J. Hydrol. Hydromech., 68, 2020, 1, 28–37
DOI: 10.2478/johh-2019-0026
ISSN 1338-4333



sciendo Journal of Hydrology and Hydromechanics

# Ski piste snow ablation versus potential infiltration (Veporic Unit, Western Carpathians)

Michal Mikloš[1], Dušan Igaz[2], Karol Šinka[3], Jana Škvareninová[4], Martin Jančo[1,5], Ilja Vyskot[6], Jaroslav Škvarenina[1*]

[1] Department of Natural Environment, Faculty of Forestry, Technical University in Zvolen, Ul. T. G. Masaryka 24, 960 53 Zvolen, Slovakia. E-mail: miklosmiso@gmail.com
[2] Department of Biometeorology and Hydrology, Faculty of Horticulture and Landscape Engineering, Slovak University of Agriculture in Nitra, Hospodárska 7, 949 76 Nitra, Slovakia. E-mail: dusan.igaz@uniag.sk
[3] Department of Landscape Planning and Land Consolidation, Faculty of Horticulture and Landscape Engineering, Slovak University of Agriculture in Nitra, Hospodárska 7, 949 76 Nitra, Slovakia. E-mail: sinka.karol@gmail.com
[4] Department of Applied Ecology, Faculty of Ecology and Environmental Sciences, Technical University in Zvolen, Ul. T. G. Masaryka 24, 960 53 Zvolen, Slovakia.
[5] Faculty of Ecology and Environmental Sciences, Technical University in Zvolen, Ul. T. G. Masaryka 24, 960 53 Zvolen, Slovakia.
[6] Department of Environmentalistics and Natural Resources (FRDIS), Faculty of Regional Development and International Studies, Mendel University in Brno, Tř. Generála Píky 2005/7, 613 00 Brno, Czech Republic. E-mail: vyskot@mendelu.cz
[*] Corresponding author. Tel.: +421455206209. E-mail: skvarenina@tuzvo.sk

**Abstract:** Snow production results in high volume of snow that is remaining on the low-elevation ski pistes after snowmelt of natural snow on the off-piste sites. The aim of this study was to identify snow/ice depth, snow density, and snow water equivalent of remaining ski piste snowpack to calculate and to compare snow ablation water volume with potential infiltration on the ski piste area at South-Central Slovak ski center Košútka (Inner Western Carpathians; temperate zone). Snow ablation water volume was calculated from manual snow depth and density measurements, which were performed at the end of five winter seasons 2010–2011 to 2015–2016, except for season 2013–2014. The laser diffraction analyzes were carried out to identify soil grain size and subsequently the hydraulic conductivity of soil to calculate the infiltration. The average rate of water movement through soil was seven times as high as five seasons' average ablation rate of ski piste snowpack; nevertheless, the ski piste area was potentially able to infiltrate only 47% of snow ablation water volume on average. Limitation for infiltration was frozen soil and ice layers below the ski piste snowpack and low snow-free area at the beginning of the studied ablation period.

**Keywords:** Snow water equivalent; Snow density; Artificial snow; Snow ablation; Soil temperature; Hydraulic conductivity.

## INTRODUCTION

Snow ablation water plays important role in the hydrological cycle of the snow-dominated basins, where it fundamentally affects seasonal patterns of stream flow (Barnett et al., 2005; Bartík et al., 2014; Hríbik et al., 2012). Because of climate change, the less accumulated snow and earlier snow ablation were observed in North America (Cayan et al., 2001; Mote et al., 2005) and Central Europe (Steiger, 2010; Wipf and Rixen, 2010), especially in lower altitudes (Mikloš et al., 2018a). Earlier snow ablation timing of natural snowpack in combination with the warmer climate results in earlier peak runoff, earlier increase in soil moisture, and earlier start of the vegetation period in the season (Babálová et al., 2018; Barnett et al., 2005; Igaz et al., 2008). The shift of snow ablation water available for evapotranspiration to earlier dates can fundamentally change climatic water balance on the local and regional scale (Hrvoľ et al., 2009; Ohmura and Wild, 2002). Studies focused on the precipitation variability in the Central Europe show tendency of drought occurrence in the early spring (Beniston, 2007). Prolonged ablation period of ski piste snowpack probably significantly influences availability of snow ablation water for evapotranspiration longer period than on the off-piste site.

A number of European studies identified shift in snowfall pattern (Laternser and Schneebeli, 2003; Rixen et al., 2012; Wipf et al., 2009) and increase in the mean air temperature (Kammer, 2002). Shift of liquid winter precipitation to lower elevations of Central European mountains was recorded by numerous studies (Mikloš et al., 2018a; Škvarenina et al., 2009; Steger et al., 2013; Vido et al., 2015; Wipf et al., 2009). Winter tourism that is vulnerable to the snow reliability had to adapt in the last decades. To stay operable, ski centers have had to produce artificial snow (since the middle of the 1980s), which decreased their dependency on the natural snow (Bark et al., 2010; Gilaberte-Búrdalo et al., 2014). Nevertheless, snowmaking has economic and physical boundaries, mainly for lower elevation and small-sized ski centers (Mikloš et al., 2018a; Steiger, 2010; Steiger and Mayer, 2008), because of high water and energy consumption (Damm et al., 2014) and temperature/humidity limitations. Artificial snow has different physical and chemical properties than natural snow (Minďáš and Škvarenina, 1995; Rixen et al., 2003). Nutrient-rich rounded particles of artificial snow, instead of nutrient-poor dendritic snowflakes, create homogenous snowpack with occurrence of ice layers (Rixen et al., 2003, 2008). Generally, snow production increases snow depth and snow density as well (Keller et al., 2004; Mossner et al., 2013). Compared with off-piste sites with natural snow, melting of ski piste snowpack is significantly prolonged because of the higher snow water equivalent (SWE), density, and snow/ice layers (Melanie and Rixen, 2014). Rixen et al. (2004) identified that snowmelt water volume from Swiss snowed piste with artificial snow is twice as high as that from the piste with natural snow. Snow ablation water from ski piste snowpack has significant impact on the local water cycle when it strongly influences the runoff (De Jong and Barth, 2008; Szolgay et al., 2016) and soil moisture over several weeks after natural snowmelt (Freppaz et al., 2012; Tárnik and Igaz, 2015). Volume of infiltrated water from ski piste snowpack has not yet been studied, and determining it is the aim of this current article. Volume of infiltrated water depends on the thermal and physical properties of soil (infiltrability) at the time of snowmelt (Gray et al., 1986) and structure of vegetation cover. Physical properties of soil and plant communities are degraded on the majority of ski pistes because of machine grading (Pintaldi et al., 2017; Ristić et al., 2012). Generally, the disturbed and compacted soil profile with removed or changed vegetation cover can hold less water, causing soil erosion or flood events (Freppaz et al., 2012; Muchová et al., 2015; Nagy et al., 2018). Vegetation and soil cover are being disturbed even during the winter season by the snow-grooming machines (Kňazovičová et al., 2018; Melanie and Rixen, 2014; Roux-Fouillet et al., 2011). Groomed snowpack has reduced insulation capacity because of lower air content and subsequently higher density (Newesely, 1997). Thus, the top soil layers on the pistes can suffer from long-lasting soil frost (Rixen et al., 2004). There are three soil classes, which were determined by Gray et al. (2001), according to their surface entry for meltwater if the soil is frozen during the snow ablation period: unlimited (high infiltration), restricted (low infiltration), and limited (defined by soil physical properties).

Our previous study (Mikloš et al., 2018a) showed that operability of low-elevation ski slopes in South-Central Slovakia is possible only with high snow production. Intensive snowmaking results in ski piste snowpack that is melting even a few weeks after disappearance of natural snow on the off-piste sites. The ski piste snowpack of South-Central Slovakian ski center Košútka was analyzed five seasons after snowmelt of natural snow on the off-piste sites to achieve the following objectives:

(1) to identify snow depth, snow density, and SWE during snow ablation period; to assess correlation between snow depth and snow density; and to identify occurrence of basal ice layer in snowpack and its relationship with snow depth;

(2) to identify and to compare soil temperature on the snow-free and snow-covered ski piste sites as limitation for infiltration; and

(3) to calculate potential infiltration on the ski piste and to compare calculated infiltration with modeled snow ablation water volume based on manual snow depth and density measurements.

## MATERIALS AND METHODS

### Study site

The study was conducted at the ski center Košútka (Figure 1) localized in the Slovenské Rudohorie Mts., Veporic Unit (Inner Western Carpathians; temperate zone). The ski center was established and equipped with the snowmaking technology in 2007. The stream “Slanec” flowing at the foot of the ski slope is used as the water source for snowmaking. Sole, 950-m-long ski piste with an elevation difference of 220 m (500–720 m above sea level [a.s.l.]), western-to-northern aspect and slope from 7° to 25°, was based on the partly forested slope. Smooth ski piste was built with use of machine grading; obstacles such as rocks and trees were removed, and soil surface was leveled. Disturbed parts of ground surface were visible even after 5 years (Figure 1). The original soil type Modal Cambisol, formed from andesite tuffs and granodiorites (Gömöryová et al., 2013), was degraded when its horizons were mixed or covered by soil during grading. Areas on the ski piste with bare soil were fertilized and revegetated after creation with original plant communities. Nevertheless, the high occurrence of ruderal plant species (*Sambucus ebulus*, *Calamagrostis epigejos*, *Cirsium arvense*, *Solidago canadensis*, *Tanacetum vulgare*, etc.), pioneer tree species (*Betula pendula*, *Salix caprea*, *Populus tremula*), and bare soil was identified on the piste by Mikloš et al. (2018b). According to the data from 1961 to 1990 and the Czechoslovak climate classification modified in Landscape Atlas of the Slovak Republic (2002), the climate is moderately warm with cool to cold winters, mean annual temperature and precipitation of 5.5°C and 850 mm, mean January temperature and precipitation of −5°C and 45 mm, respectively (Šťastný et al., 2002; Faško and Šťastný, 2002), and duration of 36.7-cm-thick mean snow depth of 90 days on average (Faško et al., 2002; Šatala et al., 2017).

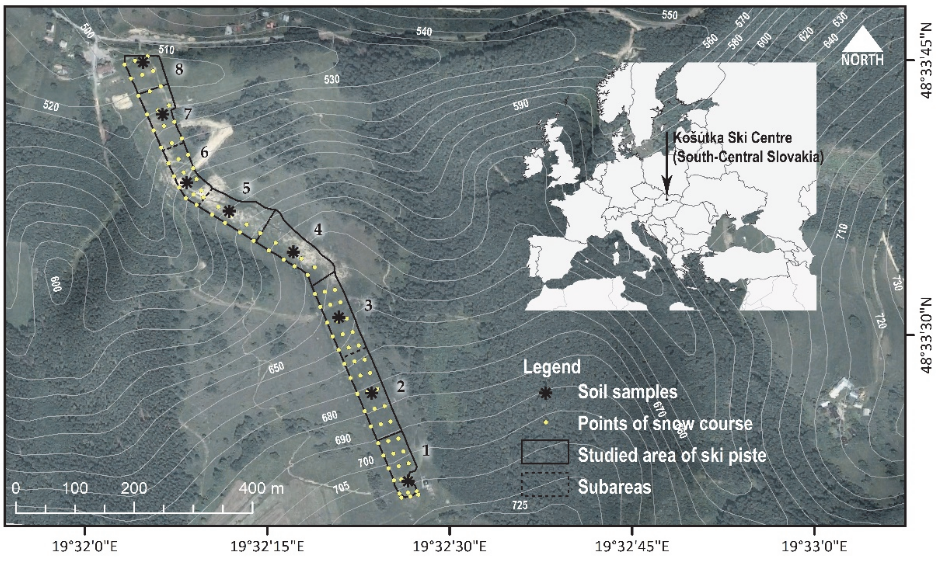


**Fig. 1.** Ski slope of Košútka ski center (Central Europe; South-Central Slovakia) with defined boundaries of ski piste area and eight subareas. Positions where the soil samples were taken and where the snow depth was measured (snow course) are displayed. Orthophotomap is from 2012.

**Soil temperature and characteristics of ski piste snowpack**

Soil temperature was logging continuously during the studied ablation period of season 2015 and 2016 in the hourly intervals on the snow-covered and snow-free part of ski piste. Data loggers Minikin Tie with built-in sensor and 20-mm diameter measured soil temperature 3 to 5 cm under the ground surface with ±0.15°C accuracy. Data loggers were placed into the relatively homogenous soil with similar environmental conditions. Data logger on the snow-covered part of ski piste was situated close to the snowmaking lance where the ski piste snowpack with addition of artificial snow has the longest duration and highest snow depth (Mikloš et al., 2018b). Natural snow absented at the time of measuring. Air temperature was recorded by its own meteorological station, which was localized at the base of ski slope of ski center Košútka. Online meteorological data of this station can be accessed from www.emsbrno.cz.

Snow depth and snow density of groomed snowpack with additional artificial snow were measured on the studied ski piste area of 4.1 ha at the end of five winter seasons from 2010–2011 to 2015–2016, except for season 2013–2014 (ski center was out of service). The first survey in each of five seasons was carried out after disappearance of natural snow on the off-piste sites at all elevations and then subsequently until the end of melting in the irregular time intervals. Ski piste (4.1 ha) represented the marked area of ski slope under the winter management (grooming, snowmaking). Snow depth was measured at 96 points, whereas snow density was at least 5 points of snow course (Figure 1). Snow water equivalent was calculated for each of the 96 points of snow course from snow depth and mean snow density identified in the particular survey. Technique of measuring the snow depth and density is described in more detail by Mikloš et al. (2018a) and in general by, for example, López-Moreno et al. (2013). In the first survey of the first three seasons, the depth of basal or bare ice layer was measured at 96 points of snow course. Basal ice could have occurred on the bottom of snowpack, whereas bare ice could have occurred instead of snow.

**Snow ablation water volume and potential infiltration**

The ski piste area under the winter management (grooming, snowmaking) was divided into eight continuous subareas because of different soil properties, slope, and aspect. For each subarea and survey, the snow water volume and the snow-free ski piste area were calculated from the model of interpolated SWE. An SWE model with raster value of 1 m × 1 m was created in ArcGIS 10.3.1 by the interpolation technique spline from 96 points of manual snow depth measurements, which were multiplied by the mean snow density. Mean density instead of interpolated density was used because of the small number of density measurements (time-consuming measurement), which were performed on at least five points of the snow course. Area of positive values of the SWE model represented the snow-covered area, whereas area of negative and zero values of the SWE model represented the snow-free area. Snow water volume stored in snowpack (in millimeters) was calculated from the SWE model as sum of positive raster values divided by the snow-covered area. If the time interval between the two surveys was longer than 8 days, the additional intermediate SWE model was created between these two surveys. The intermediate SWE model was created from the SWE of 96 points that were modeled by the linear relationship between two neighboring surveys. The difference of two subsequent snow water volumes represented the snow ablation water volume. Ablation rate was calculated by dividing the snow ablation water volume by the number of days between particular snow water volumes (Boon, 2009). The ablation period in the presented study means the period from the disappearance of natural snow on the off-piste sites until the melt of ski piste snowpack on the studied area. The ski piste snowpack was considered melted when less than 5% of the observed area (4.1 ha) was covered by snow, and similarly, the natural snowpack on the off-piste sites was considered melted when less than 5% of the adjacent off-piste area was covered by snow in all elevations and aspects.

Potential infiltration on the studied area is limited by the frozen soil below the snowpack; therefore, potential infiltration of snow ablation water was calculated only for the snow-free part of each subarea. For this purpose, snow ablation water volume had to be calculated from the SWE model in cubic meters instead of millimeters. To identify the potential infiltration of snow ablation water volume, the ablated water volume (in cubic meters) was compared with maximum volume of water ($V_i$) that was able to infiltrate between the two surveys on the snow-free subarea. If ablated water volume was higher than $V_i$, the difference represented noninfiltrated volume of water. Potentially infiltrated volume of water in eight subareas was summed together and transferred to millimeters (divided by the snow-free area) for better interpretation of the results.

The maximal volume of water ($V_i$) was calculated as follows:

$$V_i = (K_{\mathrm{SAT}}\, S\, t) - V \tag{1}$$

where $K_{\mathrm{SAT}}$ is saturated hydraulic conductivity of soil on subarea, $S$ is snow-free area identified at the first of two measurement dates, $t$ is sum of hours when average hourly air temperature was higher than 0°C, and $V$ is total rainfall volume fallen on the snow-free subarea ($S$).

One soil sample from a depth of 0 to 20 cm was taken from the middle of each subarea, to determine grain size fraction distribution. Preparation of soil samples for laser diffraction analysis was described in detail by Šinkovičová et al. (2017). The analyses were performed with use of an analyzer ANALYSETTE 22 MicroTec plus (Fritsch GmbH, Idar-Oberstein, Germany). Each soil sample was analyzed three times, and subsequently average value was calculated. If the soil was fully saturated by the meltwater, the saturated hydraulic conductivity expressed the rate of water movement through soil (Schoeneberger et al., 2002). Soil type and percentage of clay/silt/sand in the soil samples are specified in Table 1.

**Table 1.** Percentages of clay, silt and sand in the eight samples. The percentages are used for determination of soil type (according to USDA soil texture triangle).

| Subarea No. | Clay % (<0.002 mm) | Silt % (0.002–0.05 mm) | Sand % (0.05–2 mm) | Soil type (USDA classification) |
|---|---|---|---|---|
| 1 | 4.9 | 90.04 | 4.7 | Silt |
| 2 | 3.5 | 83.6 | 12.9 | Silt |
| 3 | 3.6 | 80 | 16.4 | Silt loam |
| 4 | 5.1 | 87.8 | 7.1 | Silt |
| 5 | 4.3 | 89.6 | 6.1 | Silt |
| 6 | 3.6 | 78.2 | 18.2 | Silt loam |
| 7 | 3.8 | 87.2 | 9 | Silt |
| 8 | 3.8 | 83.3 | 12.9 | Silt |

Saturated hydraulic conductivity ($K_{\mathrm{SAT}}$ in m/s) was determined from the results of grain size analyses, according to the following equation (Špaček, 1987):

$$K_{SAT} = 20.577 d_{10}^{1.013} \left( \frac{0.5}{d_{60} - d_{10}} \right)^{0.059} \qquad (2)$$

where $d_{10}/d_{60}$ represents size in millimeters, such that 10%/60% of particles are finer than this size.

## RESULTS

### Characteristics of the ski piste snowpack

Five seasons' mean snow density of ski piste snowpack was 621.6 ± 107.3 kg/m$^3$ (Figure 2). Mean snow density during the ablation period had a decreasing trend in seasons 2011, 2015, and 2016 and increasing trend in seasons 2012 and 2013 (Figure 2a). The lowest minimal density (137 kg/m$^3$) was measured in season 2013. Ski piste snowpack ablation period started at the latest in season 2013, with the lowest surveyed mean snow density. In each of the five seasons, density greater than 800 kg/m$^3$ was measured, which is the density close to the density of ice. The highest maximal and mean snow density was identified in the first survey in season 2015. Between mean snow density and corresponding depth average, the mean snow depth of the first survey in the seasons was identified to have a strong positive correlation ($r$ = 0.93; Figure 2b). Moreover, with the earlier date of the first survey, the mean snow depth ($r$ = 0.47) and mean snow density ($r$ = 0.63) of the first survey in the season were higher.

In the scale of the ablation period, negative correlation was found between snow depth and depth average snow density, in all of five seasons (Figure 3a). The snow density increased with decreasing snow depth by approximately 1 kg/m$^3$ per 1 cm if the data of all five seasons were analyzed. The depth average snow density increased with decreasing snow depth also because of the basal ice layer formation from the melted ski piste snowpack. During the three seasons, when the basal/bare ice layer occurrence was observed in the first survey in the season, the depth of the basal/bare ice layer increased from 0.04 to 0.12 cm per each 1 cm of decreasing snow depth (Figure 3b). Calculation of these trends taken into the account even measurements where only snow or bare ice was identified. Probability of basal ice layer occurrence in the bottom of snow profile was 57% (calculated from 176 measurements), while probability of bare ice layer occurrence instead of snow was 18% (calculated from 215 measurements).

In the each of the five studied seasons, the snow depth and the SWE of ski piste snowpack were highly variable after snowmelt of natural snow on the off-piste sites (Figure 4). While some parts of the studied ski piste area were covered by thick snowpack, the other parts were completely melted (Figures 4, 5). The maximum snow depth and SWE in the first survey in each of the five seasons were always higher than 100 cm and 800 mm, respectively (Figure 4). The highest maximum snow depth and SWE (225 cm and 1229 mm, respectively) were identified in season 2013, whereas the highest mean snow depth (57 cm and 349 mm, respectively) was identified in season 2012. The five seasons' average mean snow depth and mean SWE from the first surveys were 45 cm and 280 mm, respectively (mean snow depth on the studied area of ski piste). The decrease in mean snow depth during the studied ablation periods varied from 0.6 cm/d in season 2016 to 2.1 cm/d in season 2011 (five seasons' average, 1.5 cm/d). The mean SWE decreased on the studied area of ski piste in a different trend from snow depth because of the changing snow density over the studied ablation period. The decrease in SWE during the ablation periods varied from 4 mm/d in season 2016 to 12.7 mm/d in season 2011 (five seasons' average, 9.5 mm/d). The authors note that the mean snow depth was calculated from 96 points of snow course including zero values.

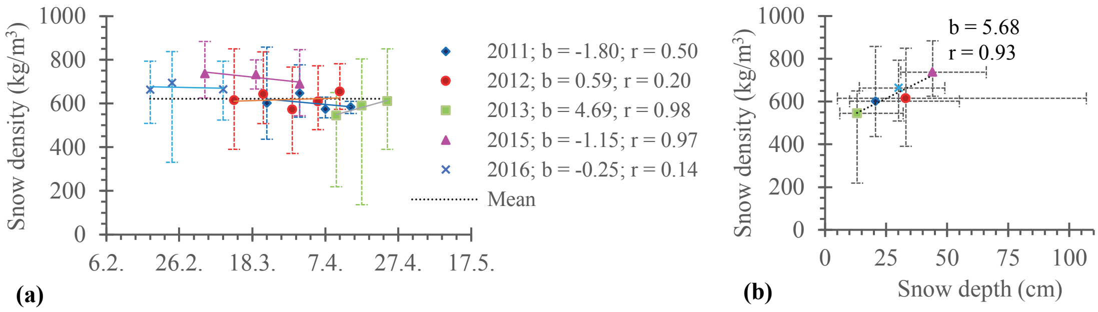


**Fig. 2.** (a) Trend of mean snow density over the ablation period of ski piste snowpack in five seasons; (b) Correlation between mean snow depth and mean snow density at first survey in the season. Signs indicate mean density. Bars indicate the maximum and minimum values measured in each survey. Horizontal dot line indicates mean density calculated from all surveys.

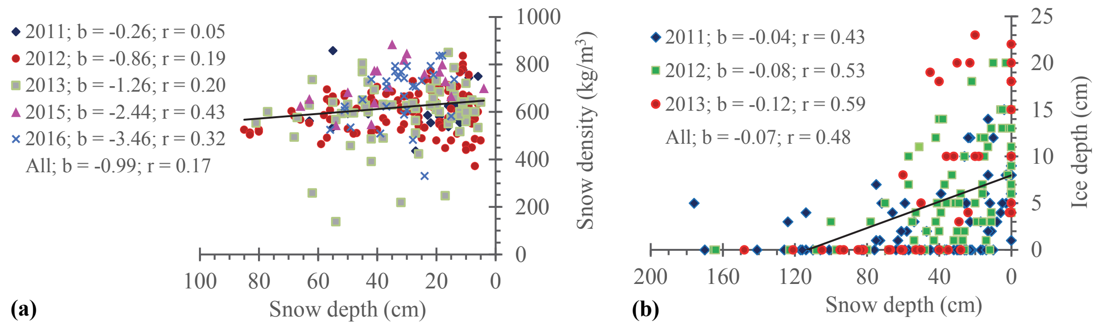


**Fig. 3.** (a) Correlation between snow depth and snow density at the individual seasons; (b) Correlation between snow depth and depth of basal or bare ice layer. Signs indicate individual measurements while solid lines indicate trend calculated from all displayed measurements.

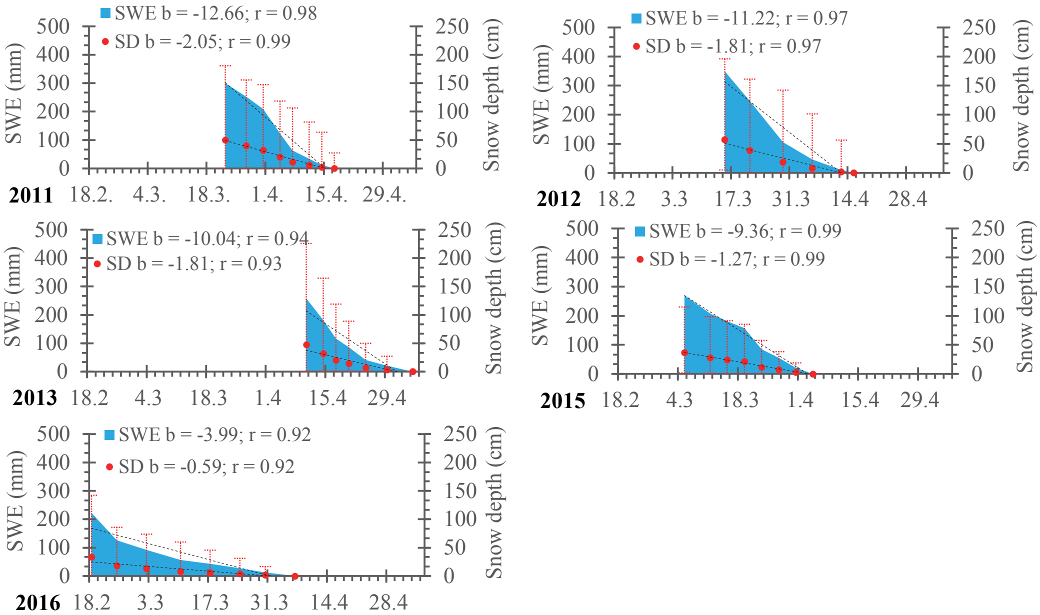


**Fig. 4.** Decrease of mean snow water equivalent (SWE) and mean snow depth (SD) on the ski piste during ablation period in the five seasons after snowmelt of natural snow on the off-piste sites. Bars indicate the maximum and minimum snow depth measured in each survey. Dash lines indicates trends.

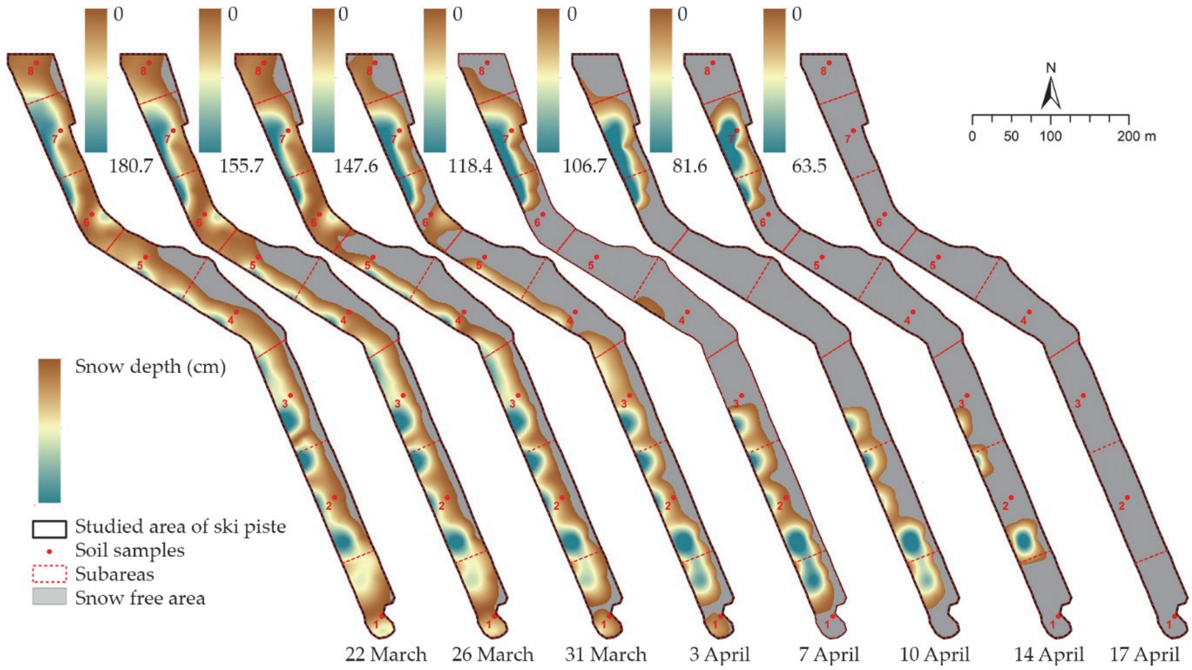


**Fig. 5.** Development of snowpack and snow-free area on the ski piste during ablation period of winter season 2010–2011.

**Soil temperature**

During the observed period, the top soil layer on the snow-covered part of ski piste with snowpack occurrence was constantly frozen, even when hourly air temperature reached its maximum of 15°C in season 2015 (Table 2). Mean hourly soil temperature under the snowpack varied maximally 1°C around zero. At the same period, the mean top soil hourly temperature on the snow-free part of ski piste was 3°C in season 2015 and 4°C in season 2016. The maximal hourly soil temperatures on the snow-free part were 12°C and 11°C, respectively. Because of the frozen top soil layer under the ski piste snowpack, the infiltration below the snowpack was limited.

**Table 2.** Mean, minimal and maximal hourly soil and air temperature (in °C; mean ± standard deviation) during observed period (seasons 2015 and 2016). Soil temperature was logged on the snow-covered part and on the snow-free part of ski piste.

| | Soil temperature (Snow) (°C) | | Soil temperature (Snow-free) (°C) | | Air temperature (°C) | |
|---|---|---|---|---|---|---|
| | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 |
| Mean | –0.1 ± 0.0 | –0.2 ± 0.2 | 2.9 ± 2.4 | 3.6 ± 2.1 | 4.6 ± 4.5 | 3.5 ± 3.3 |
| Min | –0.2 | –1.0 | –0.6 | 0.1 | –4.2 | –3.8 |
| Max | 0.0 | 0.9 | 11.9 | 11.4 | 15.1 | 12.0 |

## Ski piste snowpack snow ablation water volume versus potential infiltration

The rate of water movement through soil (saturated hydraulic conductivity) on the ski piste was identified as 89.8 ± 9.5 mm of water per day on average (Table 3). The highest saturated hydraulic conductivity ($K_{SAT}$) was identified on subarea number 2 (97.5 ± 1.4 mm/d). The average $K_{SAT}$ (89.8 mm/d) could be ranked according to Schoeneberger et al. (2002) as moderately high $K_{SAT}$ class, whose boundaries are 86.4 to less than 864.0 mm/d. The average rate of water movement through soil was 6.8 times as high as the five seasons' average ablation rate of ski piste snowpack (89.9 vs. 13.3 ± 6.1 mm/d). The ablation rate was highly variable during the ablation period and also between the seasons (Figure 6). In season 2011, the highest average ablation rate of 17 ± 7 mm/d and the steepest increasing seasonal trend of 5 mm/d were identified; thus, the ablation period in this season was the second shortest (26 days) from the five studied seasons. On the contrary, because of the lowest average ablation rate of 9 ± 5 mm/d and decreasing seasonal trend of 2 mm/d in season 2016, the ablation period of ski piste snowpack in this season was the longest (47 days).

Because of frozen soil below the snowpack, the infiltration on the studied area was limited to the snow-free part. At the beginning of each ablation period (first survey), the snow ablation water volume to the snow-free area was the highest because of the lowest snow-free area that represented 12% of the studied area on average (Figure 6). In the first survey in the season, the five seasons' average snow ablation water volume to the five seasons' average snow-free area was 137 ± 70 mm/m$^2$ and potentially infiltrated 43 ± 7 mm/m$^2$ (31%) (Figure 6a). At the beginning of season 2012, the highest snow ablation water volume to the snow-free area (247 mm/m$^2$) was identified, but potentially infiltrated only 53 mm/m$^2$ (21%) because of the low snow-free area that represented 4% of the studied area. The snow-free area expanded over the five studied ablation periods in the comparable trends (Figure 6). The five seasons'

**Table 3.** $d_{10}/d_{60}$ represents a size of particles on the subareas, such that 10%/60% of particles are finer than this size (mean ± standard deviation). On each subarea, the mean value ± standard deviation (SD) of saturated hydraulic conductivity ($K_{SAT}$) was calculated from three soil samples (mean ± SD).

| Subarea No. | Subarea (m$^2$) | $d_{10}$ (μm) | $d_{60}$ (μm) | $K_{SAT}$ (mm/day) |
|---|---|---|---|---|
| 1 | 4131 | 3.2 ± 0.1 | 14.0 ± 0.0 | 76.3 ± 1.4 |
| 2 | 6833 | 4.2 ± 0.1 | 17.0 ± 0.0 | 97.5 ± 1.4 |
| 3 | 6122 | 4.1 ± 0.0 | 17.2 ± 0.8 | 95.8 ± 0.3 |
| 4 | 6653 | 3.1 ± 0.0 | 10.7 ± 0.1 | 74.3 ± 0.1 |
| 5 | 5443 | 3.7 ± 0.1 | 10.9 ± 0.1 | 87.9 ± 2.8 |
| 6 | 3950 | 4.1 ± 0.1 | 11.4 ± 0.0 | 97.4 ± 1.4 |
| 7 | 4537 | 3.9 ± 0.1 | 11.1 ± 0.1 | 93.5 ± 2.5 |
| 8 | 3329 | 4.0 ± 0.0 | 11.2 ± 0.2 | 95.9 ± 0.1 |
| Sum/Mean ± SD | ± 40999 | 3.8 ± 0.4 | 12.9 ± 2.8 | 89.8 ± 9.5 |

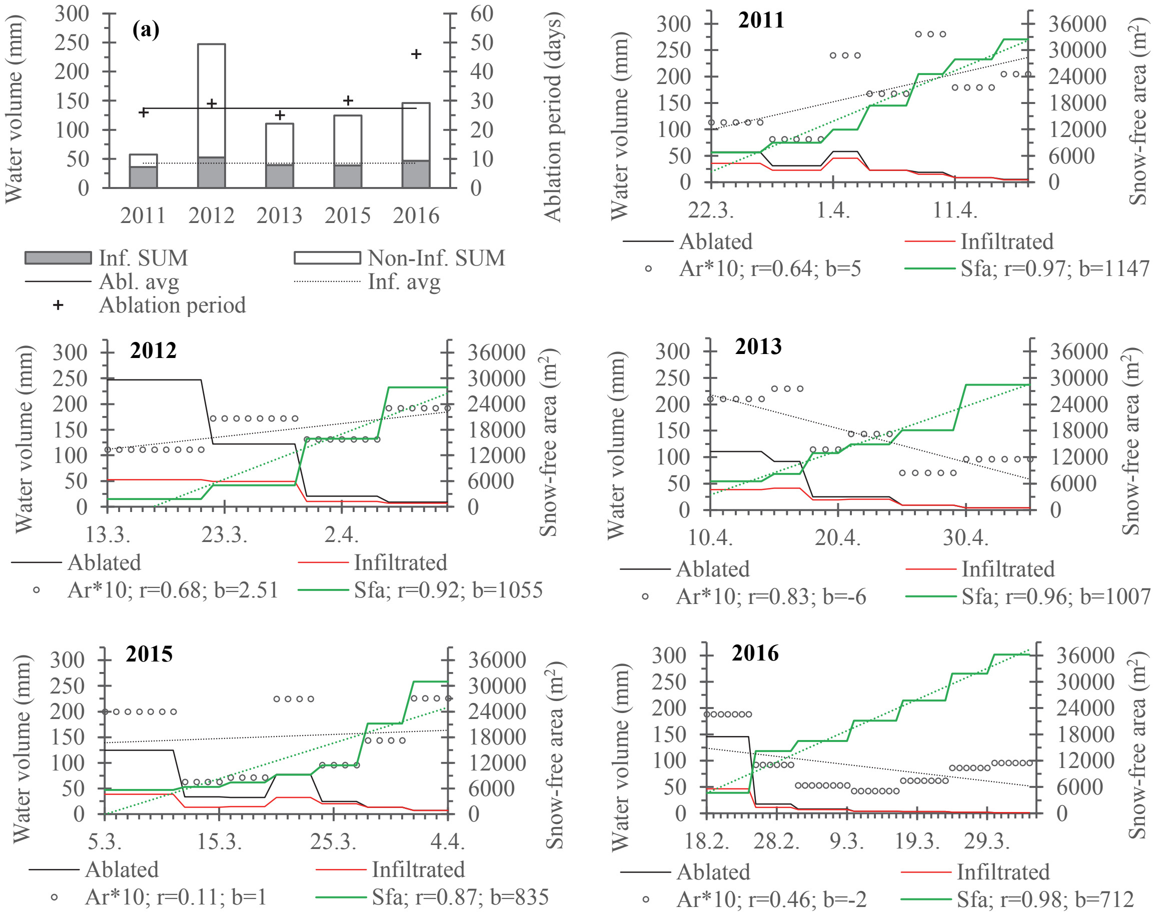


**Fig. 6. (a)** Infiltrated and non-infiltrated snow ablation water volume (abl.) to the snow-free area of ski piste, in the first survey in each season. Horizontal lines indicate averages (avg.) from displayed ablated and infiltrated water volumes while crosses indicate duration of ablation periods; **(2011–2016)** Modeled daily course of ablated and infiltrated water volume to the snow-free area of ski piste, modeled development of snow-free area (Sfa) during ablation period and modeled ablation rate of ski piste snowpack (Ar; *multiplied by ten for visualization*). Black dot line indicates trend of ablation rate while green dot line indicates trend of snow-free area over the ablation period.

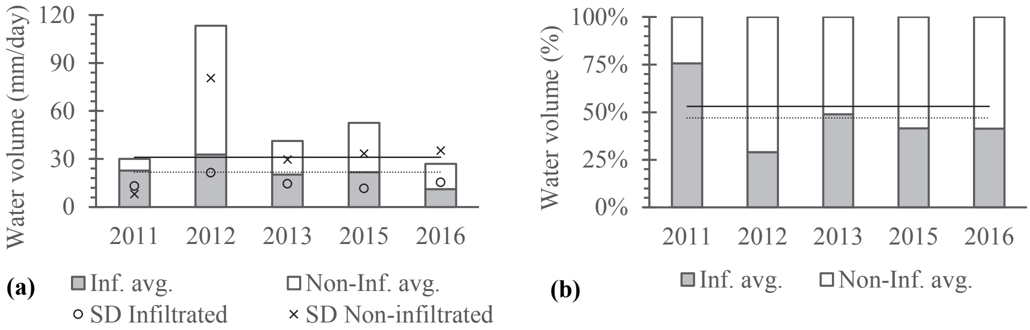


**Fig. 7.** (a) Average and (b) percentage of infiltrated and non-infiltrated (sum = ablation) snow ablation water volume during ablation period to the snow-free ski piste area. Signs indicate standard deviation (SD) of average values. Horizontal lines indicate mean from displayed values (solid line = non-infiltrated volume; dot line = infiltrated volume).

average slope of trend of snow-free area was 951 ± 175 $m^2$/d. Decrease in snow ablation water volume to the snow-free area and simultaneous expansion of the snow-free area from the first survey resulted to an increase in potentially infiltrated water volume on the snow-free square meter over the ablation periods. At the end of each ablation period, except season 2012, all the ablated water volume was potentially able to infiltrate the snow-free area. Increase in the ablated water volume over the ablation period was identified only one time in season 2011 and 2015, when comparable conditions occurred. The snow-free areas at this time were 11,968 and 9213 $m^2$, whereas ablation rates were 23 and 22 mm/d, respectively.

In the five seasons' average, the water volume of 22 ± 8 mm/d potentially infiltrated during 31 ± 9-day-long ablation period on the snow-free ski piste area (Figure 7a). This water volume represented 47% (53 ± 35 mm) of the ablated water volume per day on average on the snow-free 1 $m^2$ of ski piste area (Figure 7b). In each of the five seasons, except season 2011, the average potential infiltration on the snow-free ski piste area represented less than 50% of ablated water. In season 2011, the potential infiltration represented 76% of ablated water on average because of the low ablation rate and high snow-free area at the first surveys compared with other seasons. On the contrary, the lowest percentage of ablated water potentially infiltrated in season 2012 (29%). It was because season 2012 started and continued with high ablated water volumes that were not able to potentially infiltrate because of the low snow-free ski piste area in the first two surveys.

## DISCUSSION

### Characteristics of the ski piste snowpack and soil temperature

This study confirms the results of Rixen et al. (2003), Keller et al. (2004), and Mossner et al. (2013), which found high-density snowpack on the ski pistes of European Alps. They reported that mean density on the groomed ski pistes with artificial snow varied between 500 and 600 kg/$m^3$ on average. Our study from Košútka ski center (Central Europe, Western Carpathians) showed the higher mean snow density of 622 kg/$m^3$ probably due to intensive snowmaking in this ski center (Mikloš et al., 2018a) and late datum of measuring (end of winter season). The impact of wind packing that enhances snow density (Vihma, 2011) was negligible because of the low wind speed in the studied locality (Mikloš et al., 2018a). In contrast to the mentioned studies, the presented study was focused on the ablation period of ski piste snowpack, at the end of the winter season. Thus, the high maximal density of snow greater than 800 kg/$m^3$ and ice layer occurrence in the base of snowpack or ice instead of snowpack were found at the end of the season on the studied ski piste. Keller et al. (2004) also found increasing compaction of ski piste snowpack over the time while it becomes a mixture of ice and hard snow with a maximum density of 700 kg/$m^3$. Because of the high density and depth of the studied ski piste snowpack, the prolongation of the ablation period to about 29 days was identified (Mikloš et al., 2018a). Snow density increases over the time because of dry and wet metamorphism of snow (Domine, 2011); however, the increasing tendency of snow density was not identified in all of the five studied seasons. It is probably due to the late datum of measuring and subsequently high above-zero daily temperatures in the studied locality when snow ablation water did not refreeze in the snowpack but instead drained or sublimated. In the presented study, negative correlation was identified between snow depth and snow density, probably due to the observed basal ice layers in the ski piste snowpack. These findings are supported by Rixen et al. (2003; 2004) and Fauve et al. (2002), which attribute the occurrence of ice layers to snow compaction by the heavy machinery and warm conditions during the snow production. Both compaction and higher temperatures during snowmaking were identified in our previous study carried out in the same low-elevation Košútka ski center (Mikloš et al., 2018a). Ice occurrence instead of snowpack in the late winter was not described by other authors. This phenomenon can be explained by the occurrence of hot days and cold nights during winter time (Mikloš et al., 2018a) and the isothermal conditions that render the artificial snow more prone to melting and refreezing during daytime (Vihma, 2011).

High density of the studied ski piste snowpack resulted in the high SWE at the end of winter season. Hríbik et al. (2012), who studied natural snowpack 10 km away from Košútka ski center in the comparable elevation, identified maximum above-average mean SWE of 170 mm in March 2005 and February 2006 (studied seasons from 2004 to 2009). For comparison, the maximum mean SWE of the studied ski piste snowpack was 349 mm in March 2013, whereas after snowmelt of natural snow on the adjacent off-piste sites, the mean SWE of ski piste snowpack was 280 mm. The studied ski piste snowpack showed high snow depth maxima due to the essential high production of artificial snow (Mikloš et al., 2018a). The maximum snow depth of studied ski piste snowpack was 225 cm in April 2013, whereas the maximum snow depth of natural snow identified by Hríbik et al. (2012) was 70 cm in winter 2005 and 2006 (whole season average is 30 cm). Rixen et al. (2004) compared snow depth and SWE of the groomed/snowed ski piste snowpack with natural undisturbed snowpack in the Swiss ski centers greater than 1000 m a.s.l. at the turn of February and March 2000. They found comparable differences (approximately 40 cm and 300 mm) with the presented research from Košútka ski center (45 cm and 280 mm) where measurements for this comparison were performed directly after disappearance of natural snowpack from the off-piste sites.

The presented study confirms long-lasting soil frost beneath the snowed and groomed ski piste snowpack as reported by Rixen et al. (2003; 2004) on the Swiss pistes. Kammer (2002) and Rixen et al. (2008) proved long-lasting soil frost with high depth and density of ski piste snowpack, which extends the snow ablation period. The presented study confirms their findings and shows high difference in top soil temperature between snow-covered and snow-free sites on the piste, even at 12°C. The occurrence of basal ice layers and frozen top soil layer below the studied snowpack results in restricted infiltration of snow ablation water on the snow-covered area. Similarly, Gray et al. (2001) pointed out that soil infiltrability is restricted by impervious surface as the basal ice lens found on the pistes by Rixen et al. (2004).

**Snow ablation water volume and potential infiltration**

There is a negligible number of studies that describe snow ablation processes on the ski pistes and subsequently quantify their balance (infiltration, sublimation, evaporation, surface runoff). The presented study shows that the mean seasonal ablation rate on the ski piste ranged between 9 and 17 mm/d at the end of winter season. Ablation rate is difficult to compare between studies because of the specific characteristics of ski piste snowpack and microclimatic conditions (energy balance) of research localities. For example, the ablation rate of natural snowpack in Fraser Lake (700 m a.s.l., 53.72° N, 124.92° W) is lower than that in Košútka ski center (610 m a.s.l., 48.56° N, 19.54° E) varying between 11 and 14 mm/d. It is probably due to the northern latitude (approximately 5° N) and different climatic conditions of locality (North America). However, Mosimann (1998) and Rixen et al. (2004) declare that the snow ablation rate of ski piste snowpack is lower than the natural undisturbed snowpack because of the increased snow mass (snowmaking), ice layers in snow profile, spherical shape of ice crystals, and long-lasting soil frost below the ski piste snowpack. These findings confirm the presented study because of the prolonged ablation period of ski piste snowpack of approximately 1 month, while increased snow mass, ice layers, and soil frost on the ski piste were observed.

Infiltration of water into soil is dependent on the rate of water movement through soil (saturated hydraulic conductivity [$K_{sat}$]), which was identified as moderately high (90 mm/d) for the modal cambisol of the studied ski piste. This $K_{sat}$ was low compared with the study on Californian ski pistes in Tahoe Basin (2000 m a.s.l., approximately 39° N, 120° W), where mean $K_{sat}$ was 7968 mm/d on granitic soil and 5952 mm/d on the volcanic soil (Grismer and Hogan, 2005). High $K_{sat}$ is the result of large average particle sizes; however, the larger particle sizes suggest larger erosion events that were seen in Tahoe Basin (Grismer and Hogan, 2005). The presented study assumes with bare soil surface the calculation of infiltration; however, some parts of ski piste were covered by meadow vegetation, which can decrease the infiltration rate (Dunne et al., 1991; Lichner et al., 2018). Anyway, less disturbed soil surface and vegetation cover of ski pistes mean more water to be held in soil (Pintar et al., 2009). Infiltration of snow ablation water on the area of ski piste was limited to snow-free areas; therefore, not all ablation water could infiltrate. The part of the discussion about the volume of infiltrated snow ablation water to the soil profile of ski piste is omitted because of lack of studies dealing with this issue. The presented study showed that ski piste snowpack properties and duration of the ablation period in low-elevation ski center are comparable with the findings of other studies, even from higher elevations greater than 1000 m a.s.l. Therefore, the methods used for calculation of the ablation and infiltration can be used in these regions, while it can be assumed that the results will differ, depending on the snowpack and soil properties and the meteorological conditions of the study sites.

## CONCLUSIONS

This study shows that after snowmelt of natural snow on the off-piste sites the high volume of water is still stored in the groomed ski piste snowpack with additional artificial snow. The density of such snowpack is highly variable, while it can reach the density of ice. With lower snow depth, higher snow density and higher thickness of basal ice layer or bare ice (ice instead of snow) can be expected. The depth and SWE of such snowpack are even highly heterogeneous over the piste (marked, groomed, and snow-covered part of ski slope). Whereas some parts of the ski piste are completely melted, the others could be covered by 200-cm-thick snowpack with SWE higher than 1000 mm. The SWE of the remaining snowpack decreases 9.5 mm/d during 1-month-long ablation period on average. The ablation rate of ski piste snowpack is lower than water movement through soil. However, not all snow ablation water is potentially able to infiltrate the ski piste because of the frozen top soil layer below the snowpack and the low snow-free area. As the snow-free area increases during the ablation period over the ski piste, the higher water volume is potentially able to infiltrate the piste. Nearly 50% of snow ablation water is potentially able to infiltrate the area of ski piste on average.

*Acknowledgements.* This work was accomplished as a part of VEGA projects nos. 1/0500/19, 1/0111/18, and 1/0064/19 of the Ministry of Education, Science, Research, and Sport of the Slovak Republic and the Slovak Academy of Science and the projects of the Slovak Research and Development Agency nos. APVV-15-0425, APVV-18-0347, APVV-15-0160, and APVV-15-0497. The authors thank the agencies for their support.

## REFERENCES

Babálová, D., Škvareninová, J., Fazekaš, J., Vyskot, I., 2018. The dynamics of the phenological development of four woody species in South-West and Central Slovakia. Sustainability, 10, 1497.

Bark, R.H., Colby, B.G., Dominguez, F., 2010. Snow days? Snowmaking adaptation and the future of low latitude, high elevation skiing in Arizona, USA. Clim. Change, 102, 467–491.

Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature, 438, 303.

Bartík, M., Sitko, R., Oreňák, M., Slovik, J., Škvarenina, J., 2014. Snow accumulation and ablation in disturbed mountain spruce forest in West Tatra Mts. Biologia, 69, 1492–1501.

Beniston, M., 2007. Entering into the 'greenhouse century': recent record temperatures in Switzerland are comparable to the upper temperature quantiles in a greenhouse climate. Geophys. Res. Lett., 34, 16710.

Boon, S., 2009. Snow ablation energy balance in a dead forest stand. Hydrol. Process., 23, 2600–2610.

Cayan, D.R., Kammerdiener, S.A., Dettinger, M.D., Caprio, J.M., Peterson, D.H., 2001. Changes in the onset of Spring in the Western United States. Bull. Am. Met. Soc., 82, 399–415.

Damm, A., Köberl, J., Prettenthaler, F., 2014. Does artificial snow production pay under future climate conditions? – A case study for a vulnerable ski area in Austria. Tourism Manage., 43, 8–21.

De Jong, C., Barth, T., 2008. Challenges in hydrology of mountain ski resorts under changing climatic and human pressures. In: ESA Proceedings Surface Water Storage and Runoff: Modeling, In-Situ data and Remote Sensing. Geneva.

Domine, F., 2011. Physical properties of snow. In: Singh. V.P., Singh, P., Haritashya, U.K. (Eds.): Encyclopedia of Snow, Ice and Glaciers. London: Springer, pp. 66–75.

Dunne, T., Zhang, W., Aubry, B.F., 1991. Effects of rainfall, vegetation, and microtopography on infiltration and runoff. Water Resour. Res., 27, 2271–2285.

EMS Brno. Available online: http://www.emsbrno.cz/p.axd/sk/Lokality.TUZVO.html (accessed on 2 October 2019).

Faško, P., Šťastný, P., 2002. Mean annual precipitation totals, Mean January precipitation totals. In: Miklós, L., Hrnčiarová, T., (Eds.): Landscape atlas of the Slovak Republic. Revised 1st printing. Slovak Environmental Agency, Bratislava, p. 99.

Faško, P., Handžák, S., Šrámková, M., 2002. Number of days with snow cover and the mean height of snow cover. In: Miklós, L., Hrnčiarová, T. (Eds.): Landscape Atlas of the Slovak Republic. Revised 1st printing. Slovak Environmental Agency, Bratislava, p. 99.

Fauve, M., Rhyner, H., Schneebeli, M., 2002. Pistenpräparation und Pistenpflege – Das Handbuch für den Praktiker. Eidgenössisches Institut für Schnee- und Lawinenforschung, Davos.

Freppaz, M., Filippa, G., Corti, G., Cocco, S., Williams, M.W., Zenini, E., 2012. Soil properties on ski runs. In: Rixen, C., Rolando, A. (Eds.): The Impact of Skiing on Mountain Environments. Revised 1st printing. Bentham Science Publishers, Bussum, pp. 45–64.

Gilaberte-Búrdalo, M., López-Martín, F., Pino-Otín, M.R., López-Moreno, J.I., 2014. Impact of climate change on ski industry. Environ. Sci. Policy, 44, 51–61.

Gray, D.M., Granger, R.J., Landine, P.G., 1986. Modelling snowmelt infiltration and runoff in a Prairie environment. In: Kane, D.L. (Eds.): Proceedings of the Cold Regions Hydrology Symposium. University of Alaska-Fairbanks, Fairbanks, Alaska. American Water Resources Association, Bethesda, Maryland, pp. 427–438.

Gray, D.M., Toth, B., Zhao, L., Pomeroy, J.W., Granger, R.J., 2001. Estimating a real snowmelt infiltration into frozen soils. Hydrol. Process., 15, 3095–3111.

Grismer, M. E., Hogan, M. P., 2005. Simulated rainfall evaluation of revegetation/mulch erosion control in the Lake Tahoe basin: 2. Bare soil assessment. Land. Degrad. Dev., 16, 397–404.

Gömöryová, E., Střelcová, K., Škvarenina, J., Gömöry, D., 2013. Responses of soil microorganisms and water content in forest floor horizons to environmental factors. Eur. J. Soil Biol., 55, 71–76.

Hríbik, M., Vida, T., Škvarenina, J., Škvareninová, J., Ivan L., 2012. Hydrological effects of Norway spruce and European beech on snow cover in a mid-mountain region of the Polana Mts. J. Hydrol. Hydromech., 60, 319–332.

Hrvoľ, J., Horecká, V., Škvarenina, J., Střelcová, K., Škvareninová, J., 2009. Long-term results of evaporation rate in xerothermic Oak altitudinal vegetation stage in Southern Slovakia. Biologia., 64, 605–609.

Igaz, D., Bárek, V., Halaj, P., Takáč, J., Čimo., 2008. A comparison of measured soil moisture with simulated results obtained by selected models for Danubian lowland. Cereal Research Communications, 36, 1619–1622.

Kammer, P.M., 2002. Floristic changes in subalpine grasslands after 22 years of artificial snowing. J. Nat. Conserv., 10, 109–123.

Keller, T., Pielmeier, C., Rixen, C., Gadient, F., Gustoffson, D., Stahli, M., 2004. Impact of artificial snow and ski-slope grooming on snowpack properties and soil thermal regime in a sub-alpine ski area. Ann. Glac., 38, 314–318.

Kňazovičová, L., Chasníková, S., Novák, J., Barančok, P., 2018. Impacts of ski pistes preparation and ski tourism on vegetation. Ekol. Bratislava, 37, 152–163.

Laternser, M., Schneebeli, M., 2003. Long-term snow climate trends of the Swiss Alps (1931–99). Int. J. Climatol., 23, 733–750.

Lichner, L., Felde, V.J.M.N.L., Büdel, B., Leue, M., Gerke, H.H., Ellerbrock, R.H., Kollár, J., Rodný, M., Šurda, P., Fodor, N., Sándor, R., 2018. Effect of vegetation and its succession on water repellency in sandy soils. Ecohydrology, 11, 6, Article Number: UNSPe1991.

López-Moreno, J.I., Fassnacht, S.R., Heath, J.T., Musselman, K.N., Revuelto, J., Latron, J., Morán-Tejeda, E., Jonas, T., 2013. Small scale spatial variability of snow density and depth over complex alpine terrain: Implications for estimating snow water equivalent. Adv. Water. Resour., 55, 40–52.

Melanie, P., Rixen, C., 2014. Management, winter climate and plant-soil feedbacks on ski slopes: a synthesis. Ecol. Res., 29, 583–592.

Mikloš, M., Jančo, M., Korísteková, K., Škvareninová, J., Škvarenina, J., 2018a. 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. Water, 10, 907.

Mikloš, M., Korísteková, K., Jančo, M., Váľková, M., 2018b. Vegetation of the selected Slovakian ski pistes. In: Proceedings of International PhD Students Conference MendelNet. Mendel University in Brno, Brno, pp. 201–204.

Miklós, L., Hrnčiarová, T. (Eds.), 2002. Landscape Atlas of the Slovak Republic. Revised 1st printing. Slovak Environmental Agency, Bratislava, 344 p.

Minďáš, J., Škvarenina, J., 1995. Chemical composition of fog cloud and rain snow water in Biosphere Reserve Poľana. Ekol. Bratislava., 14, Supplement 2, 125–137.

Mosimann, T., 1998. Beschneiungsanlagen in der Schweiz. Weitere Entwicklung Umweltverträglichkeit Folgerungen für die Prüfung und Bewilligung von Beschneiungsanlagen. Schweiz. Verband der Seilbahnunternehmungen, Bubendorf and Hannover, 42 p.

Mossner, M., Innerhofer, G., Schindelwig, K., Kaps, P., Schretter, H., Nachbauer, W., 2013. Measurement of mechanical properties of snow for simulation of skiing. J. Glaciol., 59, 1170–1178.

Mote, P.W., Hamlet, A.F., Clark, M.P., Lettenmaier, D.P., 2005. Declining mountain snow pack in western North America. Bull. Am. Met. Soc., 86, 39–49.

Muchová, Z., Tárniková, M., Petrovič, F., 2015. A more detailed approach to the assessment of the water erosion threat for a territory. In: SGEM 2015. STEP92 Technology, Sofia, pp. 3–10.

Nagy, V., Šurda, P., Lichner, Ľ., Kovács, A. J., Milics, G., 2018. Impact of soil compaction on water content in sandy loam soil under sunflower. J. Hydrol. Hydromech., 66, 416–420.

Newesely, C., 1997. Auswirkungen der künstlichen Beschneiung von Schipisten auf Aufbau, Struktur und Gasdurchlässigkeit der Schneedecke, sowie auf den Verlauf der Bodentemperatur und das Auftreten von Bodenfrost. Dissertation, Naturwissenschaftliche Fakultät, Leopold Franzens Universität, Innsbruck.

Ohmura, A., Wild, M., 2002. Is the hydrological cycle accelerating? Science, 298, 1345–1346.

Pintaldi, E., Hudek, C., Stanchi, S., Spiegelberg, T., Rivella, E., Freppaz, M., 2017. Sustainable soil management in ski areas: threats and challenges. Sustainability, 9, 2150.

Pintar, M., Mali, B., Kraigher, H., 2009. The impact of ski slopes management on Krvavec ski resort (Slovenia) on hydrological functions of soils. Biologia, 64, 639–642.

Ristić, R., Kašanin-Grubin, M., Radić, B., Nikić, Z., Vasiljević, N., 2012. Land degradation at the Stara Planina ski resort. Environ. Manage., 49, 580–592.

Rixen, C., Stoeckli, V., Ammann, W., 2003. Does artificial snow production affect soil and vegetation of ski pistes? A review. Perspect. Plant. Ecol., 5, 219–230.

Rixen, C., Haeberli, W., Stoeckli, V., 2004. Ground temperatures under ski pistes with artificial and natural snow. Arct. Antarct. Alp. Res., 36, 419–427.

Rixen, C., Freppaz, M., Stoeckli, V., Huovinen, C., Huovinen, K., Wipf, S., 2008. Altered snow density and chemistry change soil nitrogen mineralization and plant growth. Arct. Antarct. Alp. Res., 40, 568–575.

Rixen, C., Dawes, M.A., Wipf, S., Hagedorn, F., 2012. Evidence of enhanced freezing damage in treeline plants during six years of $CO_2$ enrichment and soil warming. Oikos, 121, 1532–1543.

Roux-Fouillet, P., Wipf, S., Rixen, C., 2011. Long-term impacts of ski piste management on alpine vegetation and soils. J. Appl. Ecol., 48, 906–915.

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Broderson, W.D., 2002. Field Book for Describing and Sampling Soils: Version 2.0. National Soil Survey Center and Natural Resources Conservation Service, Lincoln, 228 p.

Steger, C., Kotlarski, S., Jonas, T., Schär, C., 2013. Alpine snow cover in a changing climate: a regional climate model perspective. Clim. Dynam., 41, 735–754.

Steiger, R., Mayer, M., 2008. Snowmaking and climate change future options for snow production in Tyrolean ski resorts. Mt. Res. Dev., 28, 292–298.

Steiger, R., 2010. The impact of climate change on ski season length and snowmaking requirements in Tyrol, Austria. Clim. Res., 43, 251–262.

Szolgay, J., Gaál, L., Bacigál, T., Kohnová, S., Hlaváčová, K., Výleta, R., Parajka, J., Blöschl, G., 2016. A regional comparative analysis of empirical and theoretical flood peak-volume relationships. J. Hydrol. Hydromech., 64, 367–381.

Šatala, T., Tesař, M., Hanzelová, M., Bartík, M., Šípek, V., Škvarenina, J., Minďáš, J., Waldhauserová, P. D., 2017. Influence of beech and spruce sub-montane forests on snow cover in Poľana Biosphere Reserve. Biologia, 72, 854–861.

Šinkovičová, M., Igaz, D., Kondrlová, E., Jarošová, M., 2017. Soil Particle Size Analysis by Laser Diffractometry: Result Comparison with Pipette Method. In: IOP Conf. Series: Materials Science and Engineering, 245, DOI: 10.1088/1757-899X/245/7/072025.

Škvarenina, J., Tomlain, J., Hrvoľ, J., Škvareninová, J., 2009. Occurrece of dry and wet periods in altitudinal vegetation stages of West Carpathians in Slovakia: Time-Series Analysis 1951–2005. In: Střelcová, K., Matyas, C., Kleidon, A., Lapin, M., Matejka, F., Blazenec, M., Škvarenina, J., Holecy, J. (Eds.): Bioclimatology and Natural Hazards. Revised 1st printing. Springer, Netherlands, pp. 97–106.

Špaček, J., 1987. Stanovení koeficientu filtrace z totálnich křivek zrnitosti. Meliorace, 1, 1–13.

Šťastný, P., Nieplová, E., Melo, M., 2002. Mean annual air temperature, Mean January air temperature. In: Miklós, L., Hrnčiarová, T. (Eds.): Landscape Atlas of the Slovak Republic. Revised 1st printing. Slovak Environmental Agency, Bratislava, p. 98.

Tárnik, A., Igaz, D., 2015. Quantification of soil water storage available to plants in the Nitra river basin. Acta Scientiarum Polonorum, 14, 209–216.

Vido, J., Tadesse, T., Šustek, Z., Kandrík, R., Hanzelová, M., Škvarenina, J., Škvareninová, J., Hayes, M., 2015. Drought occurrence in Central European mountainous region (Tatra National Park, Slovakia) within the period 1961–2010. Adv. Meteorol., 2015, 248728.

Vihma, T., 2011. Atmosphere-snow/ice interactions. In: Singh. V.P., Singh, P., Haritashya, U.K. (Eds.): Encyclopedia of Snow, Ice and Glaciers. London: Springer, pp. 66–75.

Wipf, S., Stoeckli, V., Bebi, P., 2009. Winter climate change in alpine tundra: plant responses to changes in snow depth and snowmelt timing. Clim. Change, 94, 105–121.

Wipf, S., Rixen, C., 2010. A review of snow manipulation experiments in Arctic and alpine tundra ecosystems. Polar Res., 29, 95–109.

Received 19 February 2019
Accepted 23 October 2019