Rockfall runout modelling for hazard zonation considering macro-topographic dispersion

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With 8 figures and 3 tables

Abstract: To avoid damage on infrastructure and loss of life, rockfall hazard zonation based on numerical simulation, has become an important tool for land use planning. Due to process-complexity and scale-dependency of input data, rockfall runout modelling is still subject to many uncertainties. Based on the specific geologic conditions (e.g. lithology, fabric, discontinuities, tectonics), detached block sizes at the cliff face vary significantly. Furthermore, released rock masses tend to disintegrate into fragments after the first impact. Depending on size and shape of the detached block and boulder/surface interaction, modelling trajectories of these fragments is a difficult task. A few sophisticated simulation tools are able to consider rebound-effects as well as macro-, and micro-topographic factors controlling lateral dispersion. However, these models require a set of high-precision terrain and vegetation roughness parameters – which are typically not available for large areas. We propose an alternative grid-based approach applicable for runout modelling at regional scale, since today high resolution digital terrain models are available for large areas. Thus, we suggest modelling rockfall propagation by considering macro-topographic lateral dispersion and different boulder sizes even at regional scale. For this purpose we used varying coefficients of friction for different boulder sizes and a rockfall model introducing a stochastic multiple flow algorithm to consider lateral dispersion. The results are evaluated by comparing model results with rockfall deposits derived from field mapping and analysis of orthophotos. Furthermore, the method’s reliability is analyzed in terms of iteration-dependency of the stochastic function. The approach and the model setup have been investigated in a small alpine study area. The results demonstrate that the presented method can contribute to rockfall runout modelling with sufficient accuracy for the generation of indicative hazard maps at regional scale.

Keywords: rockfall runout modelling; lateral dispersion; block size; regional scale; indicative hazard map

1 Introduction

Rockfall is a rapid and high-energy geomorphic process which may cause substantial damage and even fatalities. Although single rockfall events usually affect only small areas, especially in alpine regions wide areas are potentially endangered. Thus, decision makers and stakeholders are craving for models and tools producing spatially distributed process information (usually digital layers and maps) supporting rockfall assessment (Chung & Fabbri 2006). Depending on (i) scale, (ii) availability and quality of input data and – not at least – (iii) financial efforts, different types and levels of rockfall zonation are recommended (Volkwein et al. 2011). At regional scale (1:25,000; 1:50,000), indicative hazard maps have turned out to be useful pre-disaster mitigation tools (cf. Bell et al. 2013, FOEN 2016, Guzzetti et al. 2003, Jaboyedoff et al. 2005, PLANAT 2009, Proske & Bauer 2016). In contrast to hazard maps, indicative hazard maps usually do not include the estimated frequencies (i.e. annual probabilities) or intensities of future events (Fell et al. 2008). However, even if indicative hazard maps on regional scale contain an inherent degree of interpretation, they should be suitable to deal with exposed infrastructure elements (e.g. settlements, hiking trails, roads).

Taking such maps as a decision tool, one must consider that:

(1) Rockfall modelling with the objective of generating indicative hazard maps at regional scale usually
is aiming at worst case (maximum) scenarios to avoid underestimation of propagation areas (Jaboyedoff et al. 2005, Volkwein et al. 2011); (2) In general, the probability of high-magnitude events is low (cf. Guzzetti et al. 2003); (3) Public acceptance and perception of the model outcomes are recognized as important issues (cf. Keiler & Fuchs 2010).

Thus, indicative hazard maps are rather evaluated by public on the reliability with regard to frequently occurring low-magnitude events (e.g. small boulder sizes with short runout length) than on high-magnitude (worst case) scenarios (maximum potential boulder size with maximum runout length).

This paper focusses on the parametrization for rockfall runout length modelling considering macro-topographic lateral dispersion with the objectives to (a) refine rockfall zonation beyond worst case scenarios by integrating runout length modelling for different boulder sizes, and (b) simulate the resulting block size distribution on a talus. In general, there are two model groups dealing with lateral dispersion: (a) models that can tap the full 3D potential of high resolution terrain data (e.g. Bourrier et al. 2009, Christen et al. 2007, Crosta & Agliardi 2004, Dorren et al. 2006, Guzzetti et al. 2002, Li & Lan 2015). These models need a set of precise (high resolution) parameter maps (Volkwein et al. 2011). Regarding rockfall modelling at regional scale, these additional parameter maps are often not available. (b) Models related to the shadow angle concept, implying that every source area corresponds to the apex of a cone with defined slope angles (e.g. Jaboyedoff et al. 2005). Lateral dispersion is represented by the envelope of all cones (= all source areas). The major advantage of this method is that beside a Digital Terrain Model (DTM) and the identification of potential source areas, no additional parameters are needed. Nevertheless, the method gives only a rough estimation of runout lengths. Furthermore, macro-topographic features affecting the fall track cannot be taken into account.

We present a method based on a multiple flow direction algorithm (mfdf criterion, Gamma 2000) to close the gap between these two groups of models. This algorithm is suitable to model diverging and converging rockfall trajectories (lateral dispersion) on macro-topographic scale. The further aim of the study is to evaluate the applicability of this approach for area-wide modelling of rockfall trajectories.

The model setup has been investigated in a small alpine study area, aiming at reducing calculation times to a reasonable degree.

2 Study area

The study area, covering approx. 0.7 km² is located in the Rottenmanner Tauern range, NW part of Styria, Austria (Fig. 1). The dominant geomorphological structure of the study area is the alpine cirque “Ochsenkar”. Most of the area is situated above the timberline; highest summits in the surroundings are Großer Bösenstein, 2,448 m asl, and Sonntagskarspitze, 2,350 m asl. The study area is built up by the middle austroalpine nappe complex (poly-metamorphic basement), dominated by different types of biotite schists and gneisses. Tectonics are characterized by fold structures of different dimensions, imbrications, and intense younger fracturing, inducing several systems of cleavages with high degree of separation. The geomorphological impact of Pleistocene glacial processes is obvious. Thus, the area is characterized by oversteepened slopes and glacial deposits. The rockfall process area can be divided into two zones (Fig. 1): (1) a high cliff including most of the rockfall source areas. This zone is characterized by a high vertical extension (>300 m) including long free fall passages; (2) a steep transport talus (starting at approx. 1,900 m asl) with decreasing slope towards the base of the talus (approx. 1,600 m asl). The upper part of the talus is characterized by a coarse grained composition due to fragmental rockfall and channelled erosion (accompanied by levee-structures); the talus deposits of the lower part consist mainly of large rockfall boulders.

3 Method

We use a grid based slope profile velocity calculation incorporated in a stochastic multiple flow direction system (Wichmann et al. 2009). The direction of moving boulders on macro-topographic scale is calculated by a stochastic function and controlled by three model parameters: (a) slope threshold, (b) exponent of divergence and (c) factor of persistence. According to Crosta & Agliardi (2004) features related to the macro-topographic scale are channels, chutes, ridges and overall slope morphology (e.g. convexity). The required topographic information was derived from a DTM with a spatial resolution of 1 m based on Airborne Laserscanning (ALS). As the used rockfall algorithm is not able to calculate potential upward trajectories, sinks in the DTM were filled using a standard hydrological correction algorithm. With regard to data processing capacities, the spatial resolution was resampled to 2 m.

The following steps were applied to calculate rockfall propagation areas: (1) detachment areas (source areas)
Fig. 1. Study area “Ochsenkar”. a: Position of the study area; The yellow box indicates the view direction of the 3D scenes (b/c). b: hillshade visualisation with 1×1 m raster resolution. c: CIR-orthophoto. d: Recent rock failure, involving large boulders with more than 100 cm edge length. e: Gneiss in rockfall source area with several systems of cleavages with high degree of separation.
were determined by a GIS-based disposition model (cf. 3.1); (2) the runout distances were estimated by velocity calculation based on a one parameter friction model (cf. 3.2); (3) potential transition cells for velocity calculation were assigned by using a multiple flow direction algorithm (cf. 3.3); (4) friction coefficients were calibrated for each defined block size (cf. 3.4). The propagation algorithm was adapted for rockfall by Wichmann (2006) and compiled in the SAGA – System for Automated Geoscientific Analyses (Conrad et al. 2015) module Rock HazardZone. For the model calibration, we mapped the position of 324 boulders using dGPS measurements and remote sensing data (0.2×0.2 m orthophotos).

Based on a validated model result of 100,000 iterations, we evaluate the model accuracy for different numbers of iterations as insufficient attention has been given to the effect of iterations to model accuracy and reliability so far. Thus, to analyze this effect, two setups with different numbers of iterations (10–100,000) are calculated: a setup with (a) only one single source area pixel (SSA) and (b) a setup with all source area pixels (ASA).

### 3.1 Disposition modelling

A geological map with 1:50,000 reference scale was used for the source area modelling process. The identification of rockfall detachment areas was based on the definition of slope threshold values (van Dijk & van Westen 1990, Guzzetti et al. 2003). Of course, this approach may be refined by considering the geotechnical properties of the release areas, the detailed tectonic situation, and morphometric parameters (cf. Melzner & Preh 2012, Lan et al. 2010). As the present study is mainly aiming at the runout length modelling, and the geological situation in the study area is uniform, we defined a single threshold value (51°), based on field observations and analysis of remote sensed data (Orthophotos, ALS-DTM).

### 3.2 Estimation of runout length – one parameter friction model

After detachment, the trajectory is modelled as freefall. During this phase, lateral dispersion is disabled – the trajectory is equal to the steepest direction. The initial motion (freefall) is modelled as long as a specified slope threshold value is exceeded. Thus, in most cases, the modelled motion freefall is not equal with the physical motion freefall, meaning the direction of gravity.

The second phase is the impact of the falling rock on the slope surface below the slope threshold value. Based on velocity reduction, Broilli (1974) specifies the absorption of energy generated by an impact with 75–85%. Rock HazardZone provides three available options to calculate energy reduction, based on the works of (a) Kirkby & Statham (1975), (b) Meißl (1998) and (c) Scheidegger (1975). The method chosen has an obvious effect on the propagation distance. Maximum distances are achieved with the algorithm of Kirkby & Statham, minimum distances with the algorithm of Meißl. Based on empirical model calibration, the best fitting propagation distance is achieved by using the energy reduction algorithm of Scheidegger. In the study of an alpine catchment area, Wichmann (2006) came to the same conclusion.

The motions after the impact are controlled by the contact with the slope surface – bouncing, rolling, and sliding. Rock HazardZone provides the motion types rolling and sliding as available options after the impact based on the Coulomb’s law of friction (Wichmann et al. 2009).

\[
\text{Sliding: } v_i = \sqrt{v_{i-1}^2 + 2g(h - \mu_i D)} \quad (1)
\]

\[
\text{Rolling: } v_i = \sqrt{v_{i-1}^2 + \frac{10}{7} g(h - \mu_i D)} \quad (2)
\]

where \(v_{i-1}\) is the velocity of the preceding cell, \(h\) is the height difference between preceding cell and processing cell, \(D\) is the horizontal distance between the preceding cell and the processing cell and \(\mu_i\) are the friction coefficients for the two different modes of motion.

The grid is divided into triangles connecting the centroid point of each cell to integrate these equations in a grid based model (Wichmann 2006). Thus, the distances between the preceding cell and the processing cell (\(D\)), are predetermined by the raster resolution (e.g. for a 2×2 m DEM, the vertical and horizontal \(D\)-value is 2 m, the diagonal \(D\)-value is 2.82 m).

Compared to the motion type rolling, the motion sliding is more sensitive to friction. The velocity calculation is continued until the radicand gets negative (cf. equations (1) and (2)). In this case the velocity is zero and the calculation stops.

### 3.3 Estimation of process paths

As mentioned above, the positions of possible rockfall start cells in the detachment areas are defined by a disposition model (see 3.1) and stored in an ancillary grid (source area file). Each neighbouring cell is coded in slope gradients, based on an eight direction flow model in hydrologic modelling. Therefore, possible transition cells must be lower than the start-, or previous transition cells. The assignment of adjacent cells as transition cells depends on:

(a) slope threshold. Rocks moving on upwardly convex surfaces and on flat to moderate slope gradients tend to lateral dispersion. The rockfall trajectory is equal to the steepest direction above the defined slope threshold value, and is modelled by a single flow direction. In case the slope gradient gets lower than the set threshold value,
lateral dispersion is enabled. On nearly flat slopes, almost every lower transition cell is assigned as possible transition cell. Therefore, the algorithm calculates the proportion of slope (tan) to slope threshold (tan) on cell by cell basis. In contrast to absolute slope values (maximum rate of change between the process cell and its eight neighbours), the obtained relative slope values represent the rate of change between the slope threshold value and its lower neighbours (at maximum eight cells). Thus the relative slope is not directly correlated with absolute slope values. The maximum relative slope value controls if either single flow or multiple flow is calculated. For lateral dispersion (multiple flow), the relative slope values of any of the neighbouring cells must not exceed 1. Figure 2/a–b illustrates relative slope calculation ($\bar{\gamma}_i$) based on a 3×3 cell neighbourhood (slope values, with slope threshold ($\tan\beta_{ST}$) being set at 60°. The three cells marked with X are higher and therefore are excluded from further calculations (direction N, NW, W). The calculated relative slope values of all remaining neighbour cells are less than 1 ($\bar{\gamma}_{i,max} < 1$). Thus, multiple flow direction calculation is enabled.
(b) exponent of divergence. The assignation of potential transition cells is based on the mfdf-criterion (Gamma 2000),

\[ \gamma_i \geq \left( \gamma_{\text{limax}} \right)^\alpha [0 < \gamma_{\text{limax}} < 1] \]  

(3)

where \( \gamma_{\text{limax}} \) is the steepest relative slope and \( \alpha \) is the exponent of divergence. Depending on relative slope, the exponent of divergence is sensitive to control lateral dispersion especially if relative slope values \( (\gamma_i) \) are close to the maximum \( (\gamma_{\text{limax}}) \). The exponent of divergence is of crucial importance for considering the aspect of spontaneous changes of direction of moving rocks (Dorren 2003). This is indicated in Fig. 2/c–d: by calculating the mfdf-criterion, where \( \gamma_{\text{limax}} \) is 0.79 and setting the exponent of divergence \( (\alpha) \) to 1.7, \( (\gamma_i) \) is \( \geq 0.67 \). Thus, two cells (direction SE and S) are assigned as potential transition cells (Fig. 2/c). By modelling the same geomorphologic setup with an increased exponent of divergence \( (\alpha = 1.8) \), five cells (direction NE, E, SE, S, SW) are assigned as potential transition cells (Fig. 2/d). High exponent values increase lateral dispersion.

In the next step the algorithm calculates the transition probabilities \( (p_i) \) of assigned transition cells, based on the work of Fairfield & Leymarie (1991),

\[ p_i = \frac{\tan \beta_i}{\sum \tan \beta_j} \]  

(4)

where \( \tan \beta_i \) is the relative slope of the process cell and \( \sum \tan \beta_j \) is the sum of all assigned transition cells. This is illustrated in Fig. 2/f and Fig. 2/j for different exponents of divergence as mentioned above. In Fig. 2/f, the transition probability for the steeper \( (\gamma_i = 0.79) \) cell (direction S) is 52%, whereas the transition probability for direction SE is 48%. On smooth topography (calculated \( \gamma_i \) values being within a small range), this calculation produces staggered trajectories.

(c) factor of persistence. Physically consistent rockfall trajectories are influenced by a variety of motion modes, terrain interactions and rock geometry. Due to rotation of moving rocks around their principal axis of largest inertia (Leine et al. 2014), the latter may cause stabilization of the direction of boulders. To consider the moment of inertia in the mfdf-criterion, the transition probabilities are weighted regarding the direction of movement. Therefore, the transition probability of the processing cell with the same direction of movement as the preceding cell is weighted by the factor of persistence,

\[ p_i = \frac{\tan \beta_i \times p}{\sum \tan \beta_j + \tan \beta_i \times p} \]  

(5)

where, \( \tan \beta_i \) is the processing cell in direction of movement of the preceding cell and \( p \) is the factor of persistence. This is illustrated in Fig. 2/g and Fig. 2/k. By considering the factor of persistence, the transition probability of the processing cell \( i \) increases from 48% up to 57% (Fig. 2/f–g). Thus, it is more likely to assign the processing cell in direction of movement of the preceding cell than the direction of the steepest path (direction S). A high persistence factor reduces abrupt changes and staggered trajectories.

In the next step, the algorithm calculates the transition probability break values (Fig. 2/h and Fig. 2/i). The range of each interval is equal to the transition probability. Finally, to assign one transition cell, a random number ranging from 0.0–1.0 is generated and compared with the transition probability break values of all potential transition cells.

The assignation of a transition cell without persistence factor is determined randomly and does not depend on the sequence of preceding transition cells. This sort of stochastic system is defined as random walk. By weighting the direction of the preceding cell (current state), the system results in a first order Markov-chain. Thus the next state depends on the preceding state only (Gamma 2000). One must consider that a single modelled trajectory is based on random variables and conditional probabilities. Thus, implementation of random walk and Markov-chain in rockfall modelling is only applicable if a statistically sufficient number of random walks is performed so that the totalized potential process area is close to ergodic distribution of real events (Monte Carlo simulation).

### 3.4 Friction

According to Coulomb’s law, the friction force is influenced by surface topography, (block)-mass and a dimensionless coefficient of friction. Based on the equations (1) and (2), the coefficient of friction is the determining factor regarding velocity calculation (due to energy reduction). Friction coefficient values can be derived from literature (e.g. Van Dijke & Van Westen 1990, Meißl 1998, Guzzetti et al. 2002, Wichmann 2006). The effect of friction is controlled by surface roughness and block size. In case the block size of a moving boulder is (much) larger than the grain size of the surface material the effective roughness is reduced (Kirkby & Statham 1975, Dorren et al. 2006). Including both, surface (roughness) and block characteristics (e.g. block size), the coefficient of friction can be used to simulate block size variations and distribution of rockfall material.

Obtaining precise rockfall block sizes and block distribution is not possible without intense field investigations (Melzner & Preh 2012, Ruiz-Carulla et al. 2015).
values were fixed with 2700 kg/m³.

Table 1. Classes of detached rock boulders. Rock density

<table>
<thead>
<tr>
<th>Modelled edge length [cm]</th>
<th>Modelled block mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1.4</td>
</tr>
<tr>
<td>16</td>
<td>11.1</td>
</tr>
<tr>
<td>40</td>
<td>172.8</td>
</tr>
<tr>
<td>100</td>
<td>2,700</td>
</tr>
</tbody>
</table>

As such efforts are not possible in a regional approach, we assume the fragmentation of the unstable rock mass is producing typical block sizes. The dominating biotite schists and gneisses of the study area tend to produce large boulders up to several cubic meters. However, the representative block size characterizing design events with a considerable probability was defined at the 95% percentile of the observed boulder sizes which results in boulders with edge lengths of approx. 100 cm. Due to intense tectonics inducing several systems of cleavages with high degree of separation and disintegration into fragments after the first impact, smaller rockfall components occur frequently. Finally, we defined four representative block sizes, covering most of the spectrum observed in the field (Table 1), following the approach of Mayer et al. (2007). We clearly point out, that these are approximate values. The coefficients of friction are obtained by comparing simulated stops with data derived from field campaigns and remote sensing data (high resolution 0.2×0.2 m orthophotos).

3.5 Raster based output options

(a) Velocity: As mentioned above, the runout distances are calculated by a one parameter friction model and the mfdf-criterion. Due to the random walk, velocity calculation is an iterative process. The generated raster contains the maximum velocity value for each cell calculated within all iterations.

(b) Process area: Based on the velocity calculation, the output raster contains transition frequencies as the accumulated weight of all iterations passing each assigned transition cell. Thus, regarding the process area and velocity, the assigned cells with a raster value >0 are identical. One must consider, that the transition frequency is related to the number of iterations. By using a ‘sufficient’ number of iterations (according to Gamma (2000) ≥1,000), cells with high transition frequencies are areas of concentrated modelled rockfall trajectories and may be used to identify areas which are prone to rockfall activity.

(c) Stops: Based on the velocity calculation, the output raster contains the number of stops (cell in which the calculated velocity becomes zero) as the accumulated weight of all iterations.

(d) Free Fall: Based on the model setup (fall threshold), the grid value contains the defined minimum slope angle with respect to the neighbour cells.

3.6 Model setup

The modelled total propagation area is the result of a high number of simulations (e.g. sum of all iterations). The model calibration was done in an iterative process by adjusting model parameters and matching (1) modelled process areas with observed areas (e.g. orthophotos) and (2) modelled process stops with mapped ones (dGPS). The finally used values are shown in Table 2. In general, the mfdf-criterion and the model parameter sensitivity are strongly influenced by the raster resolution of the used DTM (cf. Wichmann et al. 2008). The higher the resolution of the DTM the more possible trajectories are provided (cf. Jaboyedoff et al. 2005, Lan et al. 2010).

(a) exponent of divergence: high values increase the probability of cells with lower inclination to be selected as transition cells, too. As the velocity calculation is strongly influenced by the height difference between the preceding cell and the processing cell, high exponent of divergence values result in a wider propagation area (e.g. including areas with lower inclination) but with limited range (e.g. stopping criteria are achieved sooner due to less height difference). The exponent of divergence is very sensitive between values ranging from 1–2 (cf. Wichmann 2006). Above a value of 2, every potential cell has already been selected for calculation. The resulting propagation areas tend to be overestimated. We finally set the value of the exponent of divergence to 1.7. (cf. Wichmann et al. 2009: 2.0).

(b) factor of persistence: a high factor of persistence reduces abrupt changes in direction. The value has to be set to 1 to receive the maximum potential changes in rockfall directions. To consider the moment of inertia of moving boulders, a higher value forces the algorithm to select cells in the same direction as the preceding cell, even with smaller probabilities. We obtained the best results by using a factor of persistence of 1.6. Compared to other studies (cf. Wichmann et al. 2009), this value is significantly higher which is caused by using a high resolution DTM. The model parameterization without weighting of the previous direction results in very staggered trajectories. The effect of increasing persistence factor values on small grid-cell
sizes is already addressed by Wichmann et al. (2008).

(c) Friction coefficient: The model offers the use of spatially distributed friction parameters for each cell. According to Dorren et al. (2004), with regard to friction, both standing and lying trees, the surface roughness and rockfall resistant shrubs determine the rockfall propagation in decreasing order of importance. In areas with dense vegetation, we propose to use spatially distributed friction parameters on basis of ALS-data and satellite data. This data are available for Styria area wide (Schardt et al. 2015). Due to its high importance, we used this data for assigning friction parameter classes for forest stands (treetop number per unit area, crown coverage, height of upper layer and vertical forest structure) without taking into consideration surface roughness (Proske & Bauer 2016). However, in the study area, the influence of trees on rockfall propagation is low as it is situated close to the upper timberline.

Initially, to illustrate the effects of model-parameterization (Table 2), we calculated the transition frequencies of rockfall trajectories and the propagation area for only one source area pixel (single source area = SSA). We clearly point out, that this is a theoretical assumption and is used here for illustration purposes only. Subsequently, to demonstrate the potential of the model for rockfall zonation at regional scale, we calculated the maximum velocities of rockfall trajectories and propagation areas for the entire study area with four boulder size classes (8 cm, 16 cm, 40 cm, 100 cm, cf. Table 1). The disposition modelling (cf. 3.1) resulted in 35,694 source area pixels (all source area = ASA). The mode of motion was set to “rolling”, due to following reasons: (a) with increasing slope gradient, sliding rocks tend to switch the mode of motion to rolling and/or bouncing (Dorren 2003). Thus the motion “rolling” is applicable to the entire trajectory for all morphometric conditions (e.g. slope values). Moreover, (b) rockfall modelling with the objective of generating indicative hazard maps at regional scale is aiming at maximum runout distances. As mentioned above, the friction modelled for the motion “rolling” calculates higher velocities compared to the motion “sliding” and therefore results in a larger propagation area.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Annotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input elevation grid (DTM)</td>
<td>2×2 m</td>
<td>ALS-DTM (1×1 m) bilinear resampled</td>
</tr>
<tr>
<td>Input source area grid</td>
<td>2×2 m</td>
<td>disposition modelling</td>
</tr>
<tr>
<td>Slope threshold</td>
<td>60°</td>
<td>lateral spreading enabled below this value</td>
</tr>
<tr>
<td>Fall threshold</td>
<td>60°</td>
<td>min. slope angle to neighbour cell for free fall</td>
</tr>
<tr>
<td>Exponent of divergence</td>
<td>1.7↑</td>
<td>mfdf-criterion (weighting divergence)</td>
</tr>
<tr>
<td>Factor of persistence</td>
<td>1.6↑</td>
<td>mfdf-criterion (weighting of previous direction)</td>
</tr>
<tr>
<td>Iterations</td>
<td>10–100,000</td>
<td>random walk iterations</td>
</tr>
<tr>
<td>Energy reduction</td>
<td>70%</td>
<td>energy reduction at impact</td>
</tr>
<tr>
<td></td>
<td>0.92</td>
<td>8 cm edge length</td>
</tr>
<tr>
<td>Friction coefficients</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.82</td>
<td>16 cm edge length</td>
</tr>
<tr>
<td></td>
<td>0.72</td>
<td>40 cm edge length</td>
</tr>
<tr>
<td></td>
<td>0.62</td>
<td>100 cm edge length</td>
</tr>
</tbody>
</table>

↑ dimensionless

4 Results

The transition frequency calculation of the SSA modelling (Fig. 3), demonstrates that the random walk based mfdf-criterion is sensitive to slope morphology and to small scale features within the trajectories. Thus, the method is suitable to consider macro-topographic lateral dispersion.

Compared to the steepest path, the random walk approach shows limited lateral dispersion in very steep debris flow channels (Fig. 3, position 1) but increased lateral dispersion on convex debris cones (Fig. 3). Channelized water-runoff on the rockfall deposits formed a lateral, coarse-grained levee (cut-structure between position 2 and 3 in Fig. 3a). Moderate slope gradients with special consideration of the persistence of moving boulders (direction NNE) cause diverging propagation (resulting in lower transition frequencies) on the debris
cone at the upper end of this structure (Fig. 3, position 2). Modelled trajectories within the levee are congruent with the steepest path (high transition frequencies). Reduced slope gradients due to material accumulation on the front of the levee, enable stronger lateral dispersion (Fig. 3, position 3). Nevertheless, the highest transition frequencies correspond with the adjacent areas of the steepest path. The algorithm does not provide energy reduction due to the impact at obstacles (cf. the huge boulder in Fig. 3, position 5). Based on the mfdf-criterion, the rockfall trajectories are modelled around the obstacle. Thus, the area of the obstacle is not included as rockfall propagation area.

The SSA modelling (within steep mountain relief) results in a diverged propagation area consisting of both, rockfall transition areas and areas without modelled rockfall trajectories (Fig. 3, position 4). Overlapping rockfall trajectories minimize this scattering effect (Fig. 3b), caused by the mfdf-criterion. Thus, retaining the same model parameterization (Table 2) but taking into account all source areas (ASA), the multiplicity of modelled trajectories results in a “closed” propagation area. Figure 4 (c–f) illustrates the maximum velocities per cell of all iterations for each modelled rock size category in the study area. As mentioned above, movements of small boulders on rough topography (e.g. coarse grained talus) are highly energy dissipative. Due to higher friction coefficients, the calculated velocities of small-size boulders (8–16 cm edge length) are within a range from >0–30 m/s (Fig. 4c–d). Maximum velocities within these block size classes occur (1) after impacts of boulders from high vertical passages modelled as free fall and (2) on the steep talus cone near the rocky cliffs (Fig. 4a, position 1). Higher friction coefficient values also result in reduced runout distances. Maximum velocities and therefore runout distances are achieved by simulating trajectories with coefficients of friction defined for boulders with 40–100 cm edge length ($v_{\text{max}} = 45$ m/s). Perret et al. (2004) specify maximum velocities for large rockfall events from 10 m/s to 40 m/s. According to this, the modelled maximum velocities are overestimated. However, maximum velocities in the model results refer to trajectories with long passages (fall heights of more than 200 m) of modelled freefall (meaning that the specified slope threshold value is exceeded, cf. 3.2).

Gentle slope values near the valley bottom rapidly reduce velocities of boulders until the process stops ($v = 0$).

The modelled maximum velocities correspond to the maximum process propagation area. However, this area consists of both, (a) the transition area of the longest trajectories and (b) the deposit area of trajectories that do not reach so far. The modelled stops of all iterations (for each block size) are used for model calibration as well as model validation. Due to random walk (1,000 iterations for each source area pixel), the results provide information of the deposition area only, not taking into account the total block volume detached from the rock mass for

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**Fig. 3.** Transition frequencies of the SSA modelling compared to the steepest path within the propagation area. **a:** Hillshade visualisation based on ALS data with 1×1 m raster resolution; **b:** Rock HazardZone Model with 1,000 iterations and a mean block size of 100 cm. Details refer to text.
Fig. 4. Result of ASA rockfall velocity calculation for the entire study area. In total, 35,694 source area pixels have been mod-elled with 1,000 iterations each; a: Hillshade visualisation. The circle indicates the steep rocky cliff; b: Source area distribution; c: ASA rockfall velocity calculation for boulder sizes 8 cm. d: ASA rockfall velocity calculation for boulder sizes 16 cm; e: ASA rockfall velocity calculation for boulder sizes 40 cm; f: ASA rockfall velocity calculation for boulder sizes 100 cm. Details refer to text.

each class (Fig. 5a–d). The difference of modelled stops of small boulders (8 cm) and large boulders (100 cm) is significant. Due to higher friction coefficients, stops of small boulders are situated close to the source areas (cf. Fig. 4b). Energy reduction after impact of large boulders (100 cm) detached from the high rock face is not sufficient to stop the moving boulder on the steep slope of the upper talus (Fig. 5d, position 1). Thus, most of the modelled upper talus includes all block size classes, corresponding to the real image. Due to low friction coefficients, large boulders achieve the longest trajectories (Fig. 5d). Thus, the model result shows only boulders with 100 cm edge length in the valley bottom.

By calculating the number of unique values of the modelled stops on a cell by cell basis, the block size distribution is obtained. Based on this distribution, three zones can be distinguished (Fig. 5e, position 1–3):

1. Ridge – upper talus: Except in areas of gentle slopes only small boulders (8–16 cm edge length) are deposited in this zone; (2) Upper talus – middle talus: Zone of great block size varieties. Considering the mfdf-criterion mentioned above, the high number of source area pixels and the high number of iterations, the transition probabilities to cells with lower slope gradients (resulting in process-stops) are high even for large blocks; (3) Lower talus – valley bottom: Only two block size categories (40 cm and 100 cm edge length) reach the lower part of the talus. The stops within the largest block size category modelling are equal to the maximum runout distances of all block sizes.

4.1 Validation

Model validation was performed by using the ASA modelling result with 100 cm edge length (Fig. 6) and mapped rockfall boulders. One must consider, (a) that the
distribution of different block sizes on a talus is not homogeneous and (b) that the deposition is not only attributable to one single process (rockfall). For example: channelled erosion can relocate deposited smaller grain size materials downwards or change macro-topography (e.g. levees). Based on field verification (dGPS-measurements) and on remote sensing data (0.2×0.2 m orthophotos), in total 324 boulders (meeting the largest block size criteria) were mapped. Although isolated large boulders are scattered on the entire talus, the occurrence of large boulders is concentrated at the lower part of the talus due to high kinetic energies. By comparing modelled stop areas with...
mapped boulders, 272 (84%) are identified as true positive. Due to random walk and mfd/df-criterion, identified stop cells are also transition cells (except the longest trajectories). 52 mapped boulders are not identified as stops. 35 (10.8%) of these belong to modelled transition cells only (without any stop). Only 17 boulders are neither identified as transition area nor as modelled stops (false negative). Thus, only 5.2% of all mapped boulders are not considered as rockfall propagation area. These boulders are close to the modelled propagation area. This is interpreted as follows: (a) rapid decreasing slope near the valley bottom in combination with (b) rough topography due to deposited large size boulders induce the calculation break off. Especially the accumulated large boulders serve as “obstacles” in the DTM. The false negative boulders in the upper part of the talus can be explained by the influence of seasonal snow cover during ALS flight mission: macro-topography (surface roughness) packed by a small deposit of snow, caused a smoothing effect in the DTM-data. The reduced variability of plan convexity and height variations enables a more efficient movement and thus model stop conditions are not complied with.

Aiming at analyzing lateral dispersion (Crosta & Agliardi 2004), we calculated the width to length (W/L-ratio) within the SSA model setup for all iterations (cf. 5). Therefore, we set a fixed runout distance of 320 m starting from the end of the steep debris flow channel (Fig. 3). The fall track between the source area and this point is not suitable for W/L-ratio calculation since topographic conditions prevent lateral dispersion. The results demonstrate increasing modelled lateral dispersion (W/L-ratios) with increasing number of iterations (except the 5,000 iteration setup). By calculating 100,000 iterations, almost every potential mfd/df-trajectory is determined (represented by the low relative standard deviation (RSD) values, cf. Table 3). This also implies trajectories of least transition possibilities and therefore this is considered as overestimation of lateral dispersion. The calculated mean W/L-ratio of 10 model runs with 1,000 iterations each is 33.60% which is in good accordance with the results of Agliardi & Crosta (2003). By using a high resolution DTM, they obtained a W/L-ratio of 34%.

5 Discussion

One of the basic questions with regard to modelling large areas is: What is the required number of iterations (random walks) to cover (at least most of) the process propagation area? Gamma (2000) proposed 100 to 200 iterations as adequate to model debris flow propagation.
Table 3. Effects of number of iterations.

<table>
<thead>
<tr>
<th>Iterations</th>
<th>W/L-Ratio(^1) %</th>
<th>Mean(^2) %</th>
<th>SD(^3) %</th>
<th>RSD(^4) %</th>
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<tr>
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<td>SSA</td>
<td>ASA</td>
<td>SSA</td>
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<tr>
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<td>38.60</td>
<td>100</td>
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</tr>
</tbody>
</table>

\(^1\) W/L-ratio (mean value) of 10 runs each iteration setup.  \(^2\) Recognition rate (mean values) of 10 model runs each iteration setup.  \(^3\) Standard deviation between 10 model runs each iteration setup.  \(^4\) Relative standard deviation between 10 model runs each iteration setup.

Fig. 7. Errors related to high resolution DTM. a: hillshade visualisation; (1) Peak-detection of the talus cone in the study area. The few preserved ridges (black cells in Fig. 6c) in the hydrologically corrected DTM (2×2 m) cannot be reached by the mfdf-algorithm; (2) Ridge of fluvial/erosional origin. (3) Scattering effect due to preserved macro-topography on a debris fan. The local height maxima of the debris fan limit lateral dispersion. b: modelled process area (ASA, for boulder sizes 100 cm); c: modelled stops (ASA, for boulder sizes 100 cm). The black pixels represent preserved ridges.

areas based on random walk and mfdf-criterion using a DTM with 20×20 m raster resolution. Guzzetti et al. (2002) modelled 100 iterations for each source area pixel using a 10×10 m DTM. Both numbers of iterations are by far not sufficient for rockfall modelling based on a DTM of 2×2 m raster resolution. The extent of the propagation area is not only controlled by the number of iterations but also by the number of source area pixels. Since trajectories of moving rocks depend on geomorphologic conditions, an increased number of source area pixels has the same effect as a higher number of iterations. Wichmann et al. (2008) addressed the issue of scattering effects of multiple flow direction algorithms in their study of debris flow simulations. Basically, flow path routing algorithms require a lower neighbouring cell, otherwise the algorithm stops. These stopping conditions are provided by positive small scale topographical features (e.g. ridges), preserved in accurate DTMs. Thus, they conclude that high and very high resolution DTMs (≤ 2×2 m) are not appropriate for flow path routing algorithms developed
for coarser grid sizes. Based on the theoretical assumption of the SSA modelling with 1,000 iterations, the scattering effect is illustrated in Fig. 3b. But, in contrast to debris flow modelling, this effect is not as dominant in rockfall modelling: (a) the initiation sites of debris flow (especially of torrent bed-type) are more spatially concentrated (often situated in or close to channels). Thus, even if the number of iterations is increased up to more than 10,000, macro-topography (e.g. small local ridges) in the deposition area (debris fan) can prevent flow direction based trajectories from reaching all parts of the debris fan; (b) beside very small cliffs, the detachment sites of rockfall are not concentrated (only) in small areas. Spread source areas in rockfall modelling enable more possible flow paths. Furthermore, the scattering effect is minimized by overlapping rockfall trajectories; (c) Nevertheless problems arise, where: (i) the height of large boulders are preserved in the DTM after ALS last pulse point cloud classification / DTM–raster extraction and bilinear raster interpolation. These pixels act as obstacles and are not identified as rockfall propagation areas (Fig. 7a–c); (ii) the rockfall propagation areas overlap with areas which are dominated by channel fluvial processes or debris flows (Fig. 7a, position 2/3).

By calculating 10 modelling runs with 100,000 iterations each for the maximum block size (100 cm), under consideration of all 35,694 source area pixels, the deviations between the results prove to be marginal (i.e. single pixels). Thus, aiming at analyzing the effect of iterations (10–10,000) for both model setups (SSA & ASA), we assume the cumulative propagation area of 10 model runs, with 100,000 iterations each, as ergodic distribution (ED). Low recognition rate mean values as well as high and fluctuating standard deviation (SD) values within the SSA-results indicate that the number of iterations is not sufficient to cover the high count of potential trajectories due to the high resolution DTM and relief conditions (cf. Table 3 and Fig. 3b). For example, by calculating 100 iterations only approx. 41% of the ED-propagation area is identified as rockfall prone. The relative standard deviation (RSD) value of 3.27 indicates considerable statistical uncertainties between the 10 model runs.

The stochastic behaviour of the Monte Carlo simulation demonstrates that iteration dependency decreases with a high number of iterations (Fig. 8a–b).

Considering all 35,694 source area pixels (ASA), the recognition rate curve ascends rapidly up to 1,000 iterations (>95%). Above this value, the curve tends towards an asymptote (Fig. 8b). For example: by increasing the number of iterations from 5,000 up to 10,000, the recognition rate improves by +0.83% only, whereas the calculation time doubles from 200 up to 400 minutes (Fig. 8a). Defining 95% as relevant statistical threshold value, 1,000 iterations thus are sufficient to cover the propagation area. Furthermore, this is confirmed by the low RSD value (0.06%). Slight deviations are interpreted as outliers due to random walk.

In fact, the calculation time of this small catchment area (35,964 source areas) is negligible. However, with the objective of generating indicative hazard maps at regional scale, rockfall modelling based on high resolution DTMs has to deal with millions of source area pixels. For example: based on similar disposition modelling parameters as used in the study area, 15.07×10^6 source area pixels were identified in the province of Styria (16,401 km²). Applying 1000 iterations, the presented method offers the option of calculating area-wide rockfall runout trajectories including different block size distribution scenarios within reasonable (less than 3 months) processing time (Prosk & Bauer 2016).

6 Conclusions

One significant difference between the presented method and full 3D trajectory models is, that rebound heights are not calculated. We are well aware that bouncing is an important type of the block motion. However, block shapes and sizes as well as small-scale surface properties (micro-morphology) strongly influence the rebound phase, with significant consequences on the block trajectories (e.g. Dorren 2003). Currently, these characteristics cannot be identified with sufficient accuracy and/or reasonable costs in a regional approach. Furthermore, comparison studies of 3D algorithms show great variations in modelled runout lengths (e.g. Melzner & Preh 2012) and significant differences in modelled bounce heights (e.g. Li & Lan 2015). Thus, in a regional context the integration of bounce heights is disputable.

Although the presented algorithm is not able to model the kinematic behaviour of single moving rocks (e.g. due to block shape), it is suitable to model macro-topographic lateral dispersion for different block sizes. Based on the mfd-criterion, the variety of potential trajectories is strongly controlled by the raster resolution of the used DTM. This scale dependency of lateral dispersion has been already discussed by Agliardi & Crosta (2003). For reliable macro-topographic dispersion, we recommend the use of high resolution DTMs, with a maximum resolution up-scaling to 10×10 m. The method is able to calculate block size scenarios and therefore to refine runout length modelling at regional scale with reasonable effort. Furthermore, by using a high number of iterations, transition frequency values combined with velocity values can be interpreted as areas with high process intensities (Prosk & Bauer 2016). We conclude that 1,000 iterations are sufficient to cover most of the propagation area.
Fig. 8. Effects of iterations. a: ASA-recognition rate (100 cm block size) and computer calculation time using an Intel(R) Xeon(R) CPU E5–1620v2@3.70 GHz and 64gb RAM. The calculation time demonstrates a strict linear correlation. b: Recognition rates of SSA and ASA model setups (100 cm block size) Details refer to text.
The method provides either separated block size scenarios or a combined result. Level and scale of rockfall zonation depend on the addressed issue and land use planning purposes. For instance, zoning for (a) the management of alpine trails or (b) roads and traffic authorities needs different information of block size dependent runout lengths. The results of the presented method offer the required information beyond worst case scenarios.

The presented model approach is suitable for runout modelling at regional scale considering (a) the diverging effects (lateral dispersion) of surface/boulder interactions using a stochastic function; (b) the calculation of propagation areas for different boulder sizes using specific friction coefficients for each boulder size; (c) the effect of iterations on model accuracy and reliability relating to practical application (e.g. calculation time). Including macro-topographic factors for modelling lateral dispersion requires (i) a DTM with high resolution and (ii) a DTM with high accuracy. Moreover, the flow path algorithm requires a hydrological corrected DTM which can be processed with standard GIS software.

Efforts have to be made for friction coefficient definition considering the effects of surface material and vegetation (forest) cover. The latter can be derived from the detailed analysis of ALS based Digital Surface Models (DSM) as was shown in a project resulting in the generation of indicative hazard maps for the province of Styria (Proske & Bauer 2016, Schardt et al. 2015).

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