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An overview of a decade of applied debris-flow runout modeling in Switzerland: challenges and recommendations

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Abstract

Dynamic debris-flow runout models are applied by practitioners (1) to generate hazard maps, (2) to help design mitigation measures such as dams and warning systems, (3) to explore potential impacts of rare events such as pro-glacial lake failure, and (4) to illustrate the hazard process to local decision makers and stakeholders. Automated observations of debris flows in several torrents have shown a large degree of variability in the flow process, ranging from fast muddy debris floods to relatively slow debris flows with granular fronts, at any given torrent. It is not yet possible to predict with certainty which type of debris flow can be expected in any given catchment. The prediction problem is amplified by the fact that topographic data are generally coarse (2m horizontal resolution in Switzerland) compared with typical channel widths (1–10 m) and because channel topography changes with time. These challenges and their impact on hazard assessment is illustrated using recent examples of typical applied projects. Herein we use the RAMMS debris-flow runout model. However, the general procedures presented here are applicable to other similar runout models. Common points in these examples include the accurate assessment of potential erosion, deposition, and avulsion along the channel, as well as the systematic modification of the friction coefficients in the model to account for variations in water content, sediment size, channel-bed roughness, and other properties of the flow. We mention the main challenges in these steps, as the exact procedure is still not clearly regulated in Switzerland. In general, it is desirable to work with several scenarios to account for multiple flow surges and the erosion and deposition produced by each surge, and uncertainties in the expected debris-flow type (granular vs. muddy). Thus, for the generation of appropriate scenarios, experience in the field and with the use of runout models is essential.

Keywords: hazard assessment; debris-flow runout model; RAMMS; hazard maps

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1. Introduction

Debris flows are a major natural hazard in alpine regions. They can cause significant damage along steep mountain torrents and especially on their fans due to their erosion potential, high impact forces and sudden occurrence. Because of their variable composition of coarse and fine rocks, mixed with water and other material, such as woody debris, their motion (speed, flow height, inundation area) are difficult to predict. When they develop, large solid masses can be transported within a short time inducing strong impact forces on structures. In addition, strong channel erosion and massive deposit of debris may occur outside the channel. They occur rarely and only in appropriate conditions, mostly triggered by meteorological factors.

In order to counteract this danger, great efforts have been made to define the affected area and to improve the protection of persons and infrastructure by means of measures (structural and organizational ones). The reduction of the area at risk remains a challenge for natural hazard experts. In addition to field assessments, comparative considerations based on analogous examples, the numerical calculation with runout-models is increasingly being applied in practice. This requires a comprehensive and accurate knowledge of the main characteristics of the expected debris-flow events. In many mountainous countries, automated observation stations (Hürlimann et al.,

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2003) and event databases (Lateltin et al., 2005) provide such information over longer time periods for a certain location. The data can be used with restrictions for comparable sites, if there is no other information available.

Computational dynamic debris-flow runout models are used to assess flow path, runout distance, velocity and flow depth (Crosta et al., 2003; Hürlimann et al., 2008; Hungr and McDougall, 2009; Christen et al., 2012) and they are a valuable tool for hazard assessment where predictions of flow intensity are required (e.g., Lateltin et al., 2005). The methods available for runout analysis can be divided into different classes, such as empirical, analytical, simple flow routing and numerical ones (Dai et al., 2002; Rickenmann, 2005). Besides defining the magnitude of an upcoming debris flow and the probability of occurrence, the determination of the debris-flow dynamics are the most important tasks for an in-depth hazard assessment (Jakob, 2005). It is important to emphasize that practitioners are increasingly basing (1) the generation of hazard maps, (2) the design of mitigation measures, (3) the exploration of potential impacts of rare events, and (4) the presentation of the hazardous process to local decision makers and stakeholders on results provided by numerical simulations. Therefore, the quality and accuracy of the input parameters is of utmost importance.

In the last decades, a series of different debris-flow runout models became available for scientific and practical use. Many of these models remained at an academic level and where not designed for practical use in the debris-flow engineering community. Often the models relied on a small development team (sometimes even a single person) and therefore lack extensive documentation for application by practitioners.

In recent years, practitioners have made frequent use of dynamic debris-flow runout models to generate hazard maps, to help design mitigation measures such as dams and warning systems, to explore potential impacts of rare events such as pro-glacial lake failure, and to illustrate the hazard process to local decision makers and stakeholders. Guidelines and standards for the minimal requirements are not yet regulated in Switzerland. Nevertheless, practitioners evaluate their field assessments, assess their design-event scenarios and visualize their study results to the authorities using numerical simulations. They have also extensively tested the existing tools, identified gaps and weaknesses, especially regarding existing flow theories, and formulated requirements for future models. The last point is quite important and useful for model development. Exchange of information e.g. by user workshops and knowledge exchange is very important. Because many of the numerical simulation tools need calibration and lack a strict calculation procedure e.g. by decision trees, only trained and experienced users will profit from the simulation results. Others might risk to produce questionable outcomes that show misleading or even wrong effects. The present situation is Switzerland can be summarized as a healthy skepticism of existing models, with a desire to improve both application guidelines as well as some of the underlying physics of numerical models, especially with regard to the constitutive modeling of granular/muddy mixtures.

The interpretation of numerical output by practitioners is considered an important problem. Output of simulation tools depends on two main factors: a) the capabilities of the mathematical representation of the very complex process and b) the quality of the input parameters. The first problem can be solved by the choice of the appropriate tool, or better, by the choice of a small number of tools that provide results that can be compared. Often, in practical application, the use and comparison of the results from two or more numerical simulation tools is not feasible because of lack of time, money and human power. Model result comparison implies that practitioners would have to invest much more time and effort to learn the use of different tools. Presently, they rely on the results of one tool only and the choice depends on the knowledge of the available personal.

In Switzerland, hazard assessment is part of the integral approach to natural hazards in Switzerland (PLANAT, 2005). The main product is a hazard map that provides information about the natural hazard process (Lateltin et al., 2005). The hazard is defined as the probability of a potentially damaging natural phenomenon within a specific period of time in a given area. For simplification, three levels of intensity are considered, high, medium and low. Regarding probability, the same three levels, high, medium and low, are used with the corresponding return periods 1–30, 30–100 and 100–300 years. The work to be done for a potential hazard is therefore to determine its intensity for the chosen levels of probability at selected points in a specified area. The federal law requires the cantons to establish hazard maps which have to be incorporated in regional master plans and local development plans. Each canton has drawn up a specification for its preparation, which is based on the legal foundations and the general recommendations and guidelines of the federal government. The use of debris-flow runout models is mentioned in these guidelines. However, detailed instructions are not specified on how to use them. Therefore, every engineering office has established its own approach. In most cases, the choice of a specific numerical model is left to the contractor. The degree that government agencies prescribe how to assess debris-flow hazard, therefore plays a role in how numerical models are applied in practice.

In this paper, we consider more than a decade of experience gained in the use, application and expert monitoring of hazard assessment projects in the Swiss Alps, where the use of the numerical simulation tools was the main or an important part of the project. Our goal is to communicate to the modeling and debris-flow engineering community how to improve, perhaps even simplify, existing tools. The discussions were in most cases about choosing the ideal friction parameters during the calibration process. Subordinate questions were repeatedly discussed about the starting conditions (Deubelbeiss and Graf, 2013) or the inclusion of constructional measures (Graf and McArdell, 2008, Hohermuth et al., 2016). These challenges and their impact on hazard assessment is illustrated using recent examples of typical applied projects. Common points in the examples include the accurate assessment of potential erosion, deposition, and possible avulsion along the channel, as well as the systematic modification of the friction coefficients in the model to account for variations in water content, sediment size, channel-bed roughness, and other properties of the flow. Another issue is the generalization process necessary to produce reliable hazard maps. This paper focuses on the application of exiting user-friendly debris-flow simulations tools. The runout model used herein is the well-known RAMMS 2D debris-flow runout model (Christen et al., 2010). However, the general procedures presented here are applicable to other similar runout models.

2. Materials and Method

We analyzed many different case studies of debris-flow hazard analysis in Switzerland that were performed ourselves using RAMMS (Christen et al., 2010) in the last decade or that we have advised during this period. Here we sum up the experiences made and point out the main topics. The evaluation is subject to a certain subjectivity. This is because the projects are not systematically evaluated in terms of the issues covered in this study.

2.1. Case studies, main questions and guidelines

We compare three different typical situations of hazard assessment using numerical simulation in debris-flow prone torrents in the Swiss Alps: Situation (1) shows only one important and well-documented event in the last century and several small, but not well documented events in the same period. The small events didn't cause significant damage and were therefore not analyzed in detail. The date of occurrence is sometimes known, but no data is available on initial starting point, volume, flow depth and discharge of the corresponding event. Situation (2) shows regular small events that do not cause any damage and a few larger events that caused minor damage and therefor are not well documented. Field survey and geomorphic field evidence suggests that there were much larger events in the past. In situation (3) a catchment with a high potential for large debris-flow events but with only a small number of well-known events of small size has to be assessed. To protect against future major events, protection structures have to be dimensioned. We compare the three typical situations asking the following questions:

- How important are well-documented events to determine the key parameters of different return periods?
- How does one single well-known event influence the determination of these key parameters?
- How does a potential situation of debris-flow susceptibility influence the determination of the key parameters?
- How many events are needed to determine trustful key parameters, and linked to this question:
- What series (mainly in terms of number, but also in terms of data quality) of documentation of debris-flow activity is necessary to achieve a well-based data set?
- Which kind of events in regard to volume, mixture, speed variability is necessary to achieve such a well-based data set?

Finally, we study the recommendations, guidelines and regulations in view of the use for numerical simulation programs. We then identify the best procedures to use and steps to follow to make a timely and accurate assessment of the debris-flow hazard.

2.2. RAMMS

The debris-flow module of RAMMS (Christen et al., 2010) requires a terrain model and a geo-referenced map or orthoimage. The user defines a region as study area. This calculation domain covers the area from the initiation to the potential deposition area. In addition, the start volume and the start location are defined, as well as the initiation mechanism. For a simple calculation, two friction parameters are defined for the design composition to be calculated. In RAMMS, a Voellmy-Salm approach is used, which splits the total basal friction into a velocity independent dry-Coulomb term which is proportional to the normal stress at the flow bottom (friction coefficient μ)

and a velocity dependent "viscous" or "turbulent" friction (friction coefficient ξ) (Salm, 1993). Both parameters need to be calibrated carefully based on a back-calculation of known events (Christen et al., 2012). No binding classification of typical parameter sets for debris flows is available until now. The user manual provides some examples and parameter suggestions for the two friction parameters. Additional model features like entrainment of sediment or erosion (Frank et al., 2017) are not discussed in this study.

2.3. Hazard assessment

The general procedure for hazard assessment in Switzerland (FOEN, 1997, FOEN, 2016) is well-defined, including input parameters and products. It is up to the contractor how to determine and specify the input parameters in detail. The same applies to the use of numerical simulation programs. Model use is not mandatory or recommended.

Figure 1 shows the general procedure to perform a hazard assessment using numerical simulation tools. In order to perform a hazard assessment and eventually to design protective measures against debris flows, it is necessary to determine basic parameters such as potential debris volume, mean flow velocity, peak discharge, and runout distance. In several studies, empirical relationships have been proposed to estimate these parameters (Rickenmann, 1999). Other approaches are now available to define the corresponding values for the input parameters, combining field and computer work (e.g. Jakob, 2005, Frick, 2008). Basic information is gained from field work, cadastral data and characterization of the catchment area. The data must be evaluated in terms of quality. The model shall be calibrated based on well-documented events in the catchment area to be investigated.

From basic information, scenarios for different recurrence times can be defined. These are evaluated either by expert opinion or by numerical modeling, or a combination of both. Further bases for the modeling are a digital elevation model, maps or orthoimage as well as possibly a mapping of envelopes of past events including deposition height information. Results need to be carefully interpreted. A validation and a plausibility check of the results is important and necessary. This is done first at the desk and then out in the field. In the field the potentially affected area, the expected intensity and possible weak spots are evaluated. The documentation of the work is done with intensity and hazard maps and a technical report, which comprehensibly describes their derivation and delineation.

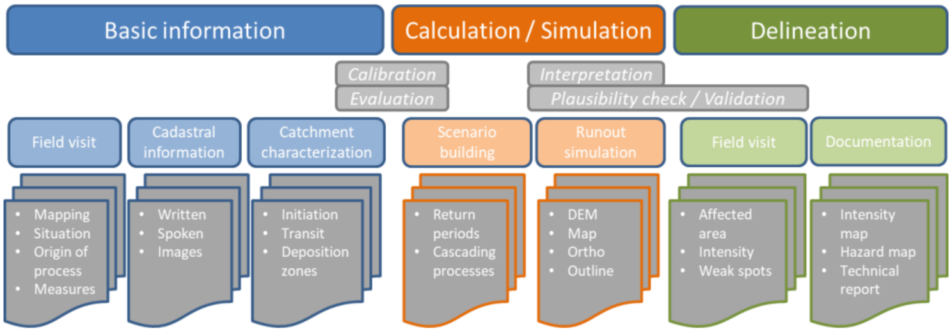
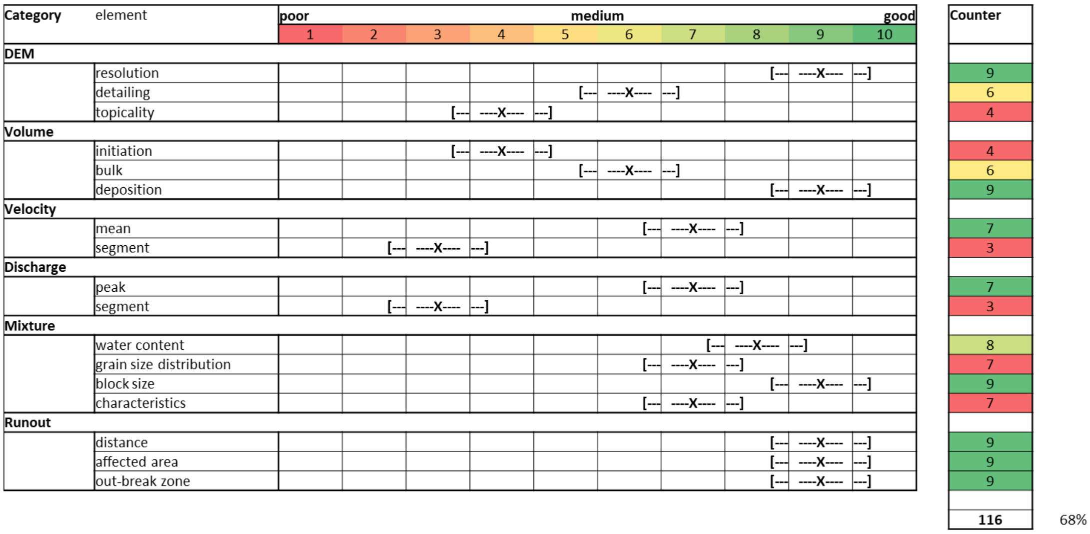


Fig. 1. Important steps in debris-flow hazard assessment using numerical runout simulation tools

2.4. Evaluation

The parameters for the input parameter in Fig. 2 are subjectively assessed on a scale (here from 1-10). The value 1 means a very poor data quality, and a corresponding high uncertainty. A value of 10 indicates a very high certainty and good data quality. The brackets, dashes and crosses indicate that scoring can be done within a bandwidth, e.g. by the assessment by several experts. The evaluation method presented here is not standardized. It merely suggests how the quality of the data could be assessed. Depending on the procedure, the category and elements may not be listed exhaustively. In this example (Fig. 2), the counter reaches 116 points or 68 % of possible score. This would mean a relatively good database and the result of the simulation would be promising. In case of less than 50% of the possible score, the result of the simulation must be considered with caution, and if less than 25 %, the result would have to be seriously doubted, since the input parameters show too much uncertainty. For such a case, the parameters would have to be varied within a bandwidth to display the uncertainty area.



Category	element	poor				medium					good	Counter
		1	2	3	4	5	6	7	8	9	10	
DEM												
	resolution								[---	----X----	---]	9
	detailing					[---	----X----	---]				6
	topicality			[---	----X----	---]						4
Volume												
	initiation			[---	----X----	---]						4
	bulk					[---	----X----	---]				6
	deposition								[---	----X----	---]	9
Velocity												
	mean						[---	----X----	---]			7
	segment		[---	----X----	---]							3
Discharge												
	peak						[---	----X----	---]			7
	segment		[---	----X----	---]							3
Mixture												
	water content							[---	----X----	---]		8
	grain size distribution						[---	----X----	---]			7
	block size								[---	----X----	---]	9
	characteristics						[---	----X----	---]			7
Runout												
	distance								[---	----X----	---]	9
	affected area								[---	----X----	---]	9
	out-break zone								[---	----X----	---]	9
												116 68%

Fig. 2. Suggestion of a rating table for valuation of main input parameters of runout simulation tools

3. Results

In the following, statements about the three typical situations are presented in generalized form. Only the most important aspects are considered and only situation (3) is described in more detail.

Situation (1) with only one documented large event in the last century and many small events points out very well the difficulties in defining the parameters for a hazard assessment. We have no indication, if the large events was an extreme one, without any chance to be repeated in the future or if it's an event size that has a return period of about 100 years. The numerous small events could be used to calculate statistics regarding volume and return period but we are not sure if we miss large events. The conclusion of situation (1) is, that the time series is perhaps too short for the determination of the expected volumes for different return periods, especially the shorter ones. Therefore, the determination of the input parameters for volume, speed and discharge may be too high and too pessimistic. This result is reflected in the numerical simulations. The results indicate too large areas and too high intensities (as a product of flow height and flow velocity). Conversely, the description of the large event is an advantage for the calibration of the model. It allows the engineer to back-calculate a relevant debris-flow event and to better estimate important indications of the expected consequences, even for unknown, possibly larger events. The score using the proposed evaluation method for the different input parameters in such an example would be in the order of >50%. This is mainly due to good data on volume, runout and mixture, velocity and discharge of the large event. However, there are to make compromises in the spatial resolution of the terrain data. This is especially true if the event took place a long time ago.

Situation (2) with many small to mid-size debris-flow events is a slightly different problem. For small to mid-size debris flows, we have at least evidence, that events with a short return period happen regularly and we can approximate the return time. We miss data for larger events and have to estimate the parameters by the use of empirical relationships, estimates, and expert knowledge. The score using the proposed evaluation method for the different input parameters in such an example would be on the order of 75%. This is mainly due to statistically well-based data available for smaller events. Information on runout distances and weaknesses for out-break for large events is much more difficult to determine. The lack of information about damages also does not help the assessment.

For situation (3) we were able to calibrate the friction parameters based on one event that caused some damage and left the channel (Fig. 3a). The total volume of 30,000 m^3 is at the top of the reasonably well-documented events. The values given in the event documentation were reduced by experts as it was considered too high. The volume was estimated from the available documents and set at a slightly lower value. The friction values were varied in such a way that resampling of the specific image simulated the main features of the deposit image as closely as possible (Fig. 3b). These were the runout distance, the break-out points and the area of the channel inundated by the event. The resulting parameter set is in the range found for other locations and was therefore assessed as plausible.

Subsequently, various structural measures could be checked by means of a numerical model for different scenarios. It was very challenging to estimate the possible volumes and the probable composition of significantly larger events. The estimation yielded very high values because of a generally high sediment availability in the catchment area. In addition, unstable rocky areas threatened to fall in the near future and the site is located in an area with high and sometimes heavy precipitation.

Since the drainage capacity of the channel on the fan is clearly too small for the assumed volumes, the out-break that happened in reality (Fig. 3a) became a model for an artificial deflection with a spillway (Fig. 3c). In the valley floor at the confluence with the receiving river there is insufficient room for deposition (Fig. 3b). For this reason, as much material as possible should be diverted in the case of a large event. The deposition is held back further down on the fan in a retention basin. If the volume deposited in it exceeds the retention capacity, the overflow returns to the main channel and flows to the receiving river. After action planning and implementation, numerical simulations proved the effects of the spillway for different event magnitudes, and have served to set the thresholds for a supplementary warning system.

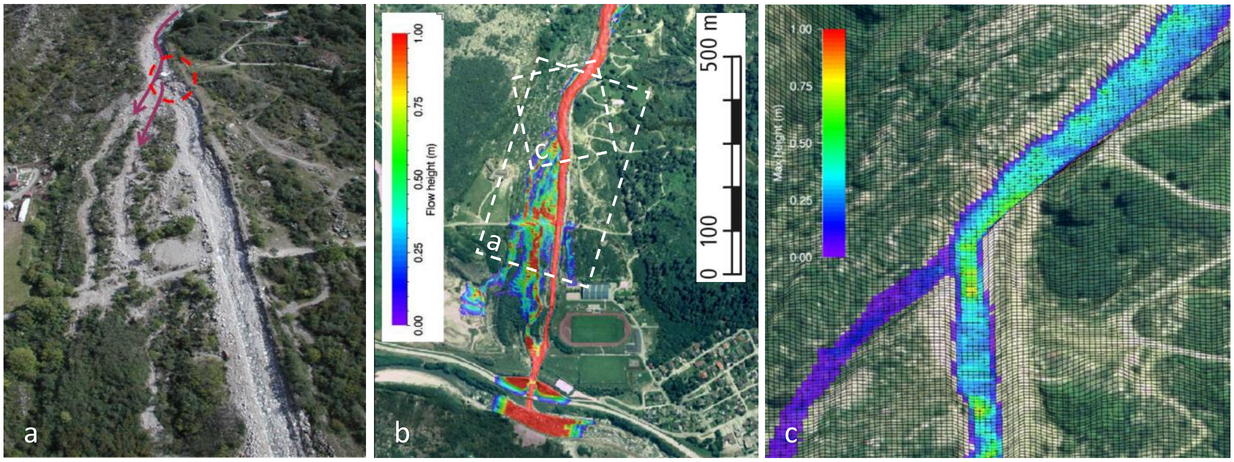


Fig. 3. (a) Aerial image of event traces with out-break (red circle) and flow direction highlighted by arrows; (b) back-calculation of documented event; approximate outline view figure a and figure c (white dashed lines); (c) oblique view of a scenario simulation evaluating new structural measure (spillway)

The score using the proposed evaluation method for the different input parameters in this example is on the order of >75%. This is mainly due to good data on volume, runout and intermediate-quality data on mixture, velocity and discharge of the well-documented events. Calibration of the model becomes easier. Thanks to detailed investigations and the planning of structural measures, good and up-to-date terrain data is available. Only when determining the parameters for large events limitations are to be expected. Generally, calibrated friction parameters are used for all event magnitudes.

4. Discussion and Conclusions

In general we found that debris-flow experts have little information on past debris-flow activity. There are exceptions; however, they are rare. Only large events, and events that caused major damage are analyzed in detail. They provide the most important parameters for the numerical modeling, such as deposited volume, run-out distance and eventually a description of the event series based on eye-witness. Additional parameters such as velocity, flow height, water content, particle size and distribution are more or less non-existent. Sometimes they are available in catchments where automated monitoring is present or in catchments of special interest after a major event. The first challenge in modeling debris flows starts with the definition of the adequate starting volume. Typically, no exact details of initiation volume of past events are known. While the initial debris-flow volumes are typically small, they can evolve to be a multiple thereof by entraining material along their flow paths (Berger et al., 2011), which means, the starting and ending volumes sometimes differ considerably. This challenge is due to the fact that debris flows tend to bulk, accumulating material from the torrential bed and the embankment, but sometimes also depositing sediment through levée formation and lateral out-breaks.

The prediction problem is amplified by the fact that topographic data are generally coarse (2m horizontal resolution in Switzerland) compared with typical channel widths (1–10 m) and because channel topography changes with time. Therefore, the data available for the representation of the terrain plays an important role, and the spatial resolution is critical. If relevant elements, such as side walls or blocks, are not given with sufficient accuracy, the simulation results are distorted. Terrain models therefore must be up-to-date. They have to reflect the condition of the channel and its surroundings for the investigation period. In addition, the geometry of protective structures, channel structures, surrounding buildings, and bridges are essential information that must be included in the terrain model. For buildings, the flow can usually be assumed during an event. This significantly influences the flow path. If, as discussed above, the grid mesh cannot provide a satisfactory and geometrically correct rendering, we recommend defining the buildings as impervious areas or no flux cells (Hohermuth et al., 2016). For structural safety measures and barriers, the question arises as to whether and when these factors are taken into account in the simulation. Investigations have shown that abrupt changes in inclination of artificial structures, such as dams or retention basins, represent major challenges for a numerical simulation model (e.g. Laigle and Labbé, 2016). If either the spatial resolution is too low or the grid size of the mesh does not optimally fit the object, incorrect effects will result, which are difficult to interpret by practitioners.

The flow properties of a debris flow (i.e. whether it is granular or low-viscosity) and the scenarios to define, must be clarified outside the application of a simulation program as part of the hazard assessment. It is not yet possible to predict with certainty which type of debris flow can be expected in any given catchment. For scenario building this is quite challenging (Jakob, 2005). If several scenarios are considered to be decisive, these can be investigated by means of numerical simulation tools. The flow properties of the debris flow to be simulated must be defined outside the application of a simulation program. If several scenarios are considered to be significant, this can be investigated by means of numerical simulation. Rare and unique events are the most difficult to classify and consider. It can be assumed that due to climate change several situations can arise that make events possible that have never occurred in the past. However, a serious hazard assessment must ask exactly this question about the conceivable extreme event and answer it meaningfully. Numerical models can assist with the answer and provide helpful results to preview infrequent and extreme situations. Cascading processes, such as rock slope failures, and more frequent debris flows involving soil masses released by permafrost play an important role in hazardous events in alpine regions as a potential impact by climate change. More than one process has to be judged, including the interaction between them.

Expert knowledge and experience continue to play an important role in the definition of input variables as well as in the interpretation of the simulation results. Very often, the basic data must be checked for plausibility and, if necessary, adapted. As a result, a lot of subjectivity comes into the choice of input data. It is therefore essential that the decisions are documented in technical reports in a comprehensible and detailed manner.

The computational power and performance of the models is still a challenge, especially if very high resolution results (sub meter) are expected. Parallelization and the exploitation of computer graphics processing units are accelerating the computations. Logical sequences and parameter variations can be automated, leaving the user time for other activities. Increasingly, automated evaluation methods are available to produce extensive results files. The effort for an accurate and transparent determination of the input parameters is not to be underestimated. The effort is worthwhile, however, because it gives one more defensible simulation results. It is often observed that under time pressure often little time is spent in the preparation of the input variables for the numerical simulation. Unfortunately, this approach is in most cases counterproductive because an inadequate exploration of input parameters will not yield trustworthy results. In addition, poor parameter selection can cause incorrect assessments of the situation. A second step, which is often overlooked, is the step of calibration. The calibration difficulty often lies in the fact that there is simply insufficient data for the location being examined. The calibration problem must therefore be remedied by analogy, assumptions, or rough estimates. Regrettably, practitioners frequently take incorrect approaches for calibrating friction parameters. Instead of an objective calibration process, the standard parameters are used, assuming that they yield an approximately correct result.

It must be noted that in the field of numerical modeling great progress has been made in recent years such that processes can be mathematically modeled with high precision. The model automates various tasks. On one hand, it delivers an independent expert opinion to the specialist. However, this requires the knowledge of the possibilities and limitations of the model and that the expert takes them into account when interpreting the results. On the other hand, in hazard assessment, the major challenge is not the model and its ability, but the adequate use of the model within the framework of the project.

We have found that the use of numerical simulation programs is desired by stakeholders and authorities. However, there are no clear guidelines for how to perform runout modeling. There are also no minimum requirements for the choice of the input parameters. This concerns both the naming of the input parameters themselves, as well as the specification of the data quality. Because numerical modeling is becoming increasingly important, new guidelines must include the role of numerical simulations in hazard assessment in general.

We also need much more data on ongoing debris-flow activity. Therefore, we have to establish a well-structured data-base of debris-flow events including information of triggering conditions and parameters, the initial starting points, transit parameters such as super-elevation, bulking and levee deposits, deposition parameters such as break-out zones, levee formation, in-channel deposits, number and characteristic of surges and their run-out distance, information on composition, including water content, grain size distribution, etc.

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References

Berger, C., McArdell, B.W., and Schlunegger, F., 2011, Direct measurement of channel erosion by debris flows, Illgraben, Switzerland: Journal of Geophysical Research, v. 116, iss. F1, F01002, doi:10.1029/2010JF001722.

Christen, M., Kowalski, J., and Bartelt, P., 2010, RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain: Cold Regions Science and Technology, v. 63, p. 1–14.

Christen, M., Bühler, Y., Bartelt, P., Leine, R., Glover, J., Schweizer, A., Graf, C., McArdell, B.W., Gerber, W., Deubelbeiss, Y., Feistl, T. and Volkwein, A., 2012, Integral hazard management using a unified software environment: numerical simulation tool "RAMMS" for gravitational natural hazards, *in* Proceedings, 12th Congress INTERPRAEVENT, Grenoble, v. 1: Klagenfurt, International Research Society INTERPRAEVENT, p. 77–86.

Crosta, G.B., Imposimato, S., and Roddeman, D.G., 2003, Numerical modeling of large landslides stability and runout: Natural Hazards and Earth System Sciences, v. 3, p. 523–538.

Dai, F.C., Lee, C.F., Ngai, Y.Y., 2002, Landslide risk assessment and management: an overview: Engineering Geology, v. 64 p. 65–87.

Deubelbeiss, Y., and Graf, C., 2013, Two different starting conditions in numerical debris-flow models - Case study at Dorfbach, Randa (Valais, Switzerland), *in* Graf, C., ed., Mattertal - ein Tal in Bewegung. Publikation zur Jahrestagung der Schweizerischen Geomorphologischen Gesellschaft 29. Juni - 1. Juli 2011, St. Niklaus: Birmensdorf, Eidg. Forschungsanstalt WSL, p. 125–138.

FOEN, 1997, Consideration of Flood Hazards for Activities with Spatial Impact: Federal Office for Water Management, Federal Office for Spatial Planning, Federal Office for the Environment, Forests and Landscape: Berne, Recommendations, 32 p.

FOEN, 2016, Protection against Mass Movement Hazards, Guideline for the integrated hazard management of landslides, rockfall and hillslope debris flows: Federal Office for the Environment, Berne, The environment in practice no. 1608, 97 p.

Frank, F., McArdell, B.W., Oggier, N., Baer, P., Christen, M., Vieli, A., 2017, Debris-flow modeling at Meretschibach and Bondasca catchments, Switzerland: sensitivity testing of field-data-based entrainment model: Natural Hazards and Earth System Science, v. 17, iss. 5, doi: 10.5194/nhess-17-801-2017, p. 801–815.

Frick, E., Kienholz, H. Roth, H., 2008, SEDEX - eine praxistaugliche Methodik zur Beurteilung der Feststofflieferung in Wildbächen, *in* Proceedings, 11th Congress INTERPRAEVENT, Dornbirn: Klagenfurt, International Research Society INTERPRAEVENT, p. 319–330.

Graf, C., and McArdell, B.W., 2008, Simulation of debris flow runout before and after construction of mitigation measures: an example from the Swiss Alps, *in* Chernomorets, S.S., ed, Debris Flows: Disasters, Risk, Forecast, Protection: Pyatigorsk, International conference on debris flows: disasters, risk, forecast, protection, 22–29 September, 2008, p. 233–236.

Hohermuth, B., Graf, C., Heilig, J., 2016, Integrated natural hazards protection concept Vitznau LU - Case study Plattenbach, *in* Proceedings, 13th congress INTERPRAEVENT, Lucerne: Klagenfurt, International Research Society INTERPRAEVENT, p. 535–543.

Hürlimann, M., Rickenmann, D., Graf, C., 2003, Field and monitoring data of debris-flow events in the Swiss Alps: Canadian Geotechnical Journal, v. 40, p. 161–175, doi: 10.1139/T02-087.

Hürlimann, M., Rickenmann, D., Medina, V., and Bateman A., 2008, Evaluation of approaches to calculate debris-flow parameters for hazard assessment: Engineering Geology, v. 102, p. 152–163.

Hungr, O., and McDougall, S., 2009, Two numerical models for landslide dynamic analysis: Computers & Geosciences, v. 35, p.978–992.

Jakob, M., 2005, A size classification for debris flows: Engineering Geology, v. 79, iss. 3–4, p. 151-161.

Laigle, D., Abbé, M., 2016, The impact of debris flows on structures: practice revisited in light of new scientific results, *in* Proceedings, 13th congress INTERPRAEVENT, Lucerne: Klagenfurt, International Research Society INTERPRAEVENT, p. 782–790.

Lateltin, O., Haemmig, C., Raetzo, H., and Bonnard, C., 2005, Landslide risk management in Switzerland: Landslides, v. 2, p. 313–320. doi: 10.1007/s10346-005-0018-8.

PLANAT, 2005, Hazard maps and related instruments, Vademecum: Berne, 19 p.

Rickenmann, D., 1999, Empirical Relationships for Debris Flows: Natural Hazards, v. 19, p. 47–77.

Rickenmann, D., 2005, Runout prediction methods, *in* Jakob, M., Hungr, O., eds., Debris Flow Hazards and Related Phenomena: Chichester, Springer, p. 305–324.

Salm, B., 1993, Flow, flow transition and runout distances of flowing avalanches: Annals of Glaciology, v. 18, p. 221–226, doi:10.3189/S0260305500011551