

Runout-modelling of shallow landslides in Carinthia (Austria)

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Abstract

Shallow translational landslides and earth-flows (mixing process between landslide and flow process) are the most common and most problematic types of landslides relating to the weathering of the bedrock and unconsolidated slope deposits in Carinthia. These types of landslides can reach high speeds and travel long distances. Usually only the uppermost meters of loose sediments of the slope are affected and heavy rain events after a pre-saturation of the soil are typically triggers for such landslides.

As part of a research project in Carinthia an Add-In for ArcGIS 10x was developed. This Add-In calculates the runout for these common types of mass movements on the basis of available data on a regional scale. The runout modelling assumes that the soil is presaturated and additional precipitation in susceptible area triggers the landslides.

The calculation of the runout distances is performed using a specially programmed ArcGIS Add-In. The calculation requires the following information:

Initiation cells of high susceptibility to landslide processes (slope failure initiation zones); digital elevation model (DEM); geology; surface roughness (generated from the landuse map); and curvature (this affects the drainage of the mass movement).

The runout modelling takes into account the variability of the „trigger“ and mobility as a function of water saturation in shallow landslides. The calibration of the parameters is based on simulations of initiation cells with known events so that it can be assumed that the simulation results match the conditions corresponding to events observed in the region. The model allows easy and fast recalculation for parts of the area if needed (new findings due to events).

Von den unterschiedlichen Rutschungstypen sind die Translationsrutschungen und Hangmuren, die die Verwitterungs- und Lockersedimentüberlagerung betreffen, die häufigsten und problematischsten in Kärnten. Meist sind nur die obersten Meter der Locker-sedimente eines Hanges betroffen und als Auslöser für derartige Rutschungen ist meist ein Starkregenereignis nach einer Vorsättigung des Bodens mit Wasser verantwortlich. Diese Rutschungstypen können große Geschwindigkeiten und große Reichweiten erreichen.

Im Rahmen eines Forschungsprojektes des Landes Kärnten wurde ein Add-In für ArcGIS entwickelt, welches für diesen häufig auftretenden Typ von Massenbewegungen den Runout auf der Basis vorhandener Daten im regionalen Maßstab berechnen soll. Die Runoutmodellierung geht davon aus, dass der Boden mit Wasser vorgesättigt ist und ein zusätzlicher Niederschlag Rutschungen in den Startbereichen hoher Suszeptibilität auslöst.

Die Berechnung der Runout-Reichweiten erfolgt mittels eines eigens programmierten ArcGIS Add-Ins.

Zur Modellierung der Wirkungsräume werden folgende Datensätze verwendet: Suszeptibilitätsflächen (Startzellen), digitales Höhenmodell, Geologie, Oberflächenrauigkeit (generiert aus der Landnutzung) und Curvature (Parameter für die Wölbung, beeinflusst u.a. die Entwässerung).

Die Rutschungsmodellierung mit dem ArcGIS Add-in (Berechnung des Wirkungsraumes) berücksichtigt die Variabilitäten bei „Auslöser“ und Mobilität in Abhängigkeit von der Wassersättigung bei seichten Rutschungen. Die Kalibration der Parameter erfolgt auf Basis von Simulation an Startzellen mit bekannten Ereignissen, so dass davon ausgegangen werden kann, dass die Simulationsergebnisse den Rahmenbedingungen bei Ereignissen entsprechen, die in der Region beobachtet wurden. Das Modell erlaubt im Bedarfsfall (neue Erkenntnisse auf Grund von Ereignissen) Nachrechnungen für Teilbereiche.

1. Introduction

Of the various types of landslides relating to the weathering of the bedrock and unconsolidated slope deposits, shallow translational slides, earth-flows and mud-flows (mixing process between landslide and flow process, Figure 1) are the most common and most problematic in Carinthia. These types

of landslides can reach high speeds and travel long distances. Usually only the uppermost meters of loose sediments of the slope are affected and heavy rain events after a pre-saturation of the soil are typically triggers for such landslides.

As part of a research project in Carinthia (Poltnig and Berg,



Figure 1: Example of a translational shallow landslide (left) and an earth-flow (right); source: http://www.provinz.bz.it/wasserschutzbauten/download/ED30_Ereignisansprachehilfen.pdf

2013) an Add-In for ArcGIS 10x was developed. This Add-In calculates the runout for these common types of mass movements on the basis of available data on a regional scale. The

runout modelling assumes that the soil is pre-saturated and additional precipitation in susceptible areas triggers the landslides.

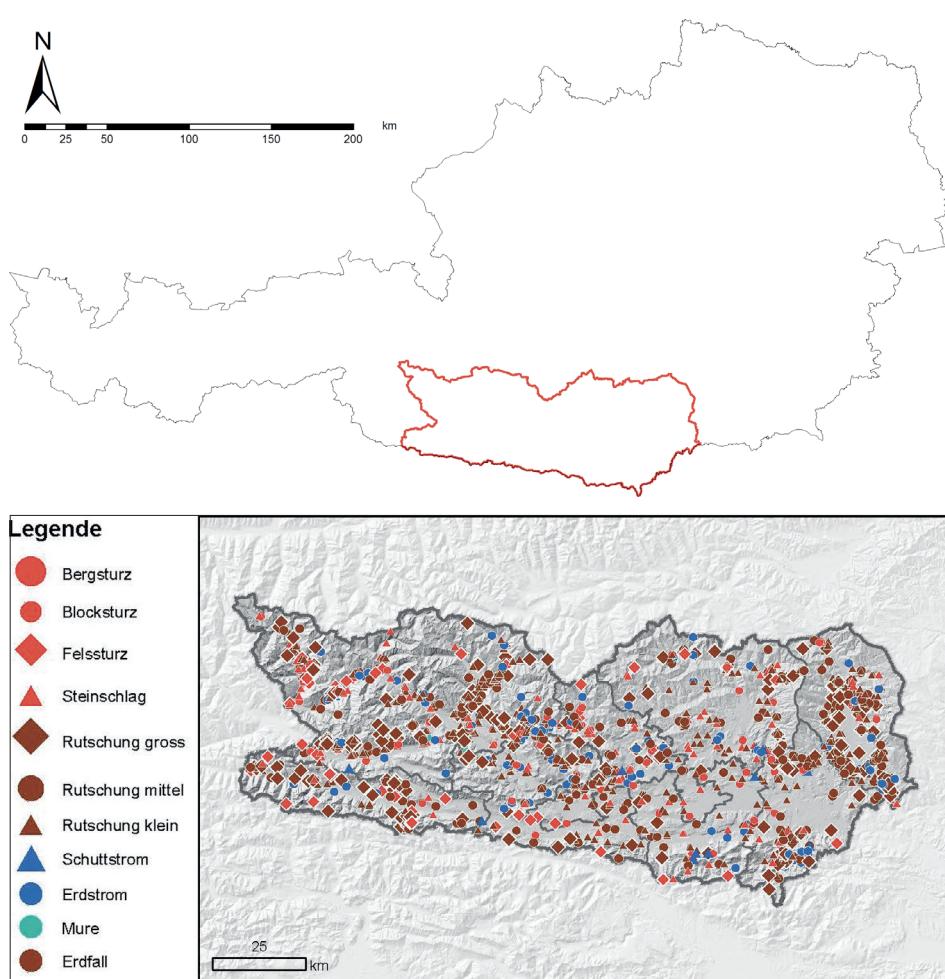


Figure 2: Georeferenced representation of events (brown – landslides, red – rockfalls, blue – earth-flows)

2. Problem

Natural hazards such as floods, avalanches, rockfalls and landslides regularly cause great damage in alpine regions. In order to adapt the space utilization to these potential hazards, the knowledge about the vulnerability of alpine slopes to landslides and rockfalls is a necessity. An areal representation of hazardous areas enables the adaptation of future landuse to reduce the risk of loss. Furthermore, a priority ranking and further measures for the protection of sensitive infrastructure in such areas are possible.

According to Carinthian Regional Planning Act (LGBL 76/1969 as amended 86/1996) the public is to be protected of these natural hazards by appropriate site planning. According to the provisions of the Carinthian Community Planning Act (Law Gazette 23/95 as amended 88/2005), designation as residential or

commercial land is only possible if no exposure to natural hazards (floods, debris flows, rock falls) is present. The Republic of Austria as a member of the Alpine Convention is committed to mapping hazardous areas according to the Protocol of Soil Protection (Federal Law Gazette III 235/2002). Thus, from factual and legal reasons, the creation of hazard index maps and hazard maps is necessary.

Austrian hazard zone maps for floods and avalanches are state of the art. While the repeatability and magnitude of flood events can be estimated from a time-series of historical measurements, for rockfalls and landslides measurement time-series (long return periods, different intensities) are hardly available, so that a different method must be used for the classification of the potential risks.

Because of the potential for damage to settlements, a spatial representation of the relevant hazard areas is required to set priorities for protective measures for existing infrastructure and to consider the future land uses. Areas that are located in the potential path of landslides are not suitable as residential or commercial land according to Carinthian Community Planning Law.

Unlike floods, gravitational mass movements are not restricted to linear structures, but affect the alpine slopes in total. Slope failure initiation zones are often away from the relevant planning areas and the associated impact space (translational and depositional environments) nevertheless affects the settlement area.

Progressive occupation of land means that there is increase likelihood that sensitive infrastructures lie within alpine hazard-related fields. This calls for national, area-wide hazard maps in order to adapt to the future use of space on this risk potential.

For this reason, in the past decade, the Austrian Geological Survey, on the basis of existing information, has developed and made digitally available the regional maps in Carinthia for danger concerning hazard areas like rockfalls and landslides (event register Figure 2; process index maps, Figure 3; (GBA, 2005).

As part of the INTERREG projects „AdaptAlp“ (Lochner, 2011) and „MassMove“ (Bäk et al., 2011) – the minimum requirements for the risk assessment for landslides were formulated: Geological maps, high resolution elevation models, land use data and event documentation form the basis for a classification of alpine slope areas with respect to landslide hazards (inventory maps and hazard maps).

Such a comprehensive assessment can only be accomplished economically and at reasonable costs using existing data. Due to lack of detailed data, and because of the scale of the inventory maps, uncertainties in the analysis are presented. In many areas there are no records or evidence of historical events, so expert knowledge must be used for classification. Geological maps at a scale of 1:50,000 to 1:200,000 are created based on stratigraphically – tectonic criteria and not by engineering geology criteria. For a heuristic method, the existing data base is sufficient and the designation of sensitive hazard areas without the evaluation of the intensity and probability of occurrence is possible. This is the primary goal.

The indexing of the parameter maps (slope, geology, landuse) for creating the susceptibility map was done in an area of about 30 km², in which more than 1500 landslide scarps were mapped and statistically analyzed (Poltnig et al., 2011). This indexing was then applied to all of Carinthia.

The ArcGIS runout-AddIn was then created and calibrated (best fitting) in another area with a high density of known

landslide events in order to be able to compare the modelled results with the known damage patterns: Extreme precipitation events in 1965, 1966, 1975 and 1993 in Central and Upper Carinthia caused numerous earth and debris flows (Figure 4: spontaneous, shallow landslides in Afritz/Feld am See, May 1975). These events of intense periods of rain led to the water saturation of the soil (Figure 5: annual hydrograph 1993 compared with the average 1951/1980, Ossiach station). Subsequent snowfall at night and heavy rain during the day triggered the spontaneous landslides (Figure 6: Precipitation hydrograph September/October 1993 measuring

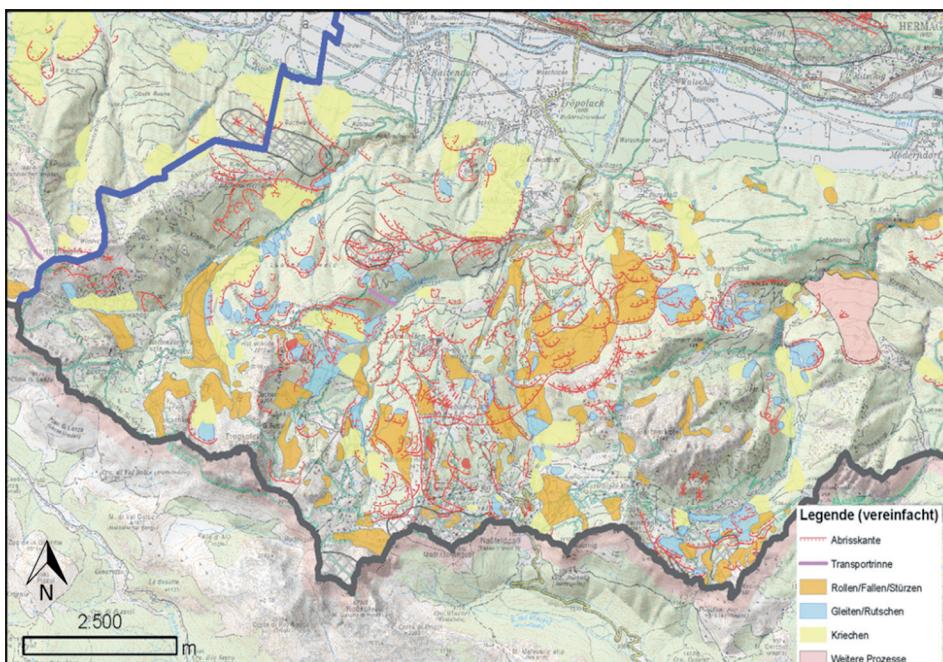


Figure 3: Section of the process index map in KAGIS, BMN-M31 (based on Project KC-29, Geo risk potential of Carinthia, mass movement structures, GBA, 2005.)

station Ossiach). These shallow debris slides and earth-flows caused considerable damage in Liesertal, Gegendtal and in the area of lake Ossiach (Moser, 1980).

The verification of the runout results for two different scenarios of different parameter settings (which are interpreted as different initial wet conditions) were then carried out on recorded landslides with known geometry of runout what has only been documented in young landslides.

The goal of the GIS-based analysis of existing data is the creation of susceptibility maps, hazard maps and regional risk potential maps for the most common and rapidly running types of shallow landslides and earth-flows in Carinthia.

3. Data base

The following data are available all over the state of Carinthia (Data source: Government of Carinthia – (KAGIS, 2015) <http://www.kagis.ktn.gv.at>):

- Airborne LiDAR data – elevation model with 1 m grid cell size (DEM);
- Digital geological map – shapefiles;
- Digital landuse map – shapefiles;
- Digital landuse map – shapefiles;
- Event register – shapefiles;
- Cultural features (i.e roads, houses) -. shapefiles

From these data, landslide onset-susceptibility-maps and runout-maps are derived and the intersection of these areas with features of human activities and buildings is used to generate risk potential maps.

4. Creating the landslide onset-susceptibility map

The onset susceptibility map for shallow landslides is created according to the Index Method (Ruff, 2005, Ruff et al.,



Figure 4: Landslides in Afritz/Feld am See, April 1975

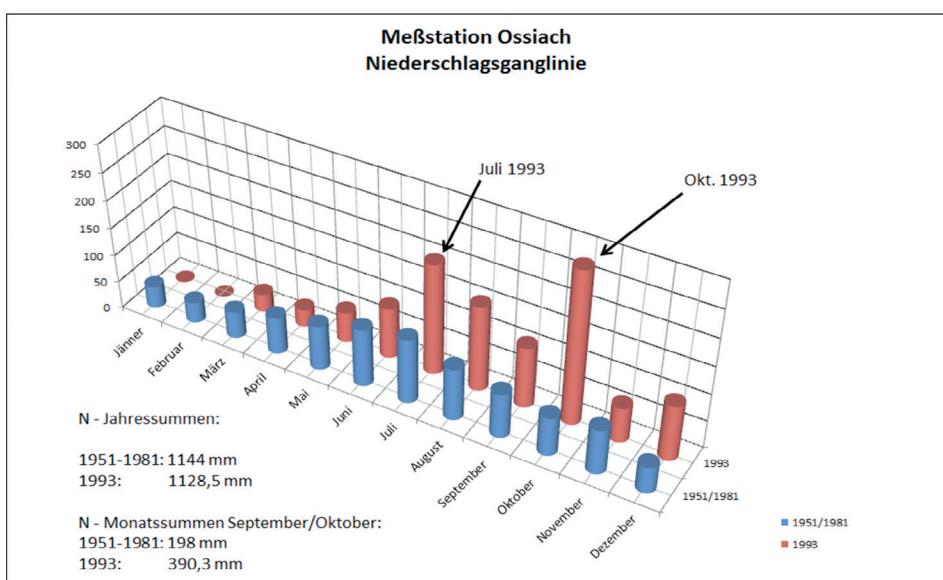


Figure 5: Annual hydrograph for 1993 compared with the average for 1951 to 1980 (station Ossiach)

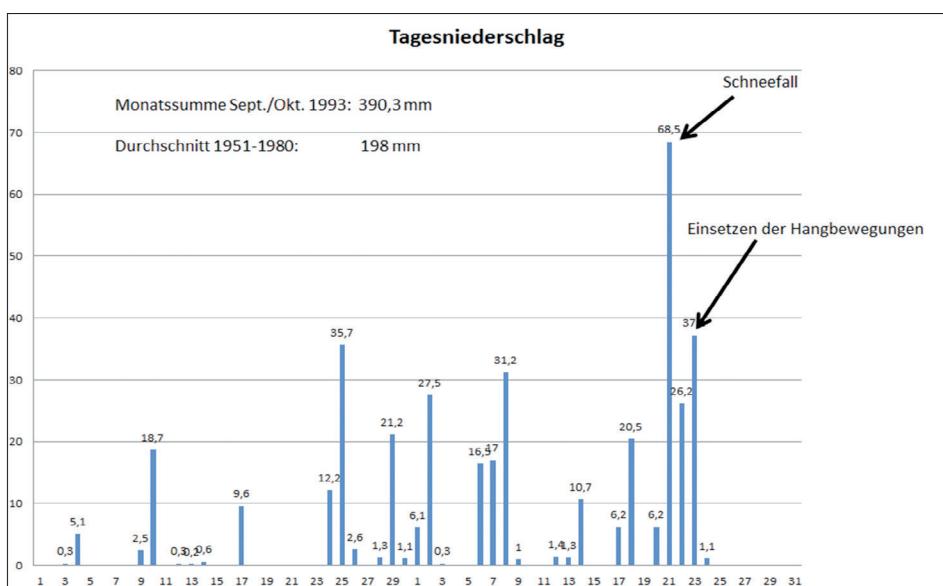


Figure 6: Precipitation hydrograph September/October 1993, station Ossiach

2005, Bäk et al., 2011, Poltnig et al., 2011).

From the elevation model, lithological and landuse maps, indicator (susceptibility) maps are derived. These maps are used individually, and/or combined to calculate the total susceptibility.

The calculation of the onset susceptibility is done by adding the susceptibilities of the indicator maps, respectively the indicator map groups (Figure 7). The resulting susceptibility areas are graded according to the Jenks algorithm in three classes of low, medium and high susceptibility.

5. Calculation of the slope failure initiation (onset) zones for the runout modelling

Areas of high susceptibility to hazards tend to be large (Figure 8), but experience in Carinthia shows that landslides usually occur below terrain edges where a restriction of the aquifer can lead to excess pore water pressures. This triggers the landslide.

Therefore, those zones, within the areas of high susceptibility, which have a convex morphology, were selected for the investigation of possible slope failure initiation (onset) zones for landslides. This selection is made by clipping the positive curvatures (derived from the DEM) with areas of high susceptibility (Figure 9).

In addition, the onset zones were restricted to areas with hill slope wetness index (WI) between 5-10.

Concave, low gradient areas will gather water (low WI values), whereas steep, convex areas will shed water (high WI values). The Hillslope Wetness Index, also called Topographic Wetness Index (TWI) uses Flow

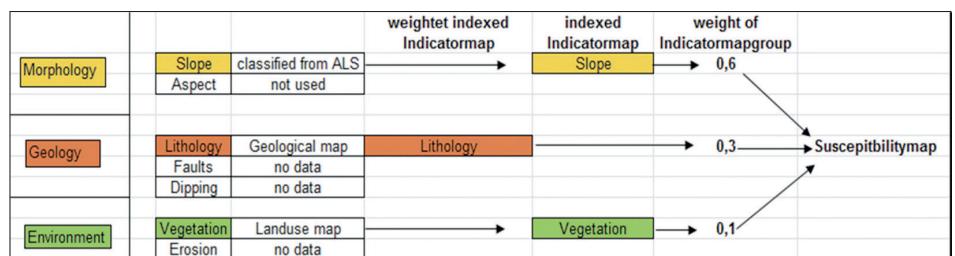


Figure 7: Calculation of the total susceptibility

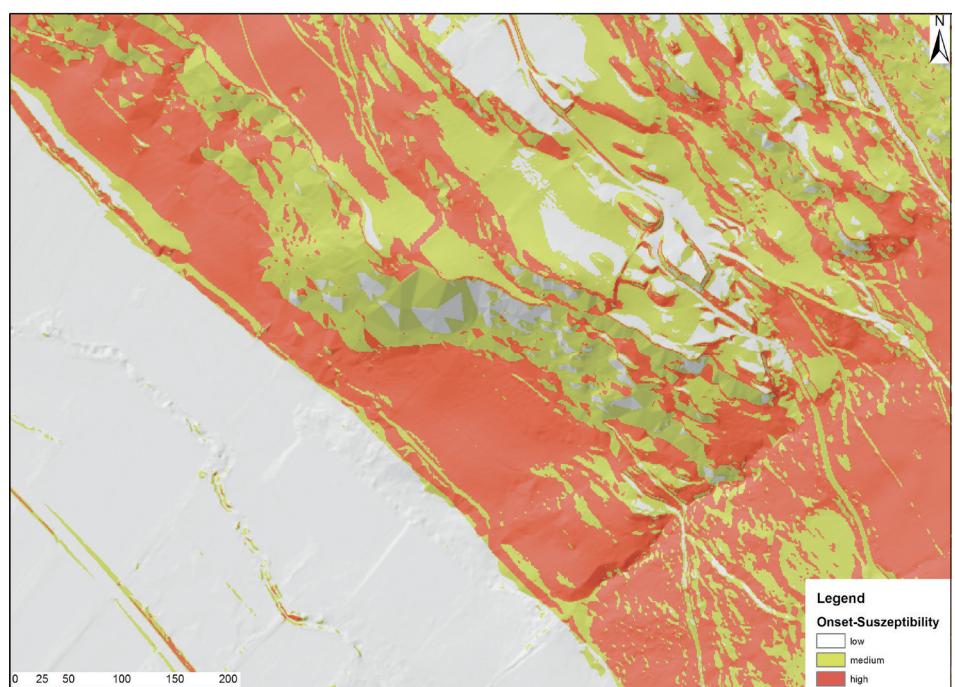


Figure 8: Onset-susceptibility-map (detail of the area Feld am See)

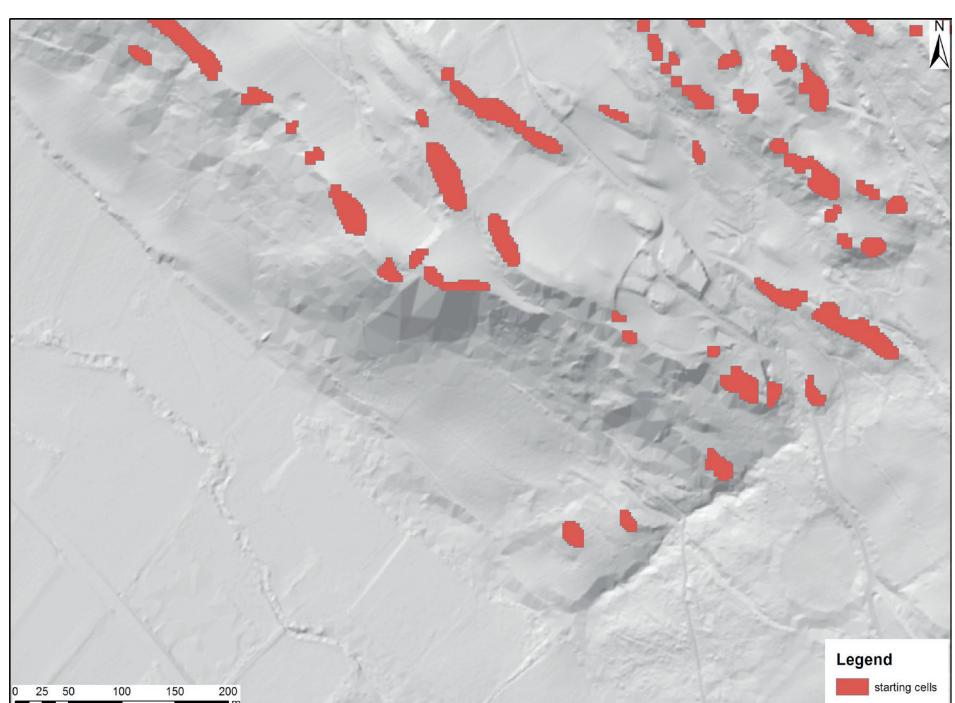


Figure 9: Determination of the slope failure initiation zones for the runout modelling by clipping the positive curvatures with the areas of high susceptibility and WI-classes 3 and 4

Direction and Flow Accumulation rasters as inputs. Create the first from a DEM, the second from the first. WI values will vary by landscape and DEM, but they typically range from less than 1 (dry cells) to greater than 20 (wet cells) (COOLEY, S.W., 2013).

$$WI = \ln("FLOWACC" * a) / \tan("SLOPE")$$

Where:

WI = wetness index (unitless);

a = area of each pixel (m^2)

FLOWACC = local upslope contributing area (m^2); and

SLOPE = local slope angle (degrees).

The model divides the WI-values into five discrete classes (natural breaks) and classes 3 and 4 are used to indicate onset zones. Classes 1 and 2 are near the watershed and relatively dry while class 5 represents the drainage pattern.

6. How the runout model works

The calculation of the runout distance is performed using a specially programmed ArcGIS Add-In. To model the affected areas following records are used:

Slope failure initiation zones; digital elevation model (DEM); geology; surface roughness (generated from the landuse map); and curvature (this affects the drainage of the mass movement).

Each polygon from slope failure initiation zone is buffered according to the chosen starting area size and then divided into hexagons. From each hexagon center a potential flow path is calculated. The flow path extends to the bottom of the valley, to a sink or the edge of the DEM. Along these flow paths, landslide velocities are calculated as a function of morphology (φ) and a coefficient of friction (μ).

As an input parameter, the slope (φ) and the μ -value of the starting cell at a specified starting velocity (usually $v_a = 0$) are given. Each subsequent calculation step uses the newly calculated velocity (v_b) as a starting velocity (v_a) according to the following equation:

$$v_b = \sqrt{v_a^2 + 2 * L * g * (\sin \varphi - \mu * \cos \varphi)} (ms^{-1})$$

Where:

L = length of calculated segment (m);

g = gravitational acceleration (ms^{-2});

φ = local slope angle (degrees); and

μ = assumed friction coefficient for weathered bedrock and unconsolidated slope deposits of lithological units.

There are no nationwide data on the values of the internal friction of weathered bedrock and unconsolidated slope deposits for the entire province of Carinthia. Therefore assumed coefficients of friction are assigned to the lithological units [$\mu = \tan(\varphi)$]. For example, limestone and rockslide deposits, of which one can assume that they form rendsina soils, or soils with angular to interlocking components in the talus deposits, are attributed the highest μ values with 0.7 to 0.58, whereas the lithological units „lake deposits“ and „sandstone, siltstone, claystone, gypsum“ get a lower μ -value from 0.14. Using these

assumed μ values plausible ranges for shallow landslides are achieved. With a reduction of the assumed start- μ values at 70%, the calculation stops later and corresponds largely with observed ranges of earth flows.

The formula has been derived from the equation of motion (equilibrium of forces) on an inclined plane. It has similarities with a formula from Heckmann & Becht (2004) concerning the process modelling of wet snow avalanches by PCM avalanche model (without the mass to drag ratio M/D). The difference with or without M/D ratio being slightly.

As factors causing the deceleration of the landslide are the different types of land use and the terrain morphology (curvature). This „slowing down“ is performed by the gradual increase of the start- μ -value. At each calculation step, a μ -value is added to the start- μ -value until the calculation leads to zero velocity.

The addition of the μ -value to the start- μ -value takes into account on the one hand the different effects of obstacles (roughness) of land use types (e.g. forest or meadow) and secondly the drainage during the flow/slippage process (increase of internal friction).

For each vertex of each flow path, the model calculation is

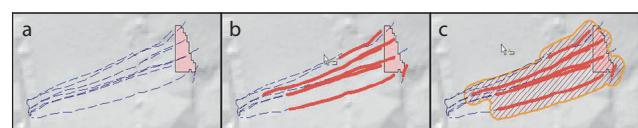


Figure 10: Potential flow paths (a), model paths (b), landslide for an initiation cell with high susceptibility (c)

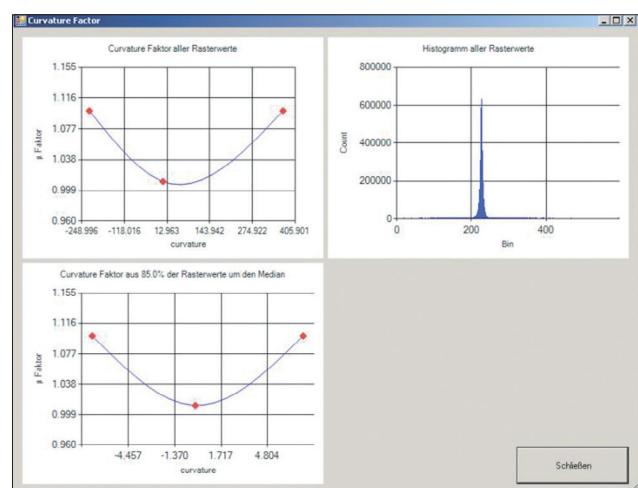


Figure 11: Analysis of curvature values (drainage factor on left axis between 1.01 and 1.10)

Parameter	Variant 1	Variant 2	Variant 3
Correction factor of start μ values	1.0	1.0	0.7
Curvature correction factor	1.000	1.005	0.990

Table 1: Different parameter settings

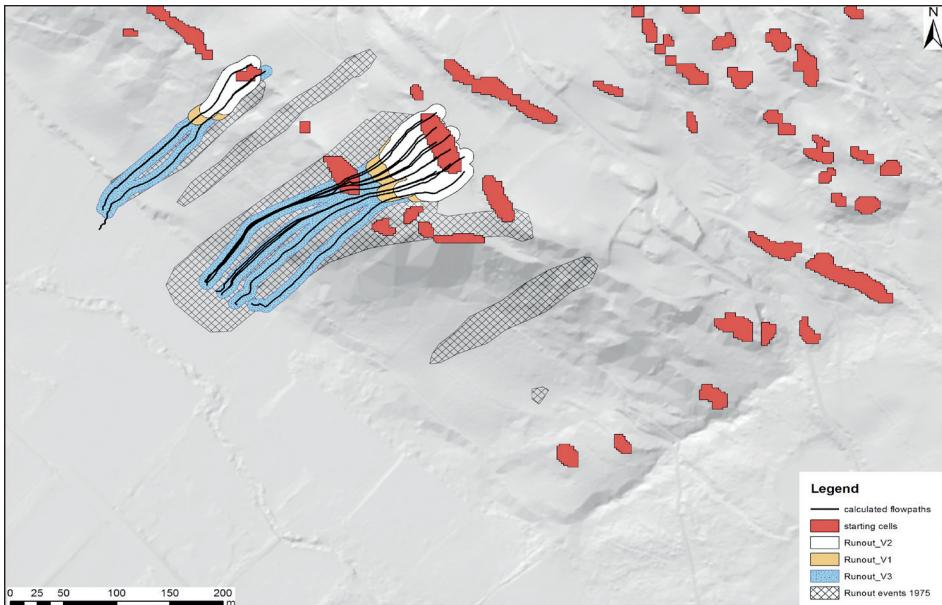


Figure 12: Example of modelled runout events focusing on actual slope failure from 1975. Results of runout modelling with three different parameter settings (Var. 1 = bright yellow; var. 2 = orange, var. 3 = bright blue)

performed and the model path is determined. Subsequently the model paths are agglomerated and combined to landslides (Figure 10).

The initial files must be prepared by means of the model „Landslides overall model Onset susceptibility“ and/or, prepared by experts in tabular form and partially loaded in the project.

6.1 Parameter adjustment

The use of the model allows for the analysis of the sensitivity of the model results on the various parameters. Calibration of these parameters is achieved by comparing model results with known well-documented shallow landslides or earth-flows.

6.1.1 Initial μ value of the starting cell:

The μ -values of the starting cells (polygons from failure initiation zones) are not known, since corresponding physical soil characteristics on a regional scale are not available and soil data are missing in many forested areas. Therefore, depending on the lithology of the subsoil, friction angles are assigned to lithological units. These are in turn converted into friction coefficients μ (editable ascii table Litho_Rwink.rmp). The estimated μ -values of all lithological units can be scaled with help of the μ -start value correction factor, and the impact of this correction can be examined in the model results.

It is assumed that the angle of friction is significantly reduced in the material of the initiation cell at the onset of the landslide due to the high water content. The μ -correction of the starting value can therefore scaled by a factor of e.g. 0.7.

6.1.2 Curvature grid

The curvature controls the amount of drainage of the sliding mass in the model. In principle, a part of the sliding mass is

dewatering at each calculation step and thereby the internal friction increases. The curvature grid is used to correct the flow velocity in convex or concave regions.

Since the curvature values vary over a wide range of values for strongly accented terrain, it is possible to limit the range of values used as a percentage around the median. The minimum and maximum values of the grid as well as the selected percent range ($\pm 15\%$ of the median in the present case) are displayed. The drainage factor can be spanned between the minimum and maximum value in a range of, for example 1.01-1.10 (Figure 11). Lands with curvature values outside

of this range have the drainage factor set to the maximum (in this case 1.1).

6.1.3 Curvature raster correction factor:

The curvature raster correction factor allows for increasing or decreasing of the dewatering along the flow path as a function of curvature. This can be useful when modelling a large sliding mass that may not be very responsive to terrain roughness due to inertia. This means that it is slowed down less for example, by shrubbery or trees as a small sliding mass. A reduction of the correction factor to the value of 0.99 (instead of 1) leads then to larger distances travelled by the landslide.

6.2 Model parameter settings

The sensitivity of the modelled runout to variations in the aforementioned parameter settings is shown in Figure 12.

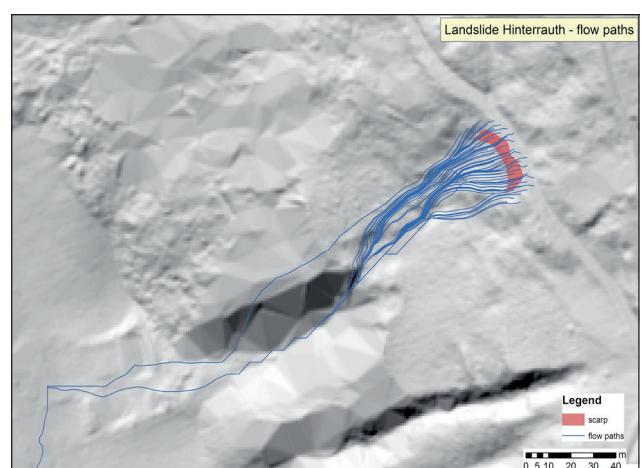


Figure 13: Flow paths along which velocities are calculated for the runout mass

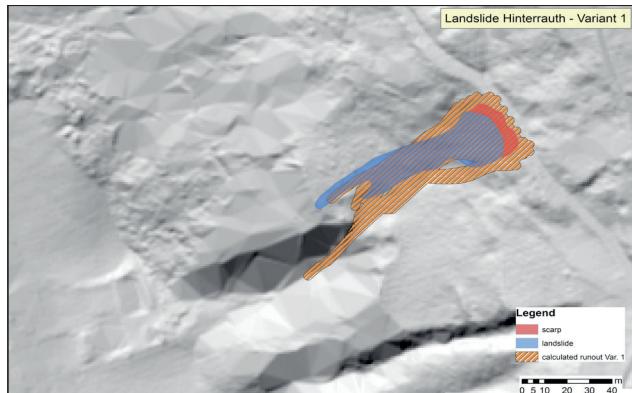


Figure 14: Modelled runout using variant 1. Scarp = red, landslide = blue, calculated runout = orange

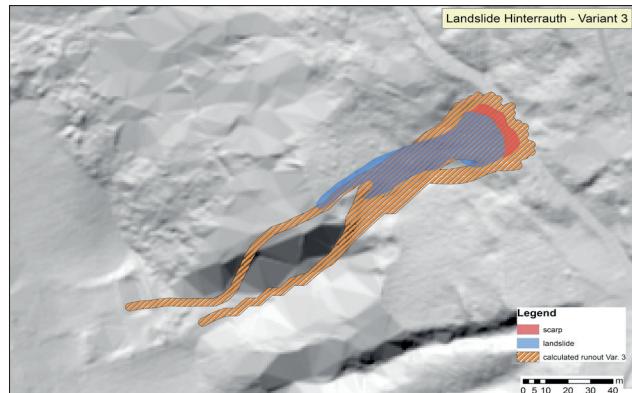


Figure 15: Modelled runout using variant 3. Scarp = red, landslide = blue, calculated runout = orange

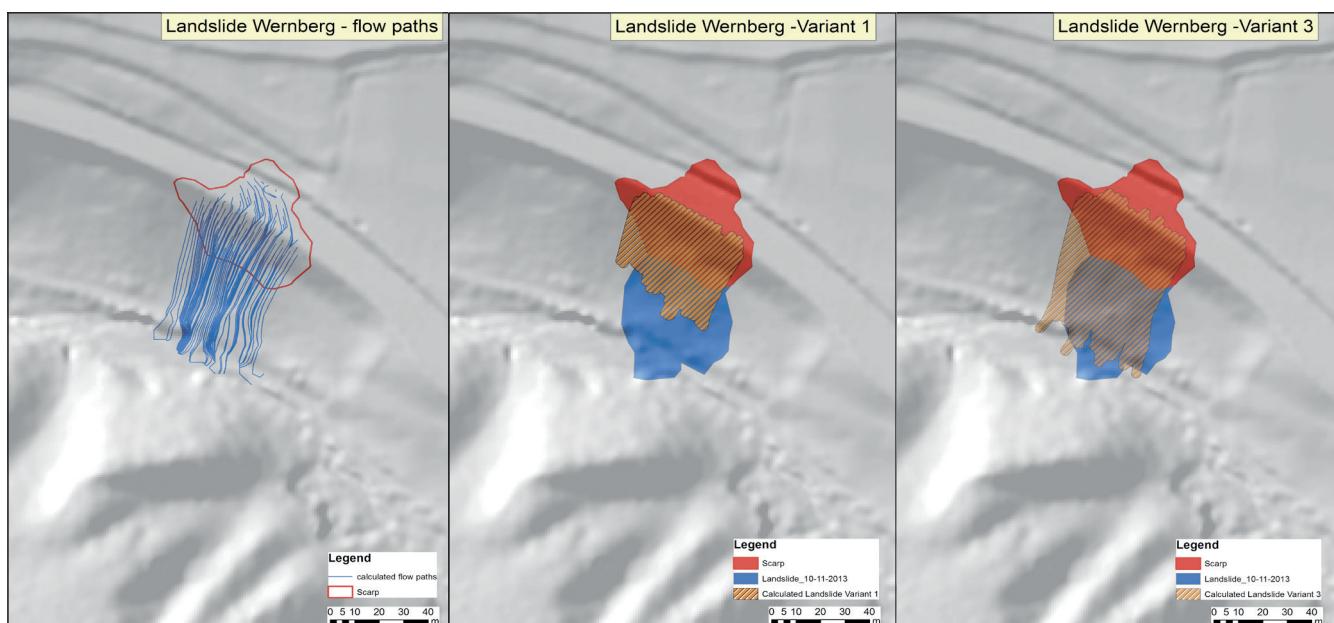


Figure 16: Earth-flow Wernberg; flow paths (a), variant 1 (b), variant 3 (c)

7. Tests of the regional-scale runout models using two landslides – Hinterrauth and Wernberg

The parameter settings used in the regional model parameter settings (Var. 1-3) were tested on two geometrically well-known landslides in Hinterrauth and Wernberg.

Variant 1 was calculated in both test areas. This variant corresponds to a sliding mass, whose water content causes shallow landslides but should not lead to the formation of earth-flows.

Variant 2 is similar but has a little more drainage than variant 1 (see Figure 12).

Variant 3 corresponds to a highly water supersaturated sliding mass, leading to the formation of earth-flows and can reach long distances.

7.1. Results and experience with the test settings

7.1.1 Landslide Hinterrauth

From an existing polygon of the scarp, the flow paths and ranges of the landslide according to variant 1 and variant 3

(Figure 13, Figure 14 and Figure 15) were calculated.

Due to the program-caused buffering of the start polygon (scarp), which is then divided into hexagons, some flow paths are created just outside the scarp, so that the sliding body thus occupies a larger runout area.

7.1.2 Landslide Wernberg

The landslide Wernberg had a very high water content and therefore developed into an earth-flow. Accordingly, the result of the settings of the variant 3 brought the best fit (Figure 16c).

8. Conclusions

Spontaneous, shallow landslides may cause substantial damage due to their frequent occurrence and potentially large transport distances and transport velocities. These shallow landslides and earth-flows are triggered by heavy rainfall periods following long-term periods of rain and/or snow. The variability of the „trigger“ makes it difficult to forecast such events.

The susceptibility of alpine slopes to spontaneous, shallow landslides can be based on lithology, slope (slope classes, slope direction) and land-use classified with the index method. The method results in large areas of high susceptibility which is contrary to professional expertise. Documented events show an accumulation of spontaneous landslides on convex terrain structures. Therefore, the high susceptible areas are superimposed with the positive curvatures in order to determine the slope failure initiation (onset) zones.

The runout modelling takes into account the variability of „trigger“ and mobility as a function of water saturation. The calibration of the input parameters is based on the simulation of known events so that it can be assumed that the simulation results match the conditions corresponding to events observed in the region. The model allows easy and fast recalculations for parts of the area if needed (new findings due to events).

Once calibrated, runout modelling may be used to areas potentially susceptible to future landslides and earth-flows. Demarcation of these hazardous areas is important for the identification of existing structures that are at risk of damage from future slides and may help with the allocation of future residential or commercial building permits.

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