Automated mapping of potential snow avalanche release areas

Report about the spatial modelling project
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1 Introduction

In mountainous regions all over the world with a permanent or seasonal snow cover, snow avalanches can occur and be a threat for humans and infrastructure (Bühler, Kumar, Veitinger & Stoffel, 2013; Bühler et al., 2018). For estimating the potential danger that avalanches pose to roads, railways and settlements, it is crucial to have knowledge about the location and extent of avalanche starting zones. The avalanche release information is required for the numerical simulation of avalanches and in a next step for the establishment of safety measures (Bühler et al., 2013, 2018). As it is not always possible to access long-term avalanche records because there are not everywhere detailed avalanche cadastre information existing and because some mountainous parts are hardly accessible and have a large area, an automated detection of potential avalanche release areas is necessary (Bühler et al., 2013, 2018). Therefore, the aim of this study project is to develop an automated procedure for mapping potential release areas (PRAs) and assigning characteristical parameters to each PRA. The analyses are done using a combination of Python and ArcGIS.

2 The model

The automated procedure for mapping the potential avalanche release areas (PRAs) is executed by running the Python script. In the current version of the script, the only input data needed is a digital elevation model (DEM) that is representing the surface of the area of interest. The procedure can be applied for any region with a potential snow cover and an available DEM. For the development of the method, an extent around Frutigen in the Bernese Oberland was used. The procedure only covers one time step, which is dependent on the creation date of the available DEM. In the following sections, some important parts of the model creation and use are explained in more detail.

2.1 Model concept

An overview over the whole procedure for the automated mapping of the potential avalanche release areas (PRAs) can be gained in the conceptual model diagram (Figure 1). The sections of this chapter further explain the most important parts of the different analysis steps.

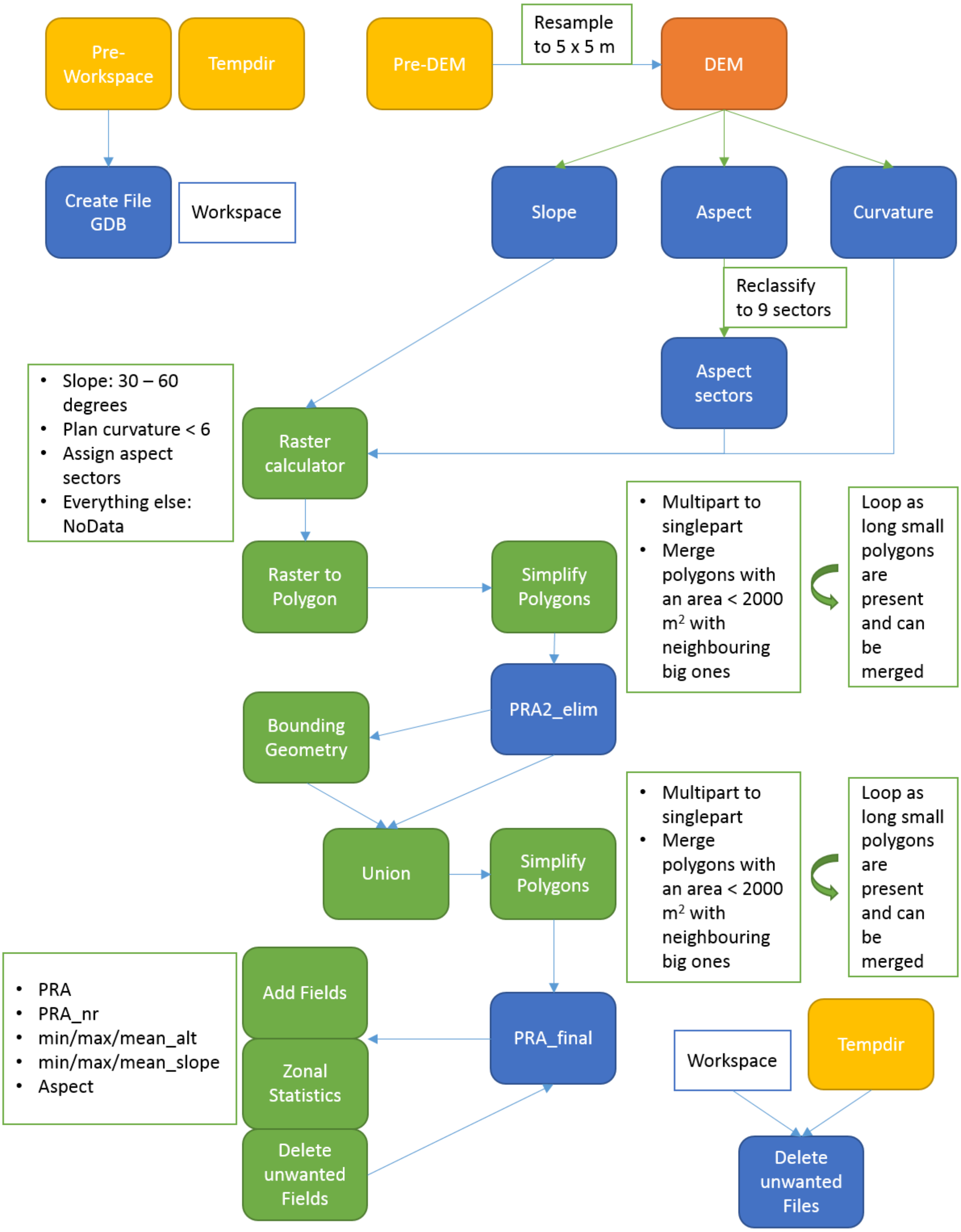

Figure 1: Conceptual model diagram.

2.1.1 Preparation

In order to run the automated procedure for mapping the PRAs the Python site package ArcPy, the library NumPy and the module OS have to be imported as well as the spatial analyst licence in ArcGIS has to be available. In the first part of the script the user has to identify two folders, one for some of the temporary files ("tempdir") and one ("preworkspace") in which the file geodatabase ("myworkspace) will be created in which all the output files and some temporary files will be saved. The input data should be stored in the "preworkspace" folder. The only input data necessary at the moment is the digital elevation model ("pre_dem"). The DEM will be resampled to 5 times 5 meter cell size ("dem").

2.1.2 Preliminary PRAs

Out of the DEM, the slope, aspect and curvature are created and the aspect is reclassified in the nine classes flat, north, northeast, east, southeast, south, southwest, west, and northwest. Then the identification of the PRAs start by excluding selected slope angles and curvature values. The nine aspect classes are attributed to the remaining raster cells. These preliminary PRAs are then converted to polygons where the simplification starts.

2.1.3 Simplification

The key process in the simplification is the merging of polygons with an area smaller than a certain threshold with neighbouring big ones. This process is executed as long as polygons smaller than the threshold are present and can be merged. Because there are still some very small polygons present that can not be merged with big ones because they do not share a common border, the simplification is not satisfying. Therefore, a feature class with a polygon is created that encloses all polygons of the PRAs. This enclosing polygon is then unified with the PRAs and represents the area of non-PRAs where it is not covered by a PRA polygon. The process of simplification is now applied a second time until no polygons smaller than the threshold are present. This time, all small polygons can be merged. It is important not to add the area of non-PRAs before the first simplification because areas of PRAs would be lost when they are merged with the area of non-PRAs. If the area of non-PRAs is added after the first simplification, only the small island PRAs that could not be merged in the first simplification are merged with the non-PRAs and therefore become non-PRAs. Figure 2 shows the PRAs before and figure 3 after simplification.

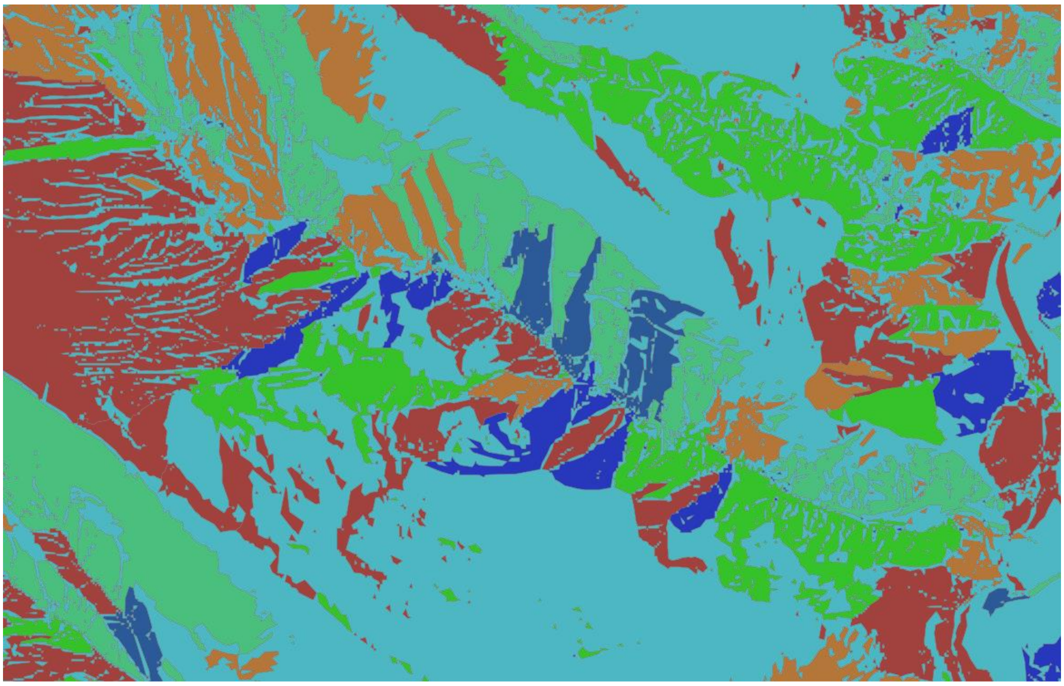

Figure 2: PRAs before simplification (non-PRAs are shown in light blue).

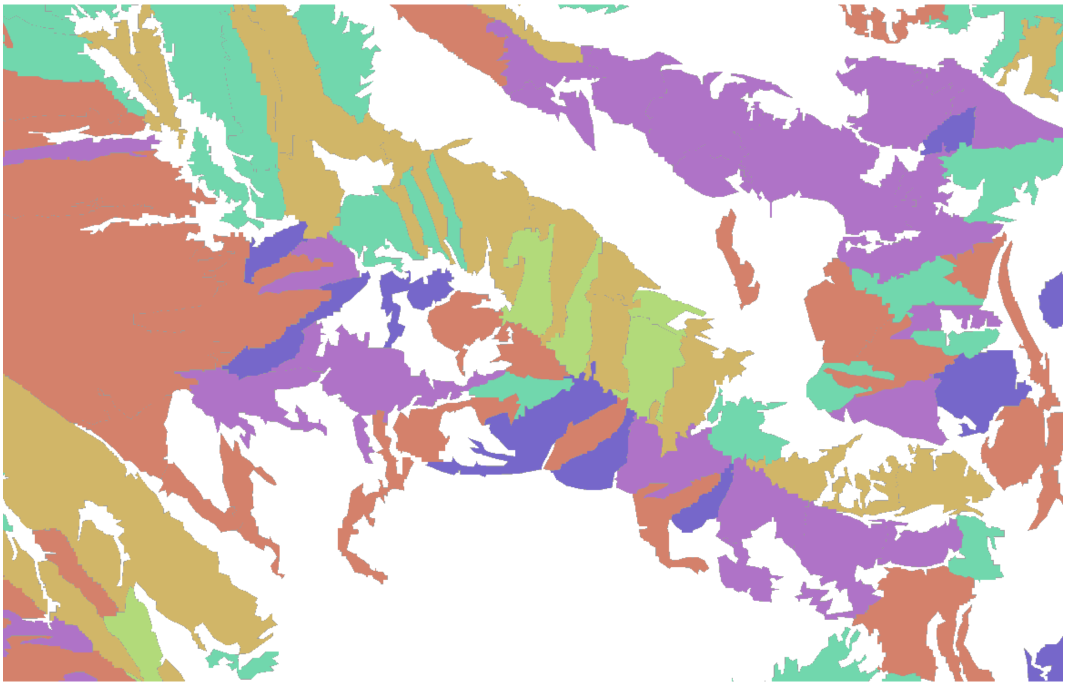

Figure 3: PRAs after simplification (non PRAs are shown in white).

2.1.4 Characteristical parameters

The polygons of the final PRA file then get new fields in the attribute table where characteristical parameters are assigned with the use of the zonal statistics tool or the calculate field tool (Table 1). The unnecessary fields in the attribute table are deleted. The attribute table of the final PRA file is visible in figure 4.

Table 1: Fields in the attribute table of the final PRA file

Field name	**Meaning**
PRA	1 for PRA; 2 for non-PRA
PRA_nr	Consecutive numbers for each feature (is used for the zonal statistics tool)
min_alt	Minimum altitude
max_alt	Maximum altitude
mean_alt	Mean altitude
min_slope	Minimum slope
max_slope	Maximum slope
mean_slope	Mean slope
Aspect	Aspect sector as text
gridcode	Aspect sector

PRA_final

OBJECTID *	Shape *	gridcode	Shape_Length	Shape_Area	PRA	PRA_nr	min_alt	max_alt	mean_alt	min_slope	max_slope	mean_slope	Aspect
461	Polygon	5	731.05579	8761.11093	1	461	1140.613	1282.65	1206.045	25.99881	42.71919	34.14843	southeast
462	Polygon	4	901.303223	11853.948216	1	462	1116.021	1222.252	1165.171	27.72537	50.45911	35.95237	east
463	Polygon	2	908.244058	13315.687325	1	463	1621.466	1708.446	1649.333	29.51896	53.40391	34.83774	north
464	Polygon	3	2661.058264	44884.386614	1	464	1921.63	2290.751	2079.903	28.65306	63.63214	41.75783	northeast
465	Polygon	5	1137.765164	21445.276081	1	465	1540.762	1731.864	1650.13	19.38193	58.8415	35.84	southeast
466	Polygon	8	787.959761	12202.990191	1	466	1640.215	1810.247	1704.862	20.51059	58.05785	41.35511	west
467	Polygon	3	975.473938	24189.836049	1	467	1997.812	2181.296	2091.654	28.53666	51.97142	38.14608	northeast
468	Polygon	3	726.48923	7842.735703	1	468	1482.071	1527.489	1507.673	29.28164	42.79554	32.16459	northeast
469	Polygon	7	510.218182	7717.596234	1	469	940.6234	1043.7	1004.792	12.65305	57.43174	36.52996	southwest
470	Polygon	2	712.3475	9411.696008	1	470	1920.493	2093.339	1975.887	29.93752	59.76627	36.43917	north
471	Polygon	4	797.458562	11990.078259	1	471	1392.749	1463.655	1430.694	12.72746	48.17574	34.02936	east
472	Polygon	3	1418.544681	14835.014303	1	472	1344.7	1446.477	1405.206	26.61344	43.02634	34.35864	northeast
473	Polygon	4	638.058553	17363.401685	1	473	1184.661	1305.219	1249.097	26.31227	45.38464	34.033	east
474	Polygon	4	6035.437657	160133.229692	1	474	1665.674	2265.374	2009.13	17.64703	59.1513	37.32793	east
475	Polygon	3	815.086437	13404.191796	1	475	1576.794	1721.942	1655.308	14.54873	64.02985	38.07053	northeast
476	Polygon	8	5130.916252	79420.247596	1	476	1127.745	1404.669	1266.644	24.45033	56.8582	33.92311	west
477	Polygon	6	655.40038	7459.649567	1	477	1448.123	1545.624	1498.307	16.73922	48.67792	39.30722	south
478	Polygon	7	1112.959219	19300.186892	1	478	1508.691	1708.32	1597.205	14.65322	52.22533	40.60015	southwest
479	Polygon	3	576.595611	6864.772297	1	479	986.155	1027.163	1005.954	26.84893	46.39857	35.71867	northeast
480	Polygon	2	708.541097	8358.543372	1	480	2137.494	2305.948	2229.912	30.06197	58.26596	40.30486	north
481	Polygon	3	1257.664007	24611.006772	1	481	1772.582	2016.335	1885.593	26.03728	50.35722	38.48101	northeast

Figure 4: Attribute table of the final PRA file.

2.1.5 Validation

The validation of the final PRAs is embedded in the script before the deletion of the unnecessary files. More information on the validation is found in chapter 2.3.

2.1.6 Delete files

If the last part of the script is used, the temporary folder and all the files in the geodatabase except the final PRA file will be deleted. Sometimes an error message appears when the whole script together with this last part is executed and PyCharm is stuck. As it is nice to have no unnecessary files left after the analysis, but as the problem with the error message could not be solved, it is recommended to run the last part of the script separately.

2.2 Parameters

The procedure for the automated mapping of PRAs involves the parameters slope range, maximum plan curvature and minimum area of the single PRA polygons. The choice of the values for these parameters is based on literature and they were not calibrated in the current development of the procedure. The chosen slope range lies between 30 and 60 degrees. Below 28 to 30 degrees the terrain is too flat for avalanches to occur and above 55 to 60 degrees the terrain is too steep for big snow accumulations (Losey, 2013). There is a common agreement on this range as several studies are using the same (Losey, 2013; Bühler et al., 2013, 2018).

The plan curvature is used to eliminate highly convex or concave areas because these parts of the terrain limit fracture propagation of avalanche release (Bühler et al., 2018). The range of the plan curvature is dependent on the terrain and therefore varies between different areas of interest. Based on the studies from Bühler et al. (2013, 2018), the maximum plan curvature is set to 6. Areas with a higher plan curvature are seen as non-PRAs.

The minimum area of a single PRA polygon is used for the simplification of the shapes. In the SilvaProtect project, a threshold of 5000 m^2 was used and seemed appropriate (Losey, 2013). The SilvaProtect project was initiated to determine protection forest on a national basis (Losey & Wehrli, 2013). According to Losey (2013), extreme avalanches were relevant for the simulations in the SilvaProtect project. Therefore, a minimum area of 5000 m^2 is rather too high for detecting also potential avalanches release areas with a higher frequency. For this reason, the minimum area threshold is preliminary set to 2000 m^2.

2.3 Validation

A validation part is found in the script for the automated mapping of potential avalanche release areas but there is no reference data set available against which the output of the model could be validated. The validation part in the script can be used as soon as an appropriate reference data set is found. In the following section, the principle of the validation is explained. To test the procedure, a simple fake reference data set was created (Figure 5).

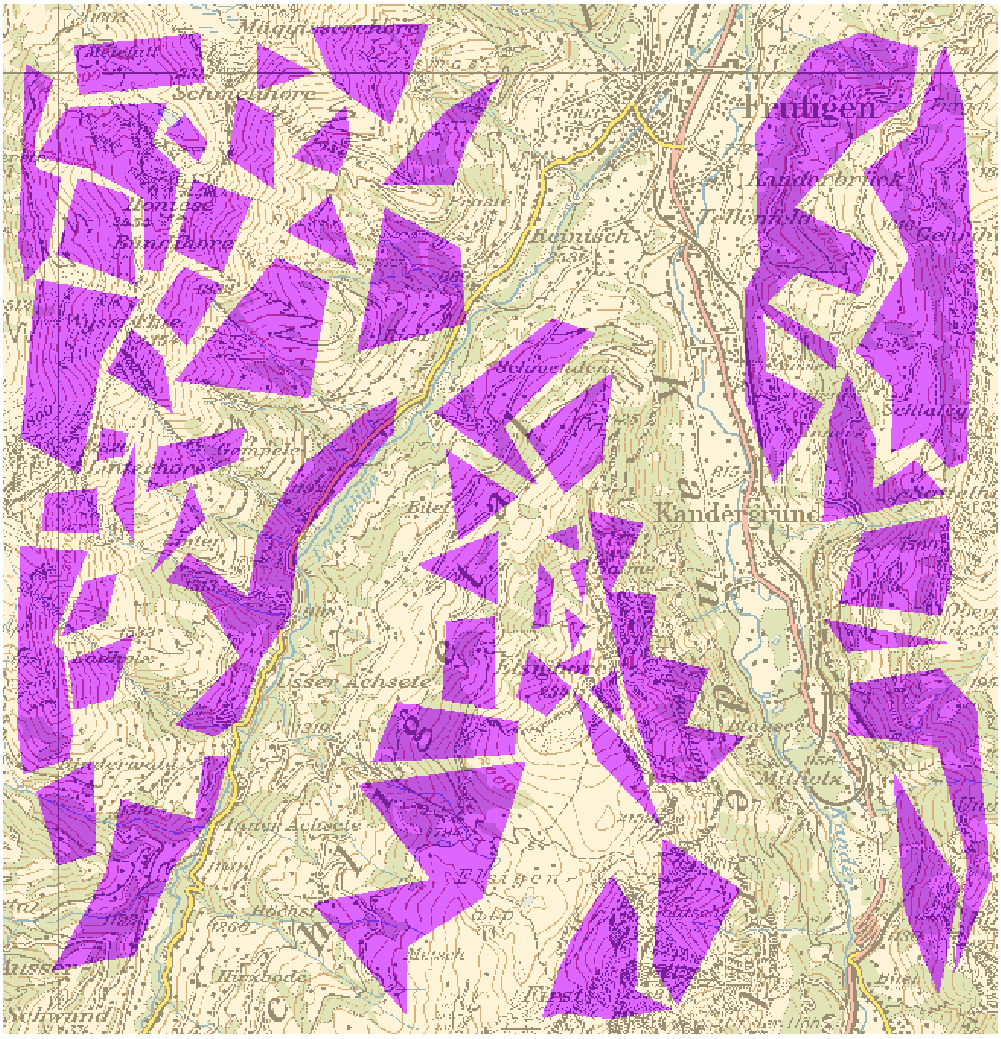

Figure 5: Fake reference data set with PRAs (purple) and non-PRAs (yellow).

In the beginning of the validation, the final PRA file as well as the reference data set are converted to a raster. Then the error matrix raster (Figure 6) is generated using the Con tool of the raster calculator in ArcGIS. Afterwards the resulting raster is converted into a NumPy array and looped through it to count the different error matrix values (Figure 7). Each value in the error matrix represents the total intersectional number of raster cells of a specific reference class and algorithm class (Bühler et al., 2018).

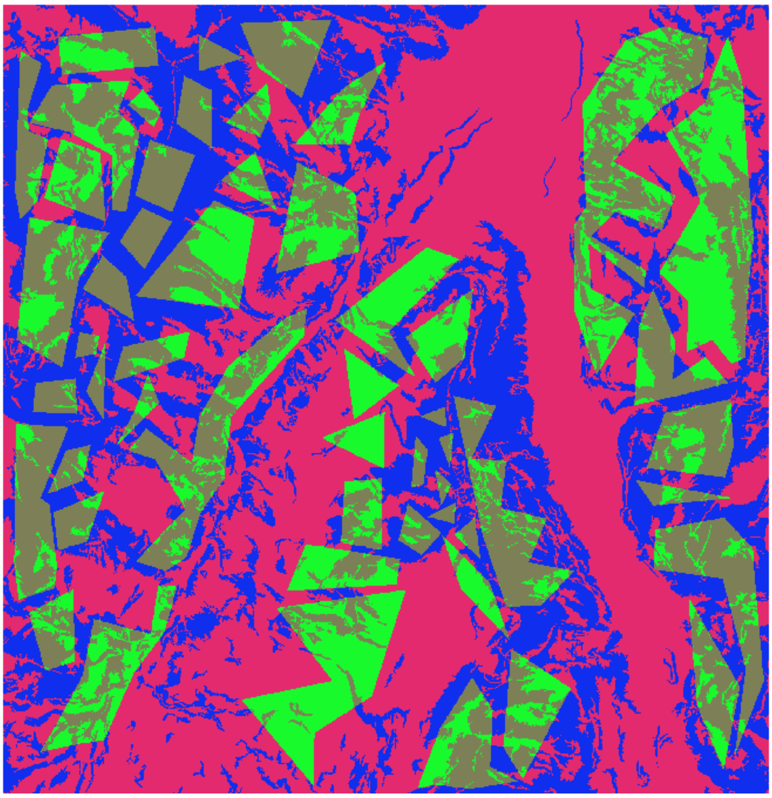

Figure 6: The raster generated with the Con tool. The colours represent the different raster cells belonging to one of the four categories of the error matrix visible in figure 7 (olive = a, blue = b, lime = c, pink = d).

		reference		
		PRA	**NoPRA**	Σ
algorithm	**PRA**	$a_1+a_2=a$	$b_1+b_2=b$	**a+b**
	NoPRA	**c**	**d**	**c+d**
	Σ	**a+c**	**b+d**	**n**

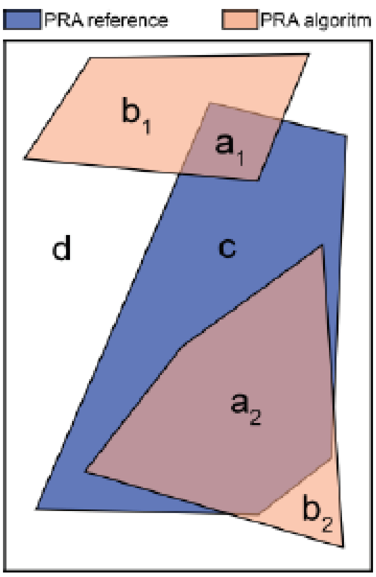

Figure 7: Principle of the error matrix (Bühler et al., 2018).

Out of the error matrix, different accuracy measures can be calculated. The preliminary accuracy measures implemented in the script are the overall accuracy, the probability of detection, the probability of false detection, the false alarm ratio and the bias score (Bennet et al., 2013; Bühler et al., 2018). In the error matrix visible in figure 7, a stands for hits, b represents false alarms, c means misses and d stands for correct negatives.

$$Accuracy = \frac{hits + correct\ negatives}{total} \quad (ideal\ value: 1)$$

$$Probability\ of\ detection = \frac{hits}{hits + misses} \quad (ideal\ value: 1)$$

$$Probability\ of\ false\ detection = \frac{false\ alarms}{correct\ negatives + false\ alarms} \quad (ideal\ value: 0)$$

$$False\ alarm\ ration = \frac{false\ alarms}{hits + false\ alarms} \quad (ideal\ value: 0)$$

$$Bias\ score = \frac{hits + false\ alarms}{hits + misses} \quad (ideal\ value: 1)$$

2.4 Results

The desired output of the model are the potential avalanche release areas stored as polygons in the PRA_final file in the file geodatabase. The PRAs are mapped using ArcGIS (Figure 8).

When looking at a terrain part with many cliffs, where it is too steep for big snow accumulations, it is visible that these features split up the PRAs and the ridges are used to differentiate between single PRAs as well (Figure 9). The distinction between single PRAs according to aspect changes is done very well in many cases (Figure 10). In some cases, the delineation between PRAs is less accurate and often very big PRAs are still present. One reason for the inaccuracy is possibly found in the simplification process.

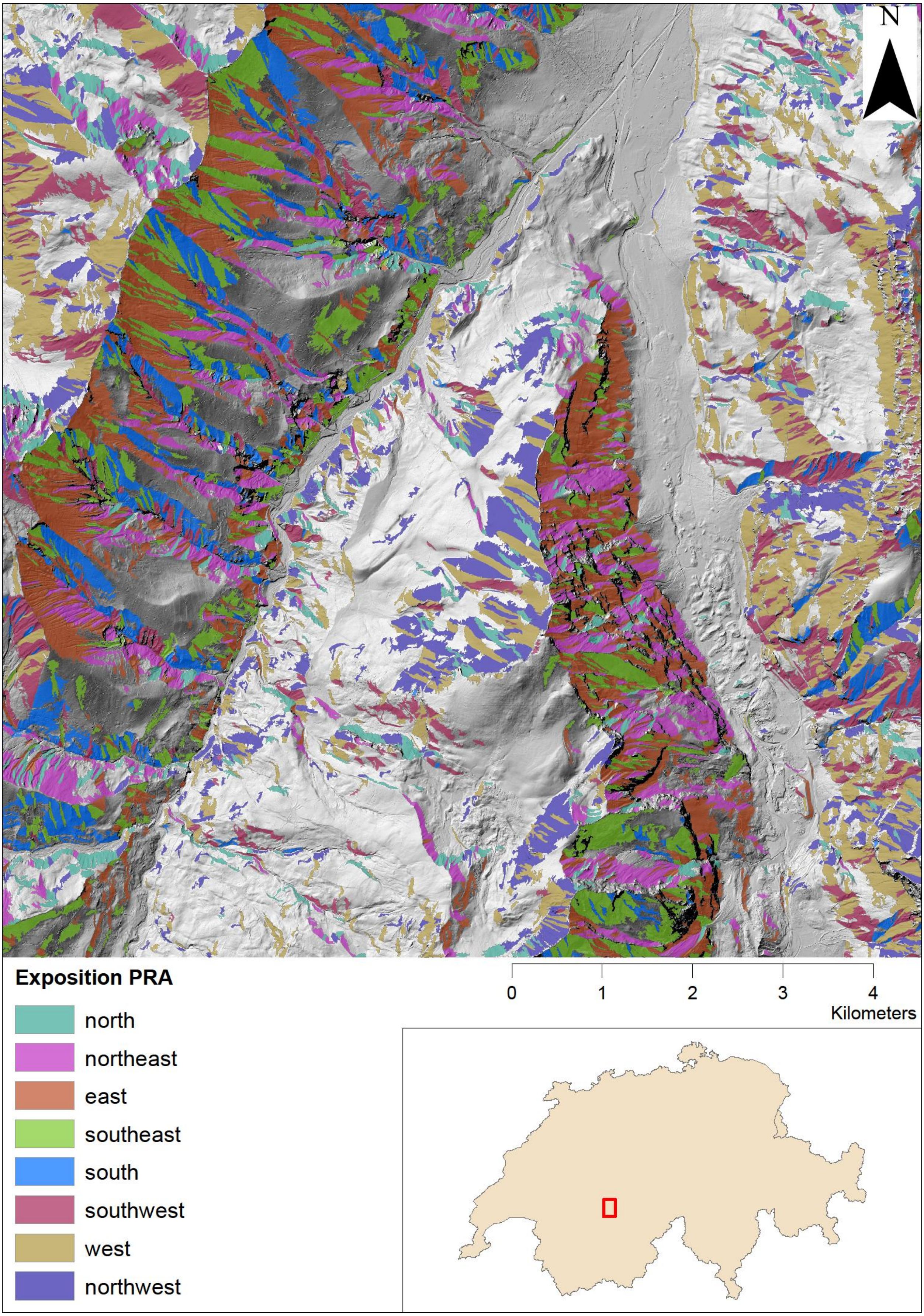

Figure 8: Test area around Frutigen with the automated mapping of potential snow avalanche release areas.

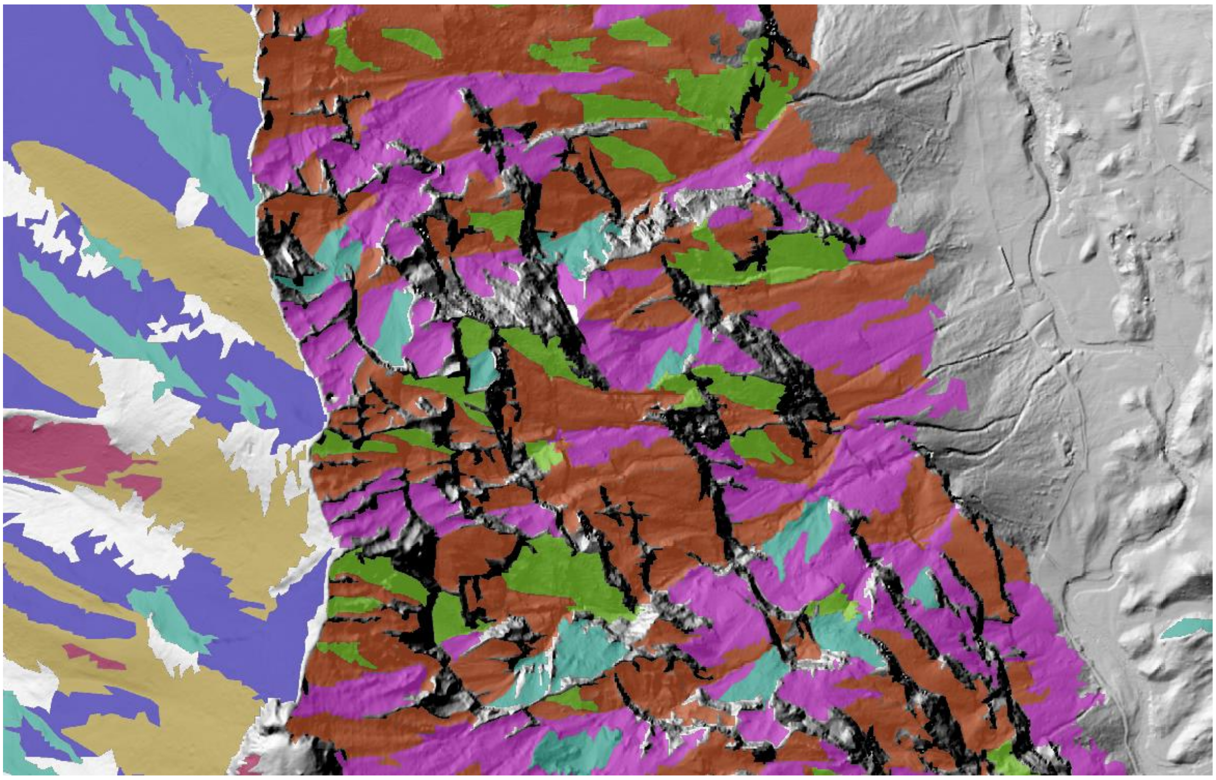

Figure 9: Example of a terrain part with many cliffs.

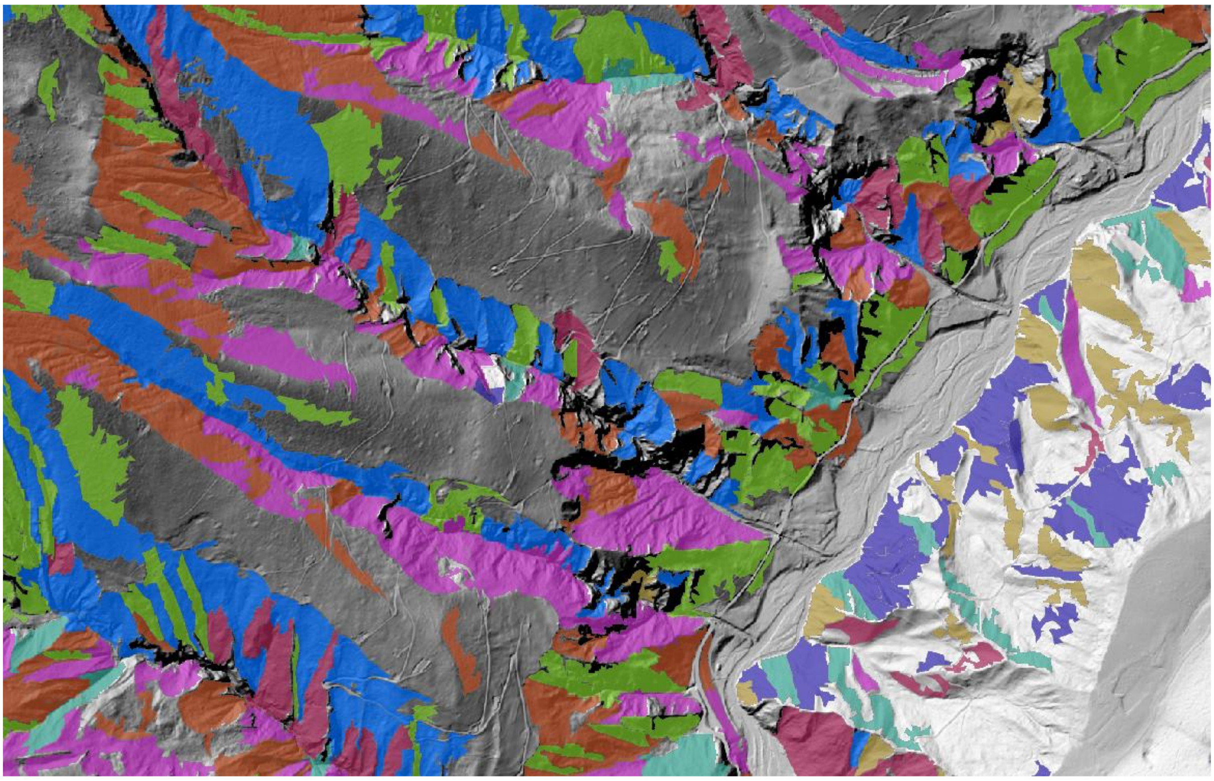

Figure 10: Example of a terrain part with quite good PRA delineation according to aspect changes.

3 Conclusions and outlook

The developed procedure is working and results can be achieved. However, there are a lot of issues that can be improved. The validation of the final potential avalanche release areas is initiated but an appropriate reference data set is missing. This is also a big problem in most of the scientific studies that cover the topic of automated mapping of potential avalanche release areas (e.g. Bühler et al., 2013, 2018). In Switzerland, it could be tried to use the avalanche cadastre for the verification of the PRAs but one has to be aware that the records in the cadastre show the release, transition and deposition area with no distinction between them. Bühler et al., (2013) calculated the upper third of each polygon in the cadastre, assuming that this area will most probably contain the avalanche release area completely. This could be a step in the further development of the procedure presented in this report.

Another point for improvement is found in the calibration of the parameters. Until now, one reason for the missing calibration is the lack of a reference data set on the basis of which the parameters could have been calibrated. Another reason for the missing calibration are the high demands of delivering a perfect model. Especially the first experiences with Python consume a lot of time. In the current version of the PRA mapping, the focus was set on delivering a working procedure as a whole, where parts can be improved later, as for example the calibration of the parameters. There are existing ideas how to approach the calibration. The principle is to use a range of values for each parameter after each other. Only one parameter is varied at a time. After each run of the whole model, the final PRAs are compared to the reference data set and the accuracy measures are calculated. In the end, you get the accuracy measures for each value in the range of values for a specific parameter. The parameter value with the best accuracy scores is chosen. This procedure is then repeated for each parameter.

Furthermore, other parameters like terrain roughness, forest cover or minimum release area altitude could be included in the automated procedure for mapping PRAs. Before the start of the calibration, it possibly makes sense to conduct a sensitivity analysis for each parameter. This shows how the output of the model changes when one parameter is modified and makes it possible to concentrate the calibration on the parameters with the biggest influence.

Another option for improvement of the procedure lies in the choice of the delineation method of the single potential release areas. In the procedure presented in this report, the PRAs are split up by the aspect sectors. A different approach is found in the watersheds tool that is based on flow direction and flow accumulation in the hydrology toolset of ArcGIS. In the watersheds approach, a threshold in the flow accumulation raster has to be determined in order to find the pour points required for the watersheds tool. In the development of this seminar project, the watersheds approach was tested in the beginning but the aspect approach seemed more convincing especially because there is one parameter less that has to be specified. A systematic comparison of these two methods could be done in the future.

One weak point in the developed procedure for the automated mapping of PRAs is found in the simplification of the polygons. A simplification has to be done because otherwise a lot of very small polygons that are not representative stay in the data set. But with the simplification, information is lost and sometimes polygons are merged over natural borders that would prevent fracture propagation. With more experience, it is maybe possible to improve the simplification process but there is still a huge problem found in the validation of the delineation of the single PRAs because no appropriate method or data set exists until now (Bühler et al., 2018). As Bühler et al. (2018) state, the delineation of the single potential release areas is one of the most difficult task in the automated mapping of PRAs.

The plan until Christmas 2018 is to apply the developed procedure and therefore to map all potential avalanche release areas for the whole canton of Bern. I will do this within my employment in the division of natural hazards and I am curious about the result.

At this point, I would like to thank Andreas Zischg, Pascal Horton and Jorge Ramirez for the realisation of the geodata analysis and modelling seminar that gave me a first big insight into the world of spatial modelling. The seminar project was demanding but I learned a lot on how to use Python and especially the combination of Python and ArcGIS.

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