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Modeling debris-flow runout patterns on two alpine fans with different dynamic simulation models

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Abstract

Predicting potential deposition areas of future debris-flow events is important for engineering hazard assessment in alpine regions. For this, numerical simulation models are commonly used tools. However, knowledge of appropriate model parameters is essential but often not available. In this study we use two numerical simulation models, RAMMS-DF (Rapid Mass Movement System – Debris Flow) and DAN3D (Dynamic Analysis of Landslides in Three Dimensions), to back-calculate two well-documented debris-flow events in Austria and to compare the range and sensitivity of input parameters for the Voellmy flow model. All simulations are based on the same digital elevation model with a 1 m resolution and similar initial conditions. Our results show that both simulation tools are capable of matching observed deposition patterns. The best fit parameter set of μ [–] and ξ [m s^{-2}] range between 0.07–0.11 and 200–300 m s^{-2}, respectively, for RAMMS-DF, and 0.07–0.08 and 300–400 m s^{-2}, respectively, for DAN3D. Sensitivity analyses show a higher sensitivity of model parameters for the DAN3D model than for the RAMMS-DF model. This study shall contribute to the evaluation of realistic model parameters for simulation of debris-flows in steep mountain catchments and highlights the sensitivity of the models.

1 Introduction

Gravitational driven processes such as debris-flows are complex grain-fluid mixtures occurring in alpine regions and cause loss of human life and property. It is therefore of great public and private interest to delineate hazardous areas where future debris-flows are expected to occur. For this, various types of simulation models provide useful guidance and are often used in engineering practice. Such models range from purely empirical-statistical approaches (e.g. Scheidegger, 1973; Körner, 1976; Rickenmann, 1999; Legros, 2002; Scheidl and Rickenmann, 2010) to more physically-based, deterministic approaches, mostly based on depth averaged flow equations and a simple flow

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resistance term (e.g. Takahashi, 1991; Hungr, 1995; O'Brien et al., 1993; Medina et al., 2008; Christen et al., 2010a, b).

Independent of the constitutive relation used, a common caveat for all numerical simulation tools remains model calibration (i.e. appropriate choice of flow-resistance parameters). In case of simple stress–strain relations (e.g. Bingham, Herschel Bulkley model), laboratory experiments have been conducted to derive material parameters for highly concentrated grain-fluid mixtures (e.g. Phillips and Davies, 1991; Major and Pierson, 1992; Contreras and Davies, 2000; Kaitna and Rickenmann, 2007; Kaitna et al., 2007). However, direct application of the results appear critical because scaled experiments as well as the simple flow resistance models themselves do not represent full mixture dynamics of a real scale debris-flow (Iverson, 1997, 2003; Ancey, 2006; Kaitna et al., 2014). Therefore, as for conceptual depth-averaged flow resistance approaches (Voellmy model, Coulomb, etc.), model parameterization based on back-calculation of well-documented past events appears to be preferable for engineering application (e.g. Hungr et al., 2005; Rickenmann et al., 2006; Hürlimann et al., 2008; Christen et al., 2010a).

Comparative studies indicate that the Voellmy model (detailed in Sect. 2), which originally was developed for modeling bulk flow propagation of snow avalanches, is also suitable for modeling other geomorphic processes, including rock avalanches and debris-flows (e.g. Hungr, 1995; Revellino et al., 2004; Naef et al., 2006; Sosio et al., 2008; Deline et al., 2011). For snow avalanches a reasonable database of model parameters for different types of snow and land cover is available (e.g. Bartelt et al., 2013a). However, there is much less experience in the case of debris-flows.

We therefore present our experiences with back-calculating Voellmy parameters for two well documented debris-flow events in Austria. We do this using the simulation platforms RAMMS-DF and DAN3D. Because a plausible representation of simulation results requires knowledge on the sensitivity of the model input parameters, we additionally carried out a comparative sensitivity analysis for both models. Section 2 gives a brief overview of the technical background of RAMMS-DF and DAN3D, the Voellmy model and the application to the two study sites. The best-fit parameters and the sensitivity analyses are presented in Sect. 3 and discussed in Sect. 4.

2 Methodology

2.1 Simulation tools and friction relation

Within this study the numerical simulation tools RAMMS-DF (Rapid Mass Movement System – Debris Flow), developed at the WSL Institute for Snow and Avalanche Research SLF and the Swiss Federal Institute for Forest, Snow and Landscape Research WSL, and the code DAN3D (Dynamic Analysis of Landslides in Three Dimensions), developed at the Department of Earth, Ocean and Atmospheric Sciences at the University of British Columbia UBC, were applied to replicate deposition pattern of two well documented debris-flow events. Both simulation tools use the equivalent fluid concept (Hungr, 1995) and assume constant density and incompressibility of the flowing media as well as the validity of the shallow water approximation (i.e. negligible slope normal accelerations). Mass and momentum balance is provided by solving the depth averaged flow equations in a Lagrangian reference framework for DAN3D (Hungr and McDougal, 2009) and with a fixed Eulerian coordinate system for RAMMS (Christen et al., 2010b). A number of studies can be found in the literature, where similar depth averaged equations were derived, such as Iverson and Denlinger (2001) and Pastor et al. (2002) for Eulerian forms and e.g. Savage and Hutter (1989) and Gray et al. (1999) for Lagrangian forms, respectively.

RAMMS uses the TVD (total variation diminishing) finite volume scheme (FVM) applied on 3-D terrain (Christen et al., 2005; Graf and McArdell, 2008). By this method, averaged cell values are calculated for each place in a grid by the means of the edge fluxes from the neighboring cells (Toro, 1999). Detailed information on the discretization technique and the numerical background of RAMMS can be found in Christen

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et al. (2008, 2010a; b). The frictional behavior in x and y is represented by the Voellmy model, which includes the resistance parameters μ and ξ (described below).

Contrary to RAMMS, DAN3D is based on Smoothed Particle Hydrodynamics (SPH) (Lucy, 1977; Gingold and Monaghan, 1977) to solve the governing equations resulting in flow depths, velocities and erosion thickness. Here the equations are solved in the center of reference columns and these mass particles are in the flow and progressed to new position for each time step individually (Monaghan, 1989; Benz, 1990; Sosio et al., 2008). The SPH method uses the Langrangian reference frame and does not need a computational grid. DAN3D allows a selection of different types of resistance laws, including a laminar, turbulent, plastic, Bingham, frictional or Voellmy rheology (Hungr, 1995; Hungr and McDougall, 2009 and references therein). For comparative reasons, in this study we only focused on the Voellmy rheology.

From theoretical reasoning, Voellmy (1955) divided total resistance of the flowing media into two parts: a Coulomb-type friction (coefficient μ [–]) that scales with the normal stress and a turbulent drag coefficient ξ [$\mathrm{m\,s^{-2}}$], that scales with velocity squared. A simplified representation of the total resistance S [Pa] used in both simulation tools writes:

$$S = \mu \rho H g \cos\phi + \left(\frac{\rho g U^2}{\xi}\right) \tag{1}$$

where ρ is the bulk density, g is gravitational acceleration, ϕ is the slope angle, H is the mean flow height and U is the mean flow velocity (Eq. 1). The snow avalanche and hillslope versions of RAMMS additionally offers the option of a velocity dependent parameter for an improved representation of physical processes within the flow. In the used version of RAMMS-DF for this study this option was not applied. Details of the random kinetic energy model can be found in Bartelt et al. (2006), Preuth et al. (2010) and Christen et al. (2010b).

In both simulation tools modeling of internal pressure gradients is guided by Rankine's earth pressure theory, similarly as applied by Savage and Hutter (1989) (Bartelt

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et al., 1999; Hungr, 2008a). Here an internal friction angle controls the resulting stresses due to longitudinal straining. A minimum value of the pressure coefficient k appears when the flowing material extends under “active” conditions. In contrast, if the flow sheet is compressed a maximum value is resulting under “passive” conditions (Bartelt et al., 1999; Hungr and McDougall, 2009). DAN3D uses the approach of Savage and Hutter (1989) to calculate stress ratios parallel and perpendicular to the bed (Hungr, 2008):

$$k_{a/p} = 2\left(\frac{1 \pm \sqrt{1-\cos^2\phi_i(1+\tan^2\phi_b)}}{\cos^2\phi_i}\right) - 1 \qquad (2)$$

where ϕ_i is the internal friction angle and ϕ_b is the basal friction angle (representing the ratio of basal shear stress to total normal stress). In case of $\phi_b = 0$ (basal friction is negligible compared to internal friction), Eq. (2) reduces to the classic Rankine form

$$k_{a/p} = \tan^2\left(45^\circ \pm \frac{\phi_i}{2}\right) \qquad (3)$$

which is implemented in RAMMS. Within our study we used the default values of $\phi_i = 35^\circ$ for DAN3D and a fixed value of $k_a = k_p = 1$ for RAMMS. The consequences of this choice are discussed in Sect. 4.

2.2 Study sites

Reiselehnrinne Creek is located in the Pitztal Valley, SW of Innsbruck, Tyrol, Austria (46°59′ N, 10°52′ E) (Fig. 1a). The catchment extends from 3343 to 1620 m a.s.l. and covers an area of 0.7 km^2. The source area of the catchment is dominated by gneiss and mica schists. The middle, channelized part of the watershed consists of debris overlaying bedrock, whereas coarse debris-flow material comprises the fan (Kogelnig-Mayer et al., 2011). Data from a rain gauge located in Plangeross (1620 m a.s.l.) shows that annual rainfall varies between 600 and 1150 mm yr^{-1}. Detailed information on the long term event history of this site can be found in Kogelnig-Mayer et al. (2011), who reconstructed several debris-flows and snow avalanches during the last century using dendrogeomorphic methods. The best documented debris-flow event occurred in August 2009 and deposited around 20 000–25 000 m^3 of material on the orographic right side of the fan and ran out onto the provincial road, which was subsequently blocked for several hours. This event was back-calculated within the present study.

The second study area is the densely forested fan of Festeticgraben Creek, situated in the Gesäuse National Park, Styria, Austria (47°35′ N, 14°38′ E). The Festeticgraben Creek extends from the Planspitze summit (2117 m a.s.l.) to 570 m a.s.l. at the confluence of the Enns River opposite of the small village Gstatterboden (Fig. 1b). The small catchment area (0.7 km^2) is dominated by Triassic limestone (Dachsteinkalk) and dolomites and the material deposited on the fan has a mean grain size of 84 mm. A rain gauge in village Gstatterboden, opposite the fan, recorded a mean annual precipitation between 1000 and 1700 mm. Schraml et al. (2015), reconstructed debris-flow events on several gullies of the steep Planspitze north face through dendrogeomorphic techniques, including an event chronology of the Festeticgraben debris fan as well as information on geology and the forest stand of the northern Planspitze area. In this study we focus on the most recent event, for which material deposited on the forested fan widely spread on both sides of the channel. Our back-calculation was for the 2006 event. Through field investigation we estimated a total volume of $\sim$ 10 000 m^3 deposited on the fan. We assume that the evenly distributed forest stand had a certain impact on the debris-flow deposition behavior, which we attempted to account for in our simulations.

2.3 Input parameters, evaluation criteria and sensitivity analysis

In engineering applications, the uncertainties are not only connected to choice of flow resistance parameters μ and ξ, but also to the magnitude of an expected fu-

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ture event. Therefore, we performed a sensitivity analyses for both, the RAMMS-DF and the DAN3D code by separately varying each Voellmy input parameters μ and ξ as well as the event magnitude (source volume), while keeping the other parameters constant. The variation of μ ranges from 0.01 to 0.32, and ξ from 100 to 1400 $\mathrm{m\,s^{-2}}$ and the initial volume has been increased up to 100 %. For the Festeticgraben Creek in the Gesäuse area (Fig. 1b) we delineated the forested area beside the channel. We tested increased μ values (between 100 and 150 %) for the forested areas to account for the resilience of trees against the impact of debris-flows. No direct relation to the calibration of frictional parameters of the topography was considered.

In both codes, we used a mass block release (e.g. an instantaneous landslide release) as the initial condition. Based on indications from aerial images, we assumed source areas in the upper part of catchments with release heights of ~ 1.5 m for the Pitztal and ~ 0.5 m for the Gesäuse resulting in total bulk volumes of ~ 23 000 and ~ 10 000 $\mathrm{m^3}$, respectively, corresponding to observed deposition volumes. Sediment entrainment along the channel was neglected and the grid resolution of all simulation runs was set to 2 m.

Because we do not have any reliable information on flow parameters in the transit reach during the events (i.e. flow depth, flow velocity), we have focused on the evaluation of model performance solely on the deposition pattern. Because the event in 2009 at the Reiselehnrinne Creek as well as first simulation runs showed limited spreading of the material, the runout length of the simulated debris-flow deposits appears to be the most useful evaluation criteria.

Mapped debris-flow material of the Festeticgraben Creek event in 2006 overtopped the channel and was widely spread over the fan in form of tongues or lobes. We therefore compared mapped and simulated deposition areas by using a similar approach as Carranza and Castro (2006) and Scheidl and Rickenmann, (2010). For this, subareas A_x, A_y and A_z resulting from superposition of mapped and simulated areas (Fig. 2) were systematically compared (Eqs. 4–6). Subsequently a coverage index (Ω) is derived using Eq. (7).

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$$\alpha = A_x / A_{\text{mapped}} \quad (4)$$

$$\beta = A_y / A_{\text{mapped}} \quad (5)$$

$$\gamma = A_z / A_{\text{mapped}} \quad (6)$$

$$\Omega := \alpha - \beta - \gamma \quad (7)$$

3 Results

3.1 Back-analysis of the events

First back-calculations of the event at the Reiselehnrinne Creek with both models led to substantial differences compared to observed deposition patterns. Specifically, most of the material left the channel close to the distal limit of the fan and ran out straight into the forest instead of following the channelized path to the orographic right section of the fan (see dashed lines in Fig. 3a and c). To overcome this problem we assigned an area with increased roughness ($\mu^* = 0.9$) at the left channel bank of the transit reach that acts like a deflection dam. Subsequent simulations with both models were successful and the parameter set for the best fit simulations using RAMMS-DF and DAN3D are $\mu = 0.11$ and $\xi = 200\,\mathrm{m\,s^{-2}}$, and $\mu = 0.08$ and $\xi = 400\,\mathrm{m\,s^{-2}}$, respectively.

For the second study site (Festeticgraben, Gesäuse) we differentiated between the roughness within the channel (μ) and the roughness outside of the channel, which is expected to be influenced by the forest stand (μ_F). With this modification we obtained a satisfying fit between observed and simulated deposition areas for the RAMMS-DF model (Fig. 3c). DAN3D was not sensitive to the separation between channelized and non-channelized flow. Best-fit Voellmy parameters for the channelized flow at Festeticgraben were $\mu = 0.07$ and $\xi = 300\,\mathrm{m\,s^{-2}}$ for both simulation models. The friction parameter representing the forest stand (μ_F) were remarkably different between the models.

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We used $\mu_F = 0.23$ for the RAMMS-DF and $\mu_F = 0.07$ – the same as for the channel – for the DAN3D code.

3.2 Sensitivity analyses

A sensitivity analysis was performed for both simulation tools, RAMMS-DF and DAN3D. As mentioned earlier, the most reasonable evaluation criteria for Reiselehnrinne Creek was the runout distance, whereas for the Festeticgraben a comparison between mapped and simulated deposition areas is favorable. Figure 4 illustrates a comparison of the runout sensitivity of the two models based on the case study site Reiselehnrinne. The Voellmy resistance parameters range from 0.03 to 0.16 for μ and from 100 to 700 $\mathrm{m\,s^{-2}}$ for ξ. Initial volumes were modified between 15 000 and 50 000 $\mathrm{m^3}$, reflecting a wide range of uncertainty during the hazard assessment.

In the case of the Festeticgraben Creek the evaluation parameter Ω gives indication on the quality of the simulated debris-flow pattern relative to the mapped deposits, where a value of 1 would indicate a perfect match. Note that material that was deposited earlier in the transit zone was neglected. We varied the Voellmy parameters in a range from 0.01 to 0.24 for μ and 100 to 1400 $\mathrm{m\,s^{-2}}$ for ξ. Different initial volumes were tested between 10 000 and 20 000 $\mathrm{m^3}$. We additionally varied the roughness of the area outside of the channel (μ_F) between 0.03 and 0.32. Intermittent variation steps are the same for both models, except the μ_F ranges which react also in this case, more sensitive in DAN3D than in the RAMMS-DF model. Generally we detected a higher sensitivity of variation of the friction parameter μ than of the turbulent coefficient ξ (Fig. 5). This is not surprising because we only evaluate deposition pattern on the fan rather than flow parameters (v, h) in the transit zone. Given the form of the Voellmy equation, one might expect that the Coulomb term in the Voellmy equation would dominate the frictional behavior in the deposition zone where the flow is relatively slow, whereas the turbulent term would be expected to dominate the total friction when the flow is fast (e.g. in the transit zone). Comparing sensitivity to variation of the friction parameters,

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as expected we detect a higher sensitivity of μ within the channel in the deposition zone than μ_F representing the forested area.

4 Discussion

First simulation runs with both simulation tools did not match the observed deposition pattern for either investigation area. In case of the Reiselehnerinne most of the material left the channel before it reached the proximal limit of the fan. This was not observed after the event in 2009. This discrepancy is most likely due to (1) the use of an outdated DEM, which was derived by air-borne laser scanning three years before the event occurred and does not account for potential morphological changes in the meantime, (2) erosion/deposition processes during the event itself, or (3) an overestimation of simulated flow depth. We have no data to quantify these effects, however, simulated maximum flow depths between 5 and 10 m are plausibe for both model results and indicate the need to use an up-to-date DEM for simulations on such a highly active debris-flow fan. The importance of accurate DEMs has been discussed also by others (e.g. Rickenmann et al., 2006; Bühler et al., 2011). For practical engineering applications, there are several ways to overcome the problem, including modification of the DEM (adding a dam structure or changing the height in the original grid of the DEM), change of resistance parameters of the flowing mass along the channel (thereby altering the shape of the hydrograph), or localized increase of roughness of one channel bank. We choose the latter approach herein and increased the left channel bank roughness to $\mu^* = 0.9$ (yellow shaded area in Fig. 3). This allows deposition along the left channel bank and generally acts like a deflection dam.

For the second study site at the Festeticgraben Creek we assumed that the forested fan has considerably influence on the deposition behavior of debris-flows and separated μ values between friction within the channel and outside of the channel. Others have addressed the significance of interactions between forest and snow avalanches (e.g. Teich, 2013; Feistl et al., 2014) which can be accounted for by adjusting the

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Voellmy friction parameters for simulations. For the RAMMS-AV model, resistance parameters of $\mu = 0.02$ and $\xi = 400\,\mathrm{m\,s^{-2}}$ for all magnitudes of avalanches can be found in the handbook (Bartelt et el., 2013a), but yet few suggestions are available for debris-flows. Within this study we differentiated between the roughness within and outside of the channel to account for the forest stand and to improve our simulation results. For the RAMMS-DF model we had to increase μ_F to 0.23 to derive satisfying results, whereas for DAN3D best results were returned with the same value of μ within and outside of the channel. Similarly Hauser (2011) increased the channel friction parameter $\mu = 0.25$ to $\mu_\mathrm{F} = 0.27$ to account for additional roughness due to a forest when reproducing a $\sim 70\,000\,\mathrm{m^3}$ debris-flow event in Switzerland with RAMMS. Our subsequent sensitivity analysis showed that the output of RAMMS-DF is mainly sensitive to variations of μ_F rather than to variations of μ in the channel. For DAN3D, μ and μ_F influence results similarly.

In spite of the different methods described earlier to solve the depth-averaged equation systems, both models should provide similar simulation results when using the same boundary conditions as well as the same basal friction law. However, some details are different. For a quick comparison, input parameters, selected boundary conditions and several other properties regarding the two models are listed in Table 1. The main differences arise from different stopping criteria, calculation of the pressure term, and the numerical solution schemes of the mass and momentum conservation equations.

For quantifying the effect of the different stopping criteria, we conducted some additional test runs to evaluate the repeatability and relative sensitivity of the outcomes. RAMMS-DF stops calculation at a user-defined percentage value of the total mass momentum (or it can be stopped manually or after a user-defined run duration). In this study we consistently used a value of 15 %. Changing this stopping criteria to other plausible values (5, 10 and 20 %), indicates that the overall sensitivity is similar to that of the variation of μ (Fig. 6). The DAN3D code can be stopped manually or automatically after a predetermined duration. Here we manually stopped the simulation when

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the flow front visually came to a halt. This method is expected to be biased to some extent, but repeating identical runs gave confidence in the repeatability of our simulations. Similarly the sensitivity criteria Ω for the Gesäuse area provides an additional assessment of the choice of the stopping criteria. We observed the same sensitivity pattern for both, the runout length and the value of Ω.

Another difference between RAMMS and DAN3D is the effect of vertical pressure gradients on the internal stress state in the 2-D momentum balance equations, which is modeled by a proportionality coefficient $k_{a/p}$ (e.g. Hungr and McDougall, 2009, Eqs. 10–11; Christen et al., 2010a, Eqs. 2–3). This pressure coefficient is defined differently in both models. On the one hand, DAN3D calculates $k_{a/p}$ by Eq. (2), which is based on Savage and Hutter's (1989) adoption of Rankine's earth pressure theory, accounting for a deviation of the direction of principal stresses from flow direction due to significant basal resistance (Hungr and McDougall, 2009). Hungr (2008) elaborates that in case of strong pressure gradients this approximation is imprecise and leads to significant deviations from experimental observations, especially in the initial phase of a dam break situation. For these situations Hungr (2008) suggests an empirical equation to modify ϕ_b. In the current study we neglected this effect and only Eq. (2) was applied, using an internal friction angle of 35° which is expected to be realistic for debris-flow material.

RAMMS simplifies the classic Rankine approach (Eq. 3) by setting $k_a = k_p$ (Bartelt et al., 1999, 2013a). In our study we used the default value of 1 which corresponds to a hydrostatic stress distribution. Variations of $k_{a/p}$ by a factor of 2–3 had similar effects on the runout as variation of the Voellmy friction parameter μ (Bartelt et al., 2013b).

We suppose that the influence of the stopping criteria has a similar influence on the runout distance as small variations in the value of the μ coefficient. The effect of the method for describing the earth-pressure would also influence the runout in a similar way, but it may also change the mobility of the flow in general.

Using two different evaluation criteria our results indicates that DAN3D generally reacts more sensitively to varying the Voellmy resistance parameters than RAMMS-DF for both cases of relatively small alpine debris-flows (Figs. 4 and 5).

A further observation is that for both programs changing the friction parameter μ has a stronger influence on the runout distances of the simulated debris-flows than varying the ξ value in the case of the Pitztal area. This is in accordance to expectations, because also other studies showed that ξ is mainly responsible for the flow behavior along the channel and μ determines runout (e.g. Barbolini et al., 2000). A similar sensitivity behavior is observed for RAMMS-DF for the evaluation parameter Ω at the Festeticgraben Creek where again, ξ plays a secondary role when depicting observed deposits. Interestingly, the variation of the initial volume provides little variations of the output of RAMMS-DF for both of our study sites. In contrast, DAN3D shows more pronounced sensitivity to initial volume variations, but sensitivity is similar as for the variation of resistance parameters. This moderate sensitivity to event magnitude uncertainty of ±20 % may be considered for scenario design for runout prediction.

In this study we only focused on the sensitivity of model outcome on variations of resistance parameters and event magnitude. However, there are also several other model input settings that may significantly influence model output, like DEM resolution or accuracy (Rickenmann et al., 2006; Bühler et al., 2011), erosion along the path (e.g. Hungr, 1995; McDougall and Hungr, 2005; Sovilla et al., 2006; Christen et al., 2010b), or coefficient of horizontal pressure gradient (mostly represented by active/passive earth pressure theory, Christen et al., 2010b; Hungr, 2008).

For the simulation of our small alpine debris-flow events, the best-fit Voellmy parameter sets of RAMMS-DF and DAN3D are in the range of $\mu = 0.07$–0.11 and $\xi = 200$–$400\,\mathrm{m\,s^{-2}}$ for channelized flows and with μ values up to 0.32 for forested areas outside of the channel. To compare our results, we plot the μ/ξ parameter space together with other published results from simulations with DAN3D and RAMMS, including rock avalanches, snow avalanches and other debris-flows (Fig. 7). We find that μ and ξ values for debris-flows are rather low compared to other processes, indicating lower velocities in the transit zones, but larger runout in the deposition zone. A study performed by Scheidl et al. (2013), where they compared several back-calculated debris-flow events based on the Voellmy friction relation, is in agreement with our results.

Rock avalanches (most often modeled with DAN3D) tend to have μ values in a similar range, but mostly higher ξ values. Ice-rock avalanches were similarly simulated with high ξ parameters, but much lower μ values, consistently for DAN3D and RAMMS. This parameter space may reflect lower friction of the ice and the presence of pore water due to melting of the ice (Schneider et al., 2011). Data for snow avalanches are only available from RAMMS simulations and are based on experience of back-calculating observed snow avalanches. The Voellmy parameters are rather large and represent the envelope of parameter space currently available for geophysical flows. The data shows that μ decreases and ξ increases with increasing event volume (Bartelt et al., 2013), reflecting higher velocities and larger runout for large avalanches. Searching for a similar relation published data available for other processes we only find the weak trend for rock avalanches that the ξ decreases with increasing event volume.

5 Conclusions

Two well documented debris-flow events in Austria were back calculated with two different simulation tools, the RAMMS-DF code and the DAN3D code. The Reiselehnrinne Creek (Pitztal) event in 2009, which released a total volume of $\sim 23\,000\,\mathrm{m}^3$, and a debris-flow in the Festeticgraben Creek (Gesäuse), which delivered $\sim 10\,000\,\mathrm{m}^3$ of material to the fan. Areas of increased roughness were included to account for additional surface roughness due to the interaction of the flow with the forest. Best fit parameter sets for both models and for both study sites are in a similar range ($\mu = 0.07$–0.11 and $\xi = 200$–$400\,\mathrm{m\,s}^{-2}$), which is in accordance with experience of other studies. Focusing only on deposition pattern, sensitivity analyses using two different evaluation criteria showed a significant sensitivity to the variation of μ and event volume, and lower sensitivity to variation of ξ. DAN3D and RAMMS-DF react differently on variation of input parameters, which might be due to different numerical solution schemes to solve the depth-averaged equations of motion in th models or the calculation of the resultant of the internal pressure gradients in the momentum equations. For an improved

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engineering hazard assessment it is desirable that reliable parameter ranges for the Voellmy model should be available for different geophysical processes. Additionally future simulations of debris-flows using the Voellmy model may be useful to differentiate between different types of surface roughness, with the goal of providing a database of recommended model parameters, similar as is available for snow avalanches.

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Table 1. Comparison of model input conditions within our study. Grids, triggering conditions, excluded erosion, rheology and the governing equations are identical, whereas the numerical solution, the reference system as well as the stopping of the simulations are different.

	RAMMS-DF	DAN3D
Depth-averaged shallow water equations conserving mass and momentum	✓	✓
Friction relation used	Voellmy	Voellmy
Numerical solution scheme	FVM (Finite Volume)	SPH (Smoothed Particle Hydrodynamics)
Reference system	Cartesian framework	Lagrangian framework
Grid	Fixed grid in the space	Affiliated to the flowing material
Applied DEM	1 m	1 m
Source	Block release mass	Block release mass
Erosion	Neglected in this study	Neglected in this study
Stopping criteria	Percentage of momentum	End of visual movement
Pressure term	Dynamic $k_{a/p}$ (Eq. 2)	$k_a = k_p = 1$

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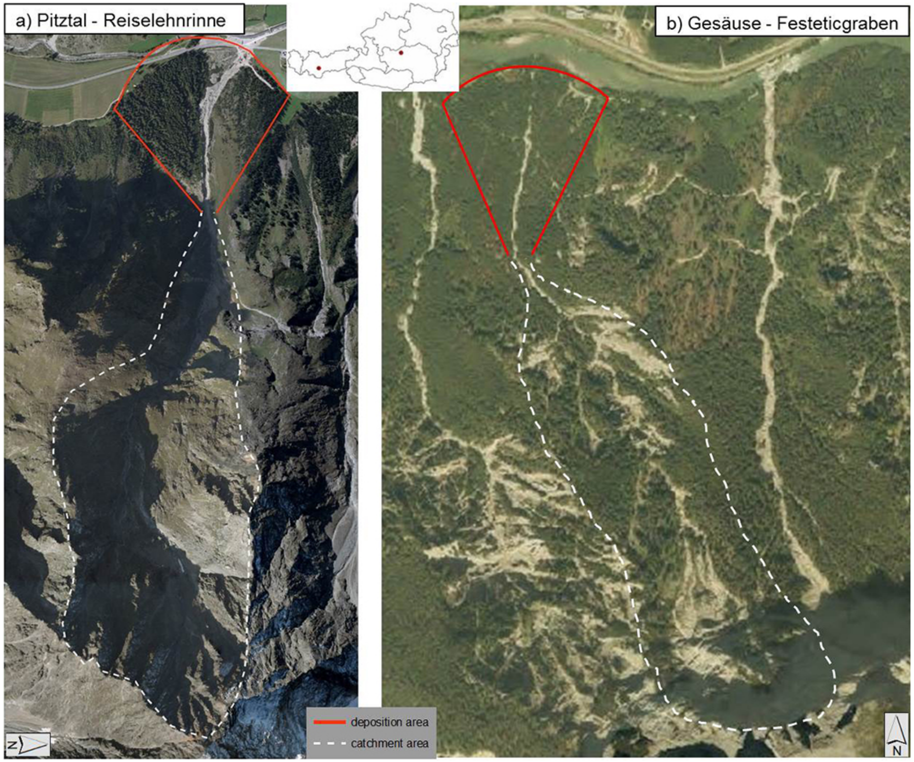

Figure 1. (a) The Reiselehnrinne Creek in the Pitztal study area in the western part of Austria, and **(b)** Festeticgraben Creek (areal picture: GIS-Steiermark, 2013) in the eastern part of the Austrian Alps. The upper parts of the watersheds are presented in white dashed lines and deliver material to the fans (red solid line).

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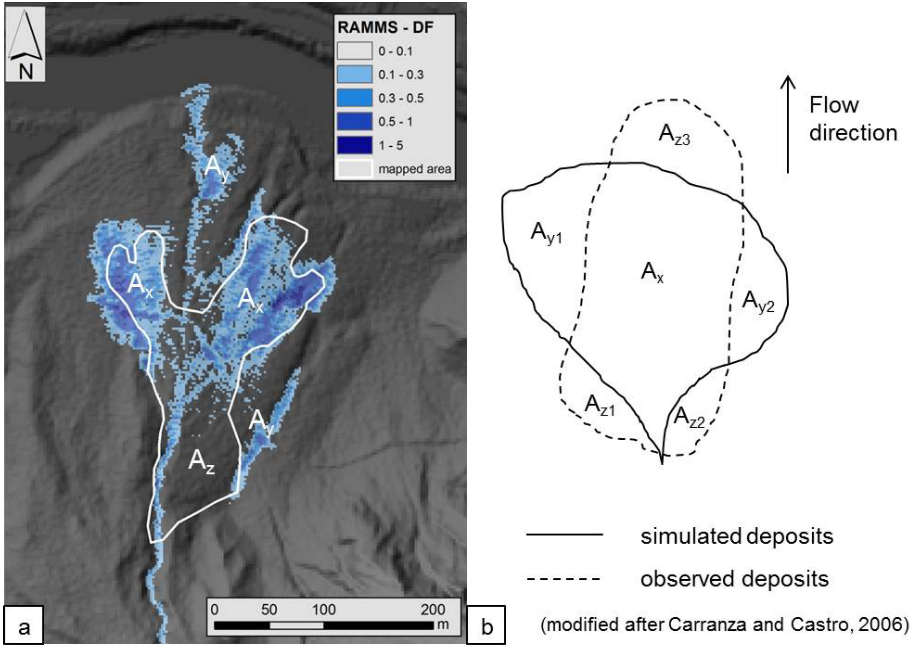

Figure 2. Superposition of the simulated area with the mapped area of recently deposited debris-flow material at the Festeticgraben debris fan **(a)**. Sub-areas where derived through overlapping the simulated deposits with the observed deposits **(b)** and following the approach of Carranza and Castro (2006), we assessed our simulation results. Area A_x represents the simulated deposits within the mapped area whereas A_z indicates the non-simulated debris-flow deposits within the observed area. Simulated deposition outside the mapped area is shown as A_y.

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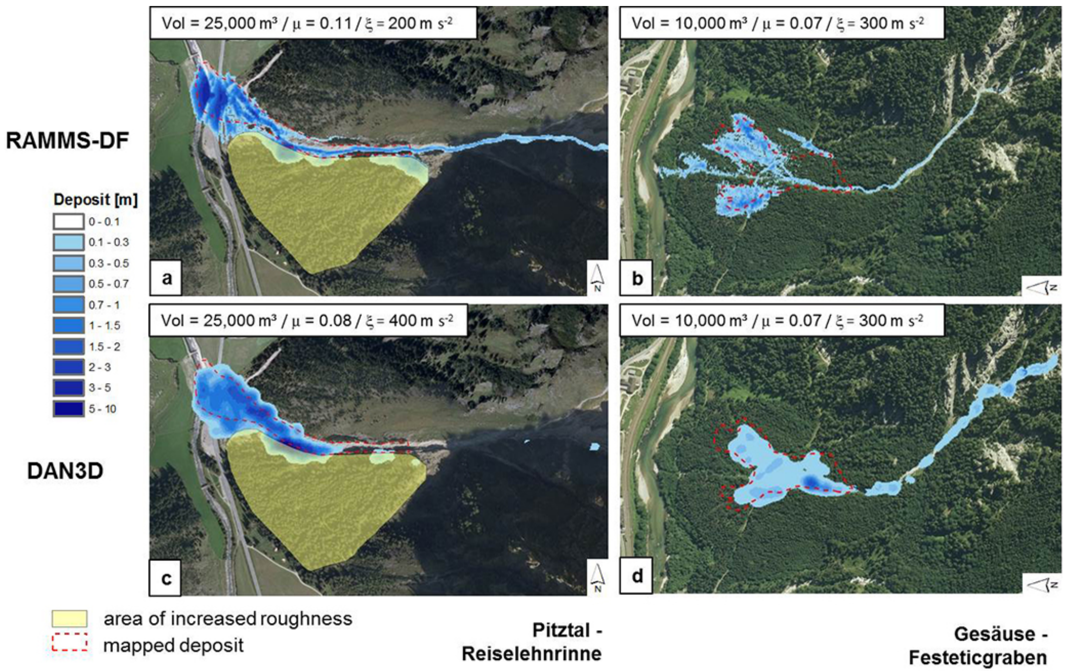

Figure 3. Best fit simulations of RAMMS-DF and DAN3D for both study areas, the Reiselehnrinne **(a, c)** and the Festeticgraben **(b, d)**. Deposition heights are represented using blue color shades, for the results for the event in 2009 at the Reiselehnrinne Creek as well as for the event in 2006 at the Festeticgraben Creek. The red dashed lines represent the mapped deposits. Areas of increased roughness are depicted in light yellow.

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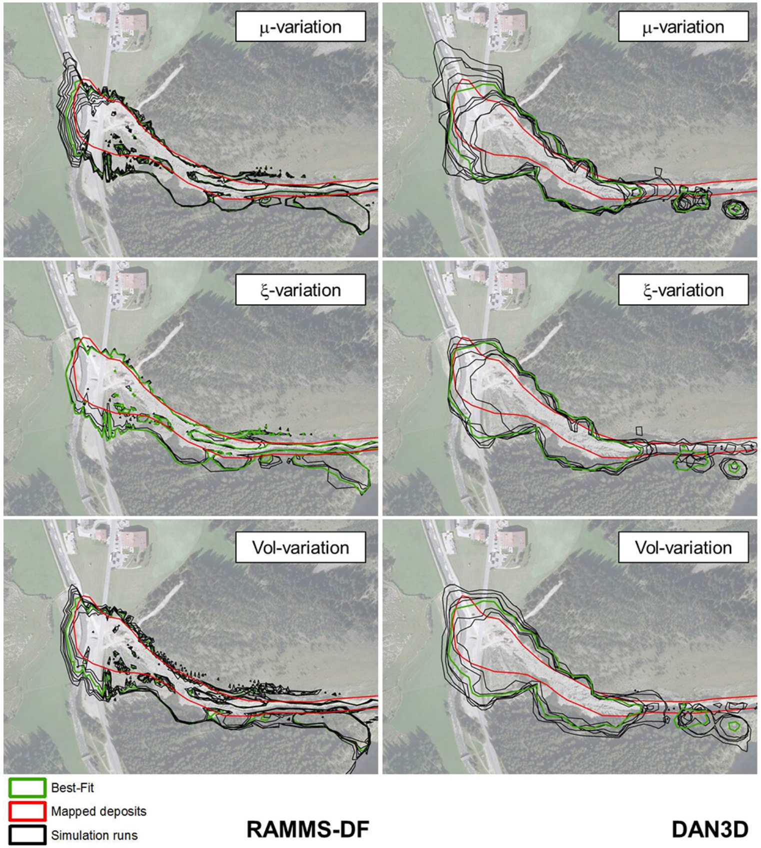

Figure 4. Variation of the Voellmy parameters (0.03–0.16 for μ and 100–700 m s^{-2} for ξ) and the initial volume (from 15 000 to 50 000 m^3) for the RAMMS-DF and the DAN3D code for the Pitztal study area. Outlines of the simulation runs are given in black, respectively the best fit simulation in green. The mapped deposits of the event in 2009 are presented in red.

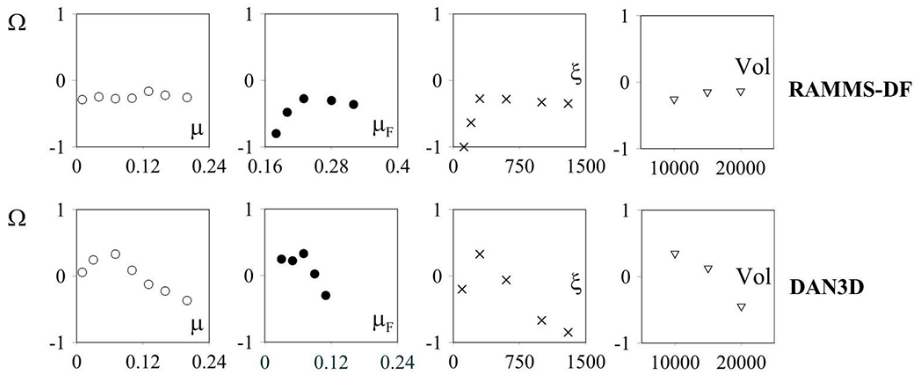

Figure 5. Sensitivity analysis of RAMMS and DAN3D for the Gesäuse case study. The Voellmy parameters in combination with an additional area of increased roughness as well as the initial volume were modified with focus on the dimensionless Ω value (Eq. 7).

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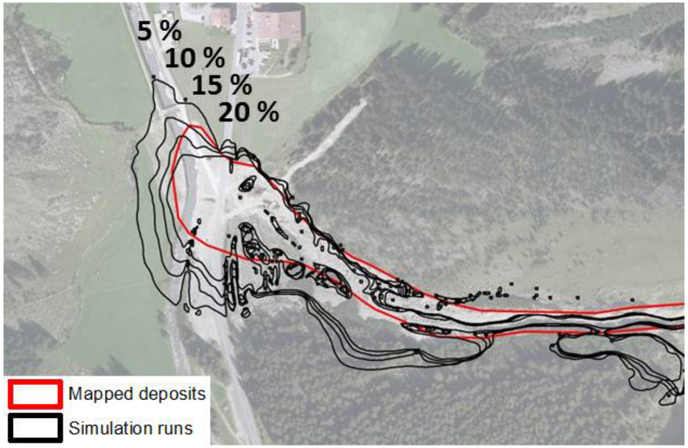

Figure 6. Variations of stopping criteria using the RAMMS-DF model for the Reiselehnrinne Creek case study. Outlines of the simulations are presented in black, mapped deposits are given in red.

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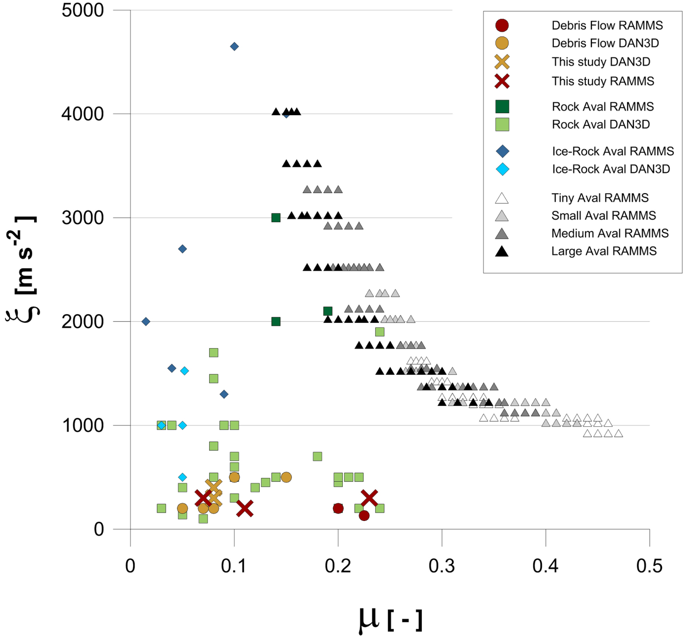

Figure 7. Voellmy resistance parameter sets from back-calculation of different events. Debris-flow parameters from our evaluations are presented as red and brown crosses, from other studies (Hungr et al., 2002; Hungr, 2008b; Jakob et al., 2000; Revellino et al., 2004) parameters are given in a red and brown circular shape. Rock avalanches are illustrated as green squares, ice-rock avalanches are blue diamonds and snow avalanches are shown as grey shaded triangles (Hungr and Evans, 1996; Sosio et al., 2008, 2012; Lipovski et al., 2008; Schneider et al., 2010; Bartelt et al., 2013b).

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