des volumes importants de sédiments de toutes tailles mélangés à de l'eau s'écoulant dans le lit d'un torrent. La plupart des études concernant la modélisation des laves torrentielles sont toujours en cours. L'objectif de ce travail est de calibrer un modèle conçu pour simuler des laves torrentielles et des mouvements de terrain sur trois événements bien documentés. Le modèle est très simple d'utilisation et fortement lié à un logiciel de SIG. Plusieurs rhéologies peuvent être utilisées pour décrire au mieux le comportement du fluide. Les événements sont analysés a posteriori à l'aide de simulations numériques, pour en déduire les paramètres rhéologiques des coulées. Una analyse de sensibilité du modèle est également effectuée.