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The Suitability of Snow and Meteorological Conditions of South-Central Slovakia for Ski Slope Operation at Low Elevation—A Case Study of the Košútka Ski Centre

Michal Mikloš [1,*], Martin Jančo [2], Katarína Korísteková [3], Jana Škvareninová [4] and Jaroslav Škvarenina [1]

1 Department of Natural Environment, Technical University in Zvolen, 960 53 Zvolen, Slovakia; skvarenina@tuzvo.sk
2 Department of Biology and General Ecology, Technical University in Zvolen, 960 53 Zvolen, Slovakia; martinjanco11@gmail.com
3 Department of Fire Protection, Technical University in Zvolen, 960 53 Zvolen, Slovakia; katarina.koristekova@gmail.com
4 Department of Applied Ecology, Technical University in Zvolen, 960 53 Zvolen, Slovakia; skvareninova@tuzvo.sk
* Correspondence: miklosmiso@gmail.com; Tel.: +421-949-263-801

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Abstract: In this study, the snow conditions of South-Central Slovakia (Inner Western Carpathians; temperate zone) were analyzed to assess the suitability for ski slope operations without snow production under 1000 m a.s.l. For the study site of the Košútka Ski Centre, meteorological conditions for snowmaking, snowpack characteristics, and snow water equivalent (SWE) compared with seasonal precipitation were identified. To identify the months suitable for snowmaking, the number of potential snowmaking days (PSD) and the required number of snowmaking days (RNSD) were calculated for six winter seasons from 2010–2011 to 2015–2016. The results showed that the conditions of natural snow cover were not appropriate for ski slope operation because of a low natural snow depth. For the Košútka Ski Centre, it was concluded that the essential base layer snowmaking for ski slope operation is possible only for a few days in the winter season because of the increasing mean value of the mean average daily temperature and the consequently higher occurrence of liquid precipitation in the winter season. Essential high snow production results in the heterogeneous distribution of snow on the ski slope, and in high snow depth, density, and SWE of the ski slope snowpack, and in prolonged melting.

Keywords: precipitation; snow water equivalent; snowpack; snowmaking; ski resort; snow depth

1. Introduction

Snowfall and snow cover have a significant impact on different human activities and, therefore, on the entire society and environment. This impact is obvious mainly in mountainous regions of the world with an abundance of natural snow [1]. In Central Europe (above 500 m a.s.l., but mainly above 1000 m a.s.l.), such regions are, particularly, the Alpine and Carpathian regions. In these parts of Europe, the amount of snow and the duration of snow cover are of great social and economic importance. The amount of snow mainly affects winter tourism and water supplies for hydroelectric power stations [2]. Winter tourism is one of the most important economic sectors of mountainous regions in the world [3]. However, winter tourism depends on good snow conditions and is very sensitive to the lack of snow [4]. The majority of climate change scenarios predict the shortening of the duration of seasonal snow cover [5]. Studies on precipitation variability show decreasing trends of precipitation totals in Central and Southern Europe [6–8]. In the context of climate change, areas with persistent snow cover shrink relatively quickly, and occasional snow cover with liquid precipitation in the middle of winter expands over the territory of Slovakia [9]. Vojtek et al. [10] and Škvarenina et al. [11] pointed out the general tendency of the decreasing duration of snow cover and solid precipitation occurrence at lower altitudes in Slovakia (Central Europe). Approximately, 55% of Slovakia has altitudes between 300 m a.s.l. and 1000 m a.s.l., but only 5.4% of its territory is higher than 1000 m a.s.l. [12]. Due to the low altitude of many Slovak ski areas, snow coverage is not always guaranteed [13]. The winter season at the study site (Košútka Ski Centre; 610 m a.s.l.; Inner Western Carpathians) usually lasts three months, from the end of December to the middle of March, because of heavy base layer snowmaking at the beginning of each season. Low-altitude valley runs in the Alps can also be reliably opened for three months only with the help of intensive snowmaking [14].

Winters with a lack of snow have caused significant, sometimes even existential, problems for ski resorts since the mid-1950s [15]. Systems for artificial snowmaking have become the main strategy to reduce the dependency on natural snow. A dynamic increase of artificial snowmaking was observed since the middle of the 1980s in parallel with more abrupt climate changes [16]. Snow production is coupled with some environmental doubts. These doubts mainly include the overconsumption of water and energy during snow production [17] and the negative impacts of snowmaking on vegetation, soil, and water balance [18,19]. The negative effects are primarily caused by the physical and chemical characteristics of the snowpack on the artificially covered ski slopes [20,21]. It was proved that covering high-altitude ski resorts (above 1000 m a.s.l.) with artificial snow results in a significant increase of snow water equivalent, snow depth, and density of snow [22]. The duration of the snowpack with added artificial snow is prolonged by more than two weeks in comparison with natural snow in the surrounding ski slope [19]. This discovery is of great importance because the duration and the distribution of snow cover affects the beginning and the duration of the growing season, and melted water from snow is the source of water and nutrients for plant growth [23]. Thus, it is crucial to know the characteristics of the snow cover at the end of the winter seasons to evaluate its impact on vegetation, water balance, and the calculation of water supplies in snow cover.

Winter sports, mainly skiing, have a long tradition in high- as well as low-elevation regions of Central Slovakia. Nevertheless, under the present climate change, snow conditions in the Slovakian ski resorts have changed considerably, especially at low elevations. The first aim of the presented study was to analyze six seasons of data of four precipitation stations in South-Central Slovakia to assess the suitability of natural snow conditions (natural snow depth) for the ski slope operation under 1000 m a.s.l. The representative Košútka Ski Centre, located close to one of the four analyzed precipitation stations, was determined as a study site to achieve the following aims:

- to assess the suitability of meteorological and snow conditions for the ski slope operation without snow production;
- to assess the suitability of meteorological conditions for snow production and for base layer snowmaking at the beginning of winter season;
- to identify the seasonal variability of the ski slope snowpack characteristics (snow depth, as well as spatial variability, snow density, and snow water equivalent "SWE") and to compare the ski slope snowpack SWE with seasonal precipitation.

2. Materials and Methods

2.1. Study Site

The study was conducted at the Košútka Ski Centre (48.559° N, 19.535° E; Figure 1a) in the Inner Western Carpathians (Slovenské Rudohorie Mts., Veporic Unit, Slovakia; Figure 2). The study site belongs to the moderately warm climatic region with cool to cold winters [24], a mean annual temperature of 5.5 °C [25], a mean annual precipitation total of 850 mm [26,27], 90 days with snow cover, and a mean snow depth of 36.7 cm [28] (data from 1961 to 1990). The length of the ski slope is 950 m with an altitudinal difference of 220 m (500–720 m a.s.l.), western to northern aspect, and slope from 7° to 25° (Figure 2). Since the establishment of the ski center in 2007, the ski slope has been covered by artificial snow (Figure 1b). At the end of the winter season, a high volume of snow remains on the slope (Figure 1a). Fixed snow-making lances, which can reach a distance from 5 to 30 m and operate at a maximum working temperature of −4 °C, have been used to produce snow. The stream "Slanec" running at the foot of the ski slope is used as the water source.

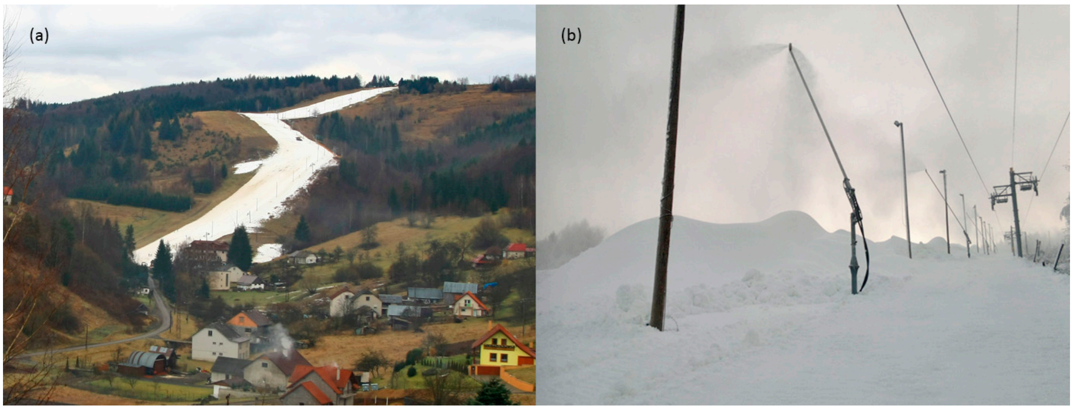

Figure 1. (**a**) The studied ski slope of the Košútka Ski Centre after the snowmelt of natural snow in the surroundings of the ski slope on 18 February 2016; (**b**) The beginning of the season started with an enormous production of snow (base layer snowmaking; 21 December 2016). Shown are snowmaking lances beside the ski lift at the orographic left side of the slope.

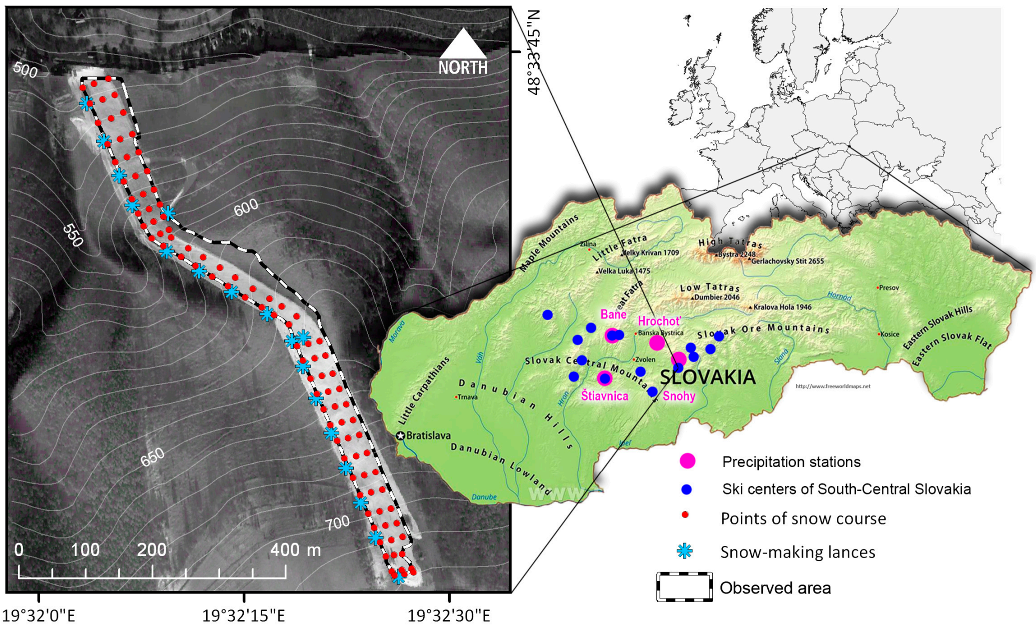

Figure 2. Remaining snowpack on the investigated ski slope of the Košútka Ski Centre (22 March 2011). At the 96 points of the snow course (red dots), the snow depth and density of the snow were measured, while the occurrence of snow was regularly recorded on the "observed area". The Košútka Ski Centre is situated in South-Central Slovakia (Central Europe), where 15 ski centers (blue dots) and four investigated precipitation stations (pink dots) are located.

The Košútka Ski Centre is one of the 15 South-Central Slovakian ski centers in operation (Figure 2). Other ski centers are out of service because of a lack of natural snow or because of economic problems. The average length of the winter season at the 15 ski centers is 87 days (start: 20 December; end: 17 March; Table 1), while the average ski slope elevation in all the ski centers is lower than 1000 m a.s.l., except for Skalka arena (1105 m a.s.l.). Ski slopes of the South-Central Slovakian ski centers are 68% artificially covered on average (Table 1). At eight ski centers, ski slopes are fully artificially covered, while in three ski centers snowmaking is not used. The investigated precipitation stations of the Slovak Hydrometeorological Institute (SHMÚ) have comparable elevation (from 575 to 771 m a.s.l.) and location in the South-Central Slovakia to the 15 ski centers (Figure 2). The macro climate conditions of the localities where the precipitation stations are situated are comparable to the characteristics of the Košútka Ski Centre study site (see above).

Table 1. Characteristics of the South-Central Slovakian ski centers. Probable start/end of the expected winter season 2018–2019, determined according to www.onthesnow.sk [29]. Artificially covered slopes = the percentage of the artificially covered ski slopes. Investigated ski center highlighted in bold.

Name of the Ski Center	Winter Season 2018–2019		Elevation (m a.s.l.)			Artificially Covered Slopes (%)
	Start–End	Length	Min.	Max.	Average	
Ski Cigeľ	26 December–17 March	81	630	825	728	100
Dačov Lom—Lomník	2 January–17 March	74	425	530	478	100
Biele Vody—Hriňová	2 January–3 March	60	874	992	933	100
Košútka Ski Centre	**25 December–10 March**	**75**	**500**	**720**	**610**	**100**
Ski Krahule	7 December–24 March	107	900	1060	980	100
Ski Kráľová, Zvolen	2 January–10 March	67	650	800	725	0
Hotel Royal Látky	15 December–31 March	106	927	1025	976	33
Salamandra Resort	8 December–24 March	106	579	850	715	100
Skalka arena	8 December–7 April	120	958	1252	1105	72
Ski Blanc Ostrý Grúň	22 December–10 March	78	453	560	507	53
Ski TMG Remata	21 December–3 March	72	500	590	545	100
Ski centrum Drozdovo	8 December–31 March	113	690	810	750	56
Skicentrum Kokava—Línia	8 December–24 March	106	660	820	740	100
Tisovec–Bánovo	2 January–10 March	67	600	790	695	0
SKI Park Závada	2 January–10 March	67	555	700	628	0
Average	20 December–17 March	87	660	822	741	68

2.2. Meteorological, Snow, and Snowmaking Conditions

Four precipitation stations (Figure 2) situated below 1000 m a.s.l. were selected to identify the mean monthly snow depth in South-Central Slovakia. A depth of natural snow cover of at least 30 cm on grassland is considered sufficient for skiing [30]. In this study, a month was considered as suitable for ski slope operation when the mean monthly snow depth of natural snow cover was higher than 30 cm. Steiger [31] defined the minimum depth of the artificially covered ski slope snowpack as 20 cm, because of the higher snow density compared to natural snow cover. The artificially covered ski slope snowpack at the Kośútka Ski Centre was considered as suitable for operation when its depth was at least 20 cm. To analyze the meteorological and snow conditions, the mean monthly values were calculated from six seasons (from 2010–2011 to 2015–2016) and mean seasonal values were calculated from six months (XI–IV; the period with snow occurrence) or from four months (XII–III; the period when the South-Central Slovakian ski centers are in operation). To distinguish the seasonal values, the proper months are shown in brackets).

The daily values of precipitation totals, the depth of new snow, and the depth of natural snow cover were measured by the Slovak Hydrometeorological Institute (SHMÚ) at the Snohy precipitation station (Figure 2; 771 m a.s.l.; 48.628° N, 19.550° E), 7 km away from the ski center (air direct distance). The daily average temperature, wind speed, and wind direction was recorded by the meteorological station at the ski center. The analyzed data were from seasons 2010–2011 to 2015–2016, and, during each season, the months XI–IV were evaluated.

The number of potential snowmaking days (PSD = days with optimal snowmaking conditions) and required number of snowmaking days (RNSD = number of days required for balancing snow melt by snow production) was identified for each month from XI to IV [15]. The number of PSD was calculated as a sum of days that reached the threshold of −2 °C daily average temperature [15]. The RNSD value was calculated according to a formula described in Steiger and Mayer [15]. A degree day factor of 3 mm was used in the formula because of the ski center's low elevation. This factor describes the runoff (in mm) per degree day (the sum of all positive daily average temperatures). A month in which the PSD value is greater than the RNSD value is defined by Steiger and Mayer [15] as a month suitable for snowmaking. If a positive difference between PSD and RNSD was determined in several days greater or equal to five days in a month, the month was considered suitable for base layer snowmaking. This is because the average snowmaking systems can produce snow cover suitable for skiing (20 cm thick) in five days [31]. Base layer snowmaking is defined as "the first area-wide snowmaking of a ski season, mostly started between mid-November and beginning of December" [32].

2.3. Characteristics of the Ski Slope Snowpack

After the natural snow had melted away in the surroundings of ski slope (Figures 1a and 2), the snow depth and density of the snow were measured on the artificially covered ski slope. The measurements were performed for only one day in each of the winter seasons from 2010−2011 to 2015−2016, except for 2013−2014 (when the ski center was out of service). The depth of the snow was always measured at 96 points, and the snow density was measured at least five points of the snow course (Figure 2). The points of the snow course were localized by a GPS receiver and the SKPOS service (Slovak real-time positioning service). A model VS-43 snow sampling tube was used to obtain gravimetric samples of snow to measure the depth-averaged snow density. The method of the manual snow depth and density measurement is more thoroughly described in Hríbik et al. [33]. Ninety-six values of snow water equivalent were calculated from 96 values of snow depth multiplied by the mean value of the snow density.

The ski slope snowpack was observed in the field and on ski center webcams to detect the date of its snowmelt. The duration of the examined snowpack melting, compared to off-piste sites with natural snow, represents the period between the date of our measurements and the date of its snowmelt. The snowpack was considered melted when less than 5% of the observed area (4.1 ha) was covered by snow (Figure 2).

To assess the distribution of snow over the groomed ski slope, the relationship between the snow depth and the closest distance from the fixed snow-making lances was tested using the set of 96 points of the snow course (Figure 2). The distance of the points from the snow-making lances was generated in a GIS environment using the command "Near". Only those lances which were in operation in a particular season were used in the analyses.

2.4. Statistical Analysis

The relationship between the dependent variables (mean seasonal value of daily air temperature; mean seasonal depth of the ski slope snowpack; melting period of the ski slope snowpack; mean daily average temperature during the melting period) and the independent variables (six winter seasons; snowmelt day of natural snow cover) was tested in STATGRAPHICS using a simple linear regression. The output of the analyses included the Pearson correlation coefficient (r), which quantifies the strength of the linear statistical relationship. The significance of the relationship was examined by testing the variance of the values around the linear regression at the 95% significance level. If the "p" value was equal to or greater than 0.05, the relationship was not significant. In the chapter results, the mean values are presented with standard deviations (mean ± SD). To analyze the relationship between the snow depth and the closest distance from the fixed snow-making lances, the statistical tests of the logarithmic relationships (ANOVA) were used. The strength of each relationship was determined with the correlation coefficient (r). For the five-season multiple comparison of the ski slope, snowpack characteristics (snow depth, snow density, and snow water equivalent) used the multiple comparison procedure in STATGRAPHICS to determine which means were significantly different from each other. The output shows the estimated difference and statistically significant differences between each pair of means.

3. Results

3.1. Meteorological and Snow Conditions

3.1.1. South-Central Slovakia

The depth of natural snow cover on grassland is considered to be sufficient for skiing (ski slope operation) when it is at least 30 cm [30]. In the six-season average, the mean monthly depth of natural snow cover in South-Central Slovakia was sufficient for ski slope operation for, maximally, two months (January, February; Figure 3b) in two of six seasons (Table 2). The probability that, in the winter season, a month with sufficient monthly average snow depth will occur varied from 17% to 33%. High standard deviations displayed in Figure 3a express high inter-seasonal variability of the monthly average snow depth, which was the highest at all precipitation stations ("station") in February. The highest variability in February was detected at the Bane station, where the monthly average snow depth in February 2012 was 66 cm and in February 2014 was 1 cm. Seasons 2011–2012 and 2012–2013 were snow-rich because the monthly average snow depth in all precipitation stations was higher than 30 cm for at least one month (Table 2). Two month-long periods, when the monthly average snow depth was higher than the threshold of 30 cm, were detected at the Bane station in the 2011–2012 and 2012–2013 seasons and in the Snohy station in the 2011–2012 season. At all precipitation stations, the threshold of 30 cm (mean average snow depth) was not reached in four of six seasons, indicating that they were snow-poor (seasons 2010–2011, 2013–2014, 2014–2015, and 2015–2016) (see Table 2).

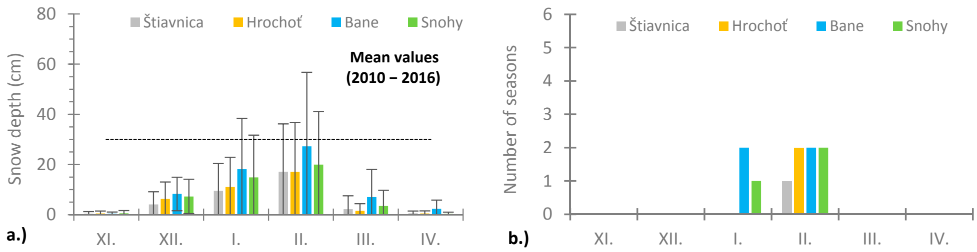

Figure 3. (**a**) Six-season mean values (mean ± SD) of monthly average snow depth at the four precipitation stations, which are sorted in ascending order according to their elevation (Štiavnica–lowest station). The horizontal dashed line indicates the depth of snow that is sufficient for skiing on natural snow (>30 cm); (**b**) The number of seasons (from the six analyzed seasons) in which the monthly average depth of natural snow cover was sufficient for skiing.

Table 2. Monthly average snow depth at the four precipitation stations from the 2010–2011 to the 2015–2016 season. Values > 30 cm (sufficient natural snow depth for skiing) are highlighted in yellow.

	Štiavnica 575 m a.s.l.							Hrochoť 652 m a.s.l.					
IX.	2	0	0	0	0	0	**IX.**	3	0	0	0	0	0
XII.	12	2	9	1	1	0	**XII.**	16	3	13	6	0	0
I.	3	18	28	0	4	4	**I.**	4	23	29	1	5	4
II.	2	28	47	0	24	1	**II.**	2	37	45	0	18	1
III.	0	0	13	0	0	0	**III.**	0	2	7	0	0	0
IV.	0	0	1	0	2	0	**IV.**	0	0	1	0	3	0
	Bane 758 m a.s.l.							**Snohy 771 m a.s.l.**					
IX.	2	0	0	1	0	0	**IX.**	3	0	0	0	0	0
XII.	16	7	15	11	1	0	**XII.**	14	7	17	5	1	0
I.	4	52	33	0	10	9	**I.**	6	43	28	2	6	5
II.	2	66	61	1	25	7	**II.**	3	38	50	1	26	2
III.	0	14	26	0	1	1	**III.**	0	5	16	0	0	0
IV.	0	0	7	0	6	0	**IV.**	0	0	0	0	2	0
Season	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	**Season**	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016

3.1.2. Košútka Ski Centre

The mean monthly values calculated from six seasons (from 2010–2011 to 2015–2016) and the mean seasonal values calculated from six months (XI–IV) for the Košútka Ski Centre showed the following patterns in precipitation, snow, and temperature.

Solid precipitation (snow) in the study site occurred from November to April (Figure 4a,c). Snow represented the highest percentage of the total monthly precipitation in January (61%), December (59%), and February (39%) (Figure 4c). Mean monthly precipitation totals (mean ± SD) higher than 55 ± 13 mm (value of XI–IV, average) were determined in February (69 ± 60 mm), November (65 ± 44 mm), and January (62 ± 27 mm) (Figure 4a), while in December the lowest mean monthly precipitation total was identified (39 ± 3 mm). A high inter-seasonal variability of the monthly precipitation totals was identified in November, January, February, and March (53 ± 36 mm) because of the high standard deviation of the mean monthly precipitation totals (Figure 4a).

The highest seasonal precipitation totals were found in the 2012–2013, 2015–2016, and 2010–2011 seasons (more than 328 mm–value of six-season average; Figure 4b). In the 2012–2013 season, the highest volume of solid precipitation was identified (254 mm). Snow in the 2011–2012 (52%) and 2012–2013 (51%) seasons represented more than 50% of the seasonal precipitation totals (Figure 4d). On the contrary, solid precipitation during the 2013–2014 (12%) and 2015–2016 (13%) seasons represented the lowest percentage of the seasonal total.

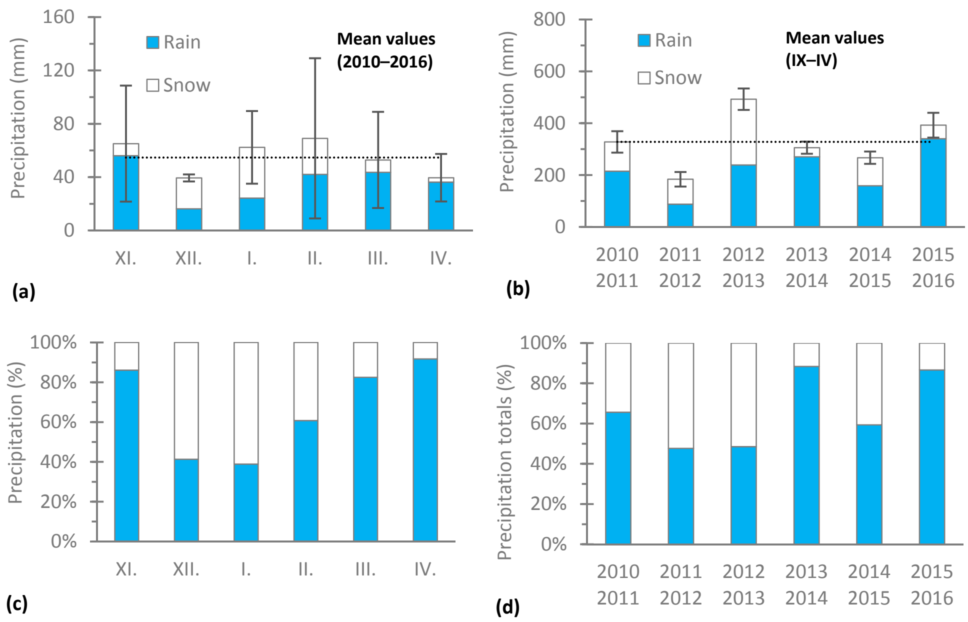

Figure 4. Mean (**a**) monthly and (**b**) seasonal precipitation totals in the solid (snow) and liquid (rain) states at Košútka Ski Centre. The standard error bars of the means were calculated from the precipitation totals. The horizontal dotted lines indicate the mean of the displayed values. The percentage component bar charts show the percentage from the mean (**c**) monthly or (**d**) seasonal precipitation totals (charts above).

In the six-season average, the mean monthly snow depth of natural snow cover was not sufficient for skiing in all months with snow occurrence (XI–IV; Figure 5a). The mean monthly snow depth was lower than the sufficient snow depth for ski slope operation without snow production (30 cm). The highest mean monthly snow depth (±SD) was determined in February (20.0 ± 21.2 cm) and January (14.9 ± 16.8 cm). The winter season at the study site starts at the end of December and ends in the middle of March (Table 1). Therefore, the mean seasonal value of snow depth for natural snow cover was calculated from these four months (XII–III). The mean seasonal depth of natural snow cover (XII–III) was lower than the sufficient snow depth for ski slope operation (30 cm) in all the six analyzed winter seasons (Figure 5c). The six-season average mean seasonal snow depth was 11.4 ± 11.3 cm (XII–III mean ± SD from seasons 2010–2016). The results showed high inter-seasonal variability in the mean seasonal depth of natural snow (Figure 5c). The highest mean seasonal values (mean ± SD) were identified in seasons 2012–2013 (27.7 ± 16.0 cm) and 2011–2012 (23.3 ± 20.1 cm). On the contrary, the lowest mean seasonal depths of natural snow were identified in seasons 2015–2016 (1.7 ± 2.2 cm) and 2013–2014 (1.9 ± 1.9 cm). The values of the mean seasonal and monthly snowfall totals showed the same pattern (Figure 5b,d). The highest mean monthly snowfall totals (mean ± SD) were determined for the following months: January (47.5 ± 32.2 cm), February (29.5 ± 29.1 cm), and December (26.5 ± 20.0 cm). No trend in the seasonal snow depth or snowfall totals was determined.

The mean seasonal value (XII–III) of daily air temperature has shown an increasing tendency ($y = 0.5979x - 1.5342$; Figure 5c) since the 2010–2011 season. The relatively strong Pearson's correlation coefficient ($r = 0.711$) only confirms this result. Mean monthly daily average temperatures (mean ± SD) under zero were indicated only in December (–0.6 ± 2.5 °C), January (–1.2 ± 1.3 °C), and February (–0.3 ± 2.3 °C) (Figure 5c). These relatively high mean winter temperatures could be considered inappropriate conditions for snowmaking.

The mean seasonal snow depth of natural snow cover in relation to the daily average temperatures (Figure 5c) resulted in the snowmelt timing of the natural snow cover (see chapter 3.3). The earliest snowmelt date of the natural snow cover (18 February) was identified in the 2015–2016 season with the highest mean seasonal daily average temperature (1.8 °C) and the lowest mean seasonal snow depth (1.7 cm). On the contrary, the latest snowmelt day of the natural snow cover (10 April) was identified in the 2012–2013 season, when the mean seasonal daily average temperature reached the lowest value (–1.3 °C), and the mean seasonal snow depth reached the highest value (27.7 cm).

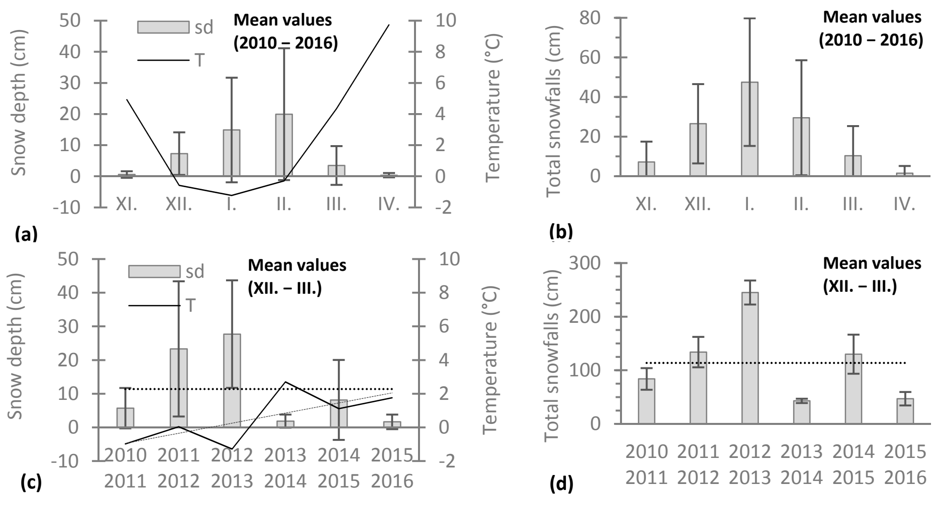

Figure 5. Mean (**a**,**b**) monthly and (**c**,**d**) seasonal values of the daily average snow depth (sd), daily average temperature (T), and total snowfall (sum of snowfalls). The horizontal dotted lines indicate the mean value from the displayed bar plot data. Bar plots are shown with SD.

3.2. Snowmaking Conditions

The main meteorological conditions affecting snowmaking are (in order of importance): (i) temperature; (ii) relative humidity; (iii) wind speed; and (iv) wind direction.

According to Steiger and Mayer [15], the days with T lower than −2 °C daily average temperature are defined as potential snowmaking days with optimal snowmaking conditions. At the Košútka Ski Centre, potential snowmaking days occurred from November to March, with a peak in January

(Figure 6a). The optimal conditions for snowmaking (Table 3) were, therefore, mainly in January (13 days), December (10 days), and February (9 days).

Table 3. The number of potential snowmaking days (PSD) when the daily average temperature reached the threshold of −2 °C, the required number of snowmaking days (RNSD), and six-season mean monthly values with standard deviation (Mean ± SD). Mean monthly values in bold identify a positive difference between PSD and RNSD.

	2010–2011		2011–2012		2012–2013		2013–2014		2014–2015		2015–2016		Mean ± SD	
	PSD	RNSD	PSD	RNSD	PSD	RNSD	PSD	RNSD	PSD	RNSD	PSD	RNSD	PSD	RNSD
XI.	2	28	6	23	0	23	2	23	0	26	2	26	2.0 ± 0.9	22.4 ± 6.2
XII.	20	2	4	1	19	1	8	5	6	11	3	12	**10.0 ± 3.1**	**5.9 ± 4.5**
I.	17	5	12	3	18	3	8	9	8	6	14	4	**12.8 ± 1.8**	**4.9 ± 2.2**
II.	15	4	18	4	9	4	1	11	13	4	0	13	**9.3 ± 3.0**	**6.6 ± 4.3**
III.	2	21	2	7	11	7	0	32	0	18	0	20	2.5 ± 1.7	20.6 ± 8.3
IV.	0	46	0	42	0	42	0	43	0	36	0	43	0	41.9 ± 3.4

On average, the months of December, January, and February were identified as suitable for snowmaking. In these months, the number of potential snowmaking days (PSD = the days with optimal snowmaking conditions) was greater than the required number of snowmaking days (RNSD = number of days required for balancing snow melt with snow production). The difference between PSD and RNSD identifies the number of days suitable for base layer snowmaking (not for the restoration of melted snow). At the study site, four such days were identified in December, eight days in January, and three days in February (six-season average; Table 3). The average snowmaking systems can produce sufficient snow cover for skiing (20 cm thick) in five days [26]. Thus, at the Košútka Ski Centre, there were enough snowmaking days (for the 20-cm-thick base layer snowmaking) only in January (eight days; Table 3) on average. According to the ski center owner, base layer snowmaking is necessary at the beginning (XII–I) of each season. In December, it was possible during two seasons and in January during four seasons (six-season average; Figure 6b). In two seasons (2013–2014 and 2014–2015), less than a 20-cm-thick snow cover could be created (insufficient for skiing). Generally, at the beginning of the winter season (XII–I) there were 11 days with optimal snowmaking conditions (PSD), but only six days left for base layer snowmaking on average. The remaining five days were necessary for the restoration of melted snow. The number of PSD and RNSD is dependent on the daily average temperature. Figure 6b clarifies that, in the months with lower mean daily average temperatures, the number of PSD increased and the number of RNSD decreased. Because of low mean daily average temperatures in December and January in two of the six seasons (seasons 2010–2011 and 2012–2013), a high number of PSD in these seasons was identified (Figure 6b).

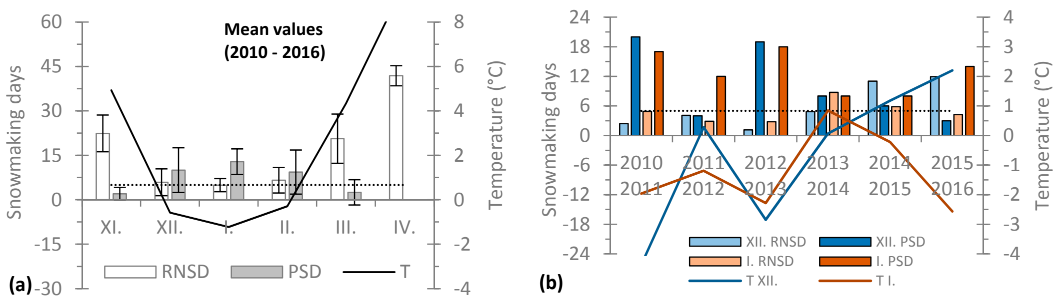

Figure 6. (**a**) The mean (±SD) number of potential snowmaking days (PSD) in contrast to the required number of snowmaking days (RND) and the monthly course of mean daily average temperature (T); (**b**) Seasonal values of PSD vs. RNSD and mean daily average temperatures in December and January. The horizontal dotted lines indicate the minimum number of five days for base layer snowmaking (20 cm thick).

Wind speed and wind direction are not crucial meteorological conditions for snowmaking. Nevertheless, wind significantly affects the accumulation of artificial snow during its production. In three-season averages, during the potential snowmaking days in December and January, wind with a maximum speed of 1 m/s occurred 73% of the time, while it blew 65% of the time from the SW–SE side (Figure 7a,b). The mean difference in the wind speed categories between December and January was 14 h (2% of occurrence; Figure 7a). During the days with optimal snowmaking conditions (PSD) at the beginning of the winter season (XII–I), the wind speed was proper for the snow production most of the time. At the beginning of the winter season, at the study site, 94% of the time the wind was calm or blew only lightly with a maximum speed of 2 m/s from the SW–SE side (Figure 8).

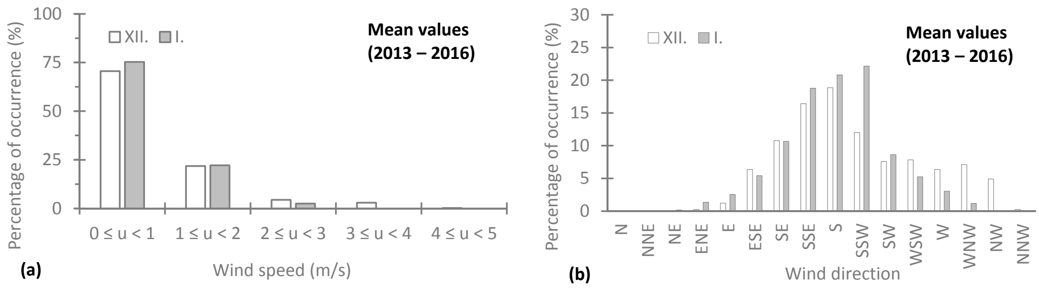

Figure 7. Percentage of (**a**) wind speed (u) and (**b**) wind direction occurrences in December and January during the potential snowmaking days (PSD).

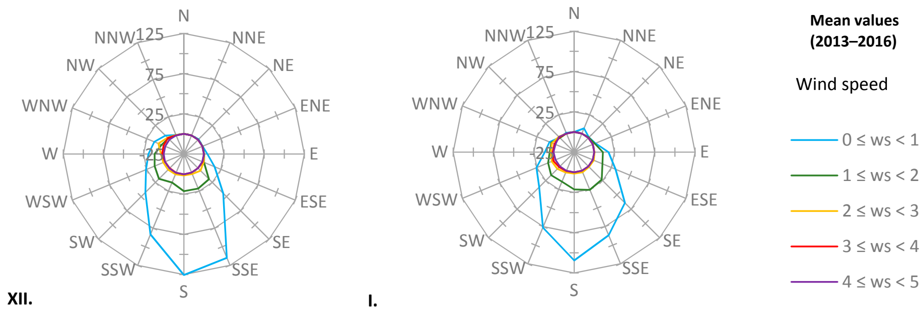

Figure 8. Three-season (2013–2016) average wind speed and direction in (XII) December and (I) January. The graph axis displays the average number of hours. The sum of the displayed hours is 676 in December and 667 in January. Wind roses were created from the mean hourly wind speed and direction data.

3.3. Characteristics of the Ski Slope Snowpack

The ski slope snowpack melts several weeks (melting period "mp") after the natural snow cover in the surroundings melts away (Figure 9b). The melting period of the ski slope snowpack was the shortest in the 2012–2013 season (25 days) and the longest in the 2015–2016 season (47 days). In the six-season average, the snowpack of the artificially covered ski slope persisted on the slope 29 days (median) longer compared to off-piste sites with natural snow. The natural snow cover on the off-piste sites was melted away each season on a different date (Figure 9a). The highest difference of 51 days was identified between the seasons 2015–2016 (18 February) and 2012–2013 (10 April). A significant, linear relationship was proved between the date in the season (independent variable) when the natural snow cover on the off-piste sites was melted away (date of snowmelt) and the duration of the ski slope snowpack melting period (dependent variable 1) or the mean daily average temperature during the melting period (dependent variable 2) (Figure 9b). With an earlier date of snowmelt, the melting period of the ski slope snowpack was longer, and the daily average temperature during this melting period was lower. The remaining ski slope snowpack that was a mixture of artificial snow and natural precipitation had the following characteristics (five-season mean values ± SD; Figure 9a,c,d): snow depth: 44.5 ± 9.5 cm, density: 618.8 ± 63.1 kg/m^3, snow water equivalent (snow water equivalent (SWE): 281.4 ± 46.2 mm.

At the Košútka Ski Centre, the depth of the ski slope snowpack at the end of the each of the five seasons was always higher than the sufficient snow depth for skiing (20 cm; Figure 9c). The mean depth of the ski slope snowpack measured at the end of the season showed a decreasing inter-seasonal trend (Figure 9c; $y = -5.181x + 60.051$, $r = 0.864$) and significant differences (Table 4). The highest difference of 22.9 cm was identified between seasons 2011–2012 and 2015–2016. The mean depth of snow measured on the artificially covered ski slope at the end of the winter season was 2.3 times higher (31.2 cm difference) than the mean seasonal depth (XII–III) of natural snow in the surroundings (five-season average; Figure 9c). The highest difference between these two values was determined in the seasons with a shortage of natural snow (seasons 2010–2011, 2011–2015 and 2015–2016). Because of the high density of the ski slope snowpack, a high amount of water was still stored in it after the natural snow had melted away. In the five-season average, the mean SWE value of the remaining ski slope snowpack (281.4 ± 46.2 mm; mean ± SD) represented 120% of the seasonal precipitation totals (XII–III; 234.1 ± 94.7 mm; Figure 9d), and the water input from the melting ski slope snowpack (=SWE; 281.4 ± 46.2 mm; mean ± SD) was 1.3 times higher than the seasonal (XI–IV) solid precipitation totals (124.6 mm). A significantly different mean SWE of the ski slope snowpack, measured at the end of these seasons, was identified between five seasons (Table 4). The highest difference (126.5 mm) was determined between the same seasons, as in the case of the mean snow depth (2011–2012 vs. 2015–2016). At the end of the season, the mean snow density of the ski slope snowpack showed significant inter-seasonal differences (Table 4). The five-season average showed above-average mean snow density (higher than 618.8 kg/m^3), identified in the 2014–2015 (737.4 ± 95.7 kg/m^3) and 2015–2016 (663.7 ± 95.0 kg/m^3; Figure 9a) seasons.

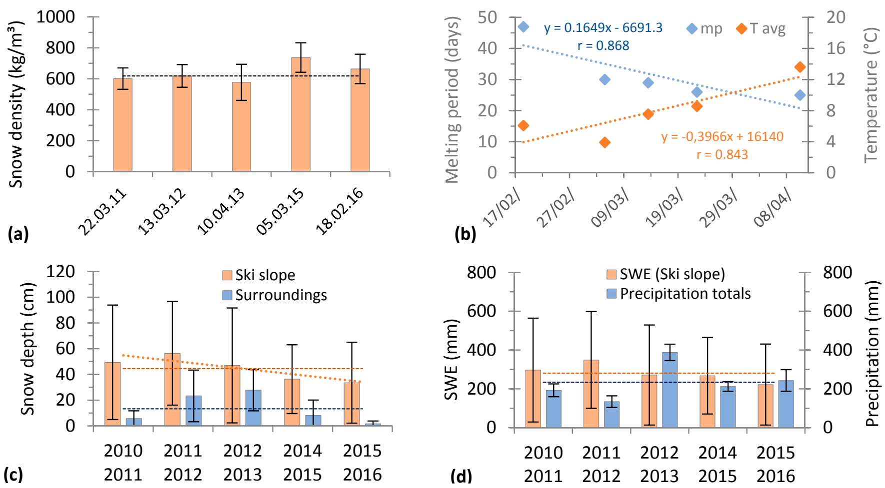

Figure 9. (**a**) Mean density of the residual snowpack on the artificially covered ski slope after the disappearance of natural snow in the surroundings (five seasons); (**b**) Relationship between the date in the season (five seasons displayed) when the natural snow cover on the off-piste sites was melted away and the melting period (mp) or temperature (T avg). The melting period expresses the prolonged duration of the melting of the snowpack on the artificially covered ski slope compared to off-piste sites. The temperature expresses the mean daily average temperature during the melting period; (**c**) Mean depth of snow on the artificially covered ski slope (at the end of winter season) in comparison to the mean seasonal depth (XII–III) of natural snow in the surroundings; (**d**) Mean snow water equivalent (SWE) of the ski slope snowpack (at the end of the winter season) in comparison to the seasonal precipitation totals (XII–III). The horizontal dashed lines indicate the mean value except for subfigure "b". Mean values are displayed with standard deviation bars.

The distribution of snow on the ski slope was highly heterogeneous (Figure 10). The high variability of the snow depth data expressing the standard deviation of the mean snow depth is shown in Figure 9c. The observed snow depth minima at the end of each season were close to 0 cm, while the maxima reached values from 100 to 200 cm. The maxima always occurred at a distance below 30 m from the lances, which is the maximum distance of the used snowmaking technique. The maximum snow depths were close to the snow-making lances. Significant logarithmic relationships were proved between the snow depth and the distance from the fixed snow-making lances in all seasons (ANOVA: $p < 0.05$; Figure 10). The snow depth decreased as the distance from the lances increased. The correlation was the lowest in the winters of 2011–2012 and 2012–2013 (Figure 10), which were characterized by the highest mean seasonal snow depth of natural snow cover in the ski slope surroundings (Figure 5a). In contrast, in the remaining three seasons with low mean seasonal depth of natural snow cover, the need to produce a high volume of snow resulted in a more uneven distribution of snow on the ski slope and, therefore, a higher correlation of the analyzed relationships (higher correlation coefficient; Figure 10).

Table 4. Multiple, inter-seasonal comparisons of mean snow depth, snow water equivalent (SWE), and snow density of the ski slope snowpack, measured at the end of the five winter seasons. Displayed are the estimated differences between each pair of means.

Inter-Seasonal Comparison	Snow Depth (cm)	SWE (mm)	Snow Density (kg/m^3)
22 March 2011 vs. 15 March 2012	−7.0	−52.0	−17.2
22 March 2011 vs. 10 April 2013	2.4	25.4	23.7
22 March 2011 vs. 5 March 2015	13.1 *	29.0	−136.1 *
22 March 2011 vs. 18 February 2016	15.9 *	74.5 *	−62.6 *
15 March 2012 vs. 10 April 2013	9.4	77.4 *	40.9
15 March 2012 vs. 5 March 2015	20.1 *	81.0 *	−118.9 *
15 March 2012 vs. 18 February 2016	22.9 *	126.5 *	−45.4
10 April 2013 vs. 5 March 2015	10.7	3.6	−159.8 *
10 April 2013 vs. 18 February 2016	13.5 *	49.1	−86.3 *
5 March 2015 vs. 18 February 2016	2.8	45.4	73.5

* denotes a statistically significant difference at the 95.0% confidence level.

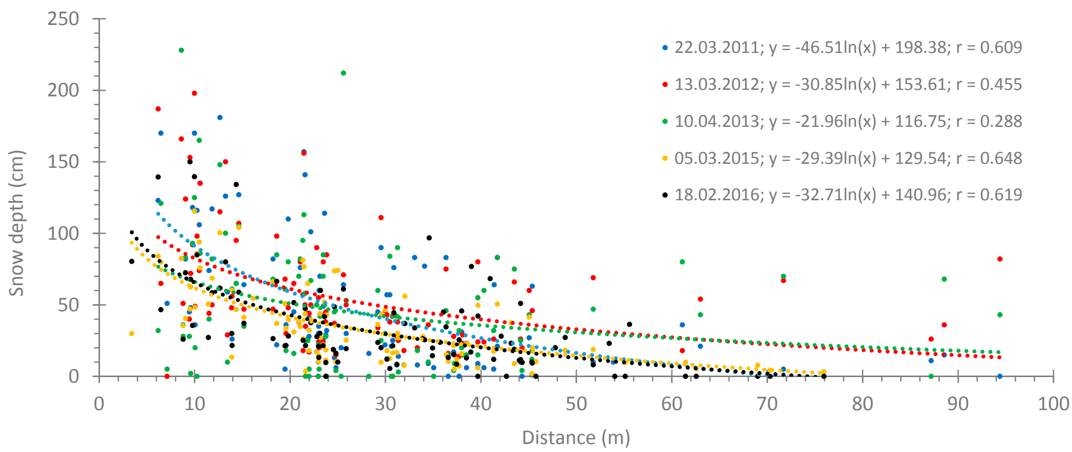

Figure 10. Relationships between the snow depth on the artificially covered ski slope and the closest distance from the snow-making lances at the end of the 2010−2011 to 2015−2016 seasons. The correlation coefficient "r" measures the strength of the logarithmic relationship. The points represent 96 measured values of the snow depth.

4. Discussion

4.1. Meteorological and Snow Conditions

4.1.1. South-Central Slovakia

If the operability of the South-Central Slovakian ski centers was dependent only on natural snow, the ski slopes could have been opened only in two of the six analyzed winter seasons. The reason for this is the low monthly average snow depth, which was highly variable between the seasons. The high inter-seasonal variability of the monthly average snow depth confirms a study by Hríbik et al. [33] which was conducted in South-Central Slovakia (660 m a.s.l.). Hríbik et al. [33] identified three of six winter seasons (snow-poor seasons 2006–2009) in which the monthly average snow depth was lower than 30 cm (snow depth > than 30 cm is sufficient for skiing). In the presented study, a monthly average snow depth higher than 30 cm occurred only in January or February, but most often in February. Therefore, continual seasonal operability of the South-Central Slovakian ski slopes could not be achieved from December to March without the help of artificial snowmaking. Hríbik et al. [33] confirmed that the peak snow depth most often occurs in February. Nevertheless, in the snow-rich season 2004–2005, March was identified by Hríbik et al. [33] as the month with the highest monthly average snow depth.

4.1.2. Košútka Ski Centre

A general high occurrence of liquid precipitation in the winter season was identified in the presented study, while this occurrence was highly variable between the individual seasons. A tendency of increasing mean seasonal value of the average daily temperature (seasonal = months XII–III) was discovered. These results are in good agreement with those of Pecho et al. [34], who have pointed out that winters after 1991 were not as cold as in the past, which resulted more often in the occurrence of mixed and liquid precipitation. From the six seasons (2010–2016) presented in this paper, the season 2012–2013 was identified as highly above average in precipitation totals (XI–IV) and in snowfall totals (XII–III). This season was described by Mikloš et al. [35] as snow-rich with high peak snow water equivalent in the mountainous watershed located only 10 km northwest of the Košútka Ski Centre. Pecho et al. [36] described this weather situation in more detail. According to Faško [37] and Falťan et al. [38], precipitations occur currently with a higher intensity than in the past. This leads to the occurrence of months with extremely above normal and below normal levels of precipitation. The presented work confirms these conclusions because of the relatively high standard deviation of the mean monthly precipitation totals in November, January, February, and March. From a comparison of climate regions in Slovakia between the Landscape Atlas of the Slovak Republic published in 2002 [39] and the Climate Atlas of the Slovak Republic published in 2015 [40] there are obvious important changes in some regions and sub-regions [37]. In the areas located approximately 20 km south of the study site (Košútka Ski Centre), the warm, dry sub-region with cold winters (T3) changed to a warm, dry sub-region with mild winters (T2). The increasing seasonal values (XII–III) of the daily average temperature confirm these warming tendencies of South-Central Slovakia [13].

The meteorological and snow conditions of the study site are not suitable for the continuous operation of the ski slope from December to March without artificial snowmaking. The reason for this is the relatively high variability of the monthly average snow depth in the individual seasons. A deficit of natural snowfall due to the variability of meteorological and snow conditions was also identified by Durand et al. [41] in the European Alps. The vulnerability of the French ski resorts to the lack of natural snow was observed by Spandre et al. [42]. The altitude of the snow line with sufficient snow conditions for skiing has a rising trend in the European Alps [43,44]. If the ski slope operation in the investigated low-elevation ski center were dependent only on natural snow, then skiing would only be possible in some days or months during the season.

4.2. Snowmaking

This study clarifies that operability during every season of the South-Central Slovakian ski slopes is not possible without artificial snowmaking. Nevertheless, snowmaking is dependent on a low air temperature [3]. In South-Central Slovakia, creation of the base layer for skiing is essential at the beginning of the winter season (end of December–beginning of January) because of the high public demand (Christmas holidays). Thus, a high number of potential snowmaking days (PSD; days with optimal snowmaking conditions) is essential mainly in the seasons with a low depth of natural snow. In the Košútka Ski Centre, a low seasonal depth of natural snow cover was identified in four of six seasons (lower than 10 cm). Because of the low air temperature in December or January, the base layer snowmaking was possible in the snow-poor seasons of 2010–2011 and 2015–2016. In the relatively warm season of 2014–2015, the number of PSD was insufficient for base layer creation, but snowmaking was supplied by the above-average seasonal snowfall totals. In the 2013–2014 season, the ski slope of the Košútka Ski Centre was out of service because of warm winter temperatures in which base layer snowmaking was not possible and because of low seasonal snowfall totals. Additionally, Hopkins and Maclean [45] concluded that some regions in Scotland were not able to produce artificial snow due to inadequate meteorological conditions. Many authors claim that the use of artificial snow is a sufficient adaptation strategy against climate change [46,47], although low-altitude resorts remain negatively impacted by seasons with poor snow conditions [48–50]. Moreover, Vojtek et al. [10] and Škvarenina et al. [11] pointed out the general tendency of the decreasing duration of snow cover and solid precipitation occurrence at lower altitudes in Slovakia (Central Europe). In the current meteorological conditions of South-Central Slovakia, the operability of the investigated low-elevation ski slope is possible because of high snow production, which is possible only for a few days in the winter season.

In the investigated low-elevation ski center, the wind speed and wind direction are probably not limiting factors for snowmaking. The reason for this is the low occurrence of wind with a speed higher than 2 m/s and a relatively constant wind direction during the days with optimal snowmaking conditions in December and January. Spandre et al. [51] also found ideal wind speed (low) and wind direction (constant) conditions for snowmaking, but in the higher elevated alpine ski resort "Les 2 Alpes" (1680 m a.s.l.). Suitable wind conditions for snowmaking in the investigated ski center could be explained by the results of Spandre et al. [52]. They concluded that the topography and vegetation have significant impacts on the efficiency of snow production. Ideal wind conditions during the potential snowmaking days increase the efficiency of the snowmaking because of low water losses. According to Olefs et al. [53], the water losses during snowmaking (evaporation, sublimation, wind erosion) varied between 5% and 15% for fan guns and from 15% to 40% for snowmaking lances. The mostly constant wind direction is, therefore, beneficial, especially for the use of snow-making lances that have fixed positions, as in the investigated Košútka Ski Centre.

4.3. Characteristics of Ski Slope Snowpack

This study confirms that the snowpack of an artificially covered ski slope characterizes high snow depth and density of snow [22]. In contrast to previous surveys [22,33], the presented research was conducted in a low-elevation ski center under 1000 m a.s.l. Mossner et al. [54] reported that snow density on the ski slope ranging between 420 and 620 kg/m^3 with a mean value of 556 kg/m^3 (undefined ski slope in Switzerland). The results of our study show a high mean snow density of 619 kg/m^3 at the end of the winter season (five-season mean value). A high density of the ski slope snowpack at the end of the winter season was also found by Keller et al. [55]. They stated that, in the middle of December, the snow density on slopes with artificial snow is around 500 kg/m^3. Such snow becomes increasingly compact over time until it becomes a mixture of hard snow with clear ice with a maximum density around 700 kg/m^3. In our case, the mean snow density was the highest at the end of the 2014−2015 season, with a value of 737 kg/m^3. Such high mean density was not recorded by the other authors, probably because of the low elevation of the study site and late date of measuring.

The high density could be the result of refreezing water or water saturation from the melting snow. The artificial snow significantly increases the depth of snow on the ski slopes [22]. Our results confirm these findings because, after the disappearance of natural snow on the off-piste sites, the depth of the snowpack with artificial snow was still 45 cm (five-season average). The mean depth of snow measured on the artificially covered ski slope at the end of the winter season was 2.3 times higher (70% difference) than at the off-piste sites with natural snow (five-season average). Stoeckli and Rixen [56] showed a 20% difference in the depth of the artificially covered ski slope snowpack compared to controlled plots with undisturbed natural snow (Swiss Alps; 1150–2515 m a.s.l.). The water input from the melting ski slope snowpack at the end of the season was 1.3 times higher than the seasonal (XI−IV) solid precipitation totals. Studies from the Alps confirmed that the water input from the melting ski slope snowpack usually reaches 0.7–2 times (up to five times) that from natural snow [56,57].

The depth of the ski slope snowpack at Košútka was significantly dependent on the distance from the snow-making lances. The maxima (over 2 m) were observed at a distance below 30 m from the lances. This is caused by the high snow production (base layer creation) at the beginning of the winter season. The influence of the wind during base layer snowmaking was probably not significant because of the low wind speed and constant wind direction. Spandre et al. [58] also showed that the highest snow depth occurred within 30 m from the snow gun while low wind speed conditions were determined. In the presented study, the ski slope snowpack (groomed) was examined at the end of the season, while Spandre et al. [58] described the characteristics of the artificial snow pile (undisturbed) from the beginning of the winter season. Therefore, for the managers of the Košútka ski slope, a more equal distribution of artificial snow would be beneficial.

The changed characteristics of the ski slope snowpack result in prolonged melting. Keller et al. [55] and Rixen et al. [22] state that artificial snow in the Alps (above 1000 m a.s.l.) melts 28 days and 17 days longer than natural snow, respectively. We observed a prolongation of about 29 days (610 m a.s.l.). The cause is probably the high snow production and the earlier snowmelt of natural snow in the low-elevation study site. In the 2015–2016 season, the natural snow cover melted away at the earliest date (18 February) in the inter-seasonal comparison. This was because of the low seasonal snowfall totals and, consequently, low mean seasonal snow depth.

The economic success during the winter season for ski centers is dependent on the income during specific periods (Christmas—end of December; spring academic holidays-February to the beginning of March) [59,60]. As deduced from the six-season average, the ski centers in South-Central Slovakia (under 1000 m a.s.l.) that do not use artificial snowmaking have no chance to expect that the mean monthly snow depth in December will be sufficient for skiing, but the probability that the mean monthly snow depth will be sufficient for skiing in February varied between 17% and 33%. Therefore, snowmaking is the only possible solution to increase the snow depth on South-Central Slovakian ski slopes. In the investigated Košútka Ski Centre, snowmaking has been effective, allowing the ski slope to be operational in five of six winter seasons.

5. Conclusions

The results from this study showed that the snow depth of natural snow cover in South-Central Slovakia under 1000 m a.s.l. is not sufficient for continuous ski slope operation from December to March. The probability that, in the winter season, there will be a month with sufficient snow depth for ski slope operation varies from 17% to 33%. At the Košútka Ski Centre (the study site in South-Central Slovakia) the seasonal snowfalls and mean seasonal snow depth are highly variable. Every season, ski slope operability in this ski center is not possible without artificial snowmaking. A high percentage of the winter precipitation consists of liquid precipitation at the study site. Because of the low snow depth of the natural snow cover in the study site, the base layer creation at the beginning of each season is crucial for ski slope operability. A sufficient number of days for base layer snowmaking was identified only in four of six winter seasons. Essential, large production of artificial snow on the ski slope results in unequally distributed snow with high density, depth, and snow water equivalent

(SWE). An inter-seasonal comparison of the ski slope snowpack characteristics, measured at the end of the season, showed significant differences in the mean snow depth, SWE, and snow density. The mean snow depth showed a decreasing trend. The distribution of snow on the artificially covered ski slope of Košútka Ski Centre is highly heterogenous. The snow depth decreases as the distance from the snowmaking lances increases. To improve the heterogeneous distribution of snow, it is necessary to move accumulated artificial snow under the snow-making lances further away to the opposite edge of the ski slope. The snowpack of the artificially covered ski slope persists on the slope longer than the natural snow on the off-piste sites. With an earlier snowmelt date of natural snow cover, the melting period of the ski slope snowpack from this date is longer, and the daily average temperature during this period is lower. Because of the high depth and density of the ski slope snowpack, a high amount of water is still stored in it after the natural snow has melted away from the off-piste sites. On average, this amount of water is higher than the seasonal precipitation (period XII–III).

We can conclude that, in the current meteorological and snow conditions of South-Central Slovakia, the operability of the low-elevation ski slopes is possible only with high snow production. From the example of the Košútka Ski Centre, it was found that essential base layer snowmaking for ski slope operation is possible only for a few days at the beginning of the winter season. The increasing mean value of the daily average temperature and high occurrence of winter liquid precipitation can finally result in inadequate conditions for ski slope operation.

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