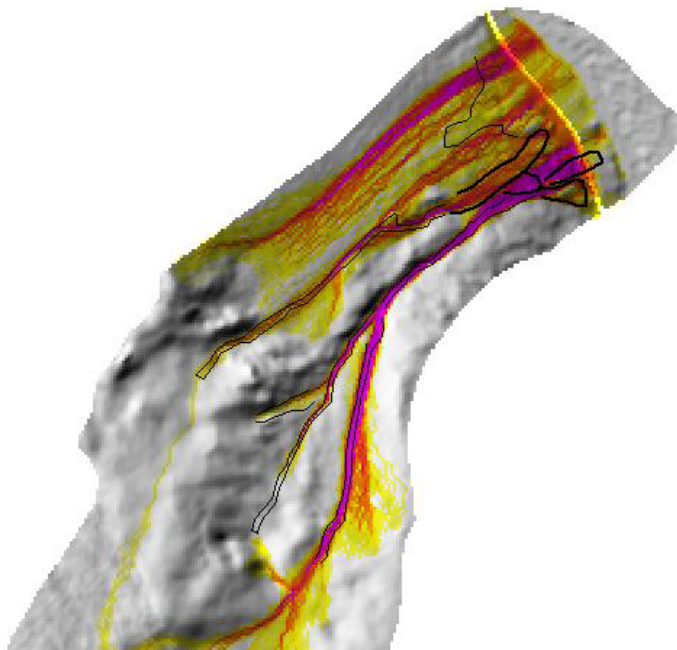


A model framework for simulating mobilization and movement
of debris flows

based on GRASS  GIS



User manual and model outline

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r.debrisflow is a GIS-supported model framework for simulating the potential spatial patterns of debris flow initiation, movement, and deposition. It is physically-based in general, but includes some empirical-statistical components. *r.debrisflow* is designed as a raster module for the software *GRASS*. The scientific concepts behind *r.debrisflow* are summarized in Chapter 1 (Model outline).

In contrast to most of the other *GRASS* raster modules, management of the data and the parameters (input and output) is not done by adding parameters to the *r.debrisflow* command, but by an additional shell script (*r.debrisflow.sh*) with various functionalities, including derivation of secondary input parameters from primary ones. This is required due to the complexity of the model framework. Instructions how to operate *r.debrisflow* are given in Chapter 2 (User's manual).

The model shows a large potential for refinements. Chapter 3 (Prospected improvements) will give a short overview of ongoing and prospected further development of *r.debrisflow*, regarding the scientific concepts as well as its mode of operation.

Every user is encouraged to report encountered bugs or errors to

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Furthermore, the developer would be grateful for receiving comments regarding

- experiences with the program, shortcomings, recommendations for improvements (scientific concepts, ease of use);
- parameters chosen for certain study areas;
- interest in cooperation in application and further development.

The model, as applicable with *GRASS*, is running under the *GNU General Public License* (www.gnu.org). *r.debrisflow* has been created with the purpose to be useful for modelling of debris flows. It has been developed with care, and much emphasis has been put on ensuring its scientific value. Nevertheless, every user has to be aware that it is only a computer program created by a human being, which may contain technical and topical errors and shortcomings. No responsibility can be taken by the developer for any types of deficiencies in the program or in the present document, or for the consequences of such deficiencies.

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1 Model outline

1.1 General aspects

The ideas for most of the model components were taken over from existing models, partly in a modified form. The model framework was named *r.debrisflow* (the *r* indicates that it is a **GRASS** raster module). It was kept relatively simple in its first version presented here, but was also designed in a way for allowing to be extended with more sophisticated modules in the future (compare Chapter 3).

r.debrisflow was implemented using a 2.5D raster data model (the vertical dimension plays an important role, but is only quantified by attributes). It combines physically-based, deterministic modules and modules based on empirical relationships. *r.debrisflow* couples a hydraulic model, a slope stability model, a sediment transport model, and a debris flow runout model:

- The deterministic hydraulic model distributes the water from precipitation or snow melt among vegetation (interception), soil (infiltration), and surface (runoff). It then approximates the soil water status and the runoff variables;
- the deterministic slope stability model computes the factor of safety for each cell, based on an infinite slope stability model, and identifies potential starting areas of debris flows;
- the sediment transport model (based on an empirical approach) provides an estimate for erosion and deposition by surface runoff, allowing to assess the tendency of bedload-rich runoff to develop into a debris flow;
- the debris flow runout model finally routes the debris flow downwards to the area of deposition, based on a two-parameter friction model.

The modules are executed in a defined sequence for a user-defined number of time steps during and after a rainfall or snow melt event. Slope stability and runout are computed at the end of the last time step.

Not all modules have to be executed – the following combinations (modes of simulation) are possible when running *r.debrisflow*:

- **1:** full mode: all modules are executed;
- **2:** geotechnical mode A: the sediment transport model is excluded, and only debris flows starting from slope failures are modelled – for conditions where it is known that debris flows only develop from slope failures;

- **3:** geotechnical mode B: the runoff and sediment transport models are excluded – like (2), but excluding the influence of runoff on infiltration: for conditions where it is known that no surface runoff develops;
- **4:** hydraulic mode: the slope stability model is excluded and only debris flows developing from sediment-laden runoff are modelled – for conditions where it is known that slope failures play no role for the mobilization of debris flows;
- **5:** fully saturated mode: it is assumed that the entire soil in the study area is saturated. With this precondition, the slope stability model and the runout model are computed;
- **6:** runout only mode: only the runout model is computed with defined areas of debris flow initiation – for testing the plausibility of the runout model for events of known patterns of debris flow initiation and deposition.

The general model layout is illustrated in Figure 1.

r.debrisflow considers the slope or catchment under investigation as six-layered system characterized by the following variables:

- the overlying atmosphere is described by air temperature T (degree Celsius) and precipitation P (m);
 - snow cover is defined as snow depth d_s (m);
 - land cover is defined by a raster layer representing nominal land cover classes. Minimum and maximum values of interception capacity ICP (m), root cohesion c_r (N m⁻²), and rooting depth d_r (m) have to be assigned to each class.
- A hydrological surface class and the width of the flow channels at a sub-cell scale are defined for each cell as well as the vegetation surcharge of Manning's n_{add} ,
- the surface water table is characterized by depth R (m) and flow velocity v_{flow} (m s⁻¹);
 - soil, here rather understood as sediment cover than as mixture of residuals from weathering and decomposed organic matter, is basically represented by a nominal soil class raster layer. A texture class, dry specific weight γ (N m⁻³), stone content s (m³ m⁻³), the hydraulic parameters θ_r , θ_s (m³ m⁻³), ψ (m) and K (m s⁻¹), and the mechanical parameters soil cohesion c_s (N m⁻²) and angle of internal friction φ are assigned to each soil class as well as minimum and maximum values for n_{bas} . Soil depth d (m) is defined independ-

ently from the soil classes. All parameters are considered constant over the entire depth of the soil column;

- bedrock is considered unconditionally stable. Its permeability for water is accounted for by the parameter p_r , denoting the ratio of total effective rainfall and snow melt which percolates through the rock. p_r is not defined as raster map, but globally for the considered study area.

The following sections give a more detailed introduction to the physical and mathematical background of *r.debrisflow*.

1.2 Hydraulic model components

1.2.1 Precipitation and snow melt

Precipitation P (m) and air temperature T (°C) are read from the prepared datasets. Precipitation is considered as rainfall P_r if it exceeds a user-defined temperature threshold T_{crit} , usually ranging between 0°C and 2°C. Snow melt M (m) is computed using a simple degree-day approach with air temperature as the only input:

$$\Sigma M = ddf \cdot T_{ddf} \quad \text{Eq. 1,}$$

where ΣM is the daily snow melt (m d⁻¹), and ddf is the degree-day factor (m °C⁻¹ d⁻¹). T_{ddf} is the temperature in °C at a defined time of the day. In order to estimate snow melt of shorter time intervals, daily snow melt is distributed over the considered day, following a linear relationship with temperature:

$$M = T_0 \Sigma M / \Sigma T \quad \text{Eq. 2,}$$

where T_0 is the temperature during the considered time step, ΣT is the daily temperature sum, based on the length of one time step Δt (s). Only temperatures above T_{crit} are included in the sum.

1.2.2 Interception

The interception capacity of the vegetation I_{pot} (m) is extracted from the land cover dataset. For each time step Δt (s) rainfall is retained as interception $I_{\Delta t}$ (m) until the interception capacity is reached ($\Sigma I_{\Delta t} = I_{pot}$). The excess rainfall is added to the soil water table R (m) as effective rainfall $P_{r,eff}$ (m).

Water from snow melt is considered not interceptable by vegetation. This worst-case assumption was chosen due to the often unknown vertical distribution of I_{pot} .

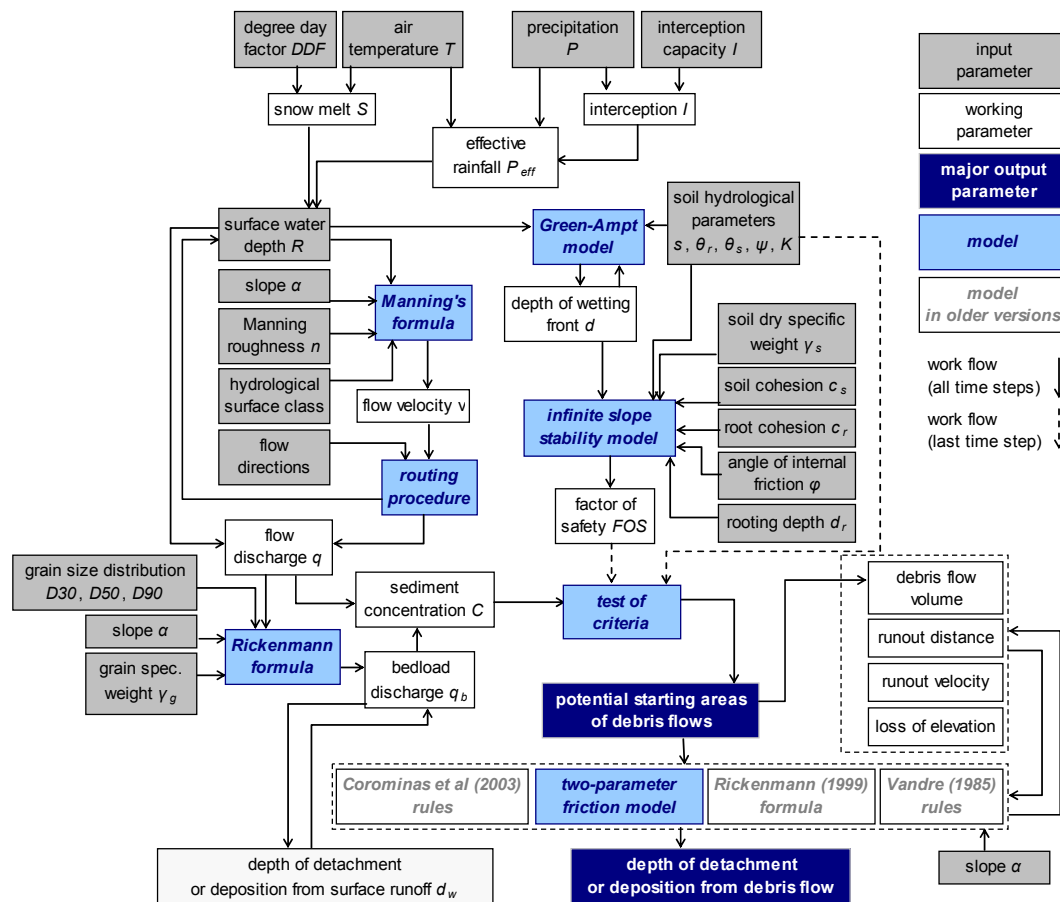


Figure 1: General model layout of *r.debrisflow*. Designed by M. Mergili

1.2.3 Evapotranspiration

Potential evapotranspiration E_{pot} (m) is set to zero. This is a worst-case assumption again which was chosen for two reasons:

- also the most simple equations for evapotranspiration require highly dynamic parameters that are usually not available at sufficient accuracy and resolution (humidity, irradiation, etc.);
- the model is designed primarily for short and intense rainfall events, where evapotranspiration is rather negligible. Regarding snow melt, neglect of evapotranspiration may lead to more significant inaccuracies.

1.2.4 Infiltration

Infiltration, runoff, and sediment transport have to be calculated at much shorter time steps Δt_{short} than the other processes, meaning that the entire sequence has to be repeated for various times within each basic time step Δt . Δt_{short} is determined according to Eq. 14.

The water input from effective rainfall and the snow melt are added to the surface water table of the cell at the beginning of each short time step:

$$R_0 = R_{prev} + \frac{\Delta t_{short}}{\Delta t} (P_{eff,t} + M_t) \quad \text{Eq. 3,}$$

where R_{prev} is the depth of the surface water table at the end of the previous time step. The infiltration of water into the soil is a complex process influenced by an interplay of factors like the depth of the surface water table, the soil parameters, and the local topography. It was chosen to use the Green & Ampt (1911) approach, assuming a sharp wetting front as the interface between saturated soil above and soil at initial moisture content below (Figure 2). The hydraulic parameters governing infiltration are derived from the grain size class of the soil. Infiltration capacity f (m s^{-1}) can be stated as

$$f = K \left(1 + \frac{R_0 + \psi}{d_0} \right) \quad \text{Eq. 4,}$$

where K (m s^{-1}) is the hydraulic conductivity, R_0 (m) is the depth of the surface water table before infiltration, ψ (m) is the matric suction at the wetting front, and d_0 (m) is the depth of the wetting front before infiltration. Eq. 4 is derived from Darcy's law (Xie et al. 2004; Chen & Young 2006). If no measurements of the soil hydraulic parameters are available, values for different texture classes can be obtained e.g. from Rawls et al. (1983) or from Carsel & Parrish (1988).

Two possible cases have to be distinguished. f has to be corrected for volumetric stone content s , which does not affect the maximum possible depth of infiltration, but the volume that fits into the soil until this

depth. For each time step it is tested which case is applicable:

- case 1: $R_0 > f \Delta t_{short} (1-s)$ – inflow to the cell exceeds maximum possible infiltration and depth of surface water table after infiltration R_f (m) is expressed as

$$R_f = R_0 - f \Delta t_{short} (1-s) \quad \text{Eq. 5,}$$

Infiltration is limited by the infiltration capacity, and the depth of the new wetting front d (m) is computed as follows:

$$d = d_0 + \Delta t_{short} f / \Delta \theta \quad \text{Eq. 6,}$$

where $\Delta \theta$ is the moisture deficit of the soil (difference between saturated water content θ_s and initial water content θ_i ; all in $\text{m}^3 \text{m}^{-3}$);

- case 2: $R_0 \leq f \Delta t_{short} (1-s)$ – inflow to the cell is equal or smaller than maximum possible infiltration capacity. In this case, the entire inflow infiltrates,

$$d = d_0 + R_0 / [\Delta \theta (1-s)] \quad \text{Eq. 7,}$$

and no surface water table remains, meaning that no surface runoff will develop from the considered cell.

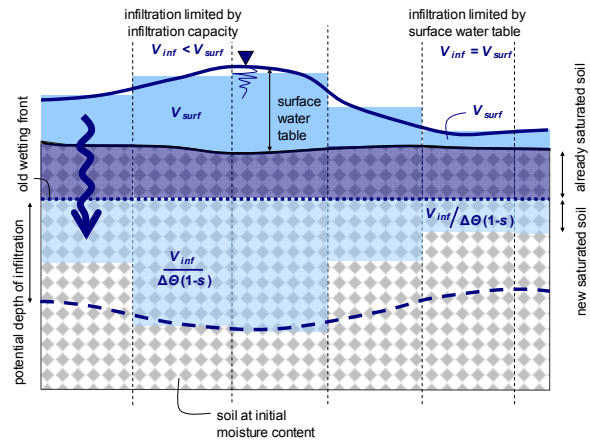


Figure 2: Infiltration into the soil according to the Green & Ampt (1911) model, as applied for the present study. V_{surf} = volume of surface water before infiltration, V_{inf} = infiltrated volume. Designed by M. Mergili.

For case 1, s has no direct influence on d , for case 2, d increases with increasing s . The application of this method has to be considered as an approximation:

- The Green-Ampt approach, in its strict sense, was developed for horizontal surfaces, but is also applied for slopes. Chen & Young (2006) showed that on slopes until 45° , the effect of slope angle is small, compared to other sources of inaccuracy;
- stone content is not accounted for in the original model. Therefore it was decided to disregard its influence on infiltration capacity, but its role as

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limiting the infiltrable volume was taken into account. More research would be necessary in order to clarify the inaccuracies connected to this simplification.

Slope-parallel seepage is neglected in the model. The infiltration is computed separately for soil below flow channels and soil in between flow channels. In between flow channels, ΣIF and OF are zero (compare Eq. 13 and 14).

The integral form of the Green-Ampt approach (compare e.g. Xie et al. 2004) is not used as the model is run in short time steps with varying rainfall intensities.

1.2.5 Surface runoff

After computing infiltration, the ponded water of the depth R_f is assumed to concentrate in the flow channels immediately and to run off superficially. Strictly spoken, $R_f = A_{flow}/P_{wet}$, where A_{flow} (m²) stands for the cross section of the flow, and P_{wet} (m) is the wetted perimeter, but in the model, R_f is approximated by flow depth. Runoff velocity v_{flow} (m s⁻¹) is computed using the Manning formula:

$$v_{flow} = \frac{1}{n_{man}} R_f^{\frac{2}{3}} (\sin \alpha)^{\frac{1}{2}} \quad \text{Eq. 8,}$$

where a is the local slope angle in degrees and n_{man} is the surface roughness (determined by vegetation, soil texture, and obstacles), which is computed using

$$n_{man} = m(n_{bas} + n_{add}) \quad \text{Eq. 9,}$$

where m is a factor accounting for meandering, n_{bas} is the basic n value, and n_{add} is a surcharge for vegetation, obstacles, etc. m is automatically set to 1.0 since the model presented here is designed for steep terrain with poor meandering of the channels.

The water discharge per unit width q (m² s⁻¹) is computed as follows:

$$q = v_{flow} R_f = \frac{1}{n_{man}} R_f^{\frac{5}{3}} (\sin \alpha)^{\frac{1}{2}} \quad \text{Eq. 10.}$$

Surface runoff is computed separately for each hydrological surface class HSC :

- $HSC = 1$ (defined channel): the water is routed through the channel, with only one possible downward direction from each cell;
- $HSC = 2$ (slope with numerous small channels or no channels at all): the water is routed downwards assuming the defined channel densities on a sub-cell scale and a random walk weighted for slope angle:

$$w = \alpha^{u_1} \quad \text{Eq. 11,}$$

where w is the weight assigned to each potential flow direction and u_1 is a user-defined exponent (values of 3 to 4 appear reasonable) – on gentle

slopes, inaccuracies of the DEM or landforms on a sub-cell scale may exert a stronger effect on flow direction than on steep slopes.

For both cases, inflow ΣIF (m) is computed with the Manning formula in the same way:

$$\Sigma IF = \sum_{i=1}^{i=n} R_{f,i} \frac{v_{flow} \Delta t_{short}}{d_{h,i}} = \sum_{i=1}^{i=n} \frac{1}{n_{man,i}} \frac{\Delta t_{short}}{d_{h,i}} R_{f,i}^{\frac{5}{3}} (\sin \alpha_i)^{\frac{1}{2}} \quad \text{Eq. 12,}$$

where n is the number of contributing upslope cells, $d_{b,i}$ (m) is the horizontal distance between the centre of the cell i and the centre of the considered cell. Outflow OF (m) is computed in an analogous way:

$$OF = R_f \frac{v_{flow} \Delta t_{short}}{d_h} \quad \text{Eq. 13,}$$

where d_b (m) stands for the horizontal distance between the centre of the considered cell and the centre of the downslope cell. The length of one short time step Δt_{short} (s) is defined as

$$\Delta t_{short} = a d_{cell} / v_{max} \quad \text{Eq. 14,}$$

where a is a factor ≤ 1 set to 0.5, d_{cell} (m) is the cell size and v_{max} (m s⁻¹) is the maximum runoff velocity over the entire area. Too short time steps would unnecessarily increase computing time. Δt_{short} is defined by the program automatically according to Eq. 14, using the maximum flow velocity of the previous time step over all cells. Δt_{short} is set to 20 s if d_{cell}/v_{max} exceeds a threshold value. If no runoff occurs at all, Δt_{short} is set to 120 s.

The depth of the water table R for each cell is computed as follows:

$$R = R_f + T + M + \Sigma IF - OF \quad \text{Eq. 15,}$$

where T is the effective rainfall, M is the snow melt, ΣIF stands for the total inflow from all the upslope cells directly draining into the considered cell, and OF stands for the outflow (all values in meters).

1.3 Sediment transport model

1.3.1 Basic assumptions

Surface runoff, independently of occurring as overland flow or channel flow, has a certain capacity to transport sediment. If the actual load is below transport capacity, soil from the bed is eroded, whilst sediment is deposited in the reverse case. The following assumptions are set in the model:

- only bedload is considered as relevant regarding the magnitude of sediment transport and the evolution of debris flows. Suspended load is neglected;

- runoff is considered to follow hydraulic principles to a certain threshold of sediment concentration; at higher sediment concentrations it is considered as debris flow.

1.3.2 Detachment and sediment concentration

The Rickenmann (1990) equation is used in the model for estimating sediment transport because it is best suited for relatively steep channels and high sediment concentrations. It only includes bedload.

The original equations, mainly derived from laboratory tests, yielded very high values of detachment when applied to the study areas. Furthermore, the equation does not say anything about detachment rates. For these reasons, the dimensionless calibration parameters ST_1 , ST_2 , ST_3 , and ST_4 had to be introduced:

$$q_b = ST_1 \frac{12.6}{(s-1)^{1.6}} \left(\frac{D90}{D30} \right)^{0.2} (q - q_{cr}) (\sin \alpha)^2 \quad \text{Eq. 16,}$$

where q_b ($\text{m}^2 \text{s}^{-1}$) is the volumetric bedload transport per unit width, s is the ratio between grain and fluid densities, $D90$ and $D30$ (m) are the grain sizes where 90% and 30% per weight, respectively, are finer, q ($\text{m}^2 \text{s}^{-1}$) is the fluid discharge per unit width, and α (degree) is the local slope angle. q_{cr} ($\text{m}^2 \text{s}^{-1}$) is the threshold discharge for sediment transport:

$$q_{cr} = ST_2 0.065 (s-1)^{1.67} g^{0.5} D50^{1.5} (\sin \alpha)^{-1.12} \quad \text{Eq. 17,}$$

where $D50$ (m) is the median grain size, and g (m s^{-2}) is the gravitational acceleration. Erosion (detachment of soil) or deposition d_w (m), depth of bedload l (m), and sediment concentration C ($\text{m}^3 \text{m}^{-3}$) can then be derived:

$$d_w = ST_3 (l_0 - q_b/v) \quad \text{for } l_0 < q_b/v \quad \text{Eq. 18,}$$

$$d_w = ST_4 (l_0 - q_b/v) \quad \text{for } l_0 > q_b/v \quad \text{Eq. 19,}$$

$$l = l_0 - d_w = q_b/v \quad \text{Eq. 20,}$$

$$C = l/(l + R) \quad \text{Eq. 21,}$$

where l_0 (m) is the depth of bedload at the start of the time step. Negative values of d_w (Eq. 18) indicate detachment, positive values (Eq. 19) indicate deposition. Only saturated soil is allowed to be detached. All the sediment deposited is considered as saturated, and the depth of the wetting front below the flow channel(s) is corrected for detachment and deposition. Eq. 18 to 20, which are not part of the original Rickenmann model, are based on two rough generalizations:

- the bedload moves at the same velocity as the water;

- the bedload discharge immediately reaches an equilibrium (only if $ST_3 = ST_4 = 1$).

1.4 Slope stability model

The hydraulic model components supply saturated depth d (m). It is assumed that

- slope failures only occur at the depth d (the wetting front);
- if total soil depth is known, slope failures are also allowed to occur at the soil-bedrock interface, but only if the entire soil is saturated (mathematically identical to slope failures at the wetting front).

An infinite slope stability model (Figure 3) is used for the calculations. Therefore a wide ratio between slope length and depth of the failure plane is required in order to yield an acceptable approximation – a condition that is usually met for shallow, but not for deep-seated failures.

Furthermore, infinite slope stability models assume a translational failure mechanism, which usually only occurs in cohesionless soils. For cohesive soils, the model may still derive reasonable approximations of the factor of safety, but is – strictly spoken – not really applicable.

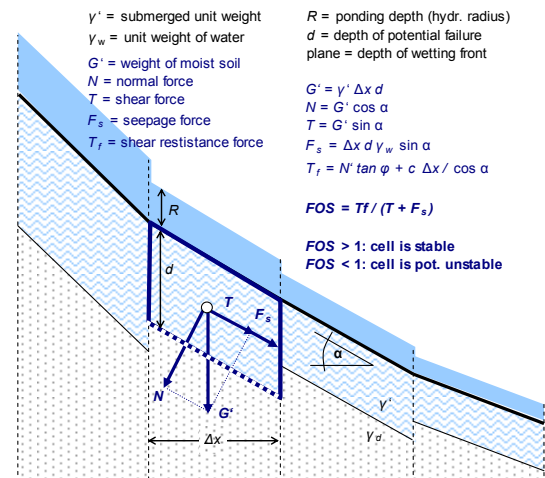


Figure 3: Mechanisms for infiltration and shallow slope failure as applied in the present study. For a detailed explanation compare text. Designed by M. Mergili.

As discussed above, the infiltration model only considers vertical seepage. Infinite slope stability models, in contrast, usually assume a slope-parallel flow, exerting a destabilizing seepage force F_s (N) parallel to the slope (compare Eq. 29). In reality, the direction of the seepage depends on the local conditions, particularly on the presence or absence of an impermeable layer. Fully including the slope-parallel seepage into the slope stability calculations is therefore a worst-case assumption. The slope stability model is executed after the computation of the infiltration has been completed (last time step), so that a slope-parallel seepage can be assumed without contradic-

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tion to the vertical seepage computed with the Green-Ampt model.

The dimensionless factor of safety FOS is stated as

$$FOS = T_f / (T + F_s) \quad \text{Eq. 22,}$$

where T_f is the shear resistance force of the soil, T is the shear force, and F_s is the seepage force (all in N; compare Figure 3). Shear resistance s (N m^{-2}) follows Coulomb's law:

$$s = c + \sigma(\tan \varphi) \quad \text{Eq. 23,}$$

and the corresponding shear resistance force is

$$T_f = N' \tan \varphi + c \cdot \Delta x / \cos \alpha \quad \text{Eq. 24,}$$

where N is the normal force, φ (degree) is the angle of internal friction, c (N m^{-2}) is the cohesion (soil cohesion c_s plus root cohesion c_r), Δx (m) is the length of the considered slope segment in downslope direction, and α (degree) is the slope angle. N and T (N) are computed from the weight of the moist soil G' (N):

$$G' = \gamma' \cdot \Delta x \cdot d \quad \text{Eq. 25,}$$

$$N = G' \cos \alpha \quad \text{Eq. 26,}$$

$$T = G' \sin \alpha \quad \text{Eq. 27,}$$

where γ' (N m^{-3}) is the specific weight of saturated soil and d (m) is the depth of the potential failure plane:

$$\gamma' = \gamma_d + \gamma_w [\theta_s (1 - s) - 1] \quad \text{Eq. 28.}$$

γ_d is the specific weight of dry soil, and γ_w is the specific weight of water (both in N m^{-2}). γ_d is derived from grain specific weight (to be specified by the user; 26.5 kN m^{-3} for quartzitic material), and θ_s and s as surrogates for pore volume.

The seepage force exerted by the soil water is stated as

$$F_s = \Delta x \cdot d \cdot \gamma_w \sin \alpha \quad \text{Eq. 29.}$$

Dry and cohesionless soils ($F_s = 0$; $c = 0$; $\gamma' = \gamma_d$) are stable when $\alpha < \varphi$, and unstable when $\alpha > \varphi$.

The forces exerted by the surface water table R (m) are neglected in the model.

1.5 Debris flow runout

1.5.1 Initiation

Debris flows are supposed to occur within a certain range of sediment concentrations, usually between $C_{min} = 0.45$ and $C_{max} = 0.55$.

- At the end of the last time step, all cells identified as potentially unstable (with $FOS < 1$) during at

least one time step are considered to fail at the deepest failure plane identified for the cell during the event. Failed soil with a sediment concentration of $C_{soil} < C_{max}$, where $C_{soil} = 1 - \theta(1 - s)$, is considered to evolve into a debris flow. In reality, debris flows with higher sediment concentration do occur, particularly in non-cohesive soils. The model therefore assumes that all failed soil with $c_s = 0$ develops into a debris flow also at higher sediment concentrations;

- for every cell where runoff is modelled to evolve into a debris flow, sediment concentration C is tested against C_{min} after each time step. If $C > C_{min}$, the material is retained from sediment load. All retained material is routed downslope as debris flow at the end of the last time step.

Before routing the debris flow downwards, the volume and the size of each patch of cells of potential debris flow initiation are calculated. If one of these variables or the depth of potential initiation is below user-defined thresholds, the patch or the cell, respectively, is excluded from runoff.

1.5.2 Routing procedure

The debris flow is not simply routed downwards the steepest slope. Similar to surface runoff, the routing algorithm is determined by the hydrological surface class:

- $HSC = 1$ (defined channel): the debris flow is routed through the channel with only one possible downward direction from each cell. As soon as deposition occurs in a channel, the corresponding cells are considered as $HSC = 2$ for the further simulation;
- $HSC = 2$ (no clearly defined channel): a random walk weighted for downslope angle is applied for routing the debris flow. The weight w is determined automatically as a function of the steepest slope. It is expressed as:

$$w = \alpha^{u_2} / \beta^{u_2 - 1} \quad \text{Eq. 30,}$$

where the exponent u_2 has to be specified by the user (values between 3 and 5 appear reasonable). β (degree) is the slope angle where deposition starts (compare below; $w = 0$) for upslope angles. Similar to runoff, this algorithm accounts for the higher tendency of debris flows to take another than the steepest slope specified in the DEM on gentle slopes than on steep slopes.

Each cell containing starting material for a debris flow is passed through the routing procedure individually. Routing continues until the debris flow has stopped, according to the criterion specified in the next section.

1.5.3 Runout distance and deposition

Runout is computed using a semi-deterministic two-parameter friction model developed by Perla et al. (1980) which was modified by Gamma (2000) and applied by Wichmann (2006) in a raster-based GIS environment. It is not only applicable to debris flows, but also to snow avalanches.

The deterministic element of the approach is the velocity of the debris flow v (m s^{-1}) which is computed for each raster cell i :

$$v_i = \sqrt{\zeta_i \left(\frac{M}{D} \right)_i (1 - e^{\eta_i})} + v_{i-1}^2 e^{\eta_i} \cos(\Delta \alpha_i) \quad \text{Eq. 31,}$$

where M/D (m) is the mass-to-drag ratio of the debris flow, and v_{i-1} is the debris flow velocity of the previous cell. The factor ζ_i and the coefficient η_i are derived as follows:

$$\zeta_i = g(\sin \alpha_i - \mu \cos \alpha_i) \quad \text{Eq. 32,}$$

$$\eta_i = \frac{-2L_i}{(M/D)_i} \quad \text{Eq. 33,}$$

where g is gravitational acceleration (9.81 m s^{-2} on the earth surface), α_i is local slope angle, μ is the dimensionless friction coefficient, and L (m) is slope length (cell size corrected for slope angle). $\Delta \alpha$ is the difference between the slope angle of the previous cell and the slope angle of the considered cell which is set to 0 for convex slopes or channels (Wichmann 2006). For concave slopes, v_{i-1} is corrected as the flow loses energy:

$$v_{i-1} = v_{i-1,0} \cos(\alpha_{i-1} - \alpha_i) \text{ if } \alpha_{i-1} > \alpha_i \quad \text{Eq. 34.}$$

The first term in Eq. 31 determines if the flow accelerates ($\zeta > 0$) or decelerates ($\zeta < 0$), the second term provides the contribution of flow velocity to the final velocity. M/D , being a surrogate for the inertia of the flow, exerts a major influence on flow velocity, while its impact on runout distance is small. The latter is primarily determined by the topography and μ (Gamma 2000; Wichmann 2006). The simulation is stopped as soon as v_i becomes undefined (square root of negative value, compare Eq. 31).

One problem regarding the calibration of this model is that different combinations of the two parameters to be calibrated (M/D and μ) may result in the same runout distance. A common way for calibration is therefore to set M/D to values leading to realistic velocities, and then calibrating μ in order to correlate simulated and observed runout distances.

Wichmann (2006) used values of $M/D = 75 \text{ m}$. The following relationship for μ was found to be useful for computing the maximum runout length (Gamma 2000):

$$\mu = 0.13A^{-0.25} \quad \text{Eq. 35,}$$

where A (km^2) is the catchment size for the considered cell. It is assumed that μ would decrease with increasing A because the water content of the debris flow would increase. This relationship was used in *r.debrisflow*, but with user-defined factor and exponent in order to allow calibration for other conditions. Following Gamma (2000), the range of values of μ would be restricted to a maximum of 0.3 and a minimum of 0.045, overruling Eq. 35.

The two-parameter friction model does not say anything about the patterns of particle entrainment and deposition. Instead of designing a more complex scheme like Wichmann (2006), simple thresholds of slope and velocity are used for delineating these processes in *r.debrisflow*, where entrainment (as far down as to the wetting front) is only assumed if both parameters are above the threshold, whilst deposition is assumed to take place only if both parameters are below the thresholds. The calibration of the thresholds is connected to the same problems as the calibration of M/D and μ (different combinations of parameter values).

1.6 Model validation

r.debrisflow is mainly based on physically based concepts, but nevertheless it contains empirical elements and an array of parameters some of which are difficult to measure or to estimate. Therefore some type of calibration of some of the parameters is required for each study area. For this purpose, datasets for validation are needed, for example:

- if the debris flows hit a road: records by the road authorities about volumes to be removed after debris flow events connected to known meteorological conditions; or
- the distribution and extent of landslide scars and patterns of deposition from debris flows visible in the field.

1.7 Acknowledgements

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1.8 References

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2 User's manual

2.1 System requirements

r.debrisflow was developed and tested under *Fedora Core 6* with *GRASS 6.2.1*. It probably works on most other *UNIX* systems as well as with other versions of *GRASS*. The module itself should also be usable under *cygwin*, but the related shell script *r.debrisflow.sh* (compare below) would probably not work.

Please make sure to have a proper installation of *GRASS* before installing *r.debrisflow*. In case of doubt, please consult www.grass.itc.it.

2.2 Test dataset

A test dataset is provided together with the program, consisting of some text files and a *GRASS* location with the name *test_rdebrisflow*. All data is packed in the file *test_rdebrisflow.zip*.

test_prec.txt and *test_temp.txt* contain precipitation and temperature data in the format described below, while *test_param.txt* is the required parameter file. *test_ctrlpoints.txt* contains the control points (compare below). Table 1 shows the names of the raster and vector maps.

Table 1: Names of the maps of the test dataset

name of the map	description
test_mask	mask for study catchment (raster)
test_elev	elevation map at 5 m resolution (raster)
test_elev10	elevation map at 10 m resolution (raster)
test_soilclass	soil classes (raster)
test_soildepth	soil depth (raster)
test_landcover	land cover classes (raster)
test_hydcl	hydrological surface classes at 5 m resolution (raster)
test_hydcl10	hydrological surface classes at 10 m resolution (raster)
test_chanw	width of flow channel(s) at 5 m resolution (raster)
test_chanw10	width of flow channel(s) at 10 m resolution (raster)
test_road	road (object at risk; raster)
test_snowdepth	depth of snow cover (raster)
test_dinitdef	predefined depth of debris flow initiation (raster)
test_dscourdef	predefined maximum depth of entrainment (raster)
test_init_observed	observed patterns of debris flow initiation (line vector)
test_depd_observed	observed patterns of deposition from debris flow (line vector)

The test dataset is suitable to run *r.debrisflow* at spatial resolutions of 5 m or 10 m. Please note that the

reclass tables described below are suitable for the soil and land cover classes in the test dataset – for other datasets, they have to be modified.

2.3 File management

The file system behind *r.debrisflow* consists of two parts:

- a *GRASS* mapset with all the spatially distributed input information as raster or vector maps, and
- a folder named *r.debrisflow*, which may be stored at any location in your home directory. The internal structure of the folder *r.debrisflow* may not be manipulated, otherwise some of the functionalities will fail.

The directory *r.debrisflow* contains the following sub-directories:

tools

The `tools` directory hosts the scripts required for installing and running *r.debrisflow*:

- *main.c*: the source code for *r.debrisflow*;
- *r.debrisflow.sh*: a shell script facilitating data input, management, and output (compare below);
- *install.sh*: a shell script helping to compile the source code (*main.c*).

data

It contains the input files of the meteorological data, the parameter file, and the file with control points (compare below), and a file for scaling the legends of the resulting maps to be displayed. The subfolder `/recl` contains reclass tables (for deriving secondary parameters from input datasets), the subfolder `/colors` contains colour tables for display.

temp

The `temp` directory contains temporary files created during the execution of *r.debrisflow.sh*. Its content shall not be manipulated manually, but only using the functionalities of *r.debrisflow.sh*.

results

It contains some simulation results (summary file, documentation file; compare below). However, the main results are stored as rasters in the active *GRASS* mapset.

docs

The `docs` directory contains this manual.

2.4 Installation

r.debrisflow has to be added to the **GRASS** raster library as a new module, based on the source code of the file *main.c*. For performing this task, log in as super user (su). call the script *install.sh* in the folder *r.debrisflow/tools*:

```
cd dir/r.debrisflow/tools
sh install.sh
```

dir may be any location in your home directory. The following prompt is displayed:

```
Full path to GRASS source (slashes at beginning and end):
```

Here, enter the path to the **GRASS** source, for example

```
/usr/local/src/grass64_release/
```

The Makefile is created, and compilation and installation are run automatically, so that *r.debrisflow* is ready to use.

Please note that you have to change to the tools directory as described above – if just entering

```
sh dir/r.debrisflow/tools/install.sh
```

an error message will display and *r.debrisflow* will not be installed.

2.5 Data management

r.debrisflow uses text files and rasters with predefined names as input. The shell script *r.debrisflow.sh* serves for creating these datasets, and for generating secondary datasets from primary information (e.g. hydraulic conductivity from grain size class). It must be run from within the used **GRASS** mapset:

```
cd dir/r.debrisflow/tools
sh r.debrisflow.sh
```

r.debrisflow.sh offers the following modules:

```
1 --> Parameter and data input
2 --> Preparation of parameters
3 --> Execution of simulations
4 --> Post-processing of model output
5 --> Display of results
6 --> Removal of result files
7 --> Cleaning of file system
8 --> Exit
```

By entering a number, the corresponding module is executed.. The modules are described in detail below. *r.debrisflow.sh* has to be called from within the **GRASS** mapset with all the required raster maps.

2.5.1 Parameter and data input

Module 1 consists of a sequence of prompts for input data and parameters. If no input is given for a prompt (by just pressing **ENTER**), the dataset specified earlier is kept. The numbers behind the prompts denote the modes of simulation (compare Chapter 1) for which the corresponding dataset is required.

- --> Catchment map (boolean): |1|2|3|4|5|6|
Boolean raster map defining the catchment of interest (identified by cell values of **1**, areas out of the catchment are defined by **0** or *no data*).
- --> Elevation map (m): |1|2|3|4|5|6|
Raster map of elevation (meters).
- --> Soil depth map (m): |1|2|3|4|5|6|
Raster map of soil depth (in meters). If soil depth is not known, it should be set to a high value. For bedrock, it has to be set to **0**.
- --> Hydrological surface classes map (integer): |1|2|3|4|5|6|
Integer raster map of the distribution of the hydrological surface classes (**1** for defined flow channel, **2** for multiple flow channel or unconcentrated overland flow). Care has to be taken that the cell size of the map corresponds to the cell size of the simulation it shall be used for. Particularly the defined channels (class **1**) have to be clean and continuous.
- --> Channel width map: |1|2|3|4|5|6|
Raster map denoting total width of flow channel(s) for each cell, connected to the hydrological surface classes: **1** (defined flow channel): width of the flow channel; **2** (multiple channels or unconcentrated overland flow): ratio between sum of width of all flow channels crossing a cell and cell width, perpendicular to the steepest slope. The advantage of this approach is to be largely independent from cell size, at least for quite uniform distributions of channels.
Also here, the cell size has to correspond to the cell size of the simulation it shall be used for. Additionally, it has to fit to the hydrological surface classes map exactly in order to avoid serious problems during simulation.
- --> Objects at risk map (boolean): |1|2|3|4|5|6|
Boolean raster map denoting objects at risk (**1** for presence of potential objects at risk like roads or buildings, else **0** or *no data*).
- --> Soil classes map (integer): |1|2|3|4|5|
Integer raster map with predefined soil classes (compare **Module 2**: Preparation of parameters). The numbers of the classes may be chosen freely, but must fit to the corresponding reclass tables (compare Table 3).
- --> Land cover classes map (integer): |1|2|3|4|
Integer raster map with predefined land cover classes (compare **Module 2**: Preparation of parameters). The numbers of the classes may be

chosen freely, but must fit to the corresponding reclass tables (compare Table 3).

- --> Estimated depth of mobilization of soil map (m): |6|

Raster map showing the patterns of estimated potential debris flow initiation (depth in meters).

- --> Estimated depth of entrainment of soil map (m): |5|6|

Raster map showing the patterns of estimated potential depth of entrainment by debris flows (meters).

- --> Snow depth map (m): |1|2|3|4|

Raster map denoting depth of snow cover (meters).

The remaining four required input datasets are the names of files which have to exist in the

`dir/r.debrisflow/data`

directory. In each of the files, each line has to consist of a label (first column) and a value (second column). The content of the label only serves for enhancing readability, it has no influence on the simulation, but it may not contain tabulators. It is important, however, that it does exist and is separated from the actual value by a tabulator, as only the part of the file after the tabulator is used. Please consult the example files (starting with *example_*) as reference.

- --> Precipitation file (mm): |1|2|3|4|

File with precipitation values (from measured data or hypothetical). header information:

- first line: elevation of rain gauge (meters);
- second line: duration of basic time step (seconds);
- third line downwards: precipitation values (mm), sum of one time step per line.

- --> Temperature file (°C): |1|2|3|4|

File with temperature values (from measured data or hypothetical). Header information:

- first line: elevation of thermometer (meters);
- second line: daily minimum temperature (°C);
- third line: daily maximum temperature (°C);
- fourth line: temperature for computing snow melt (°C);
- fifth line: critical temperature (rain-fall/snowfall boundary, °C);
- sixth line: vertical gradient for daily minimum temperature (°C m⁻¹);
- seventh line: vertical gradient for daily maximum temperature (°C m⁻¹);
- eighth line: degree day factor for snow melt (m °C⁻¹).
- Ninth line downwards: temperature values, one time step per line.

Table 2: Input parameters (single values) for *r.debrisflow*

variable	description	unit	examples of value(s)
γ_g	grain specific weight of soil	N m ⁻³	26,500 for quartzitic soil
u_1	exponent for weighting of slope angle for surface runoff random walk	exponent	3
u_2	exponent for weighting of slope angle for debris flow runoff random walk	exponent	4
p_r	percolation through rock (ratio compared to effective rainfall plus snow melt)	ratio	0.0–1.0
ST_1	factor for calibration of critical runoff formula	factor	1.0
ST_2	factor for calibration of potential sediment load formula	factor	0.005 – 0.01
ST_3	factor for calibrating detachment by surface runoff	factor	0.1 cell sizes
ST_4	factor for calibrating deposition from surface runoff	factor	
C_{min}	minimum sediment concentration for development of debris flow	ratio	0.45
C_{max}	maximum sediment concentration for development of debris flow in cohesive soil	ratio	0.55
–	minimum depth of unstable or detached soil for initiation of debris flow	m	various
–	minimum number of adjacent failed cells for development of debris flow	integer	depends on cell size
–	minimum volume of unstable or detached soil for development of debris flow	m ³	various
–	factor for computing μ (compare Eq. 35)	factor	0.13
–	exponent for computing μ (compare Eq. 35)	exponent	-0.25
–	lower threshold for μ	coefficient	0.045 – 0.15
–	upper threshold for μ	coefficient	0.3
M/D	mass-to-drag ratio	m	75
–	slope threshold for entrainment/deposition	deg	15
–	velocity threshold for entrainment/deposition	m s ⁻¹	10
–	maximum depth of debris flow deposit	m	5 – 15
–	options for distribution of material deposited from debris flow	integer	1 for wedge-shaped towards the front, 2 for even
–	Minimum slope angle for initiation of debris flows	deg.	20 – 30

Table 3: Spatially distributed input parameters of *r.debrisflow*, specified in *Module 1* or automatically created in *Module 2* of *r.debrisflow.sh*, respectively

shortcut	description	unit	derived from	name of reclass table dir/r.debrisflow/data/recl/	modes of simulation					
					1	2	3	4	5	6
catchment	definition of catchment of interest	boolean	specified as		x	x	x	x	x	x
elevation	elevation above sea level	m	input in		x	x	x	x	x	x
soildepth	depth of soil	m	<i>Module 1</i>		x	x	x	x	x	x
soilclass	class of soil	integer			x	x	x	x	x	
landcovclass	class of land cover	integer			x	x	x	x	x	
hsc	hydrological surface class	integer			x	x	x	x	x	x
chanwidth	width of flow channel	m, ratio			x	x	x	x	x	x
riskobj	definition of objects potentially at risk	boolean			x	x	x	x	x	x
dinitdef	depth of debris flow initiation	m								x
dscourdef	maximum depth of entrainment	m							x	x
snow	depth of snow cover	m				x	x	x	x	
soil	presence of soil	boolean		soildepth		x	x	x	x	x
alpha	local slope angle	deg.	elevation		x	x	x	x	x	x
my	friction coefficient for runoff	coeff.			x	x	x	x	x	x
icp	interception capacity of the vegetation	m	land-covclass	recl_lcv_icp4_min.txt	x	x	x	x		
				recl_lcv_icp4_max.txt						
croot	root cohesion	N m ⁻²		recl_lcv_croot_min0.txt	x	x	x		x	
				recl_lcv_croot_max0.txt						
droot	rooting depth	m		recl_lcv_droot_min1.txt	x	x	x		x	
				recl_lcv_droot_max1.txt						
nman_add	vegetation surcharge for Manning's <i>n</i>	summand		recl_nman_add_min3.txt	x	x		x		
				recl_nman_add_max3.txt						
textclass	texture class of soil	integer	soilclass	recl_soil_class0.txt	x	x	x	x	x	
d30	d30 grain diameter of soil	m			recl_soil_d305.txt	x	x		x	
d50	d50 grain diameter of soil	m			recl_soil_d505.txt	x	x		x	
d90	d90 grain diameter of soil	m			recl_soil_d905.txt	x	x		x	
skeleton	skeleton content of soil (> 2 mm)	ratio			recl_soil_s3.txt	x	x	x	x	x
gammad	dry specific weight of soil	N m ⁻³			recl_soil_gammad0.txt	x	x	x	x	x
csoil	soil cohesion	N m ⁻²			recl_soil_c0.txt	x	x	x		x
phi	soil angle of internal friction	deg.			recl_soil_phi1.txt	x	x	x		x
nman_bas	basic value for Manning's <i>n</i>	summand			recl_nman_bas_min3.txt	x	x		x	
					recl_nman_bas_max3.txt					
pref	factor for preferential (macropore) flow, to be multiplied with infiltration capacity	factor		recl_soil_pref_min1.txt	x	x	x	x		
				recl_soil_pref_max1.txt						
thetar	soil residual water content	ratio	textclass	recl_hyd_thetar3.txt	x	x	x	x		
thetas	soil saturated water content	ratio			recl_hyd_thetas2.txt	x	x	x	x	x
psi	matric suction at wetting front	m			recl_hyd_psi5.txt	x	x	x	x	
k	soil hydraulic conductivity	m s ⁻¹			recl_hyd_k9.txt	x	x	x	x	

Temperature is only relevant when including snow melt or when it is lower than the critical temperature separating rainfall and snow fall. If the raster map of snow depth is 0 m over the entire catchment, the specified values have no influence on the results of the simulation as long as they exceed the critical temperature.

- > Parameter file: |1|2|3|4|5|6|

File with list of parameters for simulation, one per line. The parameters have to be specified in a defined order (Table 2).

In the folder `dir/r.debrisflow/data/`, a file with example parameters (*example_param.txt*) is provided.

- > Legend file: |1|2|3|4|5|6|

File with user-specified values serving as maxima for the display of the output maps.

In the folder `dir/r.debrisflow/data/`, an example for a legend file (*example_legend.txt*) is

provided. The order shown in this file has to be kept for all legend files

- > File with coordinates of control points: |1|2|3|4|

File with coordinates of some specific points for which some variables are documented for each time step. Each line contains one coordinate – first line the x coordinate of the first point, second line the y coordinate of the first point, third line the x coordinate of the second point, etc. Please note that, if you do not wish to specify control points, the file has to exist, anyway (otherwise, *r.debrisflow* will produce an error message), but may be empty.

2.5.2 Preparation of parameters

No user inputs are required for this module, which serves for the automatic derivation of secondary input parameter maps from the maps specified in *Module 1*. A slope raster map is derived from the eleva-

tion model (*r.slope.aspect*), and a boolean presence of soil map is derived from the soil depth map. Secondary parameter maps are derived from the land cover and soil classes using reclass tables (compare Table 3; *r.reclass*). All the reclass tables have to be stored under

```
dir/r.debrisflow/data/asc/
```

and must exactly be named as shown in Table 3. All the reclass tables must correspond to the following pattern:

```
original value_1 = derived value_1
original value_2 = derived value_2
...
original value_n = derived value_n
end
```

for example

```
1 = 34
3 = 5
...
10 = 37
end
```

All numbers must be left-aligned and all equal signs have to stand in one column.

The numbers before the .txt extension of the reclass files denote the factor with which the original derived values have to be multiplied before writing them into the reclass table. This is necessary because the *r.reclass* module of *GRASS* is not able to cope with non-integer values. After reclassification, the magnitude of the derived raster maps is corrected automatically.

For parameters with *max* or *min* at the end of the name of the reclass table, the pixel values of the created raster map are randomly distributed between the minimum and the maximum values. If this is not desired, the maxima and minima have to be identical.

Example reclass tables are stored in the abovementioned directory, but the tables have to be modified for each study area, except the tables for the hydraulic parameters, which refer to grain size classes according to the following key: *1=S*; *2=LS*; *3=SL*; *4=SCL*; *5=SC*; *6=L*; *7=CL*; *8=SIL*; *9=C*; *10=SI*; *11=SI*; *12=SIC*.

It is possible to skip *Module 2* and instead create all the parameter maps manually. In this case, please note that the naming conventions have to be met exactly in order to ensure the functionality of the simulation (compare Table 3).

2.5.3 Execution of simulations

Prompts for mode of simulation and cell size are displayed:

```
--> Mode of simulation (integer):
--> Cell size (m):
```

The options for the mode of simulation are described in Chapter 1 (the corresponding number has to be entered). The cell size has to be chosen in accordance with the input datasets and the required level of detail. For test simulations it is recommended to choose larger cell sizes in order to reduce computing time.

After specifying these two parameters, the *GRASS* raster module *r.debrisflow* is called by pressing *ENTER*. Additionally to an array of raster maps, a summary file (*summary.txt*) and a documentation file (*doc.txt*) are written and stored in the

```
dir/r.debrisflow/results/
```

directory. The summary file contains variables (particularly volumes) for each basic time step. The documentation file contains variables for the coordinates specified as control points (*ctrlpoints.txt*), for each short time step (compare Table 4 for the variable names).

Please note that if you wish to run *r.debrisflow* manually, not from within *r.debrisflow.sh*, you have to copy the input files to the *dir/r.debrisflow/temp/* directory as *prec.txt* (precipitation), *temp.txt* (temperature), *param.txt* (parameter file), and *ctrlpoints.txt* (control points). These files shall not contain labels, but only the values.

2.5.4 Post-processing of model output

All the resulting raster maps are cleaned (cells outside of the defined catchment are set as no data), and the sediment balance from debris flows is computed. For the modes of simulation *1* and *4*, the sediment balance from surface runoff as well as the sediment concentration for each time step and the maximum sediment concentration are computed. Some of the major resulting maps are prepared for display (compare below). In order to ensure comparable legends, a maximum value is assigned to each type of legend (depth of wetting front; factor of safety; sediment concentration; failure, detachment, and entrainment; deposition; sediment balance; debris flow index; depth and velocity of surface runoff; depth of load). The legend file has to be stored in *dir/r.debrisflow/data/* and to be specified during the data and parameter input (compare above). The color tables have to be stored in *dir/r.debrisflow/data/colors*.

Furthermore, three prompts do appear when calling the module. Each task is accepted by typing *1*, or denied by typing *0*.

- --> Calculate statistics (boolean) ?

Maximum values of runoff velocity, runoff depth, and load depth over the entire event are computed. Please note that the option is not applicable to all modes of simulation (*1*, *2*, and *4* for the runoff variables, *1* and *4* for load depth).

Table 4: Output from *r.debrisflow* (after running *Module 4*). r=raster map, s=summary file, d=documentation file

shortcut	description	unit	versions			time steps	mode of simulation								
			r	s	d		1	2	3	4	5	6			
vflow	flow velocity of surface runoff	m s ⁻¹	x	x		all	x	x		x					
vflow_max	maximum flow velocity	m s ⁻¹	x			–	x	x		x					
dflow	depth of surface runoff	m	x		x	all	x	x		x					
dflow_max	maximum depth of surface runoff	m	x			–	x	x		x					
dload	depth of sediment load of surface runoff	m	x		x	all	x			x					
dload_max	maximum depth of load	m	x			–	x			x					
streampower	stream power (as additional information)	N m ⁻¹ s ⁻¹	x			all	x	x		x					
deltadetw	detachment by surface runoff (short time step)	m			x	–	x			x					
dsetw	cumulative detachment by surface runoff	m	x	x		all	x			x					
dsetw_val	detachment by surface runoff (basic time step)	m	x			all	x			x					
deltadepf	deposition from surface runoff (short time step)	m			x	–	x			x					
ddepf	cumulative deposition from surface runoff	m	x	x		all	x			x					
ddepf_val	deposition from surface runoff (basic time step)	m	x			all	x			x					
dbudget_wat	cumulative sediment balance from water flow	m			x	all	x			x					
dbudget_wat_val	sediment balance from water flow (time step)	m			x	all	x			x					
csed	sediment concentration of surface runoff	ratio	x			all	x			x					
csed_max	maximum sediment concentration	ratio	x			–	x			x					
dwfront_chan	depth of wetting front below flow channel(s)	m	x			pre-last	x	x	x	x					
dwfront_int	depth of wetting front between channel(s)	m	x			pre-last	x	x		x					
fos	factor of safety below flow channel(s)	ratio	x			last	x	x	x				x		
dfailpot	potential depth of slope failure	m	x	x		last	x	x	x				x		
dinit_fail	depth of debris flow initiation from slope failure	m	x	x		last	x	x	x				x		
dinit_detw	depth of debris flow initiation from detachment by surface runoff	m	x	x		last	x			x					
dinit	total depth of debris flow initiation	m	x			last	x	x	x	x	x				
dscour	depth of entrainment by debris flow	m	x	x		last	x	x	x	x	x	x			
ddepd	depth of deposition from debris flow	m	x	x		last	x	x	x	x	x	x			
dbudget_deb	sediment balance from debris flow	m	x			last	x	x	x	x	x	x			
idepG	indicator for entrainment or deposition by debris flow according to the two-parameter friction model	integer	x			last	x	x	x	x	x	x			
idepR	indicator for debris flow incidence according to Rickenmann (1999) equation	integer	x			last	x	x	x	x	x	x			
rcoef	runoff coefficient	ratio		x		all	x	x	x	x					
deltat	length of short time step	s		x		all	x	x	x	x	x	x			

- > Extract values for time steps (boolean) ?

This option is only applicable for the modes of simulation 1 and 4. Raster maps of detachment, deposition, and sediment balance for each time step are extracted from the rasters of cumulative values written by the simulation.

- > Export maps to ascii (boolean) ?

The resulting raster maps are exported as ascii rasters in order to be usable with other GIS software products like ArcGIS. The resulting files are stored in `dir/r.debrisflow/results/asc`.

In the output rasters, the display during program execution, and in the summary and documentation files, every variable is addressed by a shortcut (Table 4). The names of the resulting raster maps have the prefix *r_*. Depths (raster maps and documentation file) start with *d*. The volumes depicted in the display during simulation and in the summary file have the prefix *vol_* instead of *d*. The number at the end of

the raster map names indicates the time step. Rasters, except those of runoff and sediment transport variables, are only written for the pre-last (depth of wetting front) or last time step (all other variables).

For example, the raster *r_ddepd20* shows the depth of deposition from debris flow for each pixel at the end of time step 20, while *vol_dep* indicates the volume deposited from debris flow over the entire study area.

2.5.5 Display of results

Some of the major resulting maps can be displayed using this module. The following parameters have to be specified:

- > Azimuth of the sun for shaded relief map:

All maps are displayed with a shaded relief as background, the azimuth of which has to be specified (in decimal degrees; recommended: 315).

- > Export maps to jpg (1/0):

The displayed maps can be automatically stored as jpg graphics in `dir/r.debrisflow/results/jpg`. If you wish to do so, please specify *1*, else *0*.

- --> Height of monitor in pixels:

Please specify the height of the monitor for display – a value between 500 and 800 is recommended, depending on the size of your monitor.

- --> Observed patterns of debris flow initiation (line vector):

A line vector map with areas of debris flow initiation observed in the field may be specified, if available, for facilitating the evaluation of the model results.

- --> Observed patterns of debris flow deposition (line vector):

A line vector map with areas of debris flow deposits observed in the field may be specified, if available, for facilitating the evaluation of the model results.

A monitor opens, and a prompt with instructions appears in the terminal. The maps are displayed in a defined sequence – please enter the number of steps to move forward or backward, or *exit* to quit. If you have moved a defined number of steps fore- or backwards and would like to apply the same action again, you can just press *ENTER* to do so.

If you have chosen to export the maps as jpg, no prompts appear, but all maps are displayed and exported automatically, and the module is terminated.

Please note that the size of the monitor and the placement of some of the elements of the maps (legend, bar scale) are not suitable for all map width to height ratios. It may happen that some of the placement options have to be changed in the shell script *r.debrisflow* itself in order to design satisfactory layouts.

2.5.6 Removal of result files

All results (rasters and text files produced by *r.debrisflow* and *Module 4*) are deleted. All temporary files created in the modules *1* and *2* are kept, so that new simulations may be performed immediately.

2.5.7 Cleaning of file system

All temporary rasters and text files created by the modules *1* and *2* are deleted. They must be re-run in order to perform new simulations.

2.5.8 Exit

r.debrisflow.sh is exited and the default cell size is restored

3 Prospected improvements

3.1 Scientific concepts

This document describes Version 1.3 of *r.debrisflow*. A number of optimizations are prospected for future versions.

- The channel parameters for the hydrological surface classes 1 and 2 are rough estimates from field observations and orthophotos. For the future, it would be useful to have a tool for automatically extracting these features from a high resolution elevation model, in order to allow for a more objective down-scaling to the cell size at which *r.debrisflow* is finally run.
- Water from rainfall and snow melt is assumed to immediately concentrate in the flow channels. Introducing some sort of time of concentration could be useful.
- The sediment transport model has to be calibrated with field data at the moment (ST_1 to ST_4). It would be desirable to improve the model in a way that this calibration is only required to a lesser extent, for example by introducing maximum rates of detachment or by finding a model which suits better for steep terrain.
- The slope stability model as used in this version is, in a strict sense, only able to predict shallow translational slope failures in cohesionless soils. For the future it would be desirable to include

slope geometry and potential failure planes in a way that also deeper-seated rotational failures in cohesive soils can be predicted.

- All the mobilized material is kept at its place until the last time step and is then routed downwards together. This is more realistically for failed material than for detached material, but for both mechanisms a way should be found to let the algorithm decide when a patch of unstable material moves downwards as debris flow.
- At the moment it is attempted to implement a deterministic runout model (based on the Savage-Hutter equation also used for snow avalanches) to *GRASS* as a raster module named *r.avalanche*.

3.2 Ease of use

One of the next steps shall be to improve the quality of display of the results (*Module 5* of *r.debrisflow.sh*).

In its current version, the operation of *r.debrisflow* runs very much on text files and the command line. For the future, it would be desirable to have a user interface facilitating data management and at least partly replacing *r.debrisflow.sh*. However, such improvements is given a lower priority at the moment than those regarding the scientific concepts behind the model.