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Risk assessment in the North Caucasus ski resorts

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Abstract. Avalanches pose a significant problem in most mountain regions of Russia. The constant growth of economic activity, and therefore the increased avalanche hazard, in the North Caucasus region lead to demand for the development of large-scale avalanche risk assessment methods. Such methods are needed for the determination of appropriate avalanche protection measures as well as for economic assessments.

The requirement of natural hazard risk assessments is determined by the Federal Law of the Russian Federation (Federal Law 21.12.1994 N 68-FZ, 2016). However, Russian guidelines (SNIP 11-02-96, 2013; SNIP 22-02-2003, 2012) are not clearly presented concerning avalanche risk assessment calculations. Thus, we discuss these problems by presenting a new avalanche risk assessment approach, with the example of developing but poorly researched ski resort areas. The suggested method includes the formulas to calculate collective and individual avalanche risk. The results of risk analysis are shown in quantitative data that can be used to determine levels of avalanche risk (appropriate, acceptable and inappropriate) and to suggest methods to decrease the individual risk to an acceptable level or better. The analysis makes it possible to compare risk quantitative data obtained from different regions, analyze them and evaluate the economic feasibility of protection measures.

1 Introduction

Today, avalanche risk research is critically important for the territory of the North Caucasus. Rapid development of tourism infrastructure is taking place here due to the creation of a number of large ski and tourist resorts (The construction of infrastructure, 2015; Zalikhanov, 2014). A significantly increased number of visitors has been observed in dangerous areas during the last few years (The construction of infrastructure, 2015). The level of avalanche risk is growing at an equal rate. This activity encourages the development of avalanche risk assessment methods (Seliverstov et al., 2008; Shnyparkov et al., 2012; Zischg et al., 2004, 2005). However, the Russian guidelines (SNIP 11-02-96, 2013; SNIP 22-02-2003, 2012; Vorob'ev, 2005) require more precise investigations.

An increased number of visitors has been observed since the opening of the Rosa Khutor resort in Krasnaya Polyana, Sochi (Zalikhanov, 2014). Some new planned resort areas including Veduchi, Lagonaki and Mamison are at the stage of engineering surveys (Investment projects, 2015). Nevertheless, many avalanche-prone areas of the North Caucasus region are still poorly researched, and the lack of avalanche and meteorological data is a common problem (Myagkov and Kanaev, 1992). Specialized avalanche and snow observations are almost absent in the Veduchi (eastern Caucasus), Lagonaki (western Caucasus) and Mamison (central Caucasus) resorts. Climate and geomorphologic conditions including snow and avalanche characteristics differ significantly (Khrustalev and Panova, 2002). The analysis of this information is valuable for further research and for the development of mitigation measures.

1.1 Natural conditions

The Veduchi, Mamison and Lagonaki regions are located in the same mountain system (Fig. 1), but due to the regional heterogeneity of climate circulation and geology, natural conditions including avalanche activity differ considerably (Kotlyakov, 1997; Zalikhanov, 2004). The dominant western circulation patterns lead to great differences in pre-

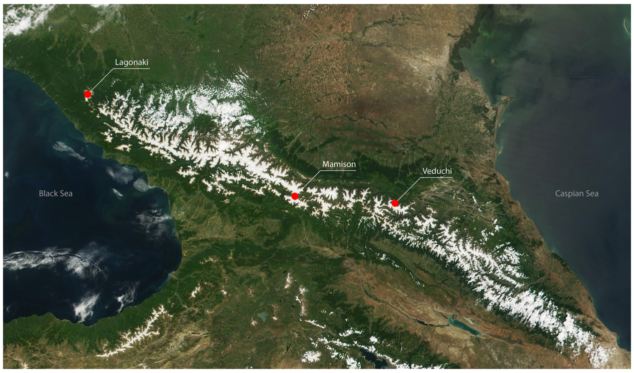

Figure 1. The North Caucasus mountain system. Locations of Veduchi (42°41′5″ N, 45°34′7″ E), Mamison (42°42′20″ N, 43°47′40″ E) and Lagonaki (44°3′0″ N, 40°0′0″ E) regions.

Figure 2. Typical terrain in the Lagonaki region.

cipitation and snow accumulation in the eastern, central and western regions.

The western region, including the Lagonaki area (Fig. 2), receives a huge amount of snow despite comparatively small altitudes (up to 2804 m in Lagonaki). The sub-latitudinal rocky and side ridges are the first barrier in air mass circulation. The ruggedness of the terrain is quite weak, but some very large avalanche catchment zones can be found in mountain river valleys. The combination of climate and morphology characteristics of this area (Tables 1, 2) provides favorable conditions for snow avalanche formation (Komarov, 2013). The considerably low slope angles and a strong vegetation cover are the limiting factors of avalanche activity. Small and medium snow slides and avalanches with high repeatability are most typical for this area.

The eastern regions including the Veduchi area (Fig. 3) are considerably drier. The average precipitation, the duration of snow cover and the depth of snowpack are much lower than in the western region (Table 1). On the other hand, the high altitudes (up to 3021 m) and an extremely rugged terrain with large slope angles and V-shaped profiles provide necessary conditions for snow avalanche formation (Table 2) (Komarov, 2013). This area is characterized by large occasional avalanches with a 50-year return period and longer. Such avalanches may be very destructive due to specific geomorphological conditions of this area. Small avalanches occur almost every year.

The central Caucasus region includes the Mamison area (Fig. 4). The ridges of this area are the main barrier for moist western air masses; heavy precipitation is typical for this highland area. The altitudes exceed 4010 m; this is one of the most high-altitude areas within the Caucasus mountain system. The typical alpine morphology of the slopes with V-shaped valley profiles provides favorable conditions for avalanches, as well as the large amount of precipitation observed here (Komarov, 2013). The duration of avalanche period, the depth of snowpack and the return period of avalanches are usually higher than in other regions (Table 1). Medium and large avalanches with large volumes, long runout distances and average return periods are most typical in this area (Bolov and Zalikhanov, 1984). The climate is, and geology factors are, almost equally important for avalanche activity in this region.

1.2 Previous investigations

At the Research Laboratory of Snow Avalanches and Debris Flows of Moscow State University, a methodology was developed to assess risk and potential natural hazard damage on different scales in order to increase the safety of the local population and tourists, and to protect infrastructure (Seliverstov et al., 2008; Shnyparkov et al., 2012). The result of practical applications of this method is a large-scale risk zoning for the studied areas in terms of quantitative values for individual fatality and total social risk. The previous small-scale studies on avalanche risk in North Caucasus allowed us to receive some important data about risk distribution in the region. However, due to economic growth, more profound investigations of particular objects on large scales have become essential. In accordance with previous studies, there are three levels of individual fatality risk, which are "appropriate" (less than 1×10^{-6}), "acceptable" (up to 1×10^{-4}) and "unacceptable" (1×10^{-4}) (Seliverstov et al., 2008; Shnyparkov et al., 2012; Vorob'ev, 2005). Economic development of the territory should be carried out in accordance with such risk levels. We used the same risk categories for large-scale assessments.

The first test of large-scale avalanche risk estimation methods was performed for the three projected ski resorts with different natural conditions – Veduchi, Lagonaki and Mamison (eastern, western and central Caucasus respectively). During the exploration stage of the project, we allocated the avalanche catchment zones and analyzed the main characteristics of avalanche activity for each of the three regions.

Using correlation dependences (Kotlyakov, 1997; Pogorelov, 1998, 2002; Myagkov and Kanaev, 1992) (that are proven and widely used in Russian glaciology) and spatial field data from expeditions, we calculated the snowpack

Table 1. Climate characteristics in Lagonaki, Mamison and Veduchi regions (Komarov, 2013).

Climate characteristics	Lagonaki	Mamison	Veduchi
Average precipitation ($mm\,yr^{-1}$)	1800	750	600
Average and maximum wind speed ($m\,s^{-1}$)	1.5–2 to 35	2–8 to 50	3–5 to 35
Average January temperature (°C)	−5	−10	−15
Cyclone frequency (%)	36	37	34
Avalanche period duration (days)	105	95	80
Duration of resort functioning (days)	120	150	100
Average maximum height of snow cover (cm)	200	150	80
Main meteorological factors of avalanches	Heavy snowfall blizzards	Heavy snowfall blizzards recrystallization	Heavy snowfall blizzards

Table 2. Morphology characteristics in Lagonaki, Mamison and Veduchi regions (Komarov, 2013).

Morphology characteristics	Lagonaki	Mamison	Veduchi
Elevations (m)	985–2804	1759–4018	873–3021
Depth of the valleys (m)	1667	2259	2148
Average slope angle (°)	20	26,3	29
Area of slopes with angles from 25 to 55° (%)	29	54	65
Prevailing expositions	North, northeast, northwest	East, southeast	North, northeast, east
Density of the avalanche catchment zones ($sites\,km^{-1}$)	3–4	8	5–6
Avalanche return period (years)	> 10	> 10	1–10
Level of avalanche activity	High/medium	High	High/medium

Figure 3. Typical terrain in the Veduchi region.

Figure 4. Typical terrain in the Mamison region.

depth, the duration of avalanche period, the duration of resort functioning, the volume of avalanches for different elevation levels and the avalanche return periods for each area. Using these values, actual snowpack depth data and the RAMMS modeling program, we simulated avalanches from all potential avalanche release zones and obtained the characteristics of avalanche dynamics. Calculated values of avalanche activity were further used to calculate the avalanche risk for ski resorts.

2 Methods

Risk can be defined as the product of the probability of an event (avalanche) and its consequences (vulnerability of the object) (Bohnenblust and Troxler, 1987). Avalanche risk can be recorded by temporal and spatial overlapping of the two independent processes of avalanche hazard and use of the area (Bartelt et al., 2012; Hendrikx et al., 2006; Seliverstov et al., 2008; Wilhelm, 1998).

The use of the area corresponds to the probability of presence and the number of people present. The vulnerability (V) is recorded as a conditional probability, under the condition that the avalanche has taken place as well as that the person was present. In this study we use the extreme values of snowpack that characterize avalanches with a 100-year return period. We choose one of extreme situations because the Federal Law of the Russian Federation (Federal Law 21.12.1994 N 68-FZ, 2016) and Russian guidelines (SNIP 11-02-96, 2013; SNIP 22-02-2003, 2012) require the most dangerous situations that may occur during resort (or other object) operation to be used.

In order to receive required individual and collective risk for ski resorts, we have defined the following indicators – the spatial (V_s) and temporal (V_t) vulnerability.

The temporal vulnerability of people characterizes the duration a person stays in an avalanche-prone area. It is calculated as a function of the duration of human presence (T_d and T_y) and their location in a dangerous area during an avalanche period (Eq. 1):

$$V_t = (T_d/T_{da}) \times (T_{ya}/T_y). \quad (1)$$

The T_d index characterizes the average period (h) a typical representative stays in the studied area during the day. T_{da} characterizes the period in which an avalanche may occur during the day (h). The T_y index characterizes the average period (days) people stay in the targeted area during the year. The T_{ya} characterizes the period in which an avalanche may occur during the year (days). The multiplication of these parameters relative to the year gives us the quantitative values of temporal probability of risk.

In this study, we have used the following values: the value of T_d, limited by the duration of the operation of ski lifts during the day within the ski complex. This value can vary depending on many factors, but in this study it is averaged to 8 h for each resort, in order to test the most dangerous scenario (required by Russian guidelines SNIP 11-02-96, 2013, and SNIP 22-02-2003, 2012). The value of T_y is limited by the duration of resort functioning during the year. As long as there is no statistical information for selected resorts, we assume that this index shall correlate with the duration of period with snow coverage and that it equals 100, 150 and 120 days for the Veduchi, Mamison and Lagonaki regions respectively (Myagkov and Kanaev, 1992). T_{da} characterizes the period an avalanche may occur during the day and equals 24 h per day. The T_{ya} value is limited by the duration of the avalanche period in the study area. For the Veduchi, Mamison and Lagonaki resorts it equals 80, 100 and 105 days respectively.

The spatial vulnerability (V_s) is defined by the exposure of the territory to the impact of snow avalanches. It is calculated as the area of the avalanche-prone territory related to the full area of the polygon (Eq. 2). All spatial calculations were performed on the basis of data obtained using MapInfo, ArcGis and RAMMS GIS software.

$$V_s = S_i/S_o \quad (2)$$

Table 3. Equations (1), (2) and (3) index values in Lagonaki, Mamison and Veduchi regions.

Resort	T_d (h)	T_y (day)	T_{da} (h)	T_{ya} (day)	V_t %	V_s %	d (ppl km^{-2})	K %	P %	R_c (ppl yr^{-1})
Veduchi	8	100	24	80	26.6	69	4500	53	1	4.37
Mamison	8	145	24	100	22.9	65	4500	53	1	3.55
Lagonaki	8	120	24	105	29.1	30	4500	53	1	2.08

S_i represents the area of the avalanche-prone part of the territory and is defined as the total area of the pistes, overlapped by avalanches with a 100-year return period (1 % probability). S_o is the total area of pistes within the resort. Using Eq. (2), we calculated that V_s values equal 0.69, 0.63 and 0.30 for the Veduchi, Mamison and Lagonaki resorts respectively.

Full social avalanche risk ("collective risk") characterizes the expected average number of people killed in avalanches during the year within the study area. Full social risk (R_c) was calculated using Eq. (3):

$$R_c = P \times \mathrm{d} \times V_t \times V_s \times K. \quad (3)$$

The K and the d indexes characterize people as elements at risk. They represent the amount of damage that can be done during the risk situation. The d is bound to the number of people using the territory – it shows the maximum possible density of sportsmen on the piste. This value was obtained using the cited materials (How to Measure Trail Capacity, 2004; Eldora Mountain Resort Master Plan, 2011). The K index represents the mortality coefficient and reflects the long-term statistics of mortality in avalanches. We use the constant value 0.53 for this coefficient (Brugger et al., 2007; Tschirky et al., 2000) that is bound to the 47 % probability of surviving an avalanche after being totally buried. In the Caucasus region this value may be considerably higher due to poor avalanche services, but no official statistics have been published yet. The P index reflects the probability of a 100-year return period avalanche, and it equals 0.01 per year.

The obtained values of collective (full social) risk R_c can be used to calculate the individual risk R_i. This index represents the risk situation related to an individual (single person), the probability of premature death of an individual in the study area. R_i is calculated as the ratio of the total social risk to the total number of people (N) on pistes during the year (Eq. 4):

$$R_i = R_c / N. \quad (4)$$

The N index can vary significantly depending on the tempo of resort development. For ski resorts that are not yet in operation, it is advisable to take different scenarios of their development into account. Assuming that the number of guests at the initial stage there will be about 50 000 people yr^{-1}, this will increase to 150 000 people yr^{-1} and will reach 600 000 people yr^{-1}. The information obtained is useful for further resort planning and the development of mitigation measures in the North Caucasus region.

Table 4. Individual risk values in Veduchi, Mamison and Lagonaki ski resorts.

Number of visitors	50 000	150 000	600 000
Veduchi	8.7×10^{-5}	2.9×10^{-5}	7.2×10^{-6}
Mamison	7.1×10^{-5}	2.3×10^{-5}	5.9×10^{-6}
Lagonaki	4.1×10^{-5}	1.4×10^{-5}	3.5×10^{-6}

Territories with individual risk values less than 1×10^{-6} have an appropriate risk level. Such territories usually do not require any avalanche protection measures or special restrictions. The values of 1×10^{-6}–1×10^{-4} characterize the acceptable avalanche risk. Regions with acceptable risk require specific measures to protect community and infrastructure. The construction is possible here, but appropriate protection measures are highly recommended. If the measures are effective enough it is possible to reduce the coefficient down to an appropriate risk level. If the individual risk exceeds 1×10^{-4} the territory has an unacceptable risk level. This level characterizes territories with high avalanche activity and rapidly developing infrastructure. Such territories require some urgent measures. The entire spectrum of risk mitigation measures shall be used in order to protect existing facilities and population, and to reduce the risk level. New construction should not be allowed in such territories without special surveys being carried out.

3 Results

Using these methods, we calculated collective and individual risk values for the Veduchi, Mamison and Lagonaki resort areas and analyzed the results. The meaning of the indexes has already been described in the previous paragraph, so we only publish results obtained here in Table 3.

The T_d, T_{da}, d, K and P indexes have constant values for all the resorts. The T_{ya}, V_t, V_s and R_c indexes vary due to different natural conditions of selected regions. Using Eq. (3) we acquire the quantitive values of temporal probability of risk situation V_t, related to the year. The index values vary from 0.266 in Veduchi to 0.229 in Mamison and 0.291 in Lagonaki.

The area of avalanche catchment zones within the pistes characterizes the V_s index, which varies from 0.69 in Veduchi (69 % of pistes are overlapped by avalanche catchment areas) to 0.65 (65 %) in Mamison and 0.30 (30 %) in Lagonaki.

Multiplying the index values using (Eq. 3), we determined the collective risk (R_c) values for each region and obtained the following results. The collective risk values equals 4.37 $km^2\,yr^{-1}$ for Veduchi, 3,55 people $km^2\,yr^{-1}$ for Mamison and 2.08 people $km^2\,yr^{-1}$ for Lagonaki.

Then, using Eq. (4), we estimated the individual risk values. R_i is calculated as the ratio of the total social risk to the total number of people (N) on pistes during the year. The N index can vary significantly depending on the temps of resorts. We assumed that the number of guests at the initial stage of resort functioning will be about 50 000 people yr^{-1}, then will increase to 150 000 people yr^{-1} and will reach 600 000 people yr^{-1}. According to these scenarios we obtained the following values of individual avalanche risk (Table 4).

All the calculated values correspond to an acceptable individual risk level. Consequently it will be necessary to take protection measures in order to decrease the figure to appropriate values, i.e., less than 1×10^{-6}. These values can be achieved by applying various risk mitigation measures, including structural avalanche protection (defensive structures, avalanche dams, snow sheds), planning, and silvicultural and temporary measures (warning, closure and evacuation, artificial avalanche triggering). Construction of special avalanche protective structures is quite expensive, but often it is the only way to make the territory safe.

4 Discussion

The obtained results allow us to estimate the risk levels for different territories and to suggest the most effective risk mitigation measures for ski resorts. These calculations represent approximations that are quite rough. Each component of the formula can be refined in order to obtain more accurate results, but this requires more precise investigations. This study is limited by a lack of historical data because none of the selected resorts are in operation yet, and statistical information is absent.

The calculation of temporal vulnerability (V_t) may be improved by clarifying its components.

The T_d index shall be refined by analyzing statistical information based on time people spend on the piste during the day, which is usually less than 8 h per day. It may be worth estimating how much time people stay in locations safe from avalanches such as hostels, restaurants and lifts. Moreover, we assume that these index values can vary for people with different training levels.

The T_y and T_{ya} values we use are calculated using correlation dependencies (Myagkov and Kanaev, 1992). The T_y index may be clarified by using factual data from ski resorts. The T_{ya} index (which represents the duration of avalanche period) may be improved by replacing it with more precise information about the number of days when avalanches occurred during the ski season, but this requires special observations.

The K mortality index shall be based on statistics obtained from the selected region. In this study we use values based on Alpine statistics (Tschirky et al., 2000; Brugger et al., 2007) because such information for the Caucasus region is not obtained yet. We expect that the avalanche mortality rate may be considerably higher for our region due to poor avalanche services and skier awareness.

The calculation of d and V_s indexes is the most controversial question so we have investigated how they can be refined. The density characteristics may be reinterpreted by adding information about the actual distribution of sportsmen on the slope, but this requires factual data from resorts, which are absent for our region. In this study we consider homogenous distribution and expect that the density of people on the slope may correlate with the professional level of the skiers (How to Measure Trail Capacity, 2004). As long as we test the most adverse scenario in our research, we use the maximum appropriate density for each professional group (Eldora Mountain Resort Master Plan, 2011). The d index can vary widely depending on many factors, such as time, season and spatial distribution of skiers on the piste. Using the cited materials (How to Measure Trail Capacity, 2004; Eldora Mountain Resort Master Plan, 2011), we tried to determine an appropriate skier density on the piste for Caucasus ski resorts for three professional levels (beginner, intermediate and professional). We have also analyzed the percentage ration of groups with different training levels, and estimated their average movement speed (Shealy et al., 2005) (Table 5).

The calculation of V_s can be refined by inputting decreasing coefficients in the formula in order to estimate the actual area of the dangerous zone for each training level depending on movement speed. The speed of sportsmen and the possibility to escape an avalanche should be taken into account as one of the factors that can be clarified in order to increase the accuracy of the method. We assume that skiers have a chance to escape the potentially dangerous zone before an avalanche reaches it and hits a sportsman. For athletes with a good training level and high movement speed, this capability is much higher than that of beginners. Thus the size of the dangerous zone may be reduced depending on the training level and speed of each group. The average movement speed of skiers was determined using the results of Shealy et al. (2005).

Comparing the calculated speeds (using RAMMS software) of avalanches in different parts of trails with average speeds of sportsmen, we determined the areas where the sportsmens' speed exceeds the speed of an avalanche, and estimated the possibilities of avoiding an avalanche for each of these groups. Comparing this area to the full avalanche-prone area, we can obtain the M coefficient that may be used in spatial vulnerability calculations (Table 7). These clarifi-

Table 5. The density (d) index and average sportsmen movement speed.

Training level	Maximum appropriate density of skiers on the piste ($\mathrm{ppl\,km^{-2}}$)	Average ratio of different training level groups on the piste (%)	Average number of skiers according to the ratio ($\mathrm{ppl\,km^{-2}}$)	Average skier movement speed ($\mathrm{km\,h^{-1}}$)
Professional	2000	15	300	65
Intermediate	4000	60	2400	32
Beginner	7500	25	1800	16
Average	4500	100	4500	

Table 6. The percentage of the area where the maximum avalanche speed exceeds the average movement speed of sportsmen (16, 32 and 65 $\mathrm{km\,h^{-1}}$).

Territory	Maximum avalanche speed exceeds 16 $\mathrm{km\,h^{-1}}$	Maximum avalanche speed exceeds 32 $\mathrm{km\,h^{-1}}$	Maximum avalanche speed exceeds 65 $\mathrm{km\,h^{-1}}$
Lagonaki	95 %	90 %	65 %
Veduchi	92 %	80 %	58 %
Mamison	(93 %)	(85 %)	(60 %)

Table 7. The area of the dangerous zone compared to the whole area of the avalanche catchment zone for each training level.

Training level	M index for the Veduchi ski resort area
Professional	0.58
Intermediate	0.8
Beginner	0.92
All (according to the ratio)	0.81

cations help us to estimate the actual number of victims more precisely. The results are shown in Tables 5, 6 and 7.

The introduction of this amendment clarifies the risk level by approximately 20 %, which is equal to or less than the errors in determining the other components of the avalanche risk. This means that clarifications based on skiers' training level and movement speed may only be applied after the other parameters are clarified in an appropriate way. Nevertheless, such amendments may be useful for further research. It may also be worth estimating such parameters as the duration of avalanche movement and the skiers' visibility area, in order to make this amendment more accurate.

5 Conclusion

An avalanche social risk assessment method for local objects such as ski resorts and other rapidly developing mountain areas was developed in this research.

The previously used methodology of small-scale avalanche risk assessment was modified for use on a large scale. This method shows good results for ski resorts in the North Caucasus, but it requires more precise investigations and more accurate statistical information. The improvement of risk assessment methods is associated with the clarification of such indicators as the number of visitors to the resort, the change in the density of tourists on the route at different times of the day and the year and long-term statistical meteorological data (including avalanche activity and snow coverage indicators).

As a result of the calculations performed, we established that all the calculated values correspond to an acceptable individual risk level. Consequently, it will be necessary to take protection measures in order to decrease the risk to appropriate values, i.e., less than 1×10^{-6}. These values can be achieved by applying mitigation measures including structural avalanche protection (defensive structures, avalanche dams, snow sheds), planning measures, silvicultural measures and temporary measures (warning, closure and evacuation, artificial avalanche triggering). It is necessary to develop interventions in order to determine how the use of different avalanche protection measures will change the risk indicators and to be able to recommend the most advantageous solutions.

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