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MODELLING OF HOMOGENEOUS REGIONS FOR AVALANCHE RISK ASSESSMENT – A COMPARISON OF TWO REGIONALISATION METHODS

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Abstract: Worldwide a plethora of people fall each year victim due to an avalanche disaster. Most of the victims are outdoor enthusiasts and athletes who are out and about in mountainous regions. An adequate estimation of the avalanche risk areas is of great importance in order to keep the number of victims as low as possible. Therefore, the avalanche warning service estimates the avalanche risk twice a day in the six regions of the Austrian state of Salzburg. These static regions were hitherto generated manually based on the experience of experts in the field. The aim of the study presented herein is the semi-automated modelling of homogenous regions that can then be used for the daily estimation of the avalanche risk. The geon-concept is the foundation on which the model is based. This concept incorporates the identification of relevant indicators, the expert-based weighting thereof using AHP, the GIS-based modelling of the regions, and the evaluation and adjustment of the results. While multiresolution segmentation is generally used as the regionalisation method for the geon-concept, the SKATER-method was additionally applied in this study. Various models were generated that differed not only in their regionalisation method, but also in terms of the parameters for homogeneity and morphology of the resulting regions. A qualitative expert-based method and a quantitative-statistical method were used for the evaluation of the results. The comparison of the two methods showed that the models based on multiresolution segmentation led to significantly better results than those based on SKATER. However, results also indicated that not only a high degree of homogeneity is of importance for the quality of the regionalisation, but that the morphological characteristics of the individual regions also play an important role.

Keywords: Geon, regionalisation, SKATER, multiresolution segmentation, avalanches

MODELLIERUNG VON HOMOGENEN REGIONEN FÜR DIE LAWINENGEFAHRENBEURTEILUNG – EIN VERGLEICH VON ZWEI REGIONALISIERUNGSMETHODEN

Zusammenfassung: Weltweit fordern jährlich Schneelawinen eine Vielzahl von Leben, wobei der Großteil Freizeitsportler sind. Um die Zahl der Opfer möglichst gering zu halten, ist eine angemessene Einschätzung der Lawinengefahr von großer Bedeutung. Im österreichischen Bundesland Salzburg wird hierfür die Lawinengefahr zweimal täglich vom Lawinenwarndienst in sechs Regionen eingeschätzt. Diese statischen Regionen wurden bisher manuell und erfahrungsbasiert von Experten generiert. Das Ziel in der hier vorgestellten Arbeit ist eine semi-automatische Modellierung von homogenen Regionen, welche für die tägliche Gefahreneinschätzung verwendet werden kann. Hierbei soll das sogenannte geon-Konzept als Grundlage für das Modell zum Tragen kommen. Dieses Konzept beinhaltet die Identifikation von relevanten Indikatoren, deren expertenbasierte Gewichtung mittels AHP, die GIS-gestützte Modellierung der Regionen, sowie die Evaluierung und Anpassung der Ergebnisse. Während für das geon-Konzept üblicherweise ‚Multiresolution Segmentation' als Regionalisierungsmethode verwendet wird, kam in dieser Arbeit zusätzlich auch noch die ‚SKATER'-Methode zum Einsatz. Es wurden unterschiedliche Modelle erstellt, welche sich neben ihrer Regionalisierungsmethode auch hinsichtlich ihrer Parameter für Homogenität und Morphologie der resultierenden Regionen nicht unterscheiden. Für die Evaluierung der Ergebnisse wurde sowohl eine qualitativ expertenbasierte als auch eine quantitativ-statistische Methode angewandt. Der Vergleich der beiden Methoden zeigte hierbei, dass jene Modelle, welchen die Multiresolution Segmentation zugrunde liegen, deutlich bessere Resultate liefern als jene von SKATER. Es wurde jedoch auch festgestellt, dass für die Qualität der Regionalisierung, beziehungsweise deren zugrunde liegenden Regionen, nicht zwingend ein hoher Grad an Homogenität ausschlaggebend ist, sondern auch die morphologischen Eigenschaften der einzelnen Regionen eine bedeutende Rolle spielen.

Schlüsselwörter: Geon, Regionalisierung, SKATER, Multiresolution Segmentation, Lawinen

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1 INTRODUCTION

Avalanches are a critical natural phenomenon that affects most mountainous regions with seasonal snow coverage. They occur not only in the untouched countryside, but also in places inhabited by humans. Past disasters such as the Galtür Avalanche (Tyrol, Austria) in 1999 with 31 fatalities clarified the danger of avalanches for human beings (Keiler et al. 2006, Pechlander et al. 2007). However, not only alpine residents are in danger, but also many outdoor enthusiasts and athletes. An appropriate assessment is therefore essential to reduce harm and to save lives. In the state of Salzburg (Austria) an official avalanche warning service is responsible for the estimation of the current avalanche risk twice a day. For this evaluation the state is divided into six separated and non-overlapping zones (see Figure 1). These regions were thus far defined manually and cognition-based with the help of expert knowledge. A semi-automated regionalisation approach has not been used until now. However, it now offers new possibilities to delineate such regions. While a manual identification and designation is limited to expert knowledge and imaginability, a GIS-based regionalisation may have benefits, since it is able to recognise a variety of relevant indicators, which could have a high spatial resolution. The aggregation of these indicators can be furthermore weighted according to their significance. The use of a GIS-based model also enables the production of multiscalar regions, which can be adjusted as required, or which may help to identify subregions (see Figure 2).

In recent decades, countless clustering algorithms were developed, but only a very small portion allows spatial relations to be considered. Furthermore, only a handful of them are able to model multi-dimensional phenomena such as avalanche risk. The Object-Based Image Analysis (OBIA)-related multiresolution segmentation is such a regionalisation method. While this approach was originally intended for remote sensing purposes, and more specifically for image segmentation, it turned out that it could also be applicable for regionalisation purposes. SKATER, a recently developed spatial clustering method for vector data, could be an appropriate alternative to the raster-based multiresolution segmentation.

1.1 AIM OF THE STUDY

In recent years, GIS-based modelling has become increasingly relevant for a wide spectrum of applications. This trend also affected avalanche research, and more specifically risk assessment. However, avalanche risk is based on a complex interplay of various indicators and conditions. Such a complex interplay may not be able to be integrated easily into a computational model. Hence expert knowledge is still the key qualification for defining avalanche risk. The avalanche risk assessment zones in the state of Salzburg are currently defined in an expert-based manner by specialists from the Central Institute for Meteorology and Geodynamics, which acts as the official avalanche warning service. Due to the difficulty of modelling appealing, complex real-world phenomena, GIS-based semi-automated methods for delineating assessment zones have not been integrated until now. However, recently developed concepts, such as the geon approach (Lang et al. 2014), which was used for this study, allow the incorporation of such methods. While this concept routinely utilizes the OBIA-related multiresolution segmentation (MRS) for aggregating relevant factors, this study additionally applied the SKATER-method, a newly presented spatial clustering algorithm.

On the one hand, the aim of this study is to delineate new GIS-based avalanche risk assessment zones for the state of Salz-

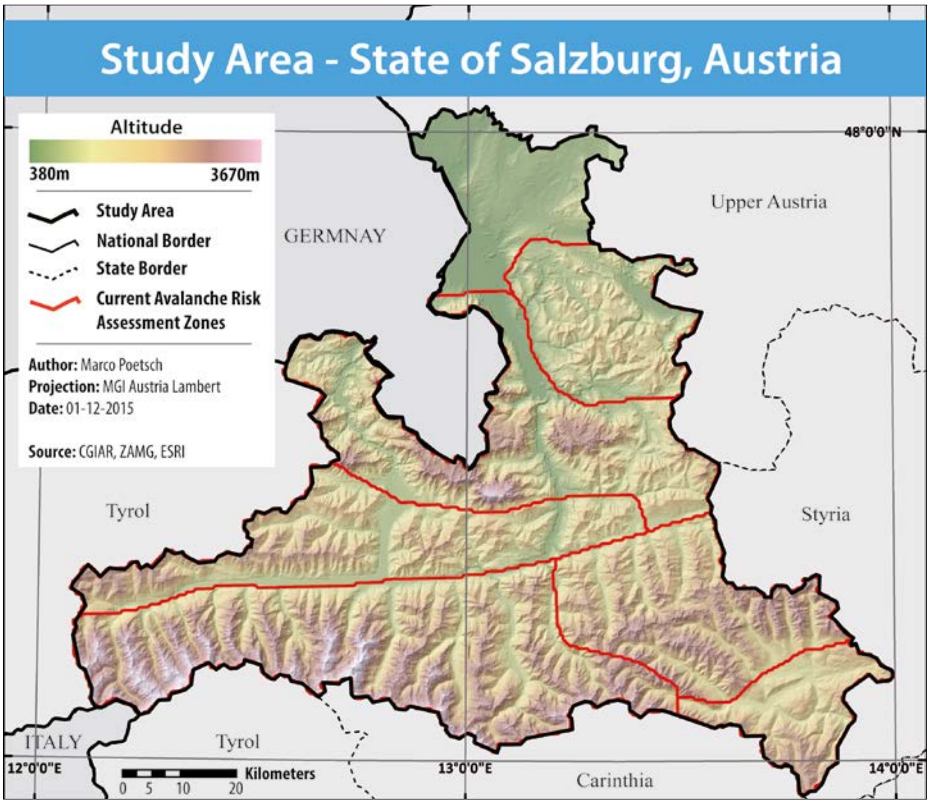

Figure 1: Current assessment zones in the state of Salzburg

burg by applying the geon-concept. Therefore, substantial influencing factors should be identified and weighted based on expert knowledge for further data aggregation. On the other hand, the used regionalisation methods, multiresolution segmentation and SKATER, are examined and compared to identify the advantages and drawbacks of both methods. The findings of this study could be relevant for other states and their avalanche warnings services, since no generally applicable procedure of defining avalanche risk assessment zones has been nationally implemented to date.

1.2 STUDY AREA

The state of Salzburg in Austria was chosen as the study area. It encompasses an area slightly over 7150 km², which is mainly characterised by an alpine landscape. A substantial change in altitude from the north (around 400 meters) to the south (over 3600 meters) can be observed. The mountain ranges in Salzburg have widely differing characteristics with regard to their land cover, altitude, slope inclination, and weather conditions. From mid-November to May the areas situated above 2000 m. a. s. l. are mostly blanketed by a thick snow cover. Winter sports, such as ski-touring, are possible and quite popular amongst locals and tourists during this time of the year.

1.3 THE GEON-CONCEPT

For certain geographical studies it is necessary to use a range of data that are not necessarily related to spatial real-world phenomena. However, due to their multidimensionality, some phenomena are difficult to handle, respectively to model. For instance, it is necessary to consider various indicators for the assessment of vulnerability. Certainly, the integration of these indicators into a geographical model might be complex and difficult. The so-called geon-concept should help to operationalise such difficult phenomena. This concept serves as a framework to model spatial units that are homogenous in a defined way, scalable to the level of policy intervention, and independent of administrative or other pre-defined boundaries (Lang et al. 2014). In the recent years the geon-concept was already successfully adapted to several studies. Kienberger et al. (2009) analysed the so-

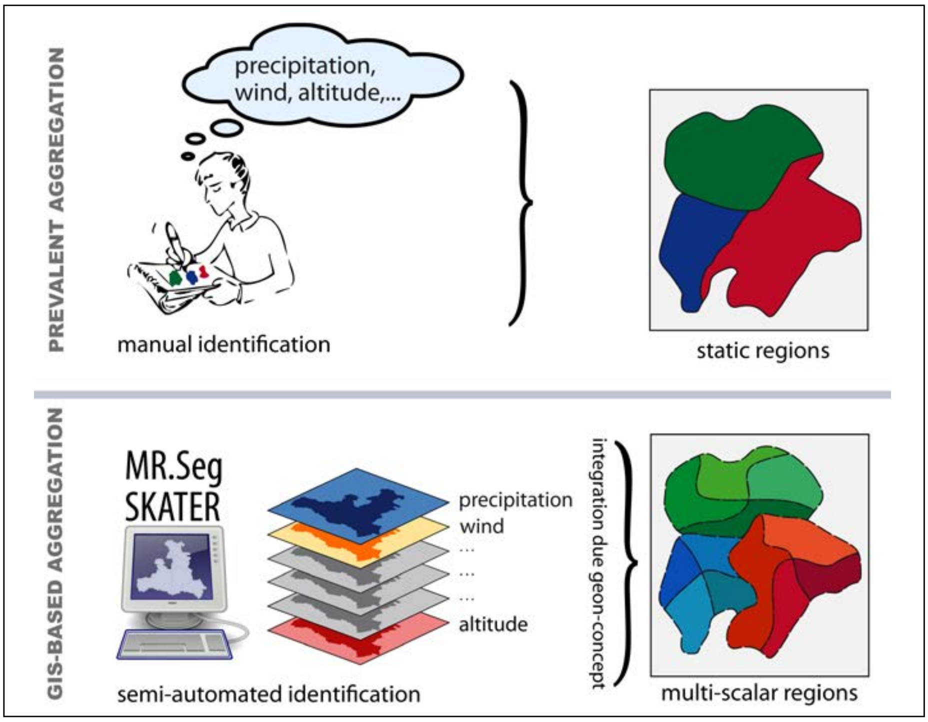

Figure 2: Manual and GIS-based aggregation

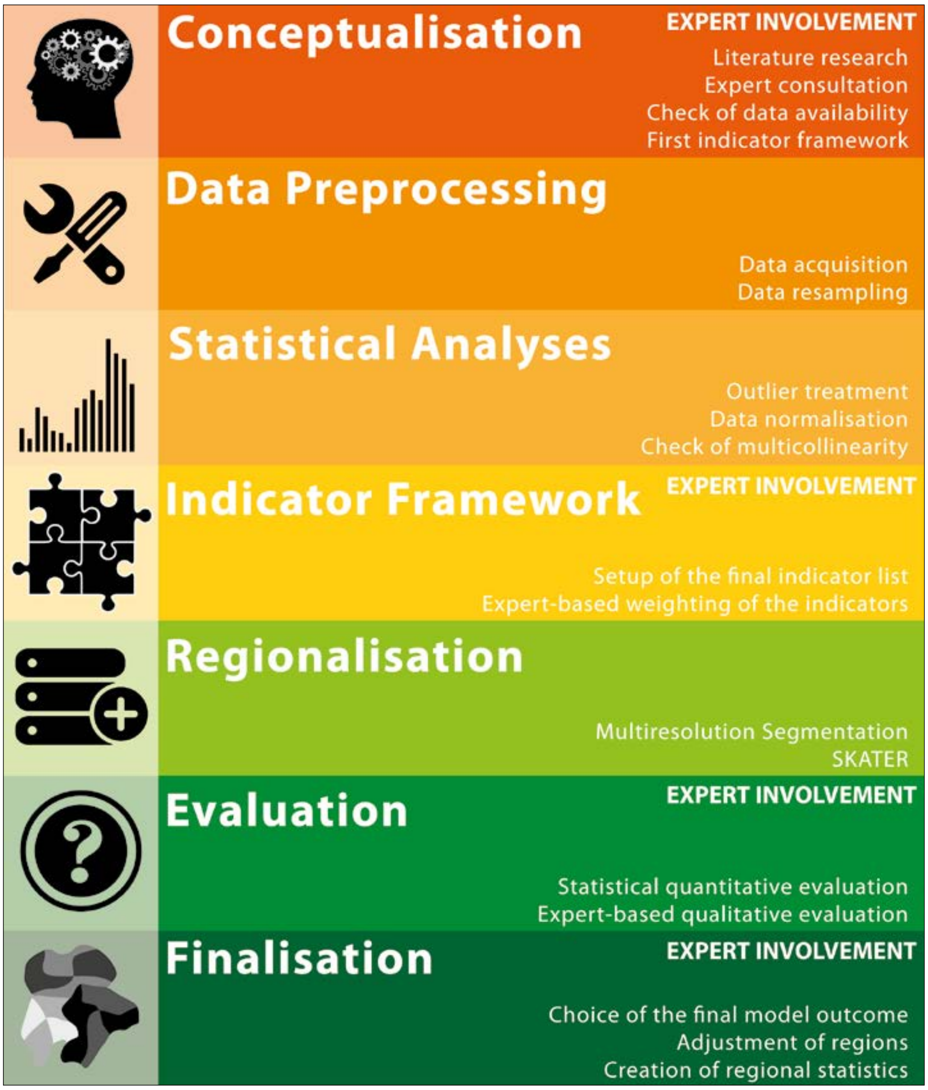

Figure 3: For some stages expert knowledge and experience were required

cio-economic vulnerability of the Salzach basin in Austria, Hagenlocher et al. (2013) used the concept to conduct a hotspot analysis of climate change in Western Africa and the Sahel zone, and Kienberger & Hagenlocher (2014) investigated the vulnerability to malaria in East Africa.

2 METHOD

2.1 WORKFLOW

Following the geon-concept (Lang et al. 2014) and the guideline for constructing composite indicators from the Organisation for Economic Co-operation and Development (OECD 2008), this study can be divided into seven stages (Figure 3), starting with the very first stage of conceptualisation, to data pre-processing, right up to indicator aggregation and the adjustment of the model outcomes. While some of these stages are discrete, others require the involvement of experts.

2.2 SELECTION OF INDICATORS AND EXPERT KNOWLEDGE

At the initial stage, a preliminary indicator framework (see Table 1) was developed based on literature research and expert knowledge, as well as on data availability. While local and short-term conditions are crucial for the prevailing avalanche risk, regional and long-term factors are decisive for the regionalisation of avalanche risk assessment zones. Generally avalanche risk can be divided into three main conditions (Fredston & Fesler 2009): (1) Terrain (e.g. slope, land coverage), (2) weather (e.g. fresh snow, air temperature change) and (3) snow pack (e.g. snow temperature, stratification) (McClung & Schaerer 2006, Bründl et al. 2010). Also for the avalanche risk assessment zones three main conditions can be noted: (1) land form (slope, aspect), (2) land cover, and (3) meteorology (e.g. air temperature, wind). Figure 4 visualizes the difference of the determining factors, which are certainly related. To obtain the final list of indicators, but also to facilitate the comparison and integration of different data, statistical analyses were essential. For this purpose, outliers respectively defective values of the input data were first detected and revised, then data were normalised using the min-max normalisation with an 8-bit range to enable the full radiometric spectrum of raster data as suggested by Kienberger et al. (2009) (see Equation 1).

The greatest advantage of the min-max method is that the value range is precisely from 0 to 1, while at the same time the outcome values do not change proportionally (Malczewski 1999). Especially with environmental phenomena, some indicators might have a high correlation to each other. In such a case, the indicator list should be reconsidered. Therefore, the Pearson's correlation coefficient was chosen to test for multicollinearity of the indicators. As suggested by the OECD (2008), layers with a high correlation that exceeds a defined threshold should either be removed or weighted. Following Kienberger et al. (2009) and the OECD (2008), a correlation coefficient of 0.9 was chosen as the threshold value to reconsider the indicator list.

For the avalanche risk assessment diverse indicators are crucial, however they are not of equal significance, and it might be necessary to apply a weighting. After the indicators were selected, experts from the avalanche warning service of Salzburg were consulted in order to ascertain the different weights for the indicators. Concerning this, the Analytic Hierarchy Process (AHP) pairwise comparison method was used. Using this method, the experts were asked to compare each indicator to every other indicator, and to determine the relative importance of each of them. Therefore, intensity values from 0 (equal importance) to 9 (extreme importance), based on Saaty (1980) and Saaty (2008), could be assigned.

2.3 REGIONALISATION

Once weights are attached to the indicators the regionalisation can be processed. For this study, two different regionalisation methods were applied, which do not only differ in their clustering principle, but also in their data input requirements. On the one hand, MRS was used, which is typically applied for (satellite) image segmentation purposes. However, it was found that this method is also appropriate for the aggregation process of the geon-concept. On the other hand, the SKATER clustering was applied, which was developed in 2001 by Lage et al., but did not gain broader recognition until 2006, when Assunção et al. presented a more detailed description of the algorithm. While MRS requires raster data as the input format, SKATER handles vector data, whereby polygons, polylines or points can be used.

MRS was developed by Definiens (Baatz & Schäpe 2000) as a patented algorithm, which is now available in Trimble's eCognition software. MRS should generate image object primitives, which offer a good abstraction of the reality in various resolutions (Oczipka 2007). Thereby, the segmentation process deals with the object value, as well as with the morphological properties of the objects. MRS multiresolution segmentation is defined as a 'region merging technique', which means that it starts with single pixels as the initial image objects, and merges them together in a pairwise manner (= bottom-up technique). At each step of the segmentation process one single pair of adjacent objects is merged to continuously growing objects. The following two conditions have to be fulfilled: (1) the two potential objects are mutually best fitting, and (2) a user-defined threshold of object heterogeneity is not over-reached. To verify the second condition the overall fusion value (f), expressed in Equation 2, is calculated (Definiens 2004).

The fusion value indicates the degree of change in heterogeneity between pre-merged and post-merged objects. The difference between two objects is expressed by a synergy of the shape heterogeneity (hshape) and value (or spectral) heterogeneity (hspectral). The latter one is defined as the degree of change resulting from the potential merge of two objects, whereby user-assigned weights for the layers (indicators), the amount of pixels comprising the objects, as well as the standard deviation of the pixel values of each indicator account for the object heterogeneity have to be given (Zhang & Maxwell 2006). Shape heterogeneity is defined in a similar manner, since it also describes the change in heterogeneity after a potential merge of two adjacent objects. However, the degree of change is a function of object compactness and smoothness. The former is described by the ratio of the actual border length and the square root of the number of pixels which make up the object. Smoothness is calculated using the ratio of the de facto border length and the shortest possible border length given by the bounding box of an image object (Definiens 2004, Oczipka 2007, Happ et al. 2010).

SKATER is an abbreviation for 'Spatial 'K'luster Analysis by Tree Edge Removal'. It is a graph-based hierarchical spatial clustering algorithm, which utilises a Minimum Spanning Tree (MST) to identify natural clusters. The SKATER approach was initially developed for the regionalisation of socio-economic phenomena (XYT), however, recent studies revealed that this approach can be further used by a large spectrum of research and application domains. Reis et al. (2007) for instance applied SKATER for the clustering of communication protocols in geo-sensor networks, Martin-Bedé et al. (2009) classified areas of high disease incidence, and Helblich et al. (2013) used the technique to segment housing markets. In contrast to MRS, SKATER follows a top-down strategy, which means that the clustering process starts with one single region containing all spatial objects, and divides it into smaller regions in a step-wise manner. The overall regionalisation process can be divided into three main steps: (1) a connectivity graph of spatially contiguous objects is built whereby a cost value for each edge is used. This cost value should represent the dissimilarity between two connected spatial objects by considering the object attribute values, (2) a spatially contiguous MST is created based on the connectivity graph and the cost value, and (3) the recursive partitioning of the MST is calculated. Edges which link dissimilar objects are sequentially eliminated to form contiguous clusters. Partitioning takes place as long as a user-defined number of regions is not reached. The edge that indicates the highest heterogeneity is thereby cut out from the MST in each iteration. The quality measure is therefore defined as the sum of intra-cluster squared deviations, as can be seen in Equation 3 (Assunção et al. 2006).

3 EVALUATION

Since the assessment is strongly dependent on the used data and the purpose of the regionalisation, no fixed guideline regarding how to evaluate the quality of the resulting regions exists. However, it is generally possible to distinguish between two kinds of evaluation methods: (1) the qualitative-visual evaluation, and (2) the quantitative-statistical evaluation. Both methods were applied in this study. The qualitative evaluation was carried out by the same experts from the avalanche warning service who carried out the indicator weightings. These experts were asked to consider their substantial knowledge of avalanche risk assessment in the study area and award score points from 0 (very bad) to 10 (very good) to the regionalisation outcomes, depending on how appropriate they thought the single regions were. A quality measurement function was created for the quantitative evaluation. Since the goal of all regionalisation's is to create regions that are as homogenous as possible, the function defines the overall homogeneity of the regionalisation, whereby the weighted standard deviations of the indicators as well as the amount and the size of the regions are considered. Equation 4 describes this function (oHet), and Equation 5 normalises the outcome value (oHet) to express the quality in percentage of homogeneity (oHom).

$$v' = \frac{v - \min}{\max - \min}(\max_{norm} - \min_{norm}) + \min_{norm} \quad (1)$$

Where: v' = new object value; v = initially object value; *max* and *min* = maximum and minimum value of the value range; max_{norm} and min_{norm} = normalised value range

$$f = \omega * h_{value} + (1 - \omega) * h_{shape} \quad (2)$$

Where: ω = user defined weight for v; h_{value} = spectral/value criterion; h_{shape} = shape criterion

$$\mathrm{Q}(\pi) = \sum_{i=0}^{k} SSD_i \quad (3)$$

Where: π = a partition of objects into *k* trees; *i* = region; *SSD* = sum of squared deviations in region *i;*

$$oHet = \sum_{k=1}^{n} \frac{\frac{\sum_{i=1}^{m} \sigma * \omega}{4}}{size^{total}} * size^{k} \quad (4)$$

Where: σ = standard deviation; ω = user defined weight; $size^k$ = size of region *k*; $size^{total}$ size of the study area; n = number of regions; m = number of indicators; k = region, i = indicator

$$oHom = \frac{(\bar{x}_{norm} - oHet) * 100}{\bar{x}_{norm}} \quad (5)$$

Where: $\bar{x}_{norm}$ = the mean value of the normalised value range; $oHet$ = overall heterogeneity

4 RESULTS

A preliminary indicator framework was developed based on literature research and expert knowledge, whereby data availability was also considered. Table 1 presents the list of indicators that were considered for further processing. At this point it is important to understand that in contrast to the actual avalanche risk, not local and short term conditions are important for modelling homogenous assessment areas, but much more regional and long-term averages. Consequently, climate conditions (annual or winter month average) were taken into consideration instead of short-term diurnal weather conditions. For the final list of indicators 'frost days' and 'maximum snow pack depth' had to been removed since they exceeded the discussed threshold of 0.9 for the Pearson's correlation.

Experts from the avalanche warning service were interviewed to obtain the indicator weighting (see Figure 5). To avoid reciprocal influencing, the experts were consulted separately. Figure 5 visualises the overall weighting of the indicators. It shows that the average wind speed (33.23%) and the amount of fresh snow (25.84%) together make up over half (59% in total) of the impact in the regionalisation approach, while aspect (3.75%) and the land cover (2.47%) have only a weak influence and consequently just a minor relevance in the regionalisation process.

Generally differing but albeit partly related models were used to achieve diverse outcomes in the regionalisation process,

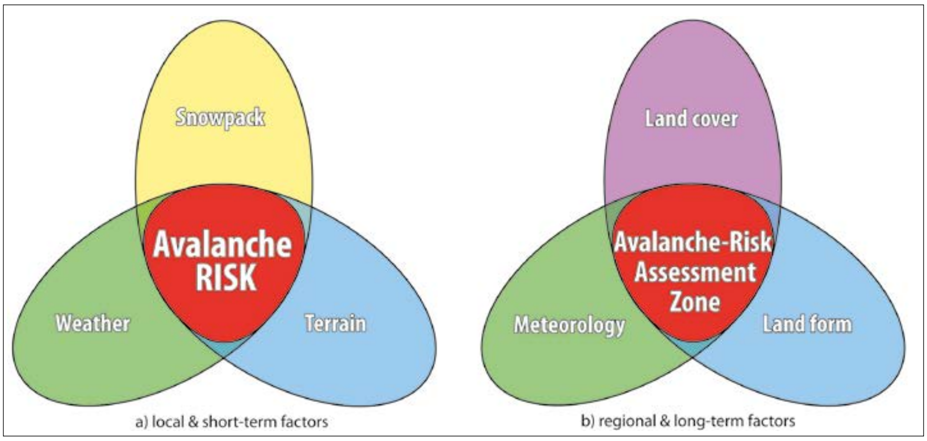

Figure 4: Determining factors for (a) avalanche risk and (b) avalanche-risk assessment zones

Indicator	Meaning**)
Fresh snow	The amount of fresh snow is often crucial that the snow pack can no longer overcome the appealing forces. Especially a high amount of fresh snow in just a short period increases the snow pack stress immensely due the rapid loading
Air temperature	The air temperature mainly influences the temperature of the snow pack. Colder air results in colder snow temperature which decelerates the solidification of the snow pack.
Max. snow pack depth*	A thicker layer of snow decreases the stability of the snow pack.
Freeze-thaw cycles	The frequency of frost changes has an impact on the snow pack density. The gentle diurnal melting and re-freezing of the snow typically forms snow crystals, which further promotes the snow pack stability.
Frost days*	Like the air temperature, also frost days influence the snow temperature. Colder regions have a negative effect on the stability of the snow pack.
Altitude	The altitude can be seen as an overall indicator for the avalanche risk. Various phenomena, especially land cover and climate conditions change along with the altitude. Generally, it can be assumed that a higher altitude has a negative effect on the snow pack stability and increases the probability of an avalanche release.
Wind speed	Wind speed controls the type, as well as the location of instability. When wind speed exceeds 7 m/s the blowing snow becomes a crucial factor.
Aspect	The aspect has profound influence on the snow pack. North facing slopes receive less sun and heat and remain colder. Consequently also the snow temperature tends to be colder and delay the snow pack stability.
Slope inclination	A slope must be steep enough that an avalanche can even emerge, however, if the slope is too steep the snow cannot accumulate. The highest avalanche danger is usually between 35° and 40°.
Land cover	Generally, it can be assumed that the higher and denser the vegetation and the rocks are, the less likely it is that an avalanche will occur. The vegetation but also rocks thereby serve as a natural anchor.

*) Were not considered in the final regionalisation due to high multi-correlation
**) Fredston & Fesler 1999, Bartelt & Stöckli 2001, McClung & Schaerer 2006

Table 1: Preliminary list of indicators

and to identify advantages and disadvantages of the used regionalisation approaches. The models do not only differ in the software and regionalisation strategy that was used, but also in terms of the applied parameters for the homogeneity threshold, for the shape criterion (only feasible in MRS), respectively for the neighbourhood definition (only feasible in SKATER). The aim was to achieve diverse regionalisation outcomes where regions vary in size and shape. 36 different regionalisation models were applied in total. Trimble eCognition 9.0 was used for the regionalisation with the MRS approach, while Terra View 4.2 respectively ArcGIS 10.2.2 served as the software solution for the SKATER algorithm.

To identify the best result of all of the models, a quantitative-statistical evaluation as well as a qualitative expert-based evaluation was necessary. However, to reduce the effort for the experts, but also to prevent redundant evaluations, only nine out of the original 36 model results were taken into account for the qualitative evaluation. The selection of these nine models was subject to three main criteria: (1) model representation, (2) quantitative eligibility, and (3) pre-qualitative evaluation. The evaluation of the nine regions was done autonomously by the same experts who were already responsible for the indicator weighting.

The quantitative and qualitative evaluations revealed that the models using the MRS strategy are preferable to those than those applying the SKATER algorithm. While the degree of the overall homogeneity for outcomes within the MRS approach ranged between 75% and 78%, those from SKATER were only between 67% and 74%. The qualitative evaluation by the experts paints a similar picture. However, it emphasised that not only the homogeneity but also the morphology of the individual regions is of relevance. Consequently, more compact regions are more desired by the experts and therefore received a better evaluation than those outcomes with rather fragmented but certainly more homogeneous regions.

For the finalisation of the avalanche risk assessment zones the experts were consulted once again to incorporate their knowledge and experience but also their ideas and desires for the new and final assessment regions. The experts largely decided to use the outcome of an MRS model, which shows a high homogeneity paired with quite compact regions. However, slight modifications were necessary for a few regions to ease the daily risk assessment by the experts and for a better comprehension by the clients. Figure 6 visualises the modelled avalanche risk assessment zones.

As already mentioned the definition of avalanche risk is vague and comprises a complex interplay of various indicators. However, considering the weighed mean values, as shown in Figure 5, conservative estimations about the general avalanche danger can be made. The assumption is that, in a static view of risk, regions with a higher mean value indicate more danger than those with a lower value. This assumption is strengthened by a comparison of the

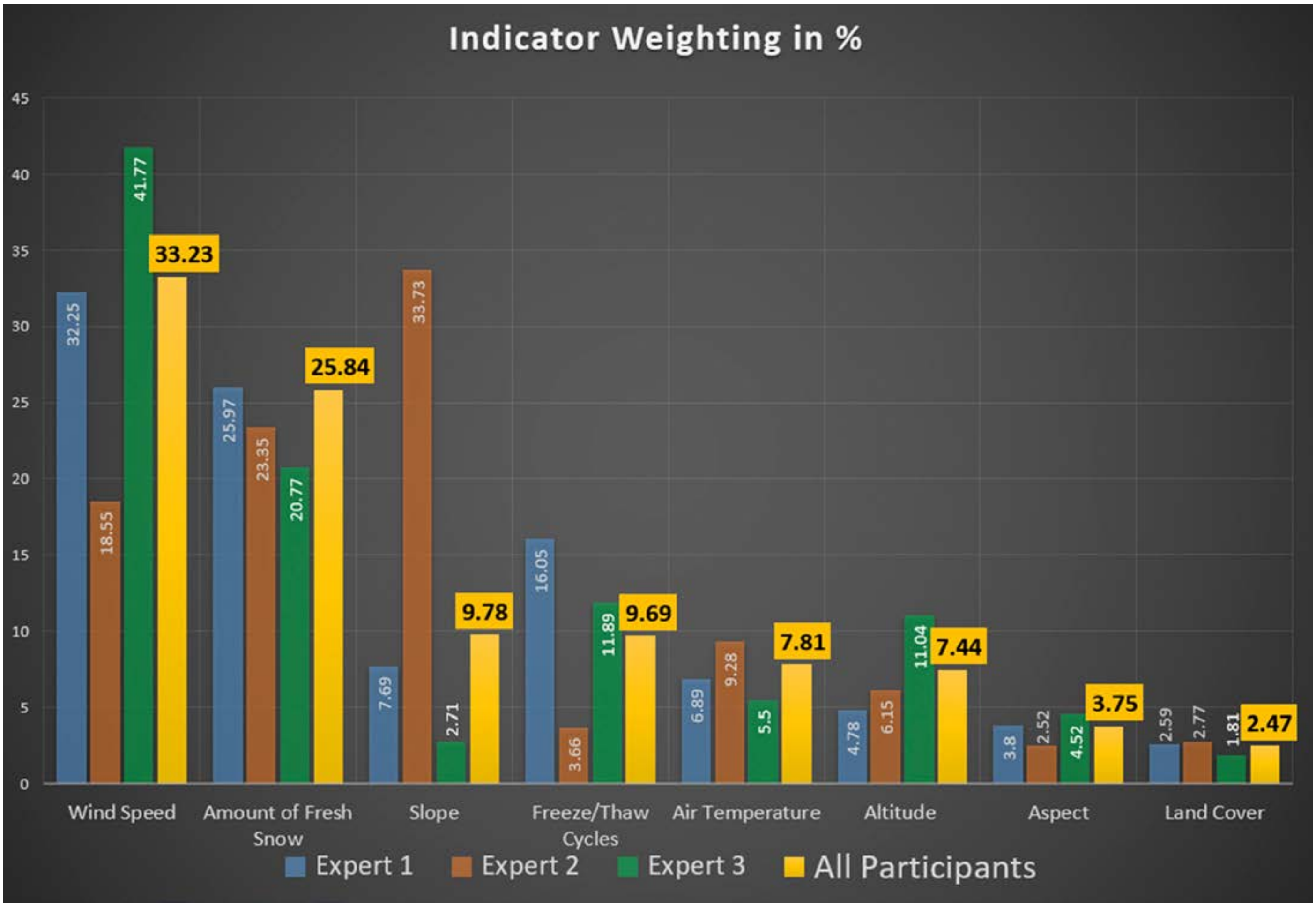

Figure 5: *Indicator weights as defined by three experts*

mean value between the resulting regions and the actual avalanche risk during the winter months in Salzburg. Regions with a high mean value are usually judged with a higher avalanche risk than the others.

5 DISCUSSION

The aim of this study was not only to model new avalanche risk assessment zones for the state of Salzburg, but also to identify the advantages and disadvantages of the regionalisation methods of MRS and SKATER. The main purpose of regionalisation is to produce regions that are internally as homogenous as possible, but at the same time differ from other regions. It was ascertained that there are some major differences between SKATER and MRS. While SKATER clustering could not cope with all requirements extensively, the multiresolution segmentation generally offered good results throughout all models. This could be validated by the quantitative evaluation and through the expert-based qualitative evaluation. However, the experts do not necessarily consistently agree with the statistical evaluation. In fact, the experts preferred compactness over homogeneity, which meant that highly homogenous but fragmented regions were not taken into further consideration. This might have two reasons, namely the assessment process and the legibility by the user. The current assessment areas are likewise compact, and the experts are accustomed to it. Furthermore, compactness means a greater regionality in a sense. This eases the risk assessment for the experts since they do not necessarily have to think about local conditions, such as the vernacular weather. More compact regions also facilitate the legibility for the user. While fragmented areas would obviously exacerbate the identification of the appropriate risk level, in more compact regions the user can identify the risk level at one quick glance. Especially after the slight adjustment of some regions, the final outcome can be seen as a potential replacement for the given avalanche risk assessment zones. The GIS-based modelled zones do not only have a greater homogeneity, they also appear to be more accurate than the current cognition-based zones. The expert-based evaluation also pointed out that the current zones are to spatially overlarge which affects negatively the homogeneity. The regional variability of these zones exacerbates an appropriate risk assessment.

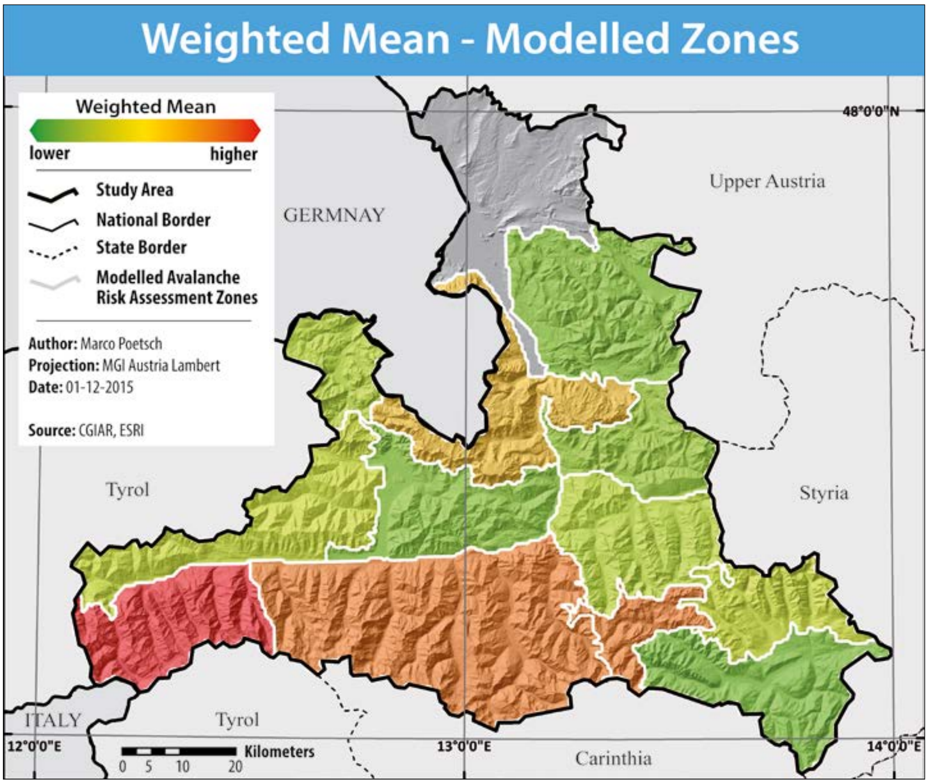

Figure 6: The final avalanche risk assessment zones, visualised by the weighted mean value

The geon-concept, which was used in this study, revealed significant strengths for the purpose of modelling avalanche risk assessment zones. It acted as a framework for modelling such homogenous regions that were initially considered to be 'unmeasurable'. Furthermore, the concept allows modelling regions without any restrictions of administrative, or other given boundaries. That could be an important circumstance since especially natural phenomena do not stick on unnatural boundaries (Lang et al. 2014). In the recent year's computational models were already applied for the assessment of avalanche risk. Most of them use classic GIS-elements and methods, such as a combination of reclassification and weighted overlays of local and regional indicators. Such studies mainly focus on identifying the diurnal avalanche risk, rather than on identifying homogenous regions of the risk assessment (Zischg et al. 2004, Rauter et al. 2006, Covăsnianu et al. 2009, Gruber et al. 2009, Klebinder et al. 2009). However, besides a lack of indicator consideration, the simplicity of these models leads to a limited reliability of the results. A well aggregated computational model may be able to support the decision making process, but professional knowledge and the human-based assessment of avalanche risk is still the major criterion.

6 OUTLOOK

This study modelled the assessment zones in a relatively static manner. The utilized indicators represent the relevant conditions in long-term averages. Accordingly, the resulting regions can be seen as homogenous areas for further risk assessment. While these areas are able to replace the existing, conceptually-delineated assessment zones, further adaptions regarding the framework could bring even more utility. One adaption could be the replacement of the long-term indicators (averaged climate conditions) with short-term indicators (weather conditions), paired with a diurnal update of the model. This way the resulting regions would change dynamically and would be more meaningful for the avalanche risk assessment. However, it has to be recognised that even if local and short-term condition were to be used, the model cannot be used as a trustworthy indicator for the actual avalanche risk. The complex interplay of causal avalanche conditions is too intricate to be expressed by any computational model. Another problem is the reliability of computational models. As Bründl et al. (2010) mentioned, an expert will only employ a computer model if it provides information beyond his experience. Expert knowledge and experience will still be the major criterion for any avalanche risk assessment. Results which are not unanimous with the experience are seen as un-trustworthy. However, recent ambitions, such as the "Lawinenbulletin" from the SLF (Institute for Snow and Avalanche Research) shows that a complex but well aggraded computer model, paired with local expert knowledge and a plethora of gaging stations for relevant indicators, allows new possibilities in the support of risk assessment (WSL 2015).

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