THE DESTRUCTIVE POTENTIAL OF LARGE AVALANCHES CLOSE TO BANSKO SKI RESORT IN PIRIN MOUNTAINS – TREE-RING AND NUMERICAL SIMULATIONS ANALYSIS

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ABSTRACT:

In our study we reconstruct past avalanches in three couloirs in close proximity to Bansko ski resort in Pirin Mountains, Bulgaria. We combined tree-ring analysis, satellite images and historical aerophotos to evaluate the effects of large avalanches. With the use of the avalanche-simulation software RAMMS (extended) we calculated the parameters of large avalanches, modelled the extent of forest destruction and compared the outputs with the reconstructed outlines of avalanches which occurred in the studied couloirs in the 20th century. We therefore linked avalanche return period to snow conditions and avalanche friction parameters.

The analysis of the 455 tree-ring cores showed that large avalanches occurred in the studied area almost every decade. The RAMMS simulations revealed that avalanches with large release areas, release depths of 100 cm or more and parameters typical for 100-year return period dry snow avalanches could cause the extent of damages reconstructed by the tree-ring analysis. Observations and video records in the last decade show that recent avalanches correspond to parameters of 10-year return period avalanches with few exceptions as the avalanche in Palashica couloir on 25.01.2021 and “Second couloir” on Todorka NW face on 24.01.2019. Some of the 30-year return period avalanches could also produce more severe damages. Our simulations demonstrate that larger avalanches similar to those that have occurred in Palashica couloir at the end of the 19th and during the 20th century could seriously affect the base area of Bansko ski resort. It is therefore necessary to address this risk with high priority.

KEYWORDS: avalanches, avalanche-forest interaction, Pirin, tree-ring analysis, RAMMS

1. INTRODUCTION

Snow avalanches are among the most important disturbances in Pirin Mountains in Bulgaria (Panayotov et al., 2017). This is due to the steep and long mountain slopes combined with deep snowcovers. After the expansion of Bansko ski resort in 2004, tourist activities in the area have strongly increased. Hundreds of people practice freeride skiing and snowboarding in the forests and couloirs on Mount Todorka in the vicinity the resort borders. This poses risk for slope safety and human life and unfortunately there have been several fatalities due to avalanches in the last decade (Panayotov et al., 2021). Based on historical evidence and several recently observed avalanches it is known that larger avalanches on Palashica slope could potentially affect one of the main activity areas of the resort. Besides posing risk to human life and infrastructure avalanches are also important factor shaping forest structure and functioning of the endemic *Pinus heldreichii* Christ and *Pinus peuce* Griseb. forests in the Pirin Mountains. They are among the few remaining old-growth forests with preserved natural dynamics in Europe (Sabatini et al., 2018), which creates an additional need for the better understanding of the role of avalanches.

Despite the importance of avalanches for the area, research activities have been limited. There is insufficient information on the magnitude and frequency of large avalanches due to lack of historical documentation. There is limited data on accidents involving humans, which unfortunately does not usually contain details on the avalanche characteristics (Panayotov et al., 2021). The protective role of forests is also not well understood and recognized by local authorities. There are only few studies (e.g. Peev, 1955; Peev and Klecharov, 1976; Panayotov et al., 2007; Panayotov, 2011) documenting avalanche activity or studying their importance for the local ecosystem.

In our study we try to partially fill-in these gaps by collecting data on past avalanches in several large couloirs and the bordering forests on the NW face of Todorka peak and analyzing the most probable avalanche characteristics by using the numerical simulation tool RAMMS. We employ

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the extended version of RAMMS which contains a forest interaction module (Feistl et al. 2014) and can predict the extent of forest damage caused by the dust cloud (see Glaus et al. 2023, these proceedings. In order to verify the model outputs for the avalanche characteristics we also compared the simulation results to few video records from one of the avalanche couloirs.

The vertical difference between the top and bottom parts of the slopes vary between 720 m ("Second couloir", Todorka NW face) and 950 m ("Third couloir", Todorka NW face), while the length of the couloirs is 1200 m ("Second couloir"), 1450 ("Third couloir"), 1740 m ("Palashica" couloir). The inclination at the top and middle parts of the couloirs is above 35° with some short steeper sections. The inner parts are cut deeply in the terrain, while the borders of the middle and bottom sections are old-growth forests.

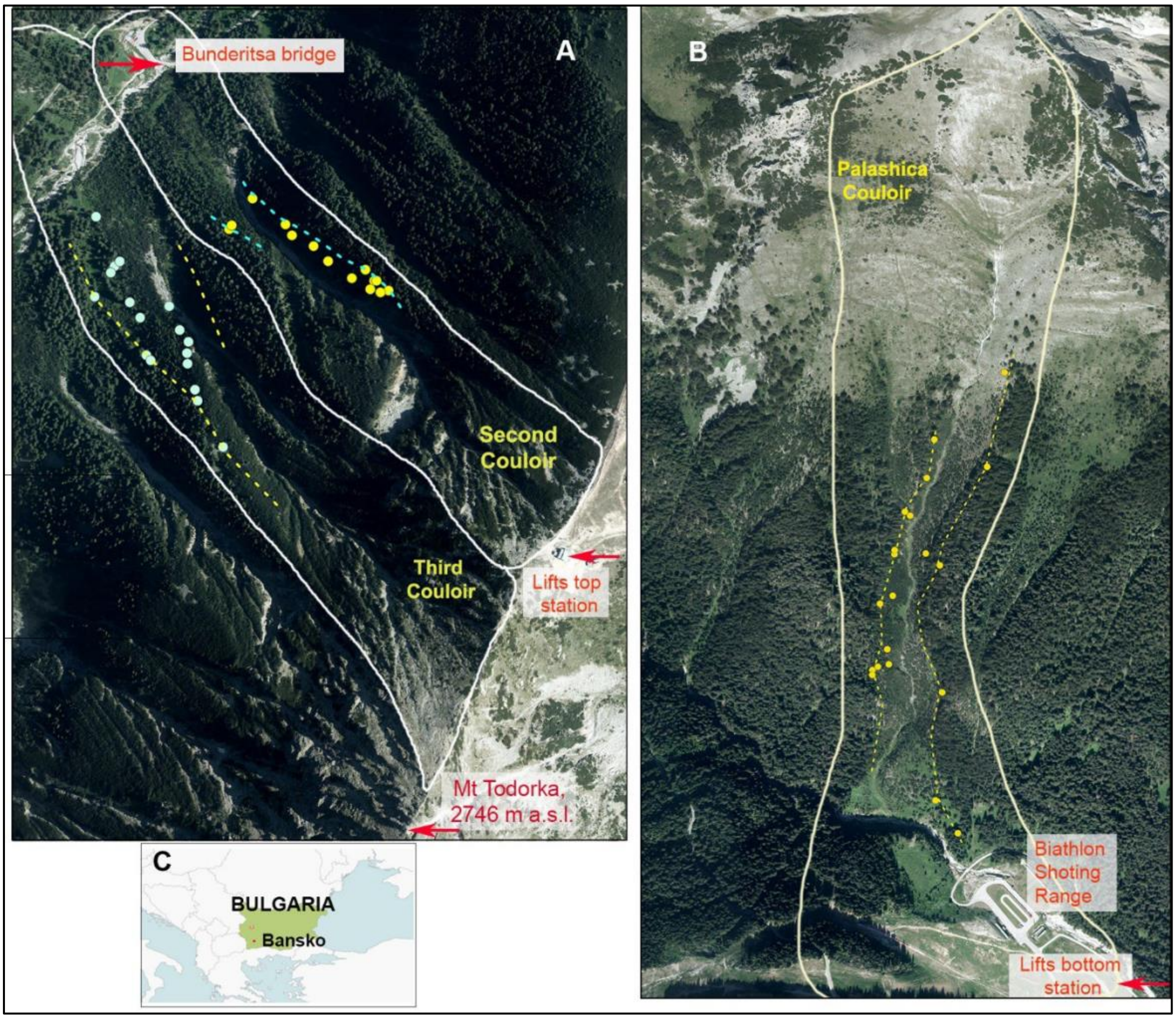

Figure 1. Study areas of the couloirs marked with white lines. The dotted lines show approx-imate outlines of affected areas by a specific past avalanche, while the dots are the trees which show evidence of the avalanche in their tree rings. The avalanches are 1969 in "Second couloir" and 1963 in "Third couloir" and Palashica couloir"

2. STUDY SITE AND METHODS

2.1 Study site

We studied two selected avalanche couloirs on the Northwestern slope of Todorka Peak (2746 m a.s.l.) and one couloir on the eastern slope of Palashica peak (slope start at 2540 m a.s.l.) in the Bunderitsa valley in Pirin Mountains in Southwestern Bulgaria (Figure 1).

2.2. Methods

We collected tree ring cores from the borders between the avalanche couloirs and the neighboring forests and from the bottom parts of the avalanche runout zones. Our collecting strategy was therefore aimed at tracing the signs of larger avalanches. The tree ring cores (272 cores from 159 trees for *Pinus peuce* situated on Todorka Northwestern slope, 183 cores from for 109 trees from *Pinus heldreichii* situated on Palashica slope) were collected with increment borers. The position of every tree was recorded with GPS device and in addition we took notes on the types of damages that the tree experienced. After preparing the cores following standard approach with gluing and sanding, we scanned the cores' surfaces with Epson Expression 11 000 XL scanner at resolution of 1200 dpi and measured the tree-ring widths from the images with CooRecorder 9.3 software (Cybis Elektronik and Data AB, Sweden). We then performed cross-dating procedures and recorded tree-ring anomalies typical for avalanche disturbances following the proposed approach by Stoffel and Corona (2014). Most of our trees experienced sharp growth suppressions related to serious tree damages (tree breakage, strong leaning or partial uprooting) or had associated reaction wood, traumatic resin ducts, visible scars and callus tissue in the tree ring cores following the avalanche events. The so-processed tree-ring data was input into GIS and the final decision on if a tree showed avalanche disturbance in a given year was based on comparing the response with neighboring trees.

In order to obtain information on the most probable physical characteristics of the avalanches we used the extended version of RAMMS (Rapid Mass Movement Simulation) (Christen et al., 2010; Feistl et al., 2014; Glaus et al., 2023). First, we analyzed the size and development of avalanches based on several video records of artificially triggered avalanches in one of our study couloirs, namely "Second couloir", known also as "The Icefall" on the NW face of Todorka peak) and performed simulations with RAMMS to verify the parameters settings associated with release depths, size of release areas and topography. After that we simulated several different avalanche scenarios with their associated friction parameters μ (Mu) and ξ (Xi): 10-year return period dry snow avalanche (0.5 m release depth of snow with small release area, Mu = 0.55 and Xi = 1800, avalanche type "Mixed Flowing/Powder avalanche"), 30-year return period dry snow avalanche (1 m snow depth, medium-sized release area, Mu = 0.49, Xi = 1850, avalanche type "Mixed Flowing/Powder"), 100-year return period dry snow avalanche (1 to 1.5 m snow depths, large release area, Mu = 0.42, Xi = 1900, avalanche type "Mixed Flowing/Powder"), and 30-year return period wet avalanche (0.6 m snow depth, medium-sized release area, Mu = 0.55, Xi = 1000, avalanche type "Flowing"). These values were based on experience with simulations of dry snow avalanches in the European Alps (Christen et al., 2010; Feistl et al., 2014; Teich et al., 2012) and moist snow avalanches in the Andes (Valero et al., 2016). The friction parameters represent the resistance of a dense flowing core, but are adapted to account for melt-water and fluidization as the avalanche flows down the mountain slope (Glaus et al., these proceedings). The choice of snow heights in the release zones we used values in analogy with recorded avalanches in Switzerland (i.e. Christen et al., 2010; Teich et al., 2012) or observations of M. Panayotov during avalanche cycles in the region of Bansko during the last 20 years and local daily records during the winters of 2021 and 2022 in the snow measurements site of the Bulgarian Avalanche Association. These observations show that release depths are often 0.3-0.5 m while in extreme cases 3-day precipitation exceeds 1-1.5 m (e.g. observed on 07-08.03.2015). The neighboring forests characteristics were input with GIS-shape files and to account for the potential of trees of snow detrainment based on DBH of trees, spacing between them and presence of large stumps and logs, which create additional friction and define snow detrainment coefficient (K-value), (Feistl et al. 2014). The resulting outputs for simulated avalanche depths, pressures, velocities and expected damages to trees were compared to known recent avalanches and to the perimeters of past larger avalanches received from our tree-ring analysis.

3. RESULTS

3.1. Tree-ring reconstruction of avalanches

Based on the tree-ring data and observations in recent years from M. Panayotov we found that smaller, but potentially lethal avalanches are frequent inside the studied couloirs, while bigger avalanches which affected the trees on the couloir banks and on the forest border edges are occurring once in a decade or more rarely. Bigger events with many affected trees occurred 1996, 1987, 1969, 1963, 1931, 1910, 1907, 1861, 1837 in "Second Couloir ("The Icefly"); in 2004, 1996, 1987, 1983, 1963, 1956, 1935, 1933, 1907 in "Third Couloir" on the NW face of Todorka; and in 2005,1987,1985, 1963, 1960, 1947, 1931, 1883, 1858 in Palashica couloir (Figure 2).

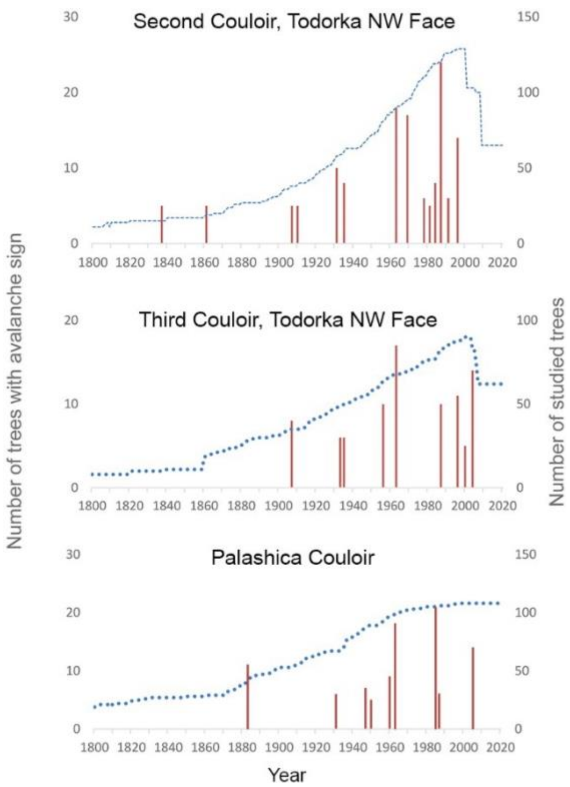

Figure 2. Tree-rings showing signs of avalanches in a given year (red bars) and number of studied trees (blue dotted line).

However, the number of reacting trees was not necessarily associated with the magnitude of the avalanches, especially in older times. This is due to the fact that fewer trees affected by large avalanches in the past are still alive compared to more recent events. In addition, if a large avalanche affects certain area in a given year, then in the next few years the trees might not be able to respond to another large avalanche in the same area. We found much more helpful to review the plotted map positions of reacting trees in a given year and then draw conclusions as to which areas were affected and how big the respective avalanche could be.

3.2. RAMMS simulations of avalanche characteristics

To verify the initial parameters and settings of RAMMS we used 8 video records in avalanches in the "Second couloir" on the NW face of Todorka which occurred between January 2019 and December 2021. These records were of artificially triggered avalanches with a GAZEX system installed in the avalanche-release zone of the couloir. Most of the records were of smaller avalanches, which did not develop large powder clouds and the avalanches stopped before reaching the usual runout zone. However, the events on 24.01.2019 and on 27.01.2021 produced bigger avalanches. The avalanche from 24 January 2019 passed through the runout zone breaking the trees at the bottom of the path, passed Bunderitsa river below the runout zone and caused minor damage on the bridge above the river. The video record allowed to reproduce well the timing and development of the powder cloud. The avalanche travelled the distance of 1200 m in 55 seconds and the powder cloud shook trees at approximately 90 m to the left and 80 to the right of the couloir (a zone with width of approximately 170 m), but did not cause damages in the neighboring forests.

The smaller avalanches were also well replicated by RAMMS when using parameters typical of more frequent avalanches with smaller size (release area with size of 2740 m^2, snow depth of 0.5 m, release volume 1370 m^3, reflecting the usually observed smaller releases. In these simulations the avalanches stopped at the beginning of the usual runout zone. This reflects also numerous observed smaller avalanches in the last two decades, including those which caused fatal accidents.

Several trial runs showed that the best replication of the 24 Jan 2019 avalanche was achieved when we used parameter settings typical for a 30-year dry snow avalanche of flowing/mixed powder type. The release area was 14500 m^2, release volume 8700 m^3, release snow depth 0.6 m and additional snow erosion of 0.3 m. In this simulation velocities of 36 m/s were calculated. The avalanche could cause minor damages to trees outside of the runout zone. The simulated tree destruction was at the lower part of the runout zone, which fits to the observations of the actual avalanche.

In order to simulate the larger events which caused damages high on the banks of the couloirs and on the forest edges we decided to try several more settings for 30-year return period avalanches and also for 100-year return period. The trial runs differed mostly in the size and position of the release zones, the release snow depth, as well as the type of avalanche - mixed flowing/powder avalanche or wet snow avalanche.

Our simulations showed that parameters for 100-year return period avalanches with snow depths of 1 m and erosion depths of 0.6 m produced large and very powerful avalanches. They had velocities of more than 35 m/s of the core avalanche parts and 45 m/s of the powder clouds (Figure 3). The powder clouds entered the neighboring forests with speeds of more than 40 m/s and pressures of 15 kPa. When deeper release snow was simulated (1.5 m) the avalanches were extremely large producing velocities of the powder clouds of more than 50 m/s and going inside the neighboring forests with very high speeds and pressures. The simulated forest destructions of the 100-year return period avalanches fit and could explain the reconstructed damages from the largest avalanches in the last 100-150 years based on our tree ring analysis.

4. DISCUSSION

We have demonstrated, that the region is periodically affected by large avalanches. Our tree-ring data showed that each of the studied couloirs had at least 8-10 avalanches in the last 100-180 years which were large enough to cause damages to trees at the borders of the forests high on the banks of the couloirs. Despite being much smaller the frequent avalanches which stay inside the couloirs and do not cause damages to the forests are large enough to cause human fatalities. This has occurred several times in the last decades. Our data showed that the 1950s and 1960s, which were characterized by very high winter precipitation and described as a period with frequent large avalanches in Pirin mountains (Peev, 1955; Peev and Klecharov, 1976) were reflected in the tree-ring data. Most impressive was 1963, which was detected with numerous damaged trees high on the banks of the three studied couloirs indicating large avalanches. For this avalanche cycle there is data written by Peev and Klecharov (1976), who claim that the Palashica avalanche fell on 12 Feb. 1963 and caused major damage to the neighboring forests. They mentioned also other large avalanches in the same cycle as well as in the region in the late 1960s and early 1970s. Our tree-ring data indicated unusually big avalanches in “Second couloir” on the NW face of Todorka peak and in “Palashica” couloir in 1969.

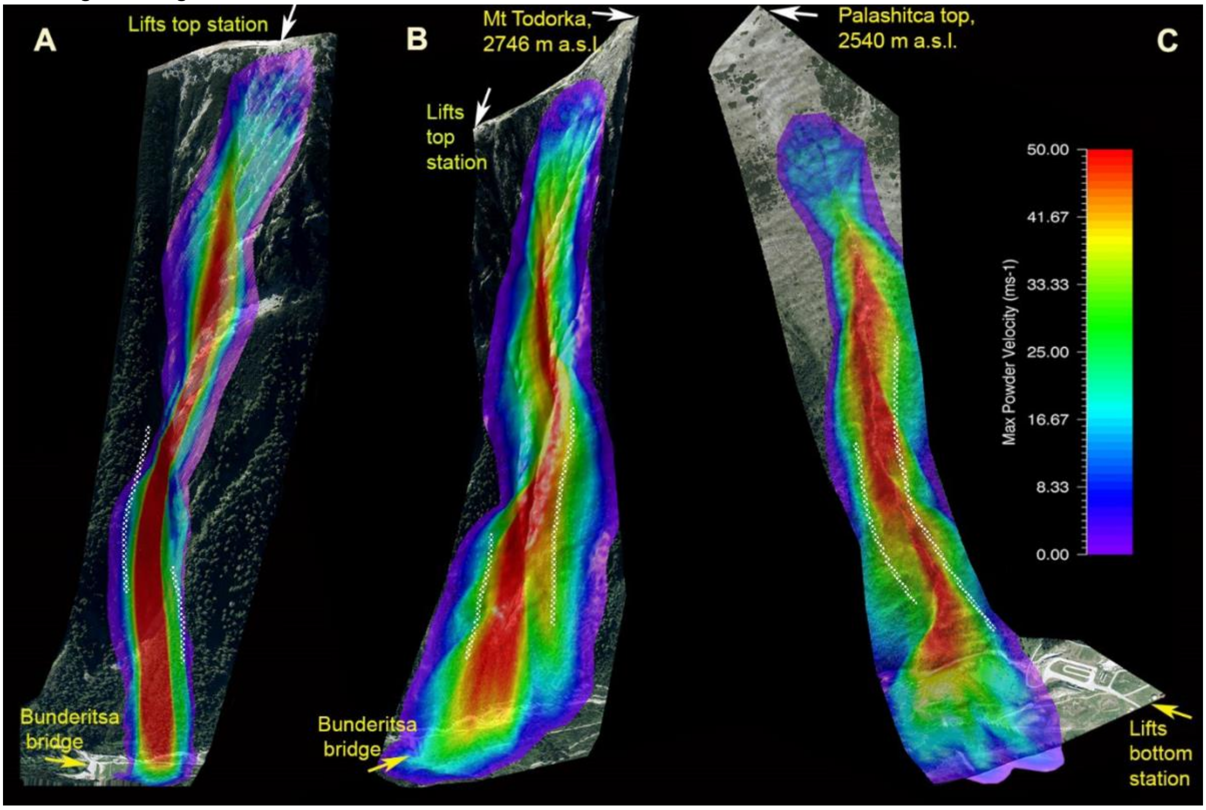

Figure 3. RAMMS simulations of 100-year return period avalanches for the studied couloirs. The images show the maximum velocities of the powder cloud. The white dotted lines are the outlines of larger avalanches in the 1960s shown at Figure 1.

We also have to consider, that after one large avalanche many of the trees on the banks of the couloirs are seriously damaged or removed and therefore other avalanche coming down in the next few years could be undetected by tree-ring analysis or indicated only by few trees. This could explain why fewer avalanches were detected in the tree-rings for the 1970s.

The RAMMS simulations showed that the largest avalanches had very high speeds/pressures and developed intense powder clouds. They could easily affect areas outside the usual runout zones, which many people consider as safe due to lack of recent memory and records of such larger avalanches. The simulated speeds and pressures of the powder clouds are high-enough to cause major damages to trees (Zhuang et al., 2023). Bigger avalanches in both couloirs on the Todorka NW slope could damage seriously the restaurant at the parking lot, which fortunately does not operate in winter. They could also inflict damages to water catchment facilities on Bunderitsa river and a bridge at the foot of the slope. The larger avalanches in the Palashica couloir pass beyond the runout zone and the river and the powder clouds enter with high velocity the Bansko biathlon shooting range on Bunderishka polyana and reach the lower parts of the ski runs. This poses very serious threat to numerous resort visitors. The simulated velocities and dimensions of these avalanches are close to the range reported for measured avalanches in test sites for larger (Christen et al., 2010) or smaller avalanches (Thibert et al., 2015).

One question that rises additional uncertainty is the potential effects of changing climate on the avalanche regime in the region. The last decade had atypical situations compared to the meteorological record with unusually warm spells in winter, low snow amounts and even rain events in January or February. This was the reason for some larger wet snow avalanches even in the typical winter months. However, there were also periods with extreme snowfalls, such as the 7-8 March 2015, when more than 1.5 meters of snow fell during a storm and caused few big avalanches in Pirin. Similar events occur several times in a decade. In addition, snow transport caused by strong winds builds thick snow slabs and especially if these are combined with weaker snow layers below the slab, this can produce larger avalanches. Such was the situation at the end of February 2019, when numerous avalanches raised concerns. The powder cloud of one falling on the West slope of Todorka peak knocked down trees just meters away from Vihren hut. All this demonstrate, that despite generally lower amounts of snowfall in the last decade and potential similar situations in future, large avalanches are possible. This requires further attention for monitoring, research and planning of appropriate mitigation measures.

5. CONCLUSION

Our study shows that big avalanches in the vicinity of Bansko ski resort in Pirin Mountains in Bulgaria occurred several times in the 20th century. They affected forests high on the couloir banks and left clear traces in the tree-rings of surviving trees. The simulations with RAMMS software showed, that avalanches with parameters of 100-year return period have very high speeds and pressures and the potential to produce large powder clouds, which can easily cause the observed damages. However, in some of the simulations we found that even 30-year return period avalanches could also inflict serious damage. It is therefore necessary to address the avalanche risk with high priority especially for the Palashica couloir, which directly threatens the lower parts of the ski runs as well as restaurants.

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