AVALANCHE HAZARD MAPPING USING THE AVALANCHE TERRAIN EXPOSURE SCALE (ATES) IN THE HIGH MOUNTAIN RANGES OF BULGARIA

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ABSTRACT: Backcountry skiing and touring has become more popular in Bulgaria in the past decade. Unfortunately, the rise in popularity of these activities has also been accompanied by avalanche accidents. In addition, there is no official avalanche center that issues regular avalanche bulletins for the Bulgarian mountains, and therefore backcountry ski tourers and hikers need to rely mostly on their own judgement. Avalanche terrain mapping using the Avalanche Terrain Exposure Scale (ATES) helps recreationists and professionals make informed decisions on how to navigate safely in avalanche terrain. We have developed procedures to create ATES maps for three pilot regions in the Bulgarian mountains – the region around Bansko Ski Resort in the Pirin Mountains and the Rila Lakes - Skakavitsa and Malyovitsa regions in the Rila Mountains. The ATES models were created using an automated approach combining geographic information systems (GIS) and geospatial technologies and software following the AutoATES v2.0 model. As initial inputs we used digital elevation models (DEM) and crown cover data as a proxy for forest density. First, potential release areas (PRAs) of avalanches were determined using a combination of several key terrain and forest characteristics. Next, the Flow-Py simulation tool was applied to model avalanche runouts, using the PRAs and DEM as input. Finally, the Flow-Py results and different terrain and forest characteristics were combined using thresholding to classify the terrain into four ATES classes – Simple, Challenging, Complex and Extreme. The resulting ATES maps were evaluated manually based on expert assessment. The main obstacles encountered during the automated procedure were related to accurately modelling PRAs and avalanche paths in forested terrain. We tested several different approaches and data sources to model forest density. The best results were achieved after modification of thresholds for forest density classes and setting a rule that forested terrain with slope inclination of more than 39 degrees could not be classified as Simple terrain. Further improvements can incorporate better algorithms for modelling avalanche-forest interactions. The manual evaluation based on expert assessment has shown that the automated ATES maps created in this work are reliable and demonstrate the applicability of the method for the Bulgarian mountains.

KEYWORDS: ATES maps, avalanches, Bulgaria, AutoATES, forest protection

1. INTRODUCTION

The popularity of backcountry skiing and touring in the Bulgarian mountains has increased in the past decade. Unfortunately, this raises the risk of avalanche accidents, and such have occurred over the years. Due to the lack of an official avalanche center that issues regular avalanche bulletins for the Bulgarian mountains, backcountry ski tourers and hikers need to rely mostly on their own judgement. Avalanche terrain maps based on the Avalanche Terrain Exposure Scale (ATES), introduced in Canada by Statham et al. (2006) can help recreationists and professionals make informed decisions on how to plan their routes and navigate safely in avalanche terrain. For this reason, ATES maps have been developed for various areas in the world (e.g. Gavaldà et al., 2013; Larsen et al., 2020; Avis et al., 2023; Huber et al., 2023; Sykes et al., 2023). In Bulgaria three-class ATES maps were produced for the Bansko ski area region in the Pirin Mountains and two popular regions in the Rila Mountains (Malyovitsa valley and the Seven Rila Lakes region). The first maps were based on expert assessment and manual GIS mapping (Panayotov et al., 2021) and then automated routines in a GIS environment were applied in search of a more robust and replicable approach (Markov and Panayotov, 2024). However, these previous works encountered issues requiring readjustment of the ATES mapping and expert modifications to achieve reliable results. This limited the opportunities to produce maps for larger mountain regions. In addition, the use of the three-class ATES approach created excessively large areas classified as Complex terrain, which made it difficult for users to distinguish between very steep and unmanageable terrain and terrain which allows for skiing and hiking in safer snow conditions. In addition, earlier work met difficulties in obtaining digital elevation models (DEM) with sufficient detail and accuracy and in finding reliable sources on forest structure data, which motivated us

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to also seek improvement in this direction.

In the present study we aimed at producing four-class ATES maps (Simple, Challenging, Complex, Extreme) for test areas in the Bulgarian mountains with an automated work flow containing solely open-source modules, as outlined in Huber et al. (2023), with publicly available data sources as input data. The method is largely based on AutoATES v2.0 (Toft et al., 2024) with some minor adaptations. Our goal is to be able to replicate the methodology for large areas and thus enable the production of large-scale maps. We also tested several different data sources and approaches to determine forest density and made slight modifications to the ATES classification algorithm, because our trials showed that forested regions were the most problematic and the initially tested automated procedure was not able to produce reliable results there.

2. STUDY SITES AND METHODS

2.1. *Study sites*

We selected three study areas as test regions: the Bansko ski resort region, the Seven Rila Lakes- Skakavitsa valley region, and the Malyovitsa region. They were chosen due to their high popularity among winter recreationalists and their diverse terrain characteristics.

The Bansko test area encompasses the entire Bunderitsa valley and part of Demyanitsa valley, in the vicinity of Bansko ski resort in the Pirin mountains. The valleys are characterized by slopes with considerable vertical extents of up to 1000 m and avalanche couloirs in which periodically large avalanches occur (Panayotov et al., 2023; Panayotov et al., 2024a) Also, parts of the slopes are covered by steep old-growth forests in which there are areas with avalanche activity (Panayotov and Tsvetanov, 2024).

The Seven Rila Lakes – Skakavitsa valley region in the Rila Mountains is characterized by a combination of very steep top sections of the slopes followed by more gentle terrain with occasional smaller steep sections, where winds frequently create deep snow slabs and produce avalanche danger. This terrain combination proved to be difficult for automated classification in the previous ATES mapping trials.

The third study area is the Malyovitsa valley region in the Rila mountains. It is characterized by steeper and longer slopes with many vertical rock bands, resulting in frequent avalanches. Some adjacent smaller valleys, which run parallel to the main one, are less steep, but they still contain isolated steep sections similar to the Seven Rila Lakes region. Forests in this area are limited to only the lower parts of the main valley and play minorl protection role.

For each test area, we obtained digital terrain models (DTM) from the Rila National Park and Pirin National Park administrations. They had a resolution of 5 m and were based on digitized maps with a scale of 1:5000. For regions without forests, we also used a 4 m resolution digital surface model (DSM) based on aerial photography produced by the Ministry of Agriculture of Bulgaria. After initial trials we found that better and “less-noisy” results were achieved by using a resampled 10x10 m DEM based on the original 4 m and 5 m resolution models. The resampling was performed by bilinear interpolation. Because the databases of both national park administrations lacked reliable information on forest density, in order to obtain information for the forest density we used as a proxy data source the Copernicus Percent Canopy Cover product. It provides a pan-European raster for crown coverage in 10 m pixel resolution based on Sentinel-2A/2B satellite sensors (Tree Cover Density, 2020). In addition, for a part of the Bunderitsa valley, where we chose to experiment with different approaches for determining percent canopy cover of forests, we also used RapidEye satellite data with 5 m pixel resolution (RapidEye ESA archive, 2024), and a very-high resolution (20 cm) orthophoto image produced with a DJI Mavic 3 drone together with a DSM model based on it with a cell resolution of 20 cm.

2.2. *Methods*

We initially applied a model chain previously used for automated ATES mapping in Austria (Hesselbach, 2023; Huber et al., 2023) to our test regions. This model chain is largely based on AutoATES v2.0 (Toft et al, 2024) and categorizes terrain into four ATES classes: Extreme, Complex, Challenging and Simple. It follows the updated suggestion for a 5-class scale by Statham and Campbell (2024) but avoids the class “Non-avalanche terrain” because our test areas are mountain valleys containing very few territories without any possibility of being affected by avalanches. This approach calculates in three steps consecutively potential avalanche release areas (PRA), then performs avalanche runout modelling, and finally classifies the terrain into the aforementioned four classes.

For calculation of potential avalanche runout distances, the model chain utilizes Flow-Py (D’Amboise et al., 2022). Model parameters are chosen in accordance with Huber et al. (2023) and Hesselbach (2023), who used the parameterization to model avalanches of size 3 according to EAWS for a study area in the Austrian Alps.

In this approach forests are grouped into 4 categories based on crown coverage data from Copernicus. Open forests have crown coverage below 10%, sparse forests - 10-25% coverage, moderate - 25% to 65%, and dense – greater than 65%. Forest density has a major impact on the definition of potential release areas (PRA) and also during the final classification steps. For example, terrain that falls into the moderate or dense categories of forest density will receive a downgraded ATES class (relative to its preliminary calculated one) during the final classification in order to account for the protective function of forests. However, it is important to note that forest density was not explicitly considered as a parameter to the avalanche runout modeling using FlowPy in this approach.

Because our trial results showed that by using the Copernicus data on forest density many forested areas were not correctly classified and their protective functions were overexaggerated, we tested several other approaches to simulate the forest density and ATES classification in forests. We isolated an avalanche-prone region that is partially covered with forests in the lower part of the Bunderitsa valley, on the western face of Todorka peak, and tried three different approaches to better capture the forest density there. The first of these additional approaches used the RapidEye satellite data and a Random Forest machine learning algorithm, which was trained to classify forested and non-forested terrain based on all five original RapidEye data bands and also calculated NDVI, NDWI, NDRE indices. We did this following the approach of Sykes et al. (2022). This approach was called “RapidEye forest”. The second approach was the same as the first, but we also added another feature that represents the difference between the DSM and the DTM and based on this value reveals territories which have a large difference, suggesting tall trees can be found there. This approach was called “RapidEye&DSM-DTM diff”. For the third approach we used a high-resolution drone-captured image, the difference between the high-resolution DSM and DTM, and also other custom features such as ruggedness and a drop raster (capturing maximum change in elevation between a pixel and its neighbors), calculated from the DSM. These features were fed into the same Random Forest ML classifier to differentiate between forested and non-forested terrain. This approach was called “CustomApproach-DroneData”. The results from these 3 approaches to simulate forest density were used to produce binary forest vs. non forest layers, which were then converted to a percent canopy cover using a 5 by 5 moving window following the approach of Sykes et al. (2022).

We then ran the same ATES calculation model chain, but using the obtained different layers of percent canopy cover data, on the selected small region on the western face of Todorka Peak. Unfortunately, the results showed that improving the forest density data alone was not enough to produce optimal results for the final ATES maps. Therefore, we decided to also make an additional modified version of the used ATES classification algorithm. We classified open forests as having less than 20% crown coverage, sparse forests - 20-55% crown coverage, moderate forest density with 55-75% crown coverage, and dense forests with more than 75% crown coverage. These definitions were used in the AutoATES v2.0 calculation model by Toft et al. (2024). In addition, we redefined a rule in the classification tree. If the inclination of the slope was calculated to be more than 39°, we changed the algorithm so that this territory could not be classified as Simple terrain, no matter how dense the forest was calculated to be. The motivation was that such steep forests, at least the subalpine ones in Bulgaria, usually contain occasional rock bands and openings, such as old avalanche tracks. We used the threshold of 39° for our new rule, as this was the chosen slope threshold to distinguish between the Challenging and Complex terrain classes based on analysis by Hesselbach (2023).

Finally, we ran this modified algorithm with the forest density results from the three different approaches on the small test region on the western face of Todorka peak.

3. RESULTS

We produced four-class (Extreme, Complex, Challenging and Simple) ATES maps for the three study areas. The Bansko ski area map encompassed 3717 ha, the Malyovitsa valley area - 1441 ha, and the Seven Rila Lakes - Skakavitsa area – 1779 ha. Most of the terrain was classified as Simple in all study areas (Table 1). Challenging was about 30% of the area in the Bansko and Malyovitsa study sites, while in both Complex terrain occupied more than 20% of the area. The Seven Rila Lakes-Skakavitsa region contained terrain mostly classified as Simple. Extreme terrain covered a very small percentage of all study sites.

Table 1. Total area of ATES maps and percentage of area in different ATES classes

Area	Bansko	Malyovitsa	Seven Rila Lakes - Skakavitsa
ATES Class	Percentage of area		
Simple	46%	41%	73%
Challenging	30%	27%	13%
Complex	21%	26%	11%
Extreme	3%	6%	4%
Total area, ha	3717	1441	1779

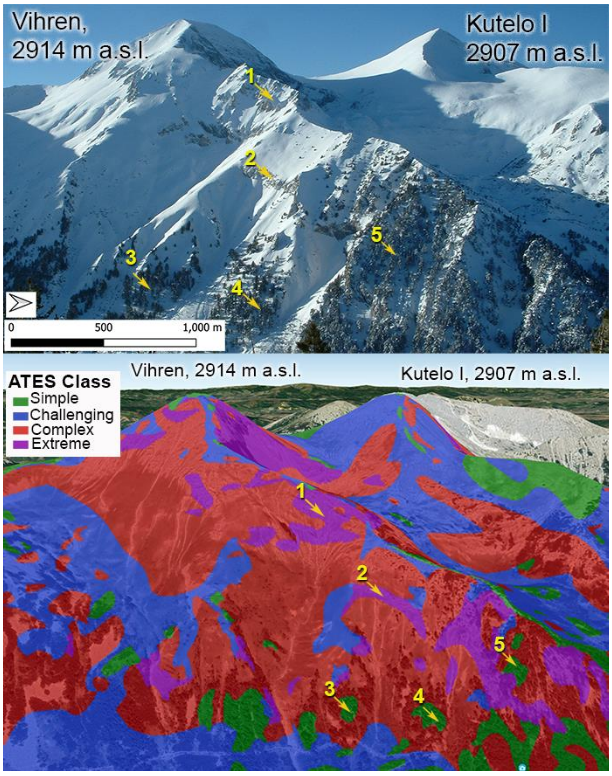

Fig. 1. Image of the eastern slopes of Vihren and Kutelo peaks in the Pirin Mountains as viewed from Todorka peak (top) and ATES map for Bunderitsa valley (Bansko ski resort area in the Pirin Mountains) produced with Copernicus Tree Cover Density and "AutoATES Austria" (bottom). Numbers indicate correctly identified Extreme terrain in rock bands (1, 2) and non-correctly identified steep, forested terrain (3, 4, 5), which was classified as Simple terrain due to the forest cover, but has periodic avalanche activity and high inclination, due to which it would be more correct for it to be classified as Challenging terrain.

The ATES maps produced by using the AutoATES Austria approach (Huber et al., 2023) classified the terrain in open areas very well, based on our expert verification. The steepest and rocky sections of the slopes were correctly classified as the Extreme ATES class. Although this class occupied less than 10% of the area in the separate study regions, it outlined these sections very well (Fig. 1, Fig. 2). In our opinion based on years of local experience and observations, we believe that the automated routine also classified the Complex and Challenging terrain classes quite well. Even the shorter steep areas amidst flatter terrain in the Seven Rila Lakes region, which were a challenge for correct classification in previous automated attempts and required manual modification or readjustment of parameters, were now classified in accordance with our expert judgement as Challenging terrain (Fig.2).

What we found as problematic were forested areas, where the initially used forest density based on the Copernicus Tree Density product was often overestimated and therefore the algorithm classified even steep forests with known avalanche activity as Simple terrain. However, in our study sites the steep forests (inclination above 35 degrees) were often with more space between the trees due to the high age of the forest and past avalanche activity.

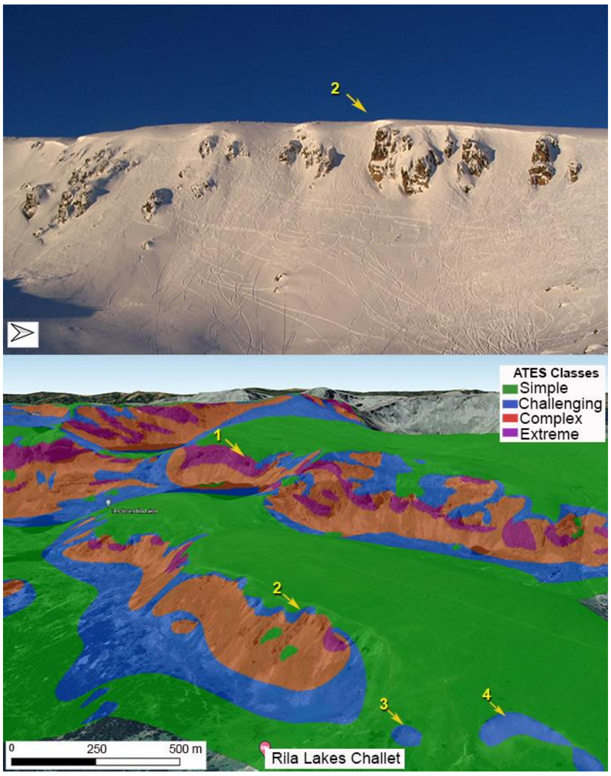

Fig. 2. ATES map of the region of the Seven Rila Lakes in the Rila Mountains (bottom) and image of the slope facing the Rila Lakes Chalet (top). The ATES map produced with the Copernicus Tree Cover Density and "AutoATES Austria" calculation chain correctly identified the rock bands (1), steep couloirs with rocks (2) and short steep terrain, which periodically has wind-slabs (3, 4).

Table 2. Percentage of total area of the test region in Bunderitsa valley per ATES class produced by the various ATES calculation approaches

	ATES calculation approach							
	AutoATES Austria model-chain				Modified model-chain			
ATES class	Copernicus forest density	RapidEye forest density	RapidEye&DSM-DTM diff	CustomApproach-DroneData	Coperniucs forest density	RapidEye forest density	RapidEye&DSM-DTM diff	CustomApproach-DroneData
Simple	73.8	86.6	77.5	71.6	57.9	49.9	51.6	40.7
Challenging	10.5	6.6	9.4	8.9	25.9	41.3	33.6	37.8
Complex	14.8	6.7	13.1	18.4	15.1	8.7	14.8	20.3
Extreme	0.9	0.1	0.1	1.2	1.1	0.1	0.1	1.2

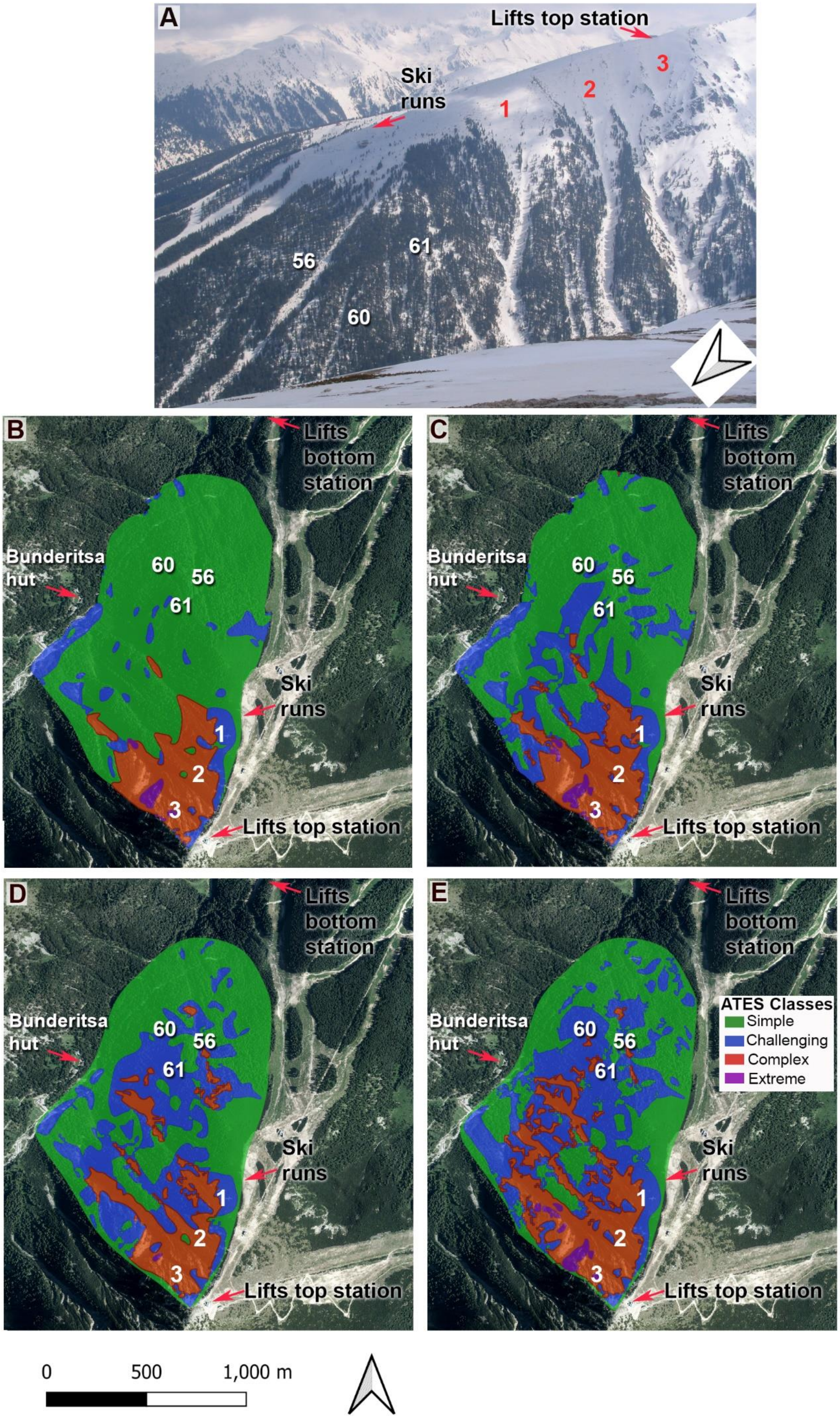
A
Lifts top station
Ski
runs
1
2
3
56
61
60
B
C
D
E
Lifts
bottom
station
Bunderitsa
hut
Ski
runs
Lifts top station
ATES Classes
Simple
Challenging
Complex
Extreme
0
500
1,000 m

Fig. 3. Different version of ATES maps for the Bunderitsa forest area produced by using varying approaches to simulate forest density and interpret slope angle. Numbers on the images show avalanche numbering following Panayotov et al., 2024.

A. Image of Bunderitsa forest and a few of the avalanche couloirs on the Northwestern slope of Todorka peak. The image was taken from the opposite slope.

B. ATES map of the selected forested region produced with Copernicus forest density, AutoATES Austria calculation approach (for details please see the methods section). Numbers indicate avalanche couloirs (1, 2, 3) and existing avalanche tracks with periodic avalanche activity (56, 60, 61). The numbers are following Panayotov et al., 2024.

C. ATES map of the selected forested region produced with Copernicus forest density, modified algorithm

D. ATES map of the selected forested region produced with “RapidEye&DSM-DTM diff” forest density calculation approach, modified algorithm

E. ATES map of the selected forested region produced with “CustomApproachDroneData” forest density calculation approach, modified algorithm

Therefore, we considered a classification of such forests as Simple terrain as not corresponding to reality. Our best illustrating example is the forests in the Bunderitsa valley, where we have observed avalanche activity (Panayotov et al., 2024), there have been accidents with people, including fatal, and our tree-ring based avalanche reconstructions have shown big avalanches in the past and recent years (Panayotov and Tsvetanov, 2024). The ATES map produced with the Copernicus Forest density and AutoATES Austria approach correctly classified the top parts of the large avalanche couloirs as Challenging, Complex and Extreme terrain (Fig. 3B, indications with numbers 1, 2, 3), but failed to classify the steep forest areas with avalanche tracks (Fig. 3B, indications with numbers 56, 60, 61) correctly and outlined them as Simple terrain. The approaches based on RapidEye satellite data performed slightly better in identifying the larger forest gaps but did not correctly distinguish areas covered with dense bushes of dwarf mountain pine (*Pinus mugo*) at the top part of the slopes and avalanche couloirs. In such areas the terrain was downgraded to the Challenging class. However, the *Pinus mugo* bushes do not provide a sufficient protection role when they are covered with snow and it is more correct for the terrain there to be classified as Complex based on slope and terrain characteristics.

The custom approach based on high-resolution images made by the DJI Mavic 3 drone camera performed better, but still misclassified some forested terrain with numerous openings as Simple.

When we applied our modified calculation model chain with different thresholds on classifying forest density and the 39-degree rule (please see Methods) the resulting ATES maps represented the terrain better. The proportion of the Simple terrain was about 50%, while that of the Challenging increased to between 26 and 41% (Table 2). Complex terrain increased its share as well. The CustomApproachDroneData correctly classified the avalanche couloirs as Complex terrain, the few very steep rocky sections as Extreme, and most of the steep forests as Challenging (Fig. 3E). The avalanche tracks in the forest where there are also small rock bands were classified as Challenging or Complex terrain (Fig. 3E, numbers 56, 60, 61). The modified RapidEye approaches correctly classified most of the steep forests and couloirs but also produced some patches of Simple terrain inside avalanche couloir number 1 (Fig. 3D). The approach based on Copernicus Tree Density with the modified rule for forest density thresholds and the limiting 39-degree rule also produced a map with fairly good identification of steeper forested sections, which although patchy, could be interpreted correctly by a user (Fig. 3C).

4. DISCUSSION

The resulting four-class ATES maps for the three study areas in Bulgaria with the AutoATES Austria model chain outlined terrain with different characteristics quite well in terms of avalanche risk. The introduction of the Extreme class allowed for separation of very steep, rocky parts of the slopes, which are not manageable in terms of selection of a safer route, from steep, but not rocky terrain. This is a definite advantage compared to previous three-class ATES maps for the same regions, where Complex terrain encompassed large areas and made it difficult even for experienced backcountry users to select the risky, but still manageable in safer snow conditions terrain. Another advantage that we found in the ATES mapping presented in this work compared to previous attempts for automated classification in the same sites (Markov and Panayotov, 2024) was that there was a very good separation of short, steep slopes situated amidst flatter terrain, which were classified as Challenging terrain. A good example of this is the Seven Rila Lakes region, which is characterized by such features (Fig. 2). In previous automated calculation experiments it was necessary to modify parameters in order to capture these zones. However, such modifications produced more Challenging terrain in other areas and the produced maps seemed unrealistic to many users. At the same time the outlining of such short, steep zones is very important because they can be prone to formation of thick snow slabs after strong winds, and at the same time unexperienced mountaineers, snowboarders and skiers may not recognize this and run into the area unaware of the potential risk.

The most challenging part of the automated classification was the forested terrain. We found that the initial avalanche terrain maps produced with the use of the widely available for Europe Copernicus Tree Density product and the specific modifications to the AutoATES 2.0 approach (following the algorithm for the study site in the Austrian Alps (Huber et al., 2023) classified as Simple terrain many steep, forested areas covered by old-growth forests. Such forests are usually not so dense and cannot completely eliminate the risk of avalanche initiation. Due to this there is a possibility of avalanche risk existing there under certain snow conditions. To try to cope with this issue we experimented with a few different approaches to produce better forest density approximations in order to improve the classification of the terrain in the ATES maps. What we found is that using better satellite data or even highly detailed images alone could not completely solve the problem. However, when we used higher thresholds to classify the forest density and in addition introduced a small modification in the model chain with a rule that slopes with inclination of above 39 degrees cannot be classified as Simple terrain, even if the forests were dense, the output results improved considerably. Even the use of the Copernicus Tree Density as the initial source of data for the forest density definition successfully identified the steeper parts of the slopes and classified them as Challenging terrain or Complex terrain, in very steep sections (Fig. 3C). If higher resolution images and DTM/DSM models were used as in our “CustomApproachDroneData” approach, results matched the real terrain situation even better and steep areas with forest openings, such as avalanche tracks, were classified as Complex terrain, which is closer to the definition of this ATES class by Statham and Campbell (2024).

Another potential improvement of automated ATES classification in forested terrain could be to use the Flow-Py functionality that considers the detrainment effects of trees in forested terrain when modelling avalanche runouts (like e.g. in Toft et al., 2024), or to adapt the avalanche mobility parametrization including maximum velocities. In the AutoATES Austria model chain forests were used in the definition of PRAs, but not in the avalanche runout modelling. At the same time a previous work for the same study area (Bunderitsa forest) by Markov and Panayotov (2024) showed that including forest effects on snow movement when calculating avalanche runouts led to a more precise delineation of their protective functions.

5. CONCLUSIONS

Based on our study we conclude that the applied AutoATES Austria model chain produced reliable ATES maps for the three studied areas in the Bulgarian mountains and can be replicated for wider regions in the Rila and Pirin Mountain ranges with the publicly available DEM models and Copernicus Tree Density data. If higher thresholds for differentiating forest density classes and a limiting rule that forested terrain with slope inclination of more than 39 degrees cannot be Simple terrain is applied, then the steep, forested terrain can be correctly classified.

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