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PRELIMINARY RESULTS OF GAMMA-RAY SPECTROSCOPY FOR DETECTION OF SNOW WATER EQUIVALENT IN JIZERA MOUNTAINS

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ABSTRACT

The snow water equivalent is an important snow characteristic as it provides hydrologically relevant information about the amount of water stored in the snowpack. The experimental catchment in the Jizera Mountains was equipped with the gamma-ray spectroscope CS725. The sensor uses emitted electromagnetic signals of isotopes ^{40}K and ^{208}Tl to remotely and continuously measure the snow water equivalent. Two winter seasons, 2018-2019 and 2019-2020, were monitored, and the obtained data were analyzed together with the complementary measurements available (snow depth, precipitation, air temperature). The sensor was tested in contrasting conditions of the precipitation-rich winter period 2018-2019 and the mild winter period 2019-2020. Our measurement showed that the SWE values derived from both isotopes are very similar and logically correspond well with the other measurements at the site. As far as we know, the first use of the sensor in the Czech Republic has proven usability in the conditions of the temperate montane catchment.

KEYWORDS

Snow water equivalent, Snow depth, Montane catchment, Temperate climate

INTRODUCTION

Precipitation measurement during winter is much less frequent, both in time and space, than in summer. However, careful monitoring of snow depth and the equivalent depth of water on the ground if all snowfall melted (snow water equivalent, SWE; [1]) is of significant importance in hydrology. Information about the snow water equivalent in the snowpack is essential for water management and water engineering authorities. The maximum value of SWE affects the groundwater replenishment in the spring and water availability for crop growth in the vegetation season. Flood protection also benefits from knowing the maximum value of SWE. Continuous measurement of snow water equivalent is still sparse [2], and new measurement techniques are welcome.

Spectroscopy as a tool for measuring snow water equivalent and soil moisture has been available for decades [3], [4]. The successful use of electromagnetic radiation for SWE measurement is based on the sufficient difference between attenuation of gamma-radiation of water and soil (typically by factor 1.11). Techniques primarily differ in the type of gamma radiation detected and/or by the type, number, and sensor position. Recently, techniques that use two neutron sensors - one above the snowpack and the second directly on the ground - were described (e.g., [5]). These techniques detect gamma radiation from the soil/bedrock. Another technique (e.g., [6]) also benefits from two sensors, but sensors detect background cosmic gamma radiation.

In contrast, the CS725 (Campbell Scientific, Inc.) detects electromagnetic radiation from soil/bedrock and uses a single sensor, significantly decreasing acquisition and maintenance costs [7]. Choquette et al. [8] studied the performance of the CS725 and highlighted the need for on-site calibration of the CS725 sensor to obtain reliable and precise data. They described a calibration method and considered saturated soil moisture to be the most sensitive parameter with the most significant impact on the correct determination of SWE. The method of Choquette et al. [8] proved to provide snow water equivalent values with an accuracy of about 90% compared to manual readings.

Smith et al. [9] compared two automated SWE measurement sensors (CS725 and SSG1000, Sommer GmbH) and periodic manual SWE measurements concerning possible poor soil moisture calibration, spatial variability of snow cover, or ice layers in the snowpack. Excellent accuracy has been achieved between automated and manual measurements (in general, correlations were higher than 0.9). For the CS725 sensor, problems mainly occurred with sandy soil and the melting period, when the sensor may not distinguish frozen water in the soil from the unmelted snow.

The present study evaluates continuous snow water equivalent measurement by the gamma-ray spectroscope CS725. Two consecutive winter periods (2018-2019 and 2019-2020) are examined. Special attention is paid to analyses of transient changes during snowmelt in the spring.

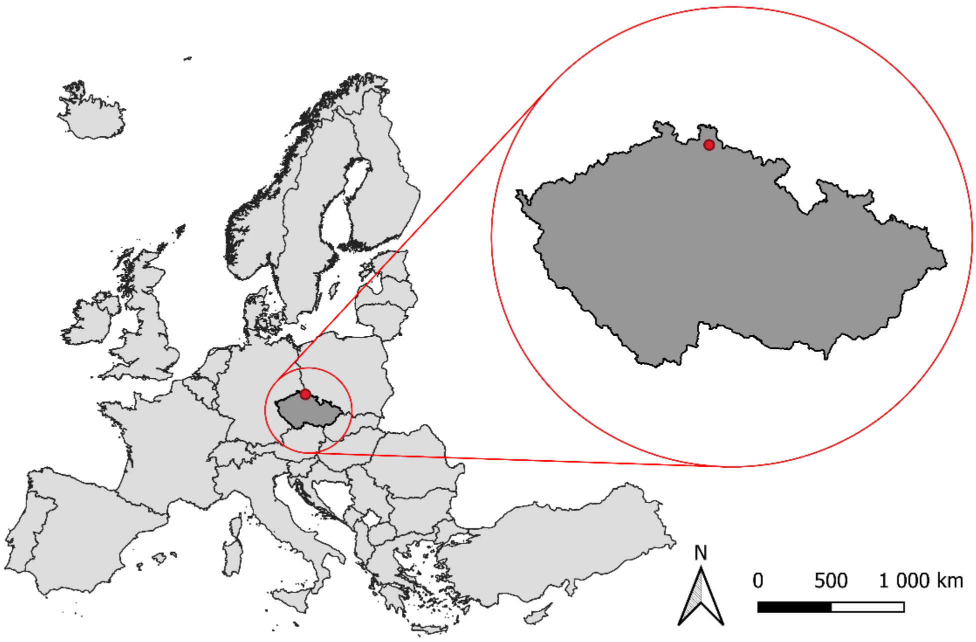

Fig. 1 – Jizera Mountains in the Czech and European context.

MATERIAL AND METHODS

The sensor is located at a mountain meadow in the Jizera mountains, called Nová Louka (50.813611N, 15.158611E; altitude of 778.6 m a. s. l.). It is situated in the north of the Czech Republic, in the district of the city Jablonec nad Nisou (Figure 1). The site has a long history of measurement [10] and it is characterized by high precipitation totals (e.g., the highest national 24-hour total). Nowadays, an automatic meteorological station is operated by the Institute of

Hydrodynamics of the Czech Academy of Sciences. The meteostation is situated in the gently inclined area (about 9 percent) exposed to the northeast (Figure 2). The station is equipped with a set of sensors for complete meteorological and climatic measurements. In the present study, data from a weighing rain gauge MRW 500 (Meteoservis v.o.s.) and standard air temperature and humidity sensor RVT11 (Fiedler AMS s.r.o.) are used. Weighing rain gauge provided accurate precipitation intensity; actual air temperature allowed to distinguish rain and snow; and air humidity facilitated fog detection. The site was found to be well suited for the measurement of SWE by detecting electromagnetic radiation from bedrock, i.e., sufficient radiation levels of ^{40}K and ^{208}Tl.

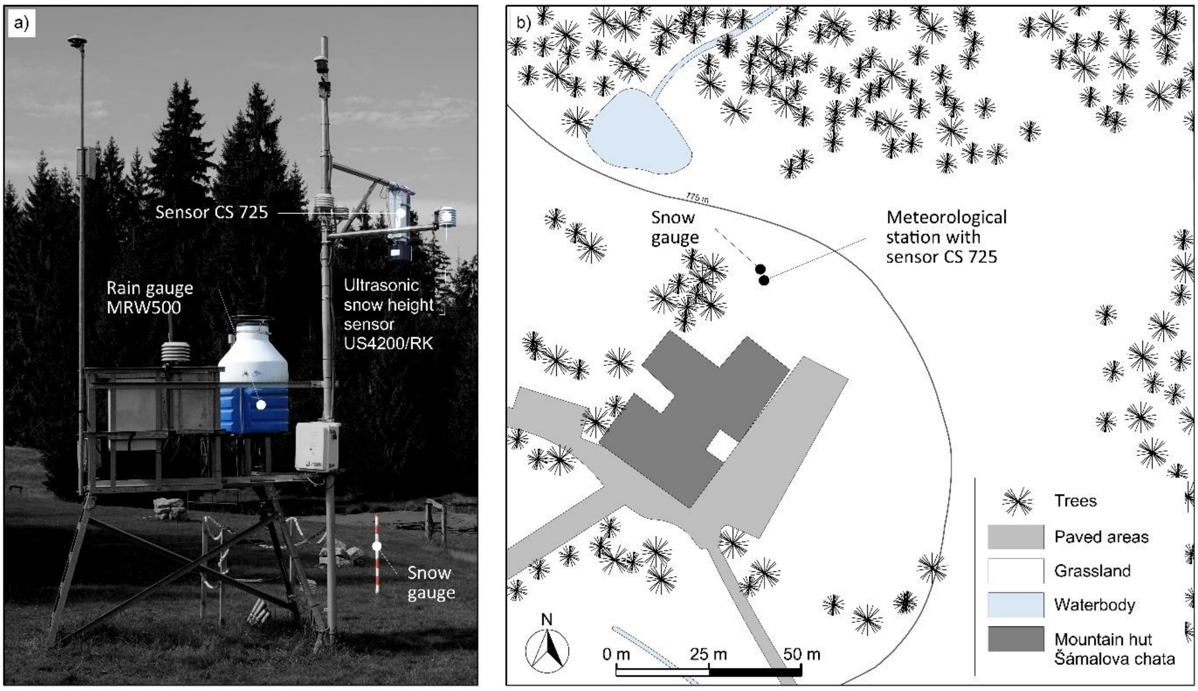

Fig. 2 - Meteorological station of the Institute of Hydrodynamics of the AS CR at locality Nová Louka.

Snow water equivalent measurement

The CS725 sensor was developed by Institute de recherche d'Hydro-Québec (IREQ, Varennes, Qc, CANADA) for the determination of the water equivalent of the snowpack [11]. The sensor has a scintillator of a thallium-doped sodium iodide crystal optically coupled to a photomultiplier tube [7]. The crystal detects the net terrestrial gamma radiation naturally emitted by isotopes ^{40}K and ^{208}Tl present in soil/bedrock. The signal emitted by dry soil and in the absence of snow or water above ground is considered a constant background value [8]. The attenuation of the gamma signal then varies with the presence of water between the radiation source and the sensor. Therefore, gamma radiation is attenuated by the presence of snowpack. The number of detected electromagnetic signals is summed up four times per day, and the resulting value is together with the background value used for *SWE* calculation [9], [8]:

$$SWE = \frac{-1}{\beta} * \ln\left[N * \frac{(1+1.11*SSM)}{N_0}\right] - (0.001165 * H) \qquad (1)$$

where β is attenuation coefficient [cm^{-1}], N is the number of radiation counts recorded per period of time [6h^{-1}], N_0 is the number of radiation counts emitted by a dry soil in the absence of snow

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or water above [$6h^{-1}$], *SSM* is saturated soil moisture [-], and *H* is sensor height above the ground surface [cm].

The sensor uses a threshold (factory pre-set value of 5 mm) that decides how the SWE is calculated. Above that threshold, SWE is calculated independently for both attenuations (SWE_K and SWE_{Tl}). Below this threshold, when there is a danger of patchy snow cover and the calculation could be affected by the soil moisture, a different approach is used based on the ratio of the two attenuations (SWE_{ratio}), which, although not as accurate, removes soil moisture from the expression.

The bottom edge of the sensor is installed at the height of 3.53 m above the ground. The sensor is equipped with a lead collimator, which prevents the counting of gamma radiation emitted from sources not in the target area [9]. The bottom edge of the collimator is 3.45 m above the ground. The collimator limited the field of view to 120 degrees [7]. Therefore, the sensor at the Nová Louka site detects gamma radiation from an area of approx. 117 m^2.

Snow depth monitoring

Snow depth is measured by an ultrasonic sensor (US4200/RK, Fiedler AMS s.r.o.) and alternatively detected from the camera record (BCC100, Brinno Inc.), which is focused on the snow gauge. The camera record was available from the end of March 2019. The ultrasonic sensor and snow gauge are located within the detection area of the SWE sensor, approximately 2 m apart in the horizontal direction.

Monitoring intervals

The snow depth, weighing rain gauge, air temperature, and humidity sensor are monitored at 15-minute intervals. The camera record is comprised of a sequence of 1-hour images. The CS725 sensor provided six-hour averages of SWE. Once a month, the sensors are checked for functionality and maintenance.

RESULTS AND DISCUSSION

Snow water equivalent

To study the performance of the CS725, two winter periods, 2018-2019 and 2019-2020, were examined. The SWE values obtained from the sensor are shown in Figure 3. The snow cover was present from December to the beginning of April in both periods. Nevertheless, these periods differ significantly. The maximum value of SWE was about 365 mm in the winter period of 2018-2019, while it was only 88 mm in winter 2019-2020 (based on attenuation of the ^{40}K isotope). During 2019-2020, several accumulation phases and thawing episodes were observed. While the season 2018-2019 was characterized by a single accumulation peak only. The overall character of SWE measurement also reflected the air temperatures and amount of precipitation in both periods. In 2018-2019 almost twice as much precipitation occurred, and temperatures were significantly lower (by about -1.02°C on average), often day-long below 0°C.

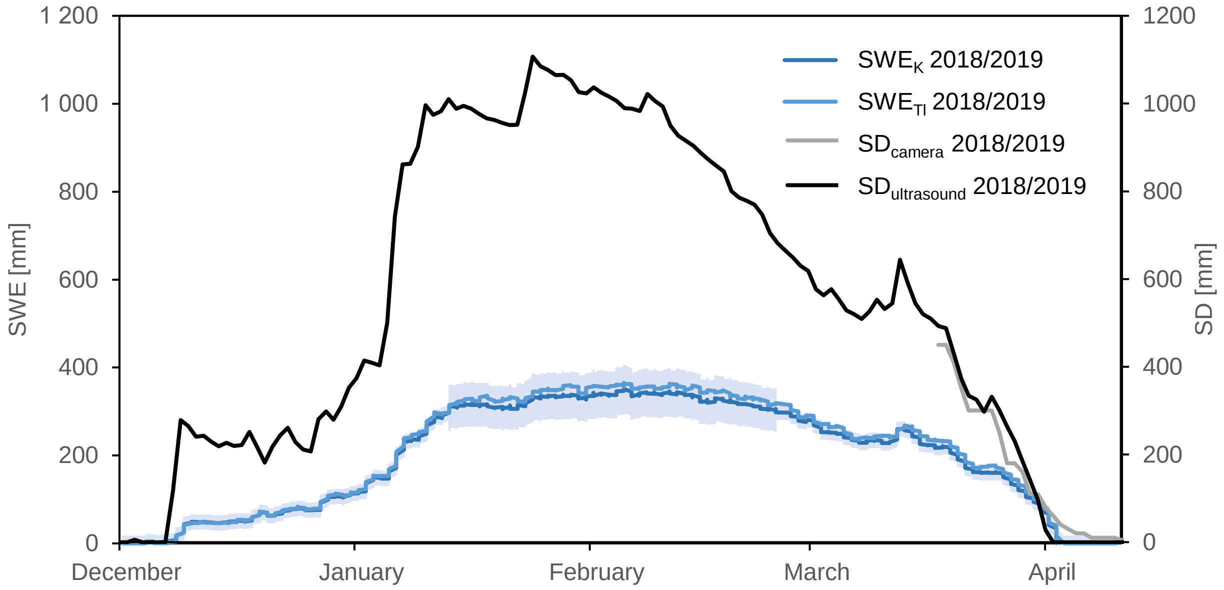

Fig. 3 - Snow water equivalent (SWE) measured by sensor CS725 and snow depth (SD) measured by ultrasound sensor and detected from the camera record at the Nová Louka site in winter period 2018-2019. SWE$_K$ and SWE$_{Tl}$ stand for snow water equivalent values determined based on attenuation of gamma radiation emitted by isotopes ^{40}K and ^{208}Tl. The shaded area represents a factory specified accuracy of the CS725 sensor.

Attenuations of electromagnetic signals emitted by both isotopes (^{40}K and ^{208}Tl) provide a similar course of SWE (Figure 3, Figure 4). Registered differences were up to 30 mm and dependent on the actual SWE values (i.e., higher values yield higher differences between SWE$_K$ and SWE$_{Tl}$). The absolute majority of the time, the differences were within the accuracy range specified by the manufacturer. Generally, the SWE values derived from isotope attenuation with the higher counts (usually emitted by isotope ^{40}K) are considered more reliable [12], [9]. At the Nová Louka site, the detected hourly totals of emitted electromagnetic signals in the period without snow cover were about 40 000 h^{-1} and 9 000 h^{-1} for ^{40}K and ^{208}Tl, respectively. Therefore, the values based on isotope ^{40}K attenuation are regarded as more accurate in our study.

The course of the snow depth is similar to the snow water equivalent (Figure 3, Figure 4). However, snow water equivalent in the period 2018-2019 demonstrates a considerably wider peak (Figure 3) associated with the gradual settling and compacting of snow, which is not reflected in the value of SWE. The differences in the snow depth obtained from the ultrasonic sensor and camera could be attributed to the snow cover spatial variability. Specifically, the average relative difference between ultrasonic sensor and camera daily average readings comprises 25% for the fragment of period 2018-2019 (Figure 3) and 35% for the whole winter period 2019-2020 (Figure 4). It is obvious that the spatial variability is more pronounced in the case of the winter period with a small amount of snow (2019-2020) and a large number of accumulation-melting cycles.

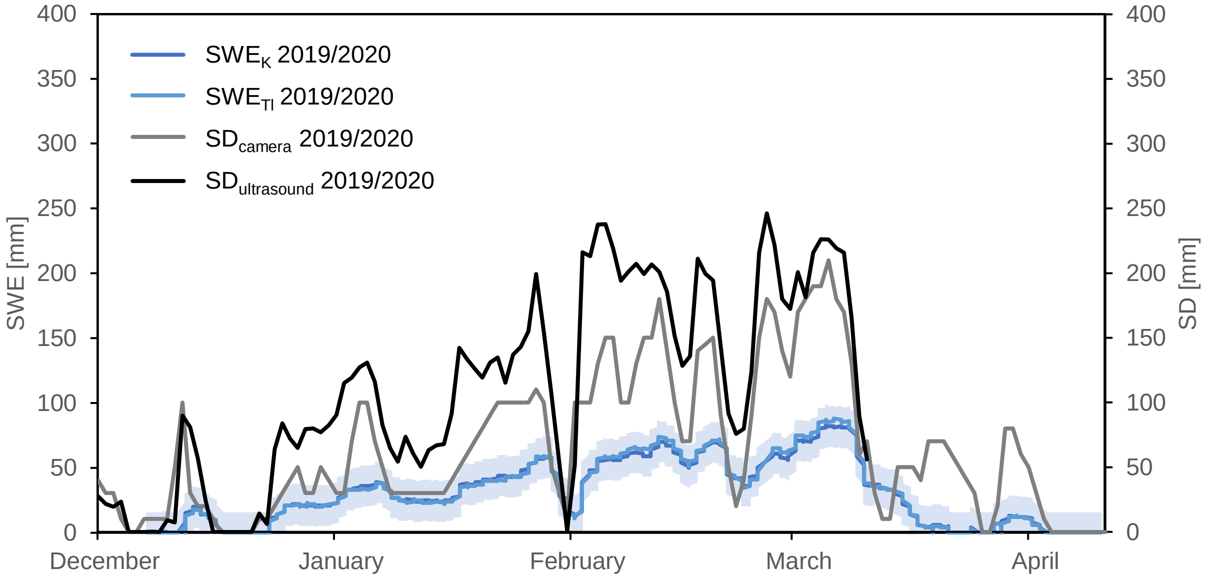

Fig. 4 - Snow water equivalent (SWE) measured by sensor CS725 and snow depth (SD) measured by ultrasound sensor and detected from the camera record at the Nová Louka site in the winter period 2019-2020. SWE_K and SWE_{Tl} represent snow water equivalent values determined based on attenuation of gamma radiation emitted by isotopes ^{40}K and ^{208}Tl. The shaded area represents a factory specified accuracy of the CS725 sensor.

Thawing snow and transient snow-rain situations

Due to the spatial variability, it is possible that even if the snow cover is still lying on some spots, the sensor evaluates the integral SWE value = 0 mm. Therefore, the calculated SWE value should be carefully analyzed, especially during periods of thawing snow and transient snow-rain situations.

Figure 5 shows a series of images capturing the soil surface under the sensor in April 2019, when the snow cover started to melt. In the first two days (April 4 and 5), the air temperature is above freezing point overnight, and the afternoon temperature peaks exceed 13°C. Although other days during the night it freezes and the thawing of snow slows down, high daytime temperatures cause even the remaining snow to disappear within six days (Table 1).

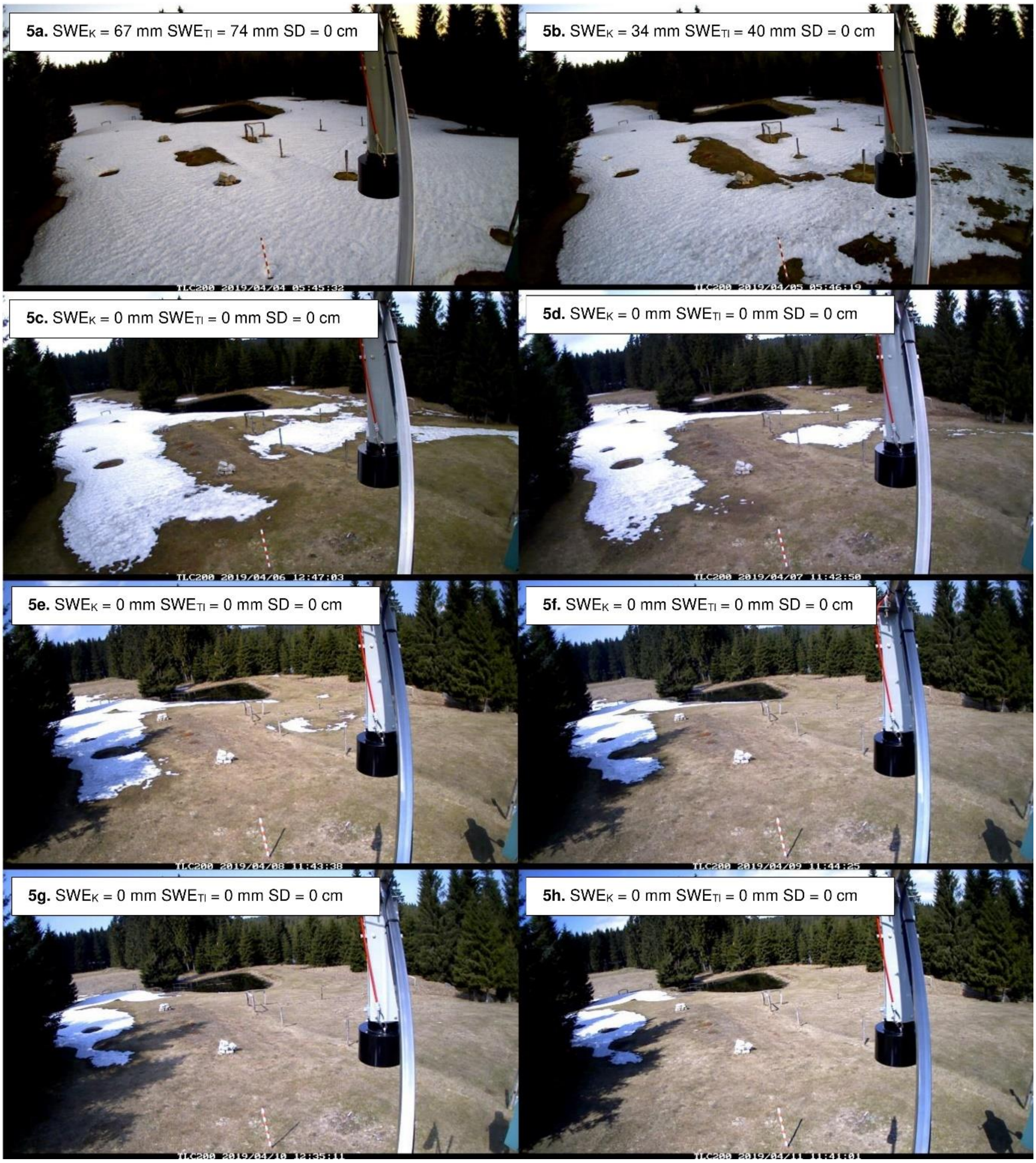

Fig. 5 - Soil surface under the CS725 sensor on April 04-11, 2019. SWE_K and SWE_{Tl} stand for snow water equivalent values determined based on attenuation of gamma radiation emitted by isotopes ^{40}K and ^{208}Tl.

The surface is covered with a discontinuous snow cover in the first two days (April 4-5). In this situation, the sensor evaluated the SWE_K to be 67 mm and SWE_{Tl} = 74 mm. At the same time, the SWE_{ratio} value independent of soil moisture was 43 mm (see Tab. 1) and corresponded better to the captured site conditions (Figure 4). On April 5, the difference, i.e., the influence of shallow soil moisture, was even more important, SWE_K = 34 mm and SWE_{ratio} = 15 mm. The snow melted even more intensively in the following days, and the sensor evaluated the SWE values as 0 mm. It is also clear from the camera record that only fragments of snow cover remain on the site outside the sensor's range.

Tab. 1 - Snow characteristics and air temperatures for selected days in April 2019. SWE_{RATIO} is used when the threshold value is exceeded, and the SWE determination is affected by soil moisture.

Fig. 5	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*
April 2019	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
SWE_{RATIO} (mm)	*43*	*15*	*0*	*1*	*-5*	*-5*	*-11*	*-12*
T_{min} (°C)	*5.1*	*0.1*	*-1.6*	*-2.7*	*-2.0*	*-2.5*	*-4.3*	*-2.2*
T_{max} (°C)	*13.8*	*15.4*	*16.8*	*15.3*	*15.1*	*13.4*	*8.4*	*3.4*

In contrast, the series of images in Figure 6 show the transient period at the beginning of the winter season 2019/2020. It freezes all day for the first four days of the December period, and snow is deposited. Subsequently, warming occurs, precipitation is mixed, and temperatures are stable above freezing (see Table 2).

A thin layer of new snow from December 11 to December 13 is obviously at the limit of the sensor's detectability (SWE_{TI} and SWE_{K} equal to zero, and SWE_{ratio} from -4 to 10 mm). The increasing snow cover and its snow water equivalent value are captured more reliably in the following days. By December 16, temperatures had already reached above freezing all day, which was reflected in the thawing of the snow cover (up to 24 mm per day) and the decrease in SWE in the next days.

Tab. 2: Snow characteristics and air temperatures for selected days in December 2019.

Fig. 6	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*
December 2019	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*
SWE_{RATIO} (mm)	*5*	*10*	*-4*	*9*	*25*	*27*	*20*	*14*
T_{min} (°C)	*-4.2*	*-5.3*	*-3.3*	*-0.9*	*-2.1*	*1.1*	*1.5*	*-1.7*
T_{max} (°C)	*-1.2*	*-2.6*	*-1.0*	*-0.2*	*2.9*	*4.7*	*6.8*	*7.6*

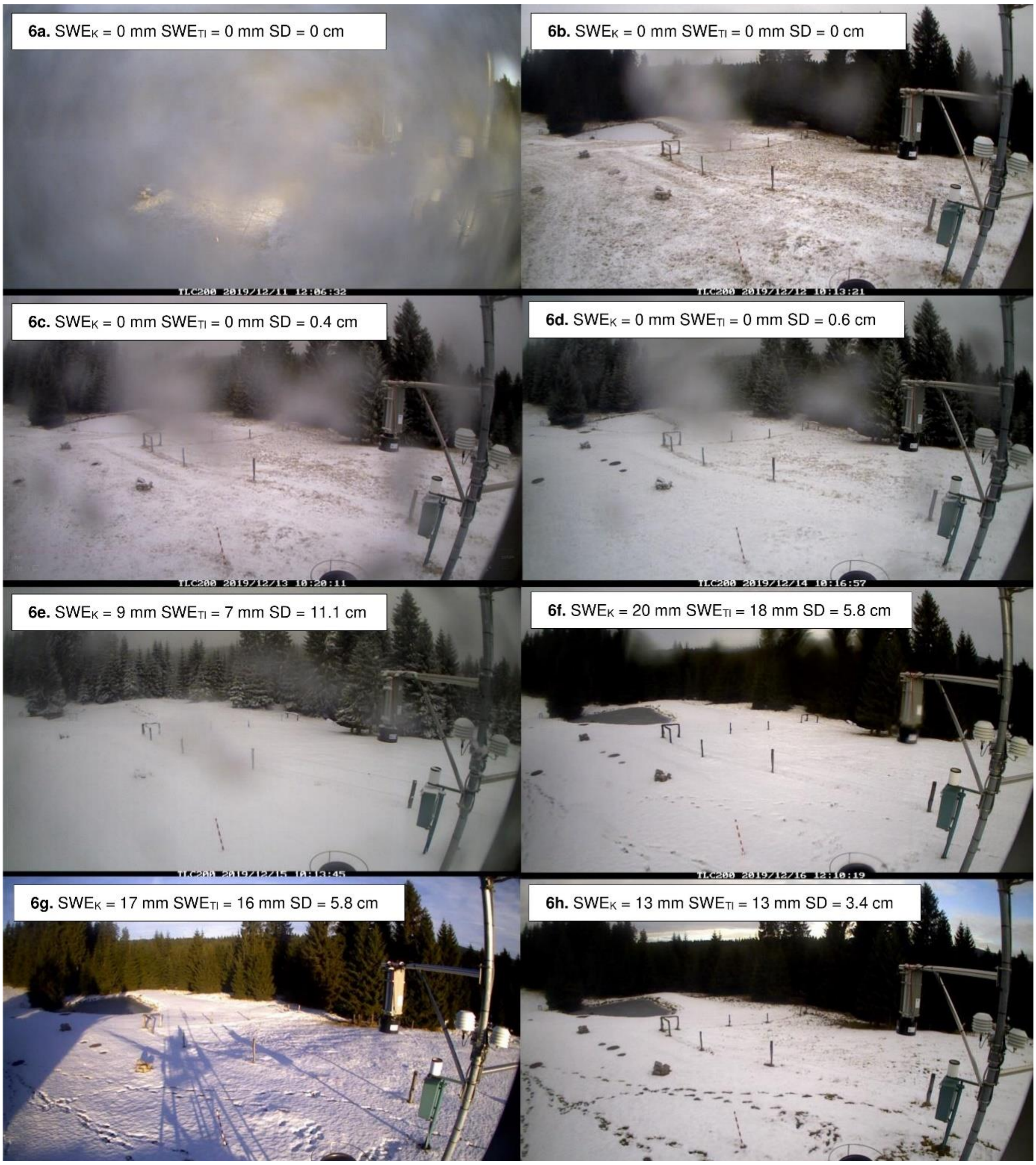

Fig. 6 - Soil surface under the CS725 sensor on December 11-18, 2019. SWE_K and SWE_{Tl} stand for snow water equivalent values determined based on attenuation of gamma radiation emitted by isotopes ^{40}K and ^{208}Tl.

CONCLUSIONS

In the present study, continuous snow water equivalent measurement by the gamma-ray spectroscope CS725 was evaluated. Two consecutive winter periods (2018-2019 and 2019-2020) were examined. Natural conditions allowed the sensor to be tested in contrasting circumstances: during the winter period 2018-2019 with the maximum value of SWE of about 365 mm and during the mild winter period 2019-2020 with the peak value of 88 mm.

Our measurement showed that the SWE values derived from both isotopes ^{40}K and ^{208}Tl are very similar. Detected differences could be attributed to the different background radiation levels available in the soil/bedrock. Because of the higher level of ^{40}K at the site, SWE values derived from this isotope are considered more accurate.

The CS725 gamma-ray spectroscope has proven usability in the conditions of the temperate montane catchment. The conditions at the beginning (when continuous snow cover is forming) and at the end of winter (during intense snowmelt when patchy snow cover occurs) require special attention.

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