Debris-flow monitoring and debris-flow runout modelling before and after construction of mitigation measures : an example from an instable zone in the Southern Swiss Alps

Christoph Graf
Brian W. McArdell

WSL Swiss Federal Research Institute
Zürcherstrasse 111
CH - Birmensdorf

E-mail:
christoph.graf@wsl.ch

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Abstract

Recent changes in the source area of an active rock avalanche catchment near Preonzo, Switzerland, resulted in an unanticipated change in the flow path of the debris flow torrent which bypassed existing mitigation structures, including a large retention basin. Two new debris flow deflection dams were built in 2007 in the transit area to re-direct future debris flows back into the old channel and the existing debris flow retention basin. The torrent is monitored by an automated debris-flow observation station providing information on velocities and flow depths of the flow processes. Due to the recent changes, the station was moved to the new channel and successfully recorded several debris-flow events. Using the RAMMS (Rapid Mass Movements) simulation software, which describes the flow of debris using the 2D shallow water equations and a Voellmy relationship for the flow friction, we describe simulations where we evaluate the effectiveness of the new deflection dams. First the model was calibrated using data from an event in 2004, then the dams were incorporated into the topography using the RAMMS model, and finally the model was run over the new topography using data from an event that occurred in 2007. Results indicate that the new deflection dams will function as intended for debris flows of up to about the same size as the event in 2004. This was confirmed by recent events of similar magnitude.

1. Introduction

Debris flows are destructive and fast flowing mass movements in mountain regions. For their formation, steep terrain, loose rock material and abundant water are needed. They happen infrequently and often unanticipated. Even small events can endanger people and damage infrastructure (Sidle and Ochiai, 2006). Debris flows show a wide variability in their flow properties depending on, for example, the triggering mechanism, available material and water input. The debris flows considered in this paper are of granular type (Pierson, 1986). The catchment is monitored by an automated debris-flow observation station by the Swiss Federal Research Institute WSL since 2002.

Debris flow monitoring provides important information for both modelling and warning (Itakura et al., 2005). Many systems have been developed worldwide and are in use for scientific or practical applications. Debris flow warning systems typically announce the detection of an event based on the exceedance of threshold values such as flow stage or discharge, or ground vibration (e.g. Badoux et al., 2009 ; Graf et al., 2007). Many sensors and methods have been developed and are in operation. Comparative studies lead to improvements in the reliability of debris-flow detection, which can then be used in an integrated system, which also ideally would incorporate preventative measures. One important goal is to develop a reliable and robust system, which can be adapted to any torrent to supplement preventative and other countermeasures (e.g. Itakura et al., 2005). The main parameters measured are the characteristics of the flow such as front velocity and flow depth. Out of this information timing and discharge of an event can be estimated. Imaging equipment is often used to independently evaluate and verify the data and differentiate among the various types of debris-flow events. One other important aspect of debris-flow monitoring is temporally high resolution information on precipitation to assess the triggering mechanism. Finally, recording and observing the general geomorphological state of the catchment area and the torrential system helps to interpret the event history and detect new trends.

Real event data describing the flow behaviour and characteristics of the moving mass in a catchment are normally not available. Therefore automated measuring systems need to be installed which are triggered in case of an event. It makes sense to install monitoring systems only in debris-flow torrents where one can expect elevated debris-flow activity or where local information is absolutely needed. For other catchments analogy approaches may help to derive characteristic parameter sets.

Numerical runout simulation models provide valuable information on potential impacts of future events (e.g. scenarios) and help to optimize the design of planned or existing mitigation measures (Rickenmann et al., 2006). The parameters obtained from debris-flow measurements can be used to calibrate a numerical runout model to help creating a hazard map and designing various types of control structures to mitigate the hazards. They show potential flow paths, runout distances and expected values for flow depth, velocity and impact forces on structures. Because the debris flow process is complex and many details are not yet fully understood, many existing simulation models use a single-phase approach to describe the frictional behaviour of the flowing debris. They thereby simplify the real mixture of water and solid material consisting of a wide range of different grain sizes. The simulation results need to be carefully evaluated and should be compared with existing field data, taking into account the variety of flow types observed in nature.

In this paper we performed post-event simulations of a mid-size debris-flow event originating from an active rock avalanche zone in the southern part of Switzerland, taking into account structural measures realized after this event and interpretation of field data but without the use of extensive studies. Newer event data were used to evaluate if the new structures are capable of performing as designed. This example shows the wide range of applied debris-flow research from monitoring to the event evaluation and runout prediction.

2. Field site

The Frana di Roscero is located in the Riviera valley in the southern Swiss Alps near Preonzo, Canton of Ticino (Fig. 1). It is an active rock avalanche and rock fall catchment producing also debris flows. Recent events took place in the last two decades due to ongoing cracking and rock deformation in the upper area of the steep slope. Situated in the valley bottom is the industrial area Sgrussa. The village of Preonzo is not endangered by the recent developments.

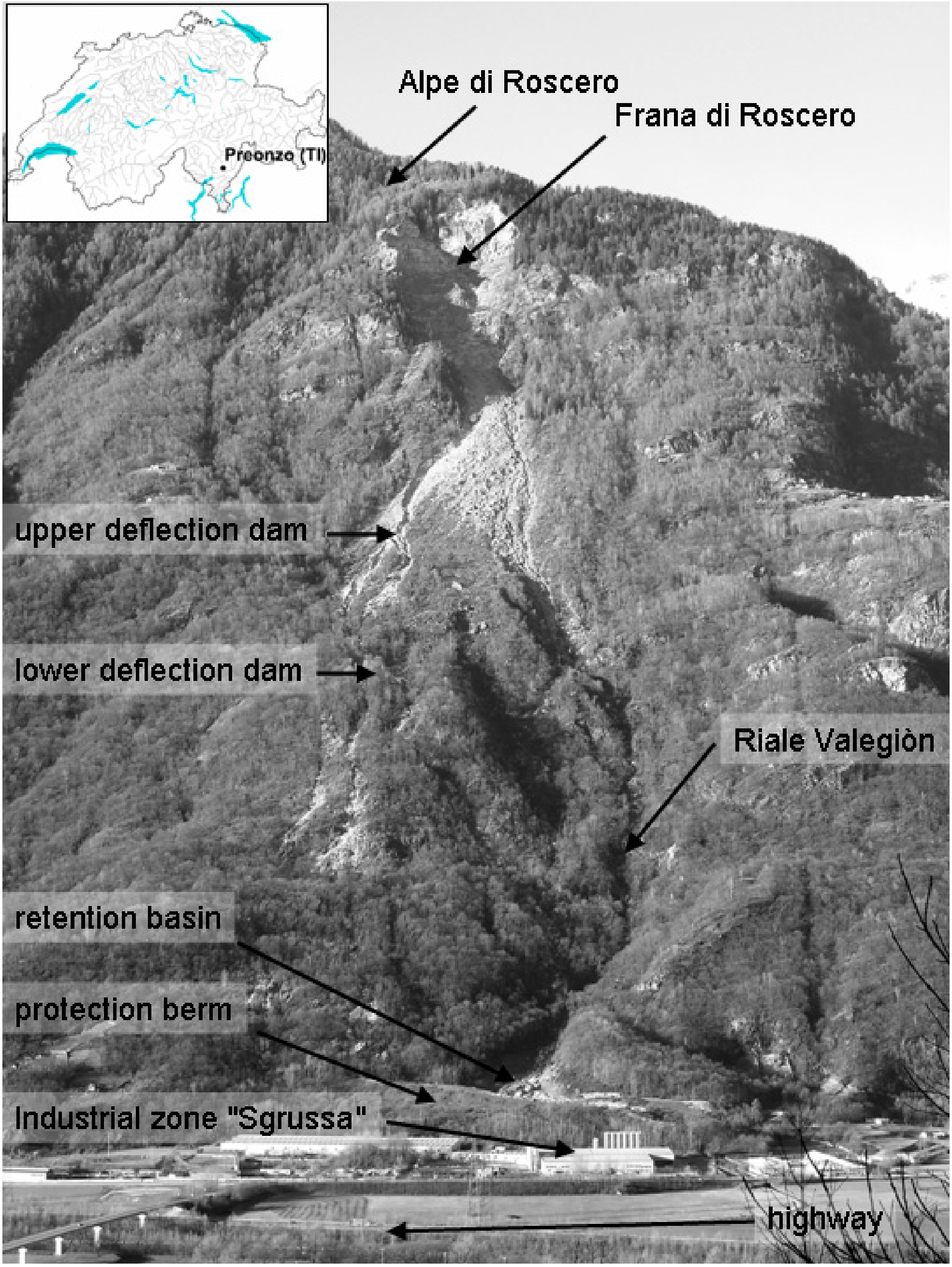

Fig. 1 : Study site (situation end of 2007) showing the Riale Valegiòn, Frana di Roscero with rock avalanche deposition cone and new channel system with the two deflection dams. In the valley bottom, the industrial zone "Sgrussa" is protected by a retention basin with a tall berm. Towards the middle of the valley bottom, the highway and the river Ticino is situated.

Alpe di Roscero above the active rock avalanche catchment is part of the Penninic Simano nappe. Lithologic units consist of upper amphibolite gneisses, augengneisses, banded gneisses and a lower schist unit with foliation and contacts striking WSW and dipping ~25° into the slope (Fig. 2). Three steeply dipping fracture sets are present in the rock mass, two striking parallel to slope while the remaining cuts these perpendicularly (see Willenberg et al., 2009 for illustrations and more details). All observed discontinuities are kinematically in favour of stability. Although ongoing slope monitoring shows displacement at the toe of slope and tension crack at the head of the slope opening at a constant rate. The presence of active springs at the contact with the low permeability schist layer suggests hydraulic connectivity between upper and lower units through permeability in the fracture network.

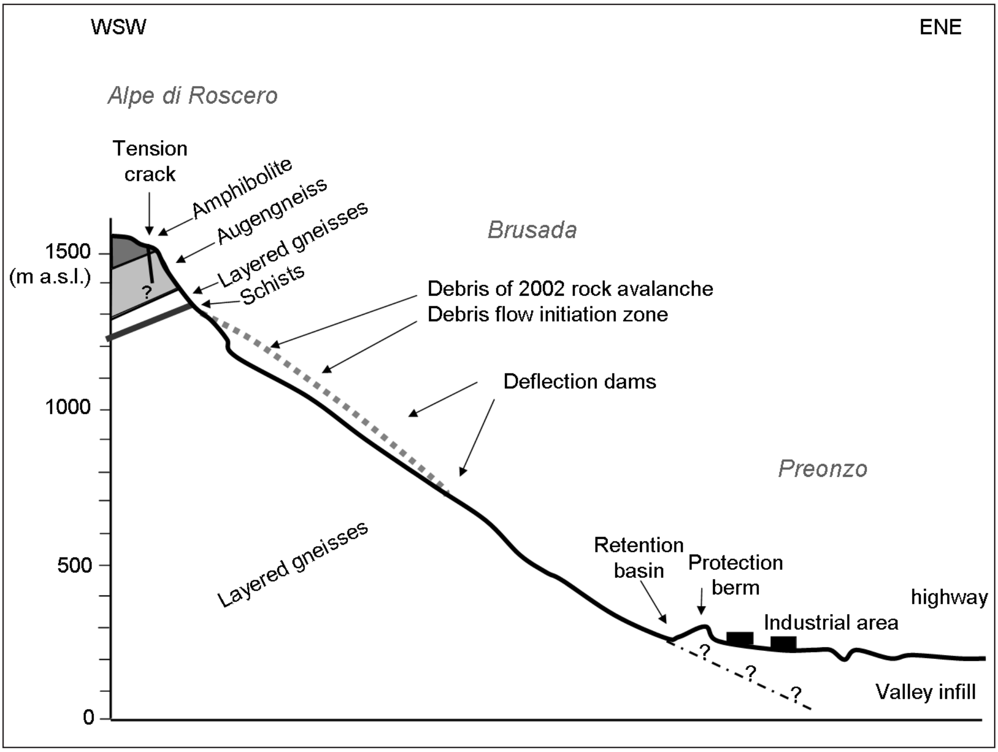

Fig. 2 : Geological cross-section slope along the Valegiòn channel (adapted from Willenberg et al., 2009).

An analysis of the unstable rock mass in the uppermost part of the slope (roughly between 1'200 and 1'500 m a.s.l) based on these observations was conducted (Willenberg et al., 2009). They postulate that failure is initiated along the weak schist layer at the toe of the rock slope. This leads to progressive yielding in shear in the upper units, which eventually localises strain to form a rupture surface. Slope movements then result in extensional strain and tension failure in the head of the slope. Based on this model, with rupture plane extending down to the basal schist layer, an unstable volume between 260'000 m^3 and 680'000 m^3 was estimated and used as input volumes for a rock-avalanche runout analysis.

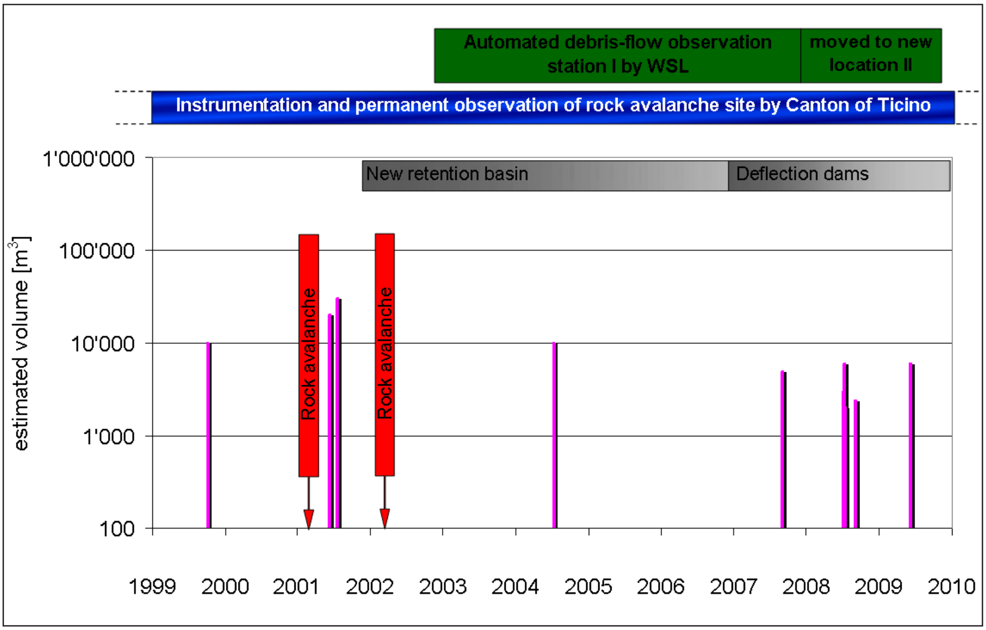

Fig. 3 : Debris flow and rock avalanche events in the last decade in the Frana di Roscero site. Construction times of the retention basin with a tall berm and the two deflection dams is indicated. The time period of observation of rock avalanche site (by the Canton of Ticino) and debris flow torrent (WSL) is also mentioned.

The Frana (= slide or rock avalanche) di Roscero drains into the Riale (= creek) Valegiòn south of the village Preonzo (Fig. 1, Fig. 4). The site has a long history of rock slope failures. In 1760, a large rock slide from the area of the Alpe di Roscero is believed to have destroyed parts of the village Preonzo (Loew et al., 2006). Sgrussa, the name of the locality of the industrial zone means "cairn" or "accumulation of boulders and stones". During the construction of the highway located in the middle of the valley 400 m from the foot of the slope (Fig. 2), boulders have been encountered, and are inferred to have originated from this rockslide. Since 1991, ongoing slope activity has been monitored across a large open tension crack at the top of Alpe di Roscero. The mobilization of this unstable zone in the upper catchment caused several debris flows. After the disastrous debris-flow events in 2001 (Fig. 3) a protection berm and a new retention basin with a capacity of 70'000 m^3 was constructed in 2002, replacing the older and smaller one from the 1990's. In May 2002 a new rock avalanche of about 150'000 m^3 occurred after a heavy rainfall and deposited new loose material, consisting of large blocks in the debris flow source area in the upper catchment. This intermediate cone is expected to move down to the valley bottom in the form of small to mid-size debris flows, as has been observed previously. However the large addition of new debris flow activity in the source area modified the channel network, resulting in a re-direction of the channel into an adjacent channel, located south of the main torrent channel, which bypasses the existing mitigation structures (Fig. 4). The former creek has been reported to be mostly dry since 2003. From summer 2004 on, rock fall activity and debris flows mostly follow the new channel network resulting in affected areas south of the retention basin. To anticipate similar or perhaps larger damages than caused by that flow, two additional deflection dams were constructed near the debris flow initiation area in spring 2007. These deflection dams control the water runoff and force the channel to return to the Riale Valegiòn and the existing retention basin (Fig. 1, Fig. 4).

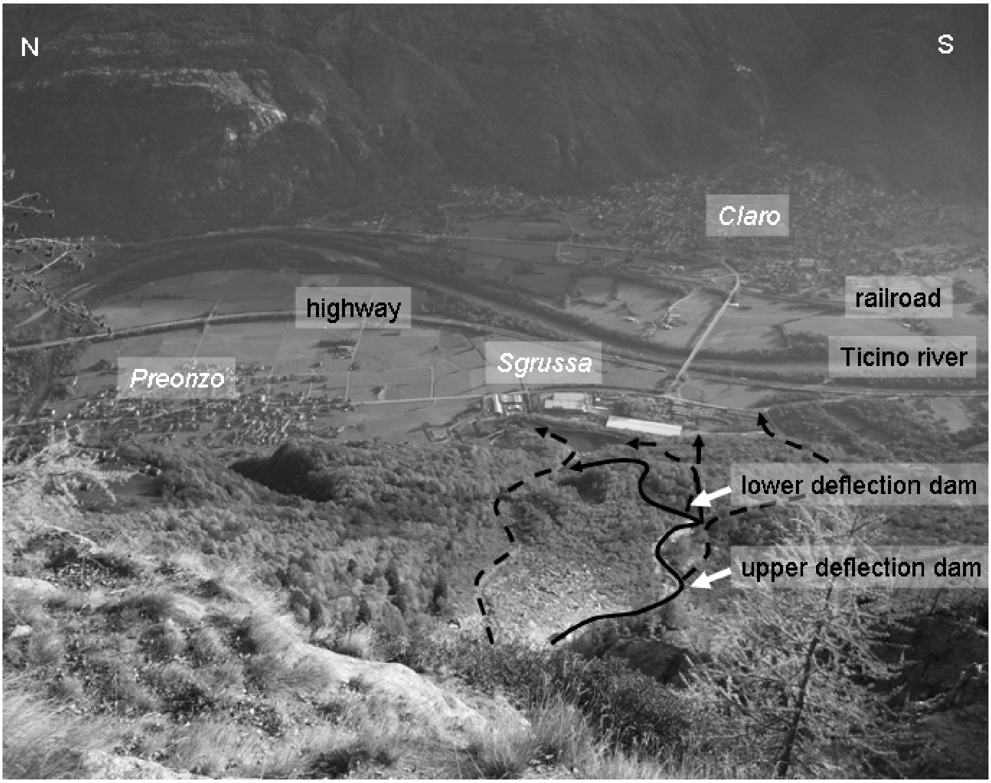

Fig. 4 : View from the Alpe di Roscero into the valley bottom. The industrial zone "Sgrussa" is located in the deposition zone of mass movements. The two villages Preonzo and Claro are not endangered by these processes. In the North, the dashed line indicates the Valegiòn channel. In the South, the dashed line indicates the flow path from 2004 - 2007 (without mitigation measures). The solid line shows the actual debris-flow channel.

Another 700'000 m^3 of potential debris is present in the rock-avalanche initiation zone, and because this mass is actively moving, it must be accounted for in the future. The rock avalanche site is instrumented and has been continuously observed by the forestry service of the Canton of Ticino since 1997. The first system was destructed during the 2002 event and was replaced by a new one based on geodetic survey and completed with extensometers and geophones serving now as a warning system.

The debris-flow triggering mechanism in Preonzo is mainly linked to rainfall. Mean annual rainfall reaches 1'600–1'800 mm/a in the upper catchment (Cotti et al, 1990).

Rainfall events with high intensities but short duration happen frequently (Pedrozzi, 2004). Highest precipitation rates on the order of 220 mm/d originate from typical weather conditions with wind direction southwest in spring and autumn. During summer local thunderstorms are predominant. Winter is normally the driest season. Debris flows can occur from May to the end of October.

3. Monitoring

Monitoring debris-flow torrents is essential to prevent and mitigate the related hazards. A number of monitoring devices and methods have been developed (Itakura et al., 2005). Since 2002 the WSL has maintained an automated debris-flow observation station in the Riale Valegiòn using geophones for estimating front velocity, a radar sensor to measure flow depth and two video cameras for visual control. Geophones are normally mounted on bedrock or large boulders. They are always in contact with the flow and the arrival of a debris flow can be accurately determined as the boulders at the front of a debris flow roll or slide over and activate the geophones. The analog signal from the geophones is digitized at the geophone itself for filtering and to reduce the data volume. The number of impulses per second and their duration is extracted from the analog signal, with an impulse defined here as the output voltage exceeding an empirically determined threshold. A debris flow is detected if the geophone signal indicates more than a predefined number of impulses in each second for more than several seconds. The radar sensor has a built-in smoothing algorithm that provides a stable signal under conditions of rapidly changing flow depth or splashing on the surface of the flow. The signal is delayed by a few seconds and changes in surface elevation are smoothed in comparison with laser sensors but still accurate (radar sensors also measure a larger area of the bed in comparison with laser sensors, typically resulting in more stable signals). The device is located at a cross section where the bed elevation does not change significantly during an event. Communication and data collection uses the public GSM network. Data are locally stored on a data logger and transfered daily or immediately after an event. Additionally, rainfall is measured with a time interval of one hour at the top of the catchment.

The debris-flow monitoring station in Preonzo also serves as an extension of the cantonal monitoring system for the rockslide as well as providing data for debris flow research. The location on the south side of the Alps in a different geological and meteorological environment and in a small but very active catchment provides an opportunity to evaluate debris-flow behaviour under different conditions than the other stations in Switzerland (Huerlimann et al., 2003).

Because of the new conditions, described earlier, the observation station was moved to the active channel system after construction of the two deflection dams, using the same instrument setup as for the first station in spring 2008. A trigger geophone was mounted at a large boulder close to the active channel at the lower end of the intermediate deposition zone, below the upper deflection dam (Fig. 4). The main part of the monitoring station was installed at the lower deflection dam with one geophone at the upper end and one at the lower end of the dam to derive information of the local front velocity. The flow depth measuring takes place in the central part of the 60 m long lateral dam where a video camera is also installed with a view of the channel along the dam (Fig. 5).

Fig. 5 : Main part of the automated debris-flow monitoring station (2008 - 2009) at the lower 60 m long deflection dam. Two geophones at the upper and lower end of the dam provide information on local front velocities, a radar sensor measures the local flow depth and a video camera in uphill direction captures images of the flow. Data are stored locally and daily transferred by GSM to WSL.

Data on debris-flow volumes of former events (estimated by a local geologist) are summarized in Table 1. These events reached the old (small) retention basin and caused damage in the industrial zone. Magnitude is indicated using S (small), M (mid-size), L (large). A magnitude-frequency relationship for debris flows could not be established due to changes in the supply of sediment and the relatively small number of debris flows. The limiting factor for debris-flow formation in Preonzo is the catchment size and the resulting limited availability of water while there is no limitation in available loose material.

date	total volume	size
04.10.1999	10'000 m^3	S
09.06.2001	20'000 m^3	M
15.07.2001	30'000 m^3	L

Tab. 1 : Debris-flow events in Preonzo not measured by automated monitoring station. Magnitude is characterised by indication of size using S for small event to L for large event. The volumes may be overestimated (source: local geologist).

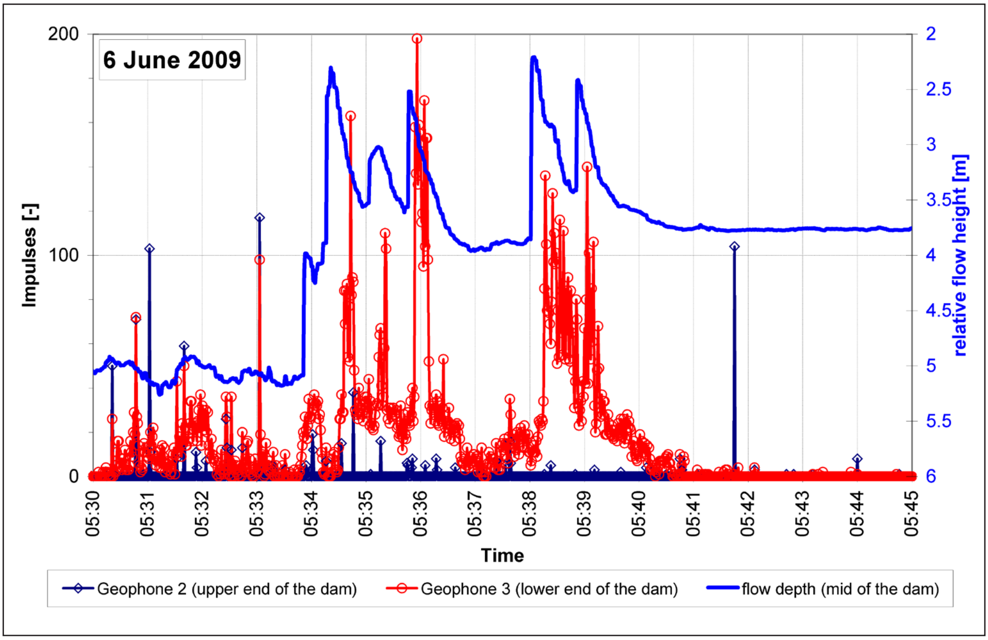

Fig. 6 : Debris flow event on 6 June 2009. The graph shows the first of three debris-flow events with several surges. The geophone on the top of the dam is less sensitive than the one at the end of the dam. Local velocities can be estimated by the travel time of the individual peaks and distance in between the sensors. Local velocities are on the order of 1.4 - 1.7 m/s and flow heights up to 2.8 m. This corresponds to a maximum discharge of 44 m^3/s.

During 2008 and 2009 ten small debris-flow events were recorded (Table 2) by the automated monitoring station. They show low local front velocities in the range of 2–4 m/s at the lower deflection dam. Volumes range from a few hundred m^3 up to 7’000 m^3, which is still small compared to the events from 1999 to 2001 and compared to the amount of available loose material in the rock avalanche deposit. Flow heights are on the order of 1 to 3 m. These heights can be controlled by the existing two deflection dams without any overtopping. Larger events with a few ten thousand m^3 could have flow depths over 5 m, which is a critical value for the structures.

The debris flows on June 6, 2009 are the last ones recorded by the automated monitoring station. The first of these events is also the largest one recorded in the new channel system, showing that the two deflection dams work for smaller debris flows. Similar flow behaviour could be observed like the events in summer 2007, with different events of multiple surges during several hours within the same rainfall event. The first series of surges (Fig. 6) occurred briefly after a first increase of rainfall intensity at a cumulative rainfall of more than 60 mm (Fig. 7). The second and third event occurred at the beginning of another increase in rainfall intensity with values up to 55 mm/h. The short response time in such a small catchment seems to be typical.

date	total volume	size	remarks
01.07.2008	3'000 m^3	S	5 surges
03.07.2008	600 m^3	XS	4 surges
06.07.2008	1'800 m^3	XS	5 surges
07.07.2008	6'000 m^3	S	2 events, several surges
13.07.2008	2'000 m^3	S	4 surges
03.09.2008	2'500 m^3	S	4 surges
06.06.2009	7'000 m^3	S	3 events, several surges

Tab. 2 : Debris-flow events in Preonzo recorded by the automated monitoring station by WSL located at the new channel system. All events are small (S) or very small (XS) compared to the ones listed in Table 1. On two dates more than one event occurred.

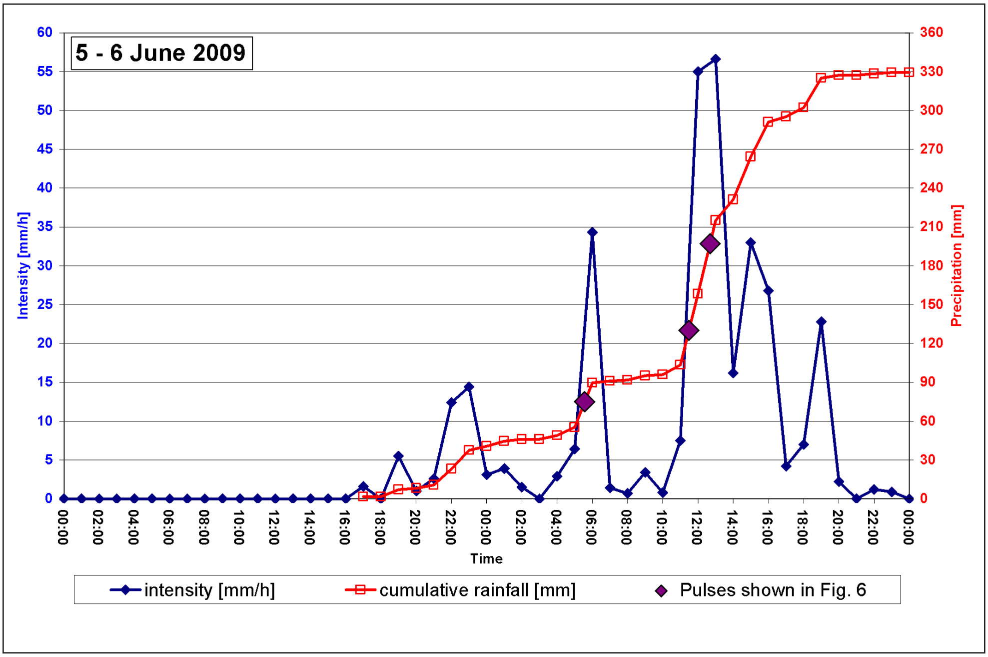

Fig. 7 : Rainfall event of 5 - 6 June 2009 with indication of debris-flow events. The first event with a series of surges (Fig. 6) with a volume of 6’000 m^3 was the largest, the total volume of the three events is 7’000 m^3 (Table 2).

4. Simulation

4.1. Runout modelling tool

RAMMS is a runout modelling system for natural hazards research and practice developed by the avalanche, debris flows and rock fall unit of WSL, Switzerland (Christen et al., 2005, Christen et al., 2008). A depth-averaged friction relation is used which describes the flow resistance as the sum of a dry Coulomb-type friction (μ) and a viscous resistance (ξ) that varies with the square of the flow velocity. A finite volume scheme is used to solve the 2D shallow water equations in general three-dimensional terrain (Christen et al., 2010; WSL/SLF, 2010). In the field of natural hazards there is a strong need for process models or tools where both the process and its interaction with proposed mitigation measures can be evaluated. RAMMS allows simulation of snow avalanches, debris flows and rock falls in one tool and thus permits evaluation of the performance of mitigation structures designed also for other processes (e.g. the influence of avalanche protection dams on debris flows). The graphical user interface incorporates GIS functions to define the boundaries of the computational grid and the definition of the initiation area for debris flows.

4.2. Simulation parameters

The debris flow event in July 2004 was simulated using parameters estimated during a field survey one day after the event. Unfortunately the debris flow did not occur in the instrumented channel Valegiòn and therefore no flow parameters could be collected. The total volume was estimated at about 10'000 m^3, maximal front velocities in the range of 6 to 10 m/s and maximal flow depths in the order of 2 m. Calculations were made using a high-resolution terrain model (Swisstopo, 2010), with a starting volume estimated from the field data. The digital terrain model (DTM) shows the topography after the 2004 event and contains all active channels, including those formed by the event. Accurate representation of the topography in the grid is essential to obtain a reasonable reproduction of the observed flow paths and deposition patterns (e.g. Rickenmann et al., 2006). For the two friction parameters in the Voellmy relation, no universally valid combination has been found which allow accurate simulation of all debris flows. For simulations of debris flows with RAMMS, we propose a ξ-value of 200 [m/s^2] and 0.1 for μ [-]. The coefficient ξ may be varied from 100 to 400 m/s^2, and μ from 0.1 up to 0.3 to match observations. In the areas of the two dams, the DTM was locally corresponding to the heights of the structures. Newer small debris-flow events in 2007 took place after construction of the two dams and followed the new channel, as anticipated. These events confirm that the physical design of the deflection dams is adequate; the events have also been parameterized and are used herein.

4.3. Results

Simulated flow paths, without taking into account structural measures, resemble the observed tracks in the field (Fig. 8a). The different deposition zones could be reproduced. Flow heights as well as frontal speed reached the values as assessed in the field. After adding the two dams to the DTM, results show the deflection to the north and to the Valegiòn channel which includes the retention basin. Some residual discharge to the south could be observed (Fig. 8b) and indicates that the structures could be further optimized. The small debris-flow events in 2007 did not show any flow out of the channel to the south due to their small volume. To re-direct larger flows, a third deflection dam in between or other measures at the initiation zone would be necessary.

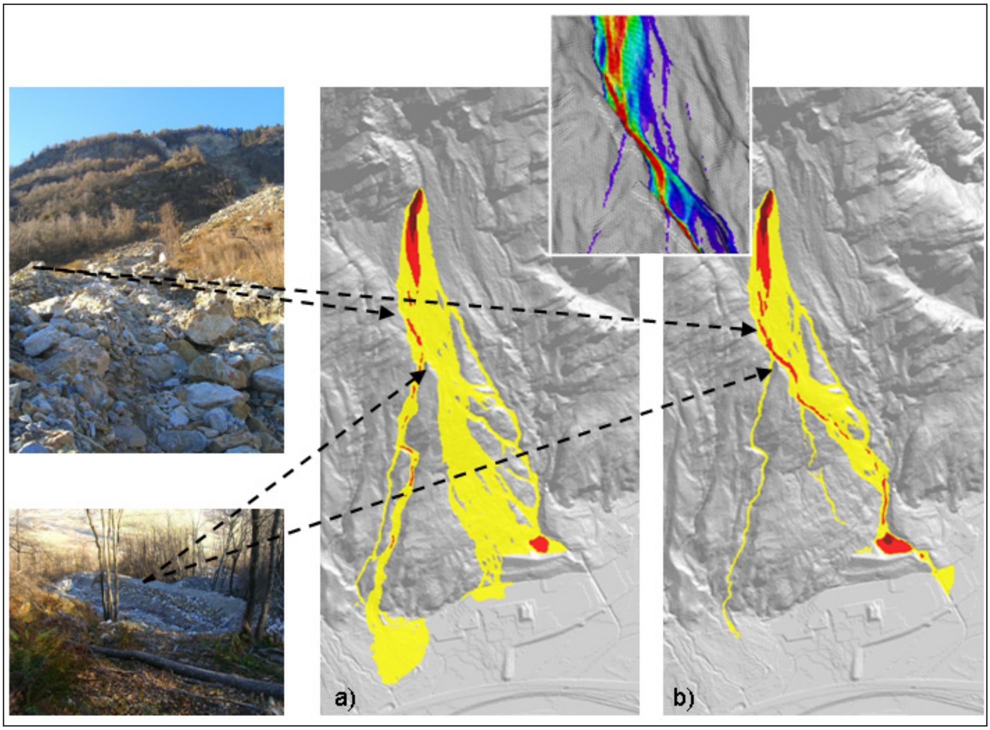

Fig. 8 : Simulated flow paths, without taking into account structural measures (left) and with the effect of the two new deflection dams (right). Note some residual discharge to the south in between the two deflection dams indicating the potentially needed third dam for larger event sizes. DTM data: DTM-AV DOM-AV © 2010 swisstopo (5704 000 000).

5. Discussion

After calibration, RAMMS is able to reproduce the observed flow paths and deposition patterns of the 2004 event. The estimated parameters derived from the field work after the event are confirmed by the more recent events and appear to be adequate. The location and geometry of the initiation zone is not exactly known and had to be iteratively optimized to generate the proper flow path in the upper catchment. Ideally a DTM from before an event should be used, however for back-calculation such information is typically unavailable. High resolution topographic data, on the order of one measurement point every few meters or higher resolution are necessary to achieve reasonable results, especially for smaller event sizes. Potential location of structural measures could be easily derived from the flow paths simulated for the 2004 debris-flow event. Exact dimensioning of new construction measures would be more difficult and indicates the need for a detailed study at the corresponding locations. New structural measures for hazard mitigation, such as deflection dams or retention basins, are easy to integrate in the DTM with the GIS tools in the user interface, providing a tool that can help to optimize the design of such structures. It is more difficult to define dimensions and exact position of modification of these measures from simulation results, especially because the debris flow process is only approximated by the use of single-phase friction relations such as the Voellmy relation used herein. Depending on the resolution of the simulation grid, structural measures have to be implemented at a somewhat larger aerial extent than they are in nature to effect the desired behaviour, because smaller structures such as deflection walls are often narrower than the typical point spacing in the model grid. Typically, structures are drawn in the user interface as somewhat wider than designed, however the side of the structure in contact with the flow is positioned as accurately as possible. In any case, care must be taken to ensure that the structures (especially the height) are adequately depicted on the model grid.

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