Modelling of individual debris flows using Flow-R: A case study in four Swiss torrents

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ABSTRACT

Recently, an empirical debris flow model called Flow-R has been added to the broad range of existing debris flow modelling software. While Flow-R's applicability on regional scale has been confirmed in several studies, it's potential in local debris flow modelling has not yet been evaluated. In this study, Flow-R's potential in debris flow modelling on local scale is tested via an application in four debris flow torrents in Switzerland. Obtained results are validated by comparison to documented debris flow events as well as model results from the commonly used hydraulic debris flow model RAMMS. Results show that due to the non-hydraulic model conception, the potential of Flow-R in individual debris flow modelling is limited. Plausible debris flow patterns are only achieved on torrents showing a low to moderate channelization, i.e. incision on the fan. Computed process velocities are unreliable due to the inability of the model to account for debris flow mass. Moreover, modelled debris flow magnitudes are biased by the compulsory non-volumetric definition of magnitudes.

KEYWORDS

debris flow modelling; Flow-R; susceptibility; debris flow hazard; case study

INTRODUCTION

In order to assess debris flow hazard, a variety of computer based debris flow models have been developed in the past decades. Recently, the empirical debris flow model Flow-R, designed for ***"susceptibility mapping of debris flows at regional scale"*** (Horton et al. 2013:1) was published. It allows the identification of potential source areas for debris flows as well as their propagation extent, essentially based on a DEM. Flow-R has been proved suitable for the production of regional debris flow ***"[...] susceptibility maps with satisfying accuracy"*** (Horton et al. 2013:870). Although Flow-R is not specifically designed for debris flow modelling on local scale, it is advisable to ***"compare the assessed susceptible zone with specific events in order to evaluate the accuracy of the results"*** (Horton et al. 2013: 870). However, a systematic comparison of individual debris flow events and Flow-R modelling results gained on a highly resolved DEM (2m) has never been con-ducted. Therefore, the assessment of the accuracy and the allegedly limited applicability of Flow-R on local scale forms the main objective of this study. It is hypothesized that when applied on a highly resolved digital elevation model, Flow-R represents an alternative to sophisticated hydraulic models, such as RAMMS (Christen et al. 2012), in the modelling of individual debris flow events.

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This hypothesis is mainly tested with respect to modelled affected areas but also considers computed process velocities and model output for different event magnitudes.

METHODS

Flow-R's potential in local debris flow modelling is evaluated by means of a reconstruction of four well-documented debris flow events in the Swiss Alps. Due to the diverse event characteristics the four torrents Richleren (UR, 1987 event: ~4'000 m³), Minstigerbach (VS, 1987 event: ~30'000 m³), Glyssibach (BE, 2005 event: ~70'000 m³) and Varuna (GR, 1987 event: ~185'000 m³) are selected for this study. Debris-flow model runs are conducted on the 2m-resolved digital elevation model SwissALTI^{3D}. The calibration of the debris-flow model is essentially based on:

- all available information from event documentations (VAW 1992, LLE 2006) comprising debris flow velocities, maximum discharge rates, event volumes and affected areas
- empirical benchmark calibration values for the model's friction parameters from literature (Horton et al. 2013, Gamma 2000, Zimmermann et al. 1997, Rickenmann & Zimmermann 1993, Christen et al. 2012).

In an iterative modelling process, the model's parameters are adjusted until the obtained output fits the observed debris flow extent as well as possible (Fig. 1). For reasons of comparison, the documented debris flows are reconstructed with the hydraulic debris flow model RAMMS following the same iterative procedure. Among all input variables, the adjustment of applied friction parameters plays a predominant role in the calibration process for both debris flow models applied. For a better understanding, the following section shortly summarizes the basic functional principles of Flow-R and RAMMS based on Horton et al. (2013) and Christen et al. (2012).

Flow-R calculates debris flows starting from either predefined source cells or from source cells empirically derived from the DEM. The direction and spreading of the debris flow is computed with a flow direction algorithm including a spreading exponent, whereas the assessment of the runout distance is based on one of two simple physical approaches. The model after Perla et al. (1980) calculates the velocity of the flow including friction parameters (μ) and mass-to-drag ratio (M/D). Alternatively the SFLM, determining the maximum runout distance based on a minimum travel angle (TA) and maximum velocity (v_{lim}) can be selected. Flow-R does not consider debris flow volume but works with a unitary mass of 1. Flow-R model outputs include raster-data of spatial susceptibility as well as relative kinetic energy.

The RAMMS debris flow model employs a modified Voellmy-fluid friction model, which includes a dry-Coulomb friction parameter (μ) and a turbulent friction parameter (ξ). In contrast to Flow-R, RAMMS requires an input debris flow volume. As applied in this study, debris flow volume and velocity can be included in a user-defined input hydrograph, which specifies maximum discharge rates and debris flow and velocity over time for given location in the torrent. The outputs generated with RAMMS comprise maximum flow height, velocity and impact pressure.

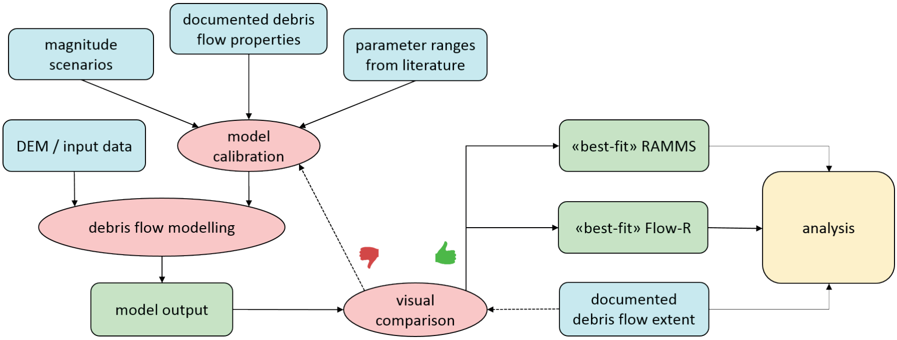
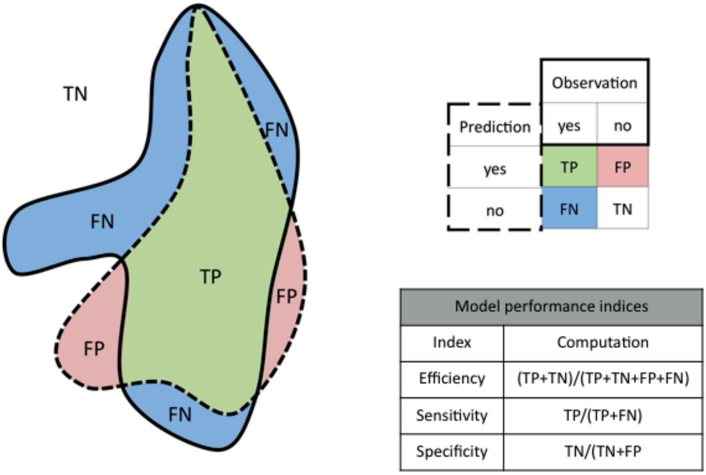


Figure 1: Schematic representation of the research design for the assessment of Flow-R's applicabil-ity in local debris-flow modelling.

In addition to the event reconstruction, the selected debris flow models are also used to simulate further debris flow magnitudes, which are based on predefined scenarios. In RAMMS, additional debris flow magnitudes are defined by means of increasing or decreasing event volumes. With respect to friction parameters, the best-fit values determined in the prior event reconstruction are adopted, as rheological properties are assumed constant. Due to the model conception, this approach is not applicable to Flow-R. Alternatively, debris-flow magnitudes are defined based on a method applied by Gamma (2000) who defines magnitude scenarios according to relative travel distances on the fan, assuming longer travel distances with increasing debris flow magnitude. In Flow-R different magnitudes are thus modelled by adjusting friction parameters or travel angle, until the model results roughly correspond to the expected runout distance.

For the appraisal of Flow-R's performance, model outputs of Flow-R and RAMMS are compared mutually as well as to the documented debris flow events. This analysis includes both qualitative and quantitative aspects. The qualitative assessment focuses on the plausibility of the obtained debris flow pattern from a geomorphologic point of view. In other words, model output is evaluated with respect to its representativity of natural process behaviour, especially in connection with outbreaks of the flow from the channel. The quantitative assessment of model performance is based on the confusion matrix methodology by Beguerìa (2006). Confusion matrices allow an evaluation of the predictive power of models based on an overlay of model results and according validation datasets (Begueria 2006:315ff).
The intersection of debris flow model output and documented debris flow extent results in four different classes of areas, composing the confusion matrix (Fig. 2). The evaluation of the debris flow models used in this study is based on the three following indices:

- Sensitivity: Proportion of area correctly modelled as affected.
- Specificity: Proportion of area correctly modelled as unaffected (Degree of underestimation or "cautiousness" of the model).
- Efficiency: Proportion of the sum of all areas correctly predicted by the model (affected and unaffected).



	Observation	
Prediction	yes	no
yes	TP	FP
no	FN	TN

Model performance indices	
Index	Computation
Efficiency	(TP+TN)/(TP+TN+FP+FN)
Sensitivity	TP/(TP+FN)
Specificity	TN/(TN+FP

Figure 2: Subarea classification and model performance indices according to the confusion matrix method by Beguerìa (2006).

RESULTS AND DISCUSSION

Best-fit calibration parameters

For comparability to other studies, the calibration parameters for Flow-R and RAMMS based on which the best-fit model output was achieved are listed below (Table 1).

Table 1: Employed best-fit calibration values for Flow-R and RAMMS debris flow event modelling.

Torrent	Calibration Flow-R					Calibration RAMMS	
	TA [°]	V_{lim} [m/s]	μ	M/D	spreading exp.	μ	ξ
Richleren	-	-	0.14	100	4	0.27	175
Minstigerbach	5.7	15	-	-	2.5	0.09	150
Glyssibach	6	11	-	-	3.5	0.1	200
Varuna	7	13	-	-	2	0.15	150

Debris-flow extents

The areas affected by debris flows as modelled with Flow-R show a respectable agreement with observed debris flow extents as well as with the results obtained with RAMMS (c.f. Richleren torrent, Fig. 3). Although not perfectly matching the extent of the calibration event, the modelled flow paths are certainly plausible. Model outputs from both RAMMS and Flow-R show a surprisingly high agreement despite the great difference in model conception. However, this agreement is restricted to sites, where a low degree of channelization i.e. incision of the torrent can be observed on the debris flow fan. In moderately to strongly channelized torrents, the non-hydraulic concep-tion of Flow-R composes an important disadvantage. Backwater effects occurring due to con-strictions in the channel or due to a confinement of the flow path cannot be simulated, resulting in a significantly reduced outbreak from the channel (c.f. Glyssibach, Fig. 4). Compared to RAMMS, Flow-R thus shows a higher sensitivity towards this "channelization" in the topography.

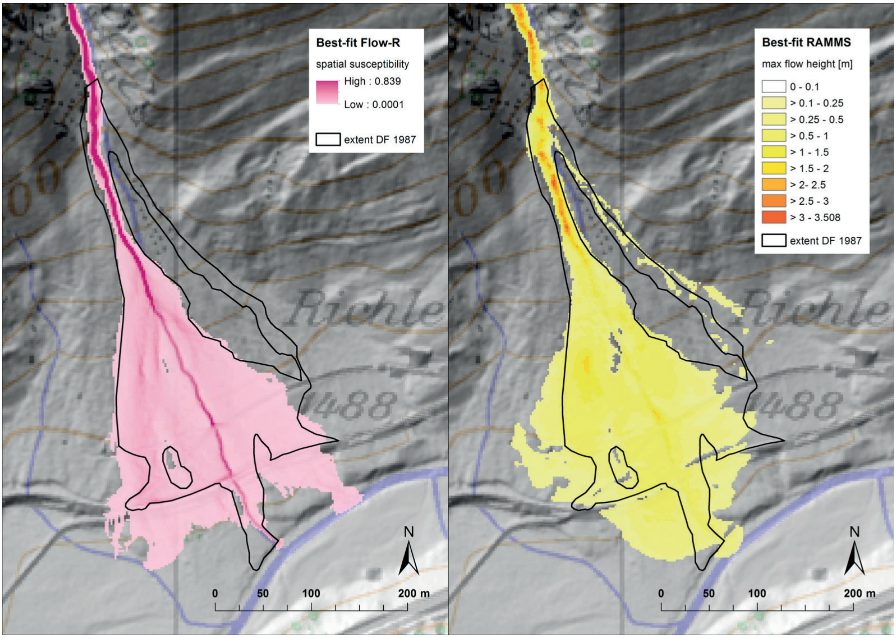


Figure 3: Best-fit modelling results (Flow-R & RAMMS) for the 1987 event in the Richleren.

The quantitative comparison of debris flow modelling results based on confusion matrices confirms the good agreement between model output and observed debris flow pattern.
As visible in Fig. 5, both models reach respectable efficiency values in all study areas. Quite contrarily to what might be expected, the sensitivity index (amount of correctly predicted affected areas) shows an inverse correlation with achieved efficiency: the model showing a lower efficiency uniformly achieves the higher sensitivity value. Additionally the variability in the sensitivity index is generally larger. Other than the efficiency, the sensitivity apparently depends on the degree of channelization of the tor-rent on the fan. As discussed earlier, this condition especially applies for Flow-R. The obtained sensitivity values confirm these findings as low sensitivity indices correspond with a higher degree of channelization.
Since the efficiency values obviously cannot be explained by the sensitivity indices due to the inverse proportions, an inclusion of the specificity index is required. The specificity, which can also be referred to as the degree of underestimation or the "cautiousness" of a model, is higher for RAMMS in larger catchments, while Flow-R shows higher values in smaller

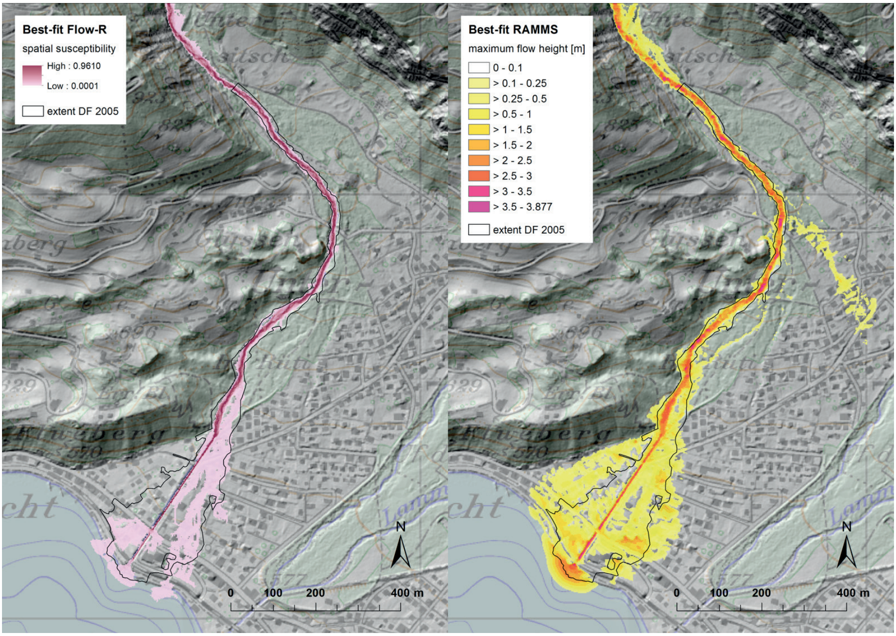


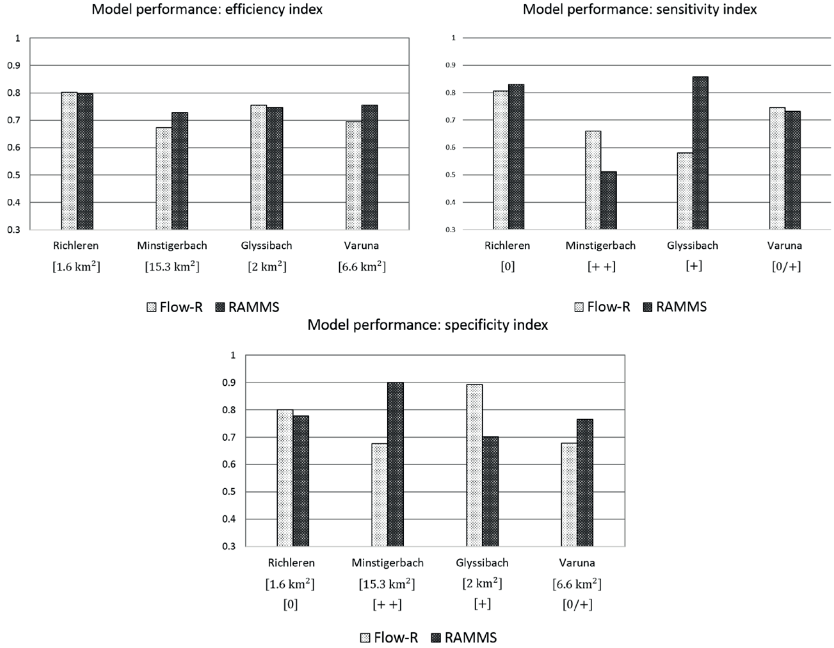
Figure 4: Best-fit debris flow modelling results (Flow-R & RAMMS) for the 2005 event in the Glyssibach torrent.

catchments. Furthermore, differences between RAMMS and Flow-R are larger in the Minstigerbach and the Glyssibach. The specificity index thus depends both on the catchment area as well as on the degree of channel-ization in fan topography.

In each of the four research areas, a lower specificity index goes hand in hand with a higher sensitivity. In other words, the less cautious a model, the more generously it classifies cells as affected by the process, which in turn leads to a higher probability of reconstructing areas actually affected in reality (true positives in the confusion matrix). However, due to this high generosity, the amount of false positives increases too. Thus, the overall efficiency (percentage of overall correctly classified cells) does not necessarily increase. Quite contrarily, the comparison between efficiency and specificity indices in all four catchments shows that higher efficiency values are achieved by the more cautious, i.e. the more underestimating model.

Debris-flow velocity

Since Flow-R does not consider debris flow mass, obtained debris-flow velocities may only be considered relatively. Based on the various model runs conducted in the course of this study it can be stated that the spatial pattern of modelled velocities is highly sensitive towards local changes in terrain slope. Even small changes in the slope gradient lead to a pronounced decline or increase of modelled velocities, which may exceed reasonable ranges. Additionally, obtained patterns of ve-locities show a regular pattern over the complete width of the flow on


Model performance: efficiency index

Model performance: sensitivity index

Model performance: specificity index

Figure 5: Efficiency, sensitivity and specificity indices for best-fit Flow-R & RAMMS model output.

uniform debris flow fans, while only in pronounced channels, a decrease of velocities towards the flow margins can be ob-served.

Debris-flow magnitudes

Concerning the modelling of different event magnitudes with Flow-R it needs to be stated that without a calibration event, a nonbiased modelling of different magnitudes is practically impossible due to the necessarily non-volumetric definition of event scenarios. A definition of magnitudes solely based on expected runout distances does not take into account channel topography (especially incision) on the debris flow fan, which majorly influences debris flow behaviour. The extent of the modelled debris flows therefore mostly reflects an expected runout pattern or –distance and does not correspond well with RAMMS model output.

CONCLUSIONS

Based on the obtained results it can be stated that due to the non-hydraulic model conception, the potential of Flow-R in individual debris flow modelling is limited. Plausible debris flow patterns are only achieved on torrents showing a low to moderate channelization, i.e. incision on the fan. Computed process velocities are unusable due to the inability of the model to account for debris flow mass. Moreover, the modelling output for different debris flow magnitudes is biased by the compulsory non-volumetric definition of magnitudes. It therefore needs to be emphasized that Flow-R is not suitable for hazard mapping in a narrow sense, but it provides first-hand information on debris-flow runout. Despite the restricted potential of Flow-R in local debris flow event modelling, an application may thus still provide valuable preliminary information on debris flow susceptibility. Based on insights achieved with Flow-R debris-flow modelling, the financial expenses connected with a hydraulic debris flow simulation may thus be substantially reduced.

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