REGIONAL-SCALE AVALANCHE MODELING WITH com4FlowPy – POTENTIAL AND LIMITATIONS FOR CONSIDERING AVALANCHE-FOREST INTERACTION ALONG THE AVALANCHE TRACK

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ABSTRACT: *Flow-Py* is an empirically motivated tool for the simulation of gravitational mass flows (GMFs) and has recently been integrated into the Open Avalanche Framework *AvaFrame* (`www.avaframe.org`), where it is now available and actively maintained under the name *com4FlowPy*. The model employs a simple angle-of-reach approach for modeling runout distances in combination with a raster-based routing routine for modeling lateral process spreading and can be used to identify process areas (paths and runout zones) and corresponding intensities of the respective GMFs. The simple model concept and open-source code have encouraged several modifications and extensions to *com4FlowPy*. Among others the model has been extended to utilize forest information as an additional input layer (e.g. forest spatial extent and a lumped forest structure index) and consider forest effects on GMF runout by modifying model behavior on forested raster cells. In recent years, the model has been used to model different types of GMFs (e.g. snow avalanches and rockfall) in several regional-scale case studies. Among other applications the simulation tool has been employed to model avalanche runout in model-chains for automated Avalanche Terrain Exposure Scale (ATES) mapping in North America and Europe. Experiences from these applications have shown that considering forest effects on avalanche runout in forested terrain tends to produce results which are in better alignment with observed runouts and local expert assessments compared to model applications neglecting these effects. However, reported model parameters (with and without consideration of avalanche-forest interaction) vary considerably across studies and different authors have stressed the need for careful adjustment of model parameters to local conditions. In this study we focus on the "forest friction" module implemented in *com4FlowPy*. We analyze parameter sensitivities for this module for a set of generic examples with controlled boundary conditions (topography, forest set-up) and also provide a case study example based on an actual avalanche path in the Austrian Alps.

Keywords: avalanche modeling, forest-effects, regional-scale, empirical, AvaFrame

1. INTRODUCTION

Flow-Py (D'Amboise et al., 2022) is an empirically motivated simulation tool for modeling the runout and intensities of gravitational mass flows (GMFs). In principle the model utilizes a simple angle-of-reach approach (Heim, 1932; Körner, 1980) to model GMF runout distances along a predefined GMF path in combination with algorithms that model lateral process spreading and perform path-routing on a digital raster elevation model.

Several models based on similar ideas have been previously developed and applied to different GMFs (e.g. Gamma, 1999; Dorren and Seijmonsbergen, 2003; Scheidl and Rickenmann, 2010, 2011; Jaboyedoff and Labiouse, 2011; Barbolini et al., 2011; Horton et al., 2013; Huber et al., 2016; Wichmann, 2017). Many of the model concepts implemented in *Flow-Py* are based on these studies.

The open-source model code and simple model concept and code design have encouraged several modifications and extensions to the model in recent years. Among others the model has been extended to utilize forest information as an additional input layer (e.g. forest spatial extent and a lumped forest structure index) to consider forest effects on GMF runout by modifying model behavior on forested raster cells (D'Amboise et al., 2021) and/or track the distance a modeled avalanche travels through forested terrain (Spannring, 2024). While these extensions have been applied in different regional-scale case studies (D'Amboise et al., 2021; von Avis et al., 2023; Sykes et al., 2024; Toft et al., 2024; Spannring et al., 2024), the respective model code has thus far only been available in dedicated development branches in the *Flow-Py* repository (`https://github.com/avaframe/FlowPy`) and code documentation of specific features has largely been limited to personal communication. Moreover, the men-

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tioned studies reporting application of the model with explicit consideration of forest effects along the track do not provide in-depth discussions of parameter choices or sensitivities for the utilized avalanche-forest interaction models.

In order to address the decentralized code and sparse documentation, we recently migrated the *Flow-Py* code to the open avalanche framework *AvaFrame* (`www.avaframe.org`, `https://github.com/avaframe/AvaFrame`), where it is now actively developed and maintained as *com4FlowPy*. The old *Flow-Py* repository will be archived and is not maintained any longer. Along with the migration of *com4FlowPy* to the new repository most of the previously developed forest extensions existing in different development branches in the old repository have been implemented in the current *AvaFrame* `master` branch along with additional features. More detailed information and documentation for the model and its extensions are now also provided in the *AvaFrame* documentation at `https://docs.avaframe.org`. With these recent developments, we provide a more centralized access point to model code and documentation for future applications.

In this study we focus on the "forest friction" extension implemented in *com4FlowPy* (D'Amboise et al., 2021). We provide an updated model description and conduct an analysis of parameter sensitivities by performing simulations with varying parameters on generic topographies and forest set-ups and also present first results for a case study example of an existing avalanche path in the eastern Austrian Alps.

2. DATA AND METHODS

As outlined, *com4FlowPy* in principal combines a simple empirical concept for modeling GMFs along a pre-defined path with algorithms for flow-routing on arbitrary 2.5-D topographies. For estimating process runouts and intensities the model employs an adapted version of the α-angle method proposed by Heim (1932) and Körner (1980), in which the energy line height z^{δ} can optionally be limited by providing an additional parameter z^{δ}_{lim} (cf. Horton et al., 2013; D'Amboise et al., 2022). z^{δ}_{lim} might more intuitively also be interpreted as a limit to maximum modeled velocities $v_{lim} = (2\,g\,z^{\delta}_{lim})^{\frac{1}{2}}$, which in turn might be estimated based on maximum observed GMF velocities. The defined α-angle can alternatively be interpreted in terms of a constant basal sliding block friction $\mu = \tan\alpha$, which is commonly used in similar models (e.g. van Dijke and van Westen, 1990; Dorren and Seijmonsbergen, 2003; Wichmann, 2017). Figure 1 schematically shows the influence of z^{δ}_{lim} in the setting of a simple α-angle or equivalent sliding block friction model. While α and z^{δ}_{lim} control modeled runout lengths and process intensities in terms of z^{δ} along the track, *com4FlowPy* uses an additional pair of parameters (exp, R_{stop}) to modify spreading behavior in the 2.5-D routing algorithm, adding up to a total of four main model parameters. For a more in-depth description of these parameters and *com4FlowPy* in general we refer to D'Amboise et al. (2022) as well as to the online documentation at `https://docs.avaframe.org` and the references cited therein.

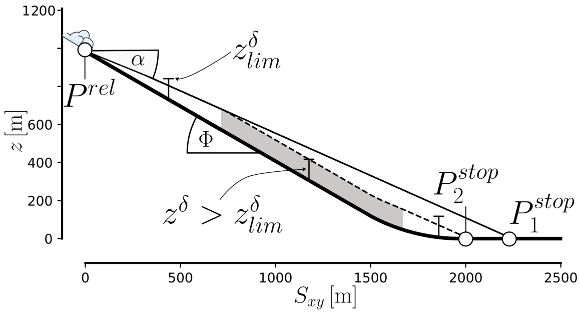

Figure 1: Main model principle of *com4FlowPy*. The angle of reach α along with the maximum energy line height limit z^{δ}_{lim} determine the runout distance of a GMF from a starting point P^{rel} along a given path (thick solid line). The thin solid straight line connecting P^{rel} and P_1^{stop} exemplifies a model run where no limit on z^{δ}_{lim} is imposed. The dashed line connecting P^{rel} and P_2^{stop} exemplifies a model run where z^{δ}_{lim} has an effect on the modeled runout length. The shaded grey area indicates where z^{δ}_{lim} effectively limits the modeled energy line heights z^{δ}, thus also affecting the modeled runout in the second case.

2.1 com4FlowPy "forest friction" module

The basic idea behind the "forest friction" module in *com4FlowPy* is to increase the α-angle or equivalent basal friction $\tan\alpha$ on forested raster cells in the model domain, thus accounting for increased energy dissipation in forests compared to open terrain. On a given forest cell an additional "forest friction" Δ^{α}_{for} [°] is added to the α-angle used on non-forested raster cells, effectively increasing the local basal friction coefficient $\alpha^{eff} = \alpha + \Delta^{\alpha}_{for}$. The amount of friction increase Δ^{α}_{for} [°] is thereby defined as a function of the following parameters:

- $\Delta^{\alpha}_{for,min}$ [°] . . . minimum added friction on forest cells
- $\Delta^{\alpha}_{for,max}$ [°] . . . maximum added friction on forest cells
- $v^{\lim}_{for}$ [m/s] . . . velocity limit for forest-effects, beyond which $\Delta^{\alpha}_{for} = \Delta^{\alpha}_{for,min}$
- FSI [−] . . . dimensionless Forest Structure Index, where 1 indicates optimal forest structure with respect to a stand's capacity to decelerate avalanches and 0 indicates no forest
- z^{δ} or v . . . energy line height or equivalent velocity of the modeled GMF at the given forested raster cell

While the first three parameters are defined as global scalars in the model (all parameters are configurable via an `.ini` file in *com4FlowPy*), the FSI is provided as an additional raster layer and the local z^{δ} or equivalent $v = (2\,g\,z^{\delta})^{\frac{1}{2}}$ is obtained at model runtime. Δ^{α}_{for} is then calculated according to

$$\Delta^{\alpha}_{for} = \begin{cases} FSI\,(1-(\frac{v}{v^{lim}_{for}})^2)\,(\Delta^{\alpha}_{for,max} \\ -\Delta^{\alpha}_{for,min}) + \Delta^{\alpha}_{for,min} & \text{if } v < v^{\lim}_{for}, \\ \Delta^{\alpha}_{for,min} & \text{if } v \geq v^{\lim}_{for} \end{cases} \quad (1)$$

for all raster cells with $FSI > 0$. A visual explanation is provided in Figure 2; in the given example a friction increase of $13.25°$ is found for a forest cell with $FSI = 1$ and a modeled velocity of $15\,\mathrm{m/s}$ for $v^{lim}_{for}, \Delta^{\alpha}_{for,min}, \Delta^{\alpha}_{for,max} = (30\,\mathrm{m/s},\ 2°,\ 17°)$. The green solid line and semi-transparent gray lines in Figure 2 show the linear scaling of Δ^{α}_{for} with FSI as well as the quadratic scaling with respect to v (because of $z^{\delta} = v^2\,(2g)^{-1}$, the scaling is linear with respect to z^{δ}).

A more elaborate explanation on the background and ideas behind the model is provided in D'Amboise et al. (2021); the version of the "forest friction" module implemented in *com4FlowPy* and used in this study modifies the version described in D'Amboise et al. (2021) by not taking into account increased friction on forest cells, if these cells act as release cell of a current model propagation. This modification prevents the GMF runout model *com4FlowPy* from essentially preventing avalanche release on forested release cells where the slope incline Φ is less or equal to the calculated α^{eff}.

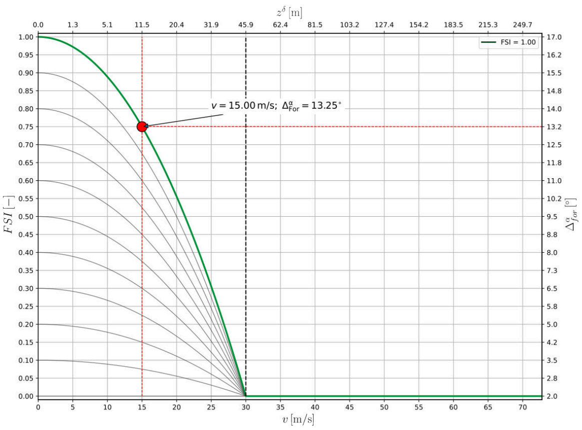

Figure 2: Main principle behind the "forest friciton" module in *com4FlowPy*. On forested cells an additional friction angle Δ^{α}_{for} is added to the globally used value of α. Δ^{α}_{for} scales linearly with respect to a lumped forest structure index (FSI, between 0 and 1). With respect to velocity v (between 0 and a velocity limit v^{lim}_{for}) the scaling is quadratic. The dashed black line indicates the value of $v^{lim}_{for} = 30\,\mathrm{m/s}$ in this case, beyond this limit $\Delta^{\alpha}_{for} = \Delta^{\alpha}_{for,min}$, which is set to $2°$ in this example.

2.2 Model set-up and parameter variations

In order to study parameter sensitivities of the "forest friction" module described in the previous section, we constructed a set of generic topographies with a hockey-stick shape, where a hypothetic avalanche track with constant inclination Φ gradually flattens out to level terrain. Scripts for generation of similar generic topographies are available in the *AvaFrame* module `in3Utils` on `https://github.com/avaframe/AvaFrame/`. We performed model runs with varying parameters on a total number of 10 distinct topographies. Five topographies representing a "large" and five representing a "small" avalanche path were used (see Fig. 3 for a profile view of all topographies).

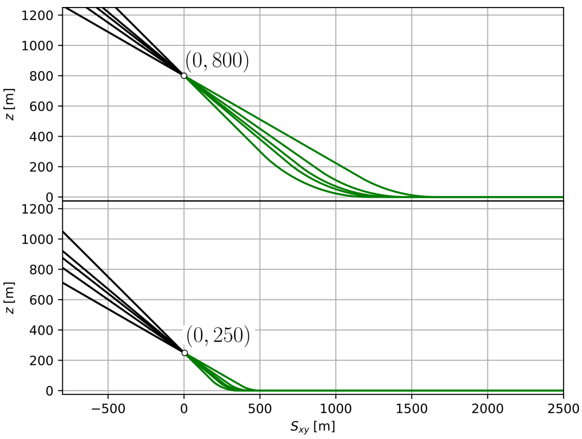

Figure 3: The 10 used generic topographies for the study. The upper panel shows the "large" topographies with forest cover (indicated by green lines) assumed downslope of point $(0, 800)$, the lower panel depicts the "small" topographies with forest cover assumed downslope from point $(0, 250)$. Slope inclines $\Phi \in \{30°, 35°, 38°, 40°, 45°\}$ for both set-ups.

For simplicity we assumed that the avalanche track and runout area are forested starting from a position $S_{xy} = 0$ for all topographies and release areas are located upslope of the forested part of the track. On each topography we then vary the FSI, the parameters of the "forest friction" module ($\Delta^{\alpha}_{for,min}$, $\Delta^{\alpha}_{for,max}$, $v^{\lim}_{for}$) and the distance of the release area from the forest $S^{rel,for}_{xyz}$. $S^{rel,for}_{xyz}$, α and Φ essentially influence the energy line height z^{δ} or equivalent velocity v of the modeled process at the points $(0, 800)$ and $(0, 250)$, where modeled avalanches enter the forested part of the tracks. Under assumption of a constant Φ from the release area to the start of the forested part of the track, z^{δ} in these points can be expressed as:

$$z^{\delta} = \sin(\Phi - \alpha)\,\frac{S^{rel,for}_{xyz}}{\sin(180 - (\Phi - \alpha) - (90 - \Phi))} \quad (2)$$

For every model run FSI was assumed uniform over the forested part of the avalanche track (parts of the profiles in green in Figure 3). Table 1 shows the used parameter ranges for all varied parameters. All possible combinations of the parameters in Tab. 1 were modeled. While the parameters of the "forest friction" module were varied, the basic four *com4FlowPy* model parameters where kept constant (see Tab. 2). For each of the resulting $2\,019\,600$ model runs we evaluate modeled runout distances along the track with (S_{xyz}^{for}) and without ($S_{xyz}^{no\,for}$) consideration of forest effects (see Figure 4 for a schematic overview), and calculate a corresponding relative runout reduction factor ($RRF\,[-]$) with:

$$RRF = 1 - \frac{S_{xyz}^{for}}{S_{xyz}^{no\,for}} \tag{3}$$

Table 1: Value ranges for varied "forest friction" and topographic parameters used in the study.

parameter	unit	value range
Φ	$^\circ$	$\{30, 35, 38, 40, 45\}$
FSI	$[-]$	$\{0, 0.1, \dots, 0.9, 1\}$
$\Delta^{\alpha}_{for,min}$	$^\circ$	$\{0, 2, 4, 6\}$
$\Delta^{\alpha}_{for,max}$	$^\circ$	$\{11, 13, \dots, 25, 27\}$
$v^{\lim}_{for}$	$\mathrm{m/s}$	$\{25, 30, \dots, 65, 70\}$
$S^{rel,for}_{xyz}$	m	$\{0, 10, \dots, 490, 500\}$

Table 2: Basic *com4FlowPy* parameters which were not varied.

parameter:	α	z^{δ}_{lim}	exp	R_{stop}
value:	24°	$270\,\mathrm{m}$	8	3×10^{-4}

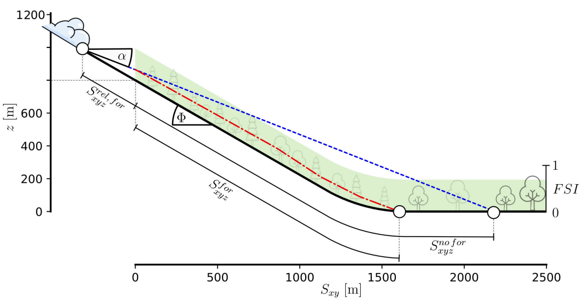

Figure 4: Exemplary set-up of the generic topography used for the parameter study ("large" path with $\Phi = 30^\circ$). Blue dashed line corresponds to the energy line height z^{δ} resulting from model run without forest-interaction ($FSI = 0$), the red dashed line shows z^{δ} with forest interaction along the track ($FSI > 0$); a constant FSI is defined for the forested part of the track. S^{for}_{xyz} and $S^{no\,for}_{xyz}$ are measured downslope from the point $S_{xy} = 0$ where the forest starts along the track, $S^{rel,for}_{xyz}$ is measured upwards from there to the release point.

2.3 Practical example

To showcase the effect of the "forest friction" module in a more practical setting, we carried out model runs with varying parameter settings for a partly forested avalanche track in the eastern Austrian Alps ("Grünes Loch" avalanche located near the "Ötscher" ski resort, Lower Austria) for which past avalanches are documented. Figure 5 shows the recorded release area and outline of observed dense flow for an artificially triggered event in February 2009 along with a recent orthoimage of the area. The release area and dense-flow outline were modified after documentation provided in Funder (2014). The projected runout length from the crown of the slab release to the end of observed deposits is around $1100\,\mathrm{m}$, the vertical drop amounts to roughly $600\,\mathrm{m}$, with the release crown being located at around $1500\,\mathrm{m}$. We used the documented release area and modeled different scenarios (forest cover and model parameterizations). While more detailed information on the pre-event forest composition are available and currently processed, we resorted to using simplified scenarios based on the current forest composition in a first step. Table 3 gives an overview of five of the modeled scenarios. The simplified forest scenarios referenced therein are depicted in Figure 6.

Table 3: Five selected scenarios modeled for the practical showcase. A fixed set of general model parameters as defined in Tab. 2 has been used, "forest friction" parameters and forest scenarios have been varied.

Nr.	gen. param.	"forest friction" param.	forest scenario
1	see Tab. 2	no forest	no forest
2	see Tab. 2	*ParamSet 1* (Tab. 4)	Var. A (Fig. 6)
3	see Tab. 2	*ParamSet 1* (Tab. 4)	Var. B (Fig. 6)
4	see Tab. 2	*ParamSet 2* (Tab. 4)	Var. A (Fig. 6)
5	see Tab. 2	*ParamSet 2* (Tab. 4)	Var. B (Fig. 6)

3. RESULTS & DISCUSSION

3.1 Parameter variations on generic topography

Due to the sheer volume of results ($> 2 \times 10^6$ model runs) the presented results only make up a fraction of the analyzed data. To exemplify the effect of different "forest friction" parameters we present results for two distinct parameterizations (Tab. 4). *ParamSet 1* in Table 4 has been selected based on parameter values reported in D'Amboise et al. (2021), while *ParamSet 2* presents a parameterization with higher assumed energy dissipation on forested cells of the model domain.

Figures 7 and 8 show the effect of the two parameter sets on modeled runouts and z^{δ} for a "large" and "small" generic topography, respectively. In both examples the slope incline $\Phi = 38^\circ$ and the distance of release area to forest $S^{rel,for}_{xyz} = 100\,\mathrm{m}$. *ParamSet 1* has almost no effect on modeled runouts in both cases, regardless of FSI (panels *a* in Fig. 7 and 8). *ParamSet 2* results in little runout reduction for $FSI < 0.6$ on the large topography, while for values of $FSI \geq 0.6$ modeled runout reduction is significant

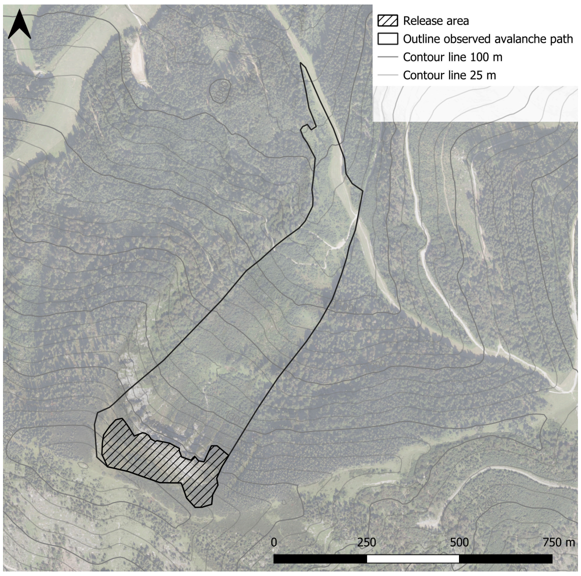

Figure 5: General setting of the real-world avalanche track located in the eastern part of the Austrian Alps. An estimate of the observed slab release (hashed polygon) and dense flow outline (solid black line) for an event in February 2009 are provided along with a recent ortho-image of the area. Ortho-image source: `basemap.at`. Release area and outline modified after Funder (2014).

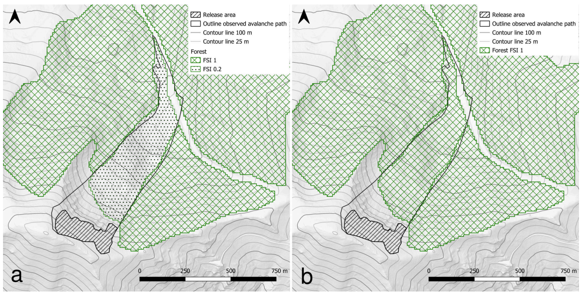

Figure 6: Forest set-ups used to showcase effects of the "forest friction" module in real-world settings. a) scenario where $FSI = 0.2$ along the short and sparse vegetation in the main avalanche path, with $FSI = 1$ on the borders (loosely resembling current situation); b) "optimal" scenario with $FSI = 1$ for all forest in the avalanche path.

and very sensitive to increases in FSI (Fig. 7 *b*). On the small topography the modeled runout reduction for *ParamSet 2* is less sensitive to FSI and relatively higher for smaller FSI (Fig. 8 *b*).

Figures 9 and 10 show the effect of the two parameterizations on modeled relative runout reduction factor RRF (eq. 3) in dependence of slope incline Φ, the distance of release area to forest $S_{xyz}^{rel,for}$ and the forest structure FSI. *ParamSet 1* results in limited runout reductions beyond $35°$ slope incline, regardless of assumed FSI on both the "small" and "large" topographies (Fig. 9 *a-d* and 10 *a-d*). *ParamSet 2* also results in modeled runout reductions on steeper slopes for both "small" and "large" paths (Fig. 9 *e-h* and 10 *e-h*). At slopes of $40°$ and greater modeled RRF also drops significantly for smaller FSI and distances of release area to forest $S_{xyz}^{rel,for}$

Table 4: Two selected variants for parameterization of the "forest friction" module. *ParamSet 1* is almost equivalent to the parameterization proposed by D'Amboise et al. (2021), with a maximal α^{eff} of $35°$, *ParamSet 2* is an example of a parameterization with more pronounced forest-braking effects with a maximal α^{eff} of 47° and higher v_{for}^{lim}.

Parameter-Set	$\Delta_{for,min}^{\alpha}$	$\Delta_{for,max}^{\alpha}$	$v_{for}^{\lim}$
ParamSet 1	$0°$	$11°$	$30\,\mathrm{m/s}$
ParamSet 2	$0°$	$23°$	$45\,\mathrm{m/s}$

beyond $100\,\mathrm{m}$. Overall the higher drop height on the large topographies (Fig. 10) results in sharper declines of RRF wit $S_{xyz}^{rel,for}$ than on the smaller topographies (Fig. 9) for both parameterizations. Also the value of $\alpha_{max}^{eff} = \alpha + \Delta_{for,max}^{\alpha}$ for the selected parameterization of the "forest friction" module determines for which slope angles Φ runout reductions by forests are modeled.

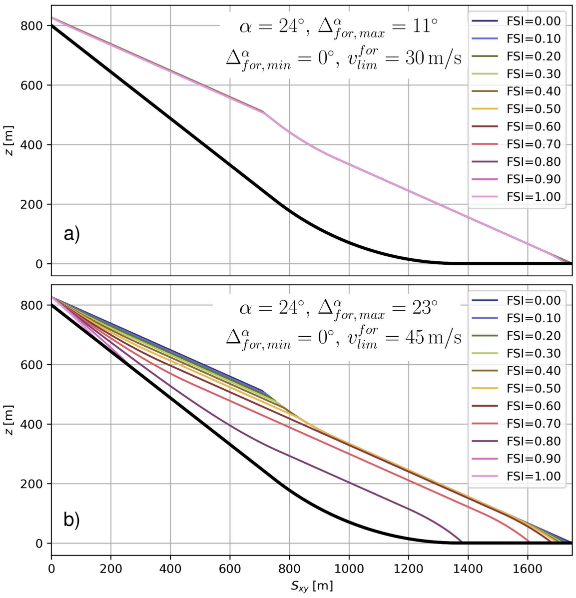

Figure 7: Effect of two different parameterizations (see Tab. 4) of the "forest friction" module for the "large" generic topography. Slope incline $\Phi = 38°$ and distance of release area to forest $S_{xyz}^{rel,for} = 100\,\mathrm{m}$; general *com4FlowPy* parameters according to Tab. 2; only forested parts of the track are shown. Color coded solid lines show modeled z^{δ} and runout distances for different FSI. Panel a) shows results for *ParamSet 1*, panel b) for *ParamSet 2*. The drop in modeled z^{δ} at $S_{xyz} \approx 700\,\mathrm{m}$ in some results is an effect of z_{lim}^{δ}.

3.2 Practical example

Figure 11 shows the modeled energy line heights z^{δ} for the five scenarios listed in Table 3 for the "Grünes Loch" avalanche. The reference run without consideration of forest effects (parameters in Tab. 2) already shows a high coincidence of the modeled process path with the observed dense flow outline. For the two variants with assumed reduced capacity of the forest vegetation to decelerate

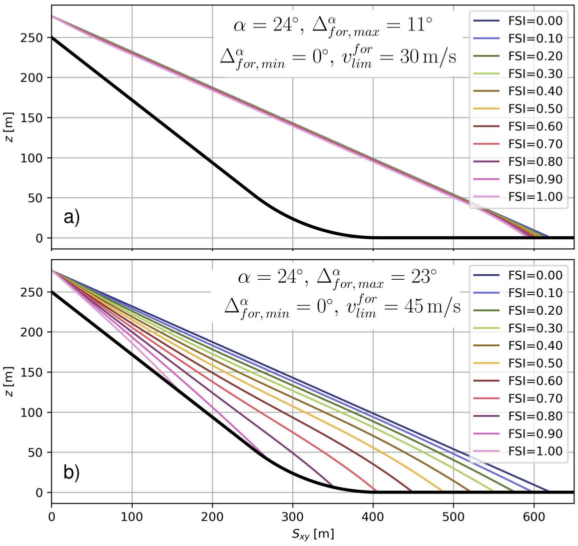

Figure 8: Modeled runouts for *ParamSet 1* (panel a) and *ParamSet 2* (panel b) for a "small" topography; All other settings identical to Fig. 7.

avalanches in the track (see Figure 6 a) we can observe almost no discernible forest effect for parameterization *ParamVar 1* (Fig. 11, panel 2) and only slight reductions of modeled intensities and runout for *ParamVar 2* (Fig. 11, panel 4). For the two variants with assumed optimal forest structure along the avalanche track (Fig. 6 b) the difference between parameterization *ParamVar 1* and *ParamVar 2* becomes apparent. While *ParamVar 1* still has very little effect on overall modeled intensities and affected area despite assumed optimal forest composition along the track, *ParamVar 2* results in a very pronounced reduction of runout lenghts and intensities (Fig. 11, panel 5).

4. CONCLUSION & OUTLOOK

We provide an updated description of the "forest friction" module (D'Amboise et al., 2021) in *com4FlowPy* and analyzed the influence of different parameterizations on model behavior for generic and practical examples.

Our results indicate that the inverse quadratic scaling of Δ^{α}_{for} with modeled velocities v results in a clear dependence of a forest's capacity to reduce modeled avalanche runout from the distance between release area and forest. This is consistent with previous studies, which confirm the limited capacity of forests to reduce the runout of avalanches that release well above the upper forest limit (Takeuchi et al., 2011; Teich et al., 2012). Likewise the greater modeled relative runout reductions on paths with smaller vertical drop align with model assumptions and observations that suggest a relatively higher braking effect of forests on smaller avalanches (e.g. Anderson and McClung, 2012; Feistl et al., 2014; Teich et al., 2014; Bühler et al., 2022).

However, the results also show that modeled runout reductions are sensitive to the model parameterizations and the avalanche track inclination. Parameters similar to the ones reported in D'Amboise et al. (2021) underestimate forest braking effects, especially on steeper slopes and for near optimal forest structure. In line with our results, we suggest using higher values of $\Delta^{\alpha}_{for,max}$ and v^{lim}_{for} to also model forest effects under these conditions.

Ongoing efforts include the compilation of datasets on avalanche events with observed forest interaction along the avalanche track for back-calculation with *com4FlowPy*, in order to get a more solid understanding of the model's limits and potential. This will also entail a more in-depth examination of how to derive spatially varying estimates of the forest structure index (FSI) from field observations and/or remotely sensed data. Performing parameter studies on arbitrary topographies, as opposed to simple generic topographies, also requires more sophisticated analysis routines. Thus, in a next step we will integrate *com4FlowPy* with existing analysis tools already implemented in *AvaFrame* (*AIMEC,* Fischer, 2013, also see `https://docs.avaframe.org/en/latest/moduleAna3AIMEC.html`).

The modification of the "forest friction" module to not influence model behavior on "release cells" also requires that potential forest effects on avalanche release are addressed by separate models, which is a current objective in our research group. Finally, we will update and expand the online documentation to reflect ongoing developments and continue to work on *com4FlowPy* features, such as tracking the distance a GMF travels through forest (Spannring, 2024) or improving the computational efficiency of the implemented "back-tracking" extension (D'Amboise et al., 2022), which can be used to delineate forests with a direct object protective function (D'Amboise et al., 2021).

We encourage new and existing users to use the *com4FlowPy* version provided on the *AvaFrame* repository, since this version is now actively maintained, while the old *Flow-Py* repository has been archived.

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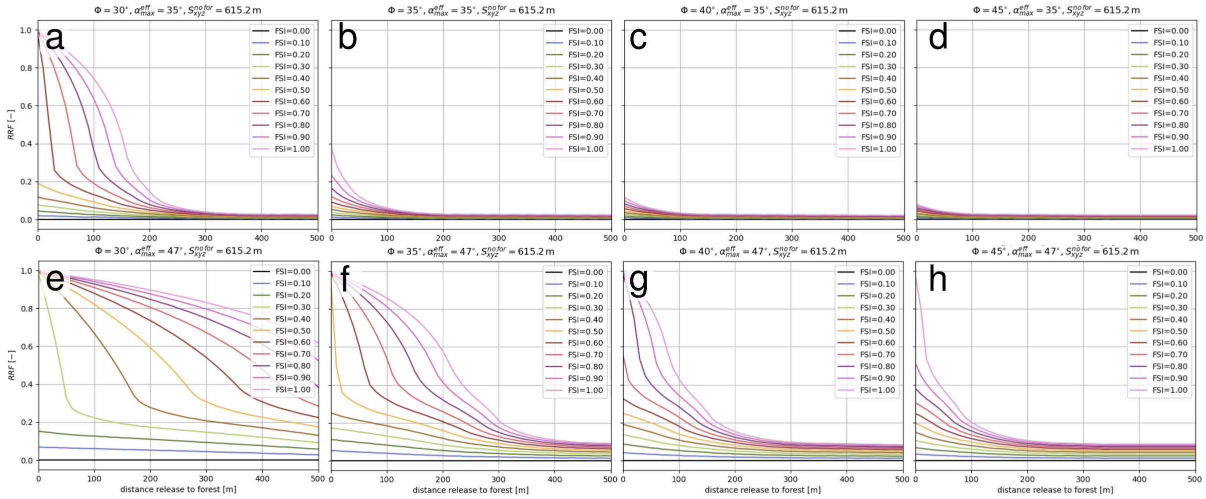

Figure 9: Modeled RRF $[-]$ in dependence of FSI and $S_{xyz}^{rel,for}$ for "forest friction" *ParamSet 1* (panels a-d) and *ParamSet 2* (panels e-h) (Tab. 4) for "small" topographies with varying slope angles Φ is $30°$(a,e), $35°$(b,f), $40°$(c,g) and $45°$(d,h).

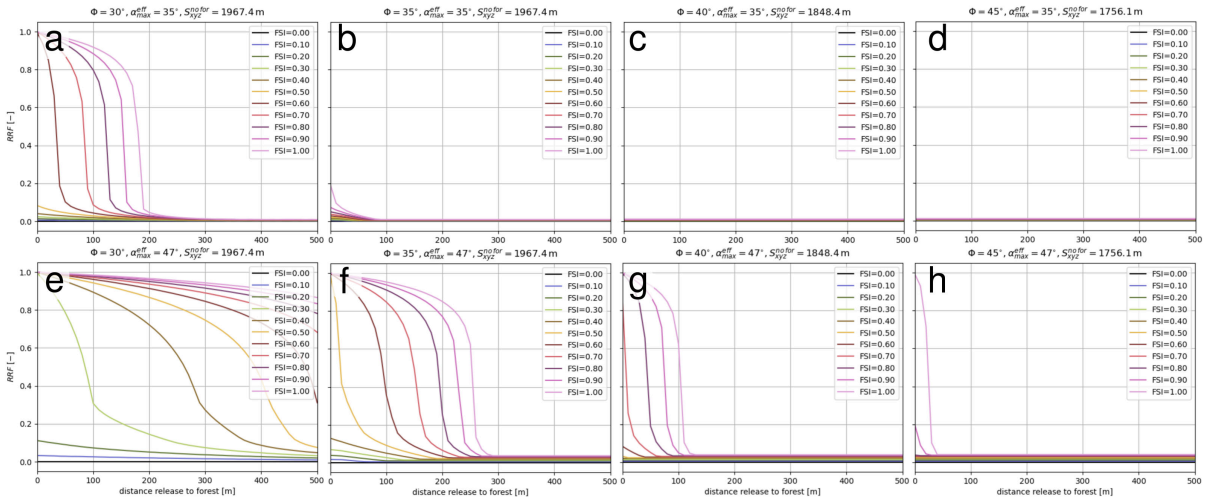

Figure 10: Modeled RRF $[-]$ in dependence of FSI and $S_{xyz}^{rel,for}$ for "forest friction" *ParamSet 1* (panels a-d) and *ParamSet 2* (panels e-h) (Tab. 4) for "large" topography with varying slope angles Φ is $30°$(a,e), $35°$(b,f), $40°$(c,g) and $45°$(d,h).

CODE AND DATA AVAILABILITY

com4FlowPy is available as part of the open avalanche framework *AvaFrame* (`https://avaframe.org`). The source-code and model documentation including the forest-interaction models are available in the current `master` branch on `https://github.com/avaframe/AvaFrame`. In case of questions you can contact *AvaFrame* support or `andreas.huber@bfw.gv.at` directly; contributions to model development are always welcome. The full dataset with modeled runouts and calculated RRF for all mentioned parameter variations is available upon request directly from the authors.

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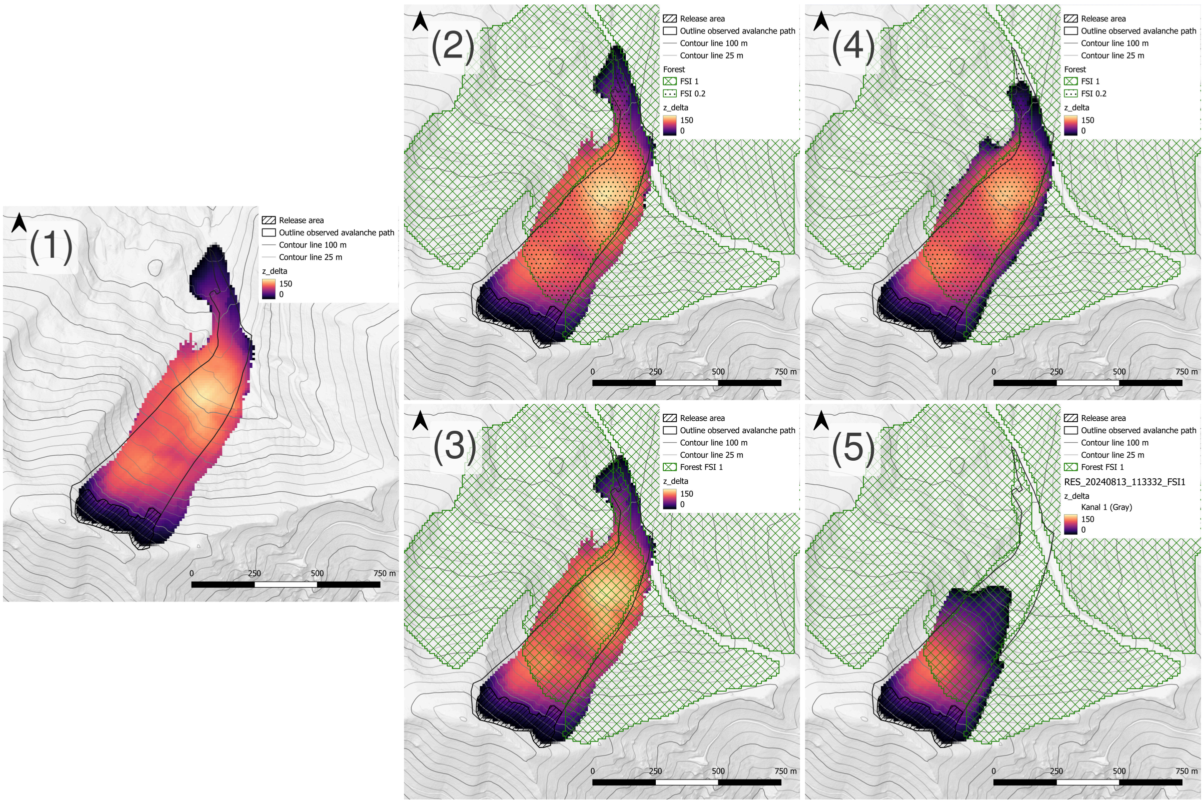

Figure 11: Results (modeled energy line heights z^{δ} [m]) for the real topography example. Panel numbers correspond to the scenario numbers provided in Table 3. Parameterization *ParamVar 1* (2,3) does not exert a significant effect on modeled runouts and intensities compared to the model run without consideration of forest effects (1); also not under the assumption of "optimal" forest conditions along the track (3). With *ParamVar 2* (4,5) reduced runout intensities and distances in areas with high FSI values can be observed.

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