SNOW DATA MANAGEMENT WITH THE USAGE OF GEOGRAPHICAL INFORMATION SYSTEM

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ABSTRACT: Our paper represents a review of the role of Geographical Information Systems (GIS) in Snow data management at the Czech Hydrometeorological Institute (CHMI) by i) presenting and discussing methods and systems used to snow data collecting, evaluating, controlling and sharing, ii) spatial and statistical analysis of meteorological and snow data and iii) the evaluation of water reserves in the snow cover using GIS. Snow cover and especially the snow water supplies are an important part of the hydrological balance of water quantity in the Czech Republic and one of the most important CHMI output for data users.

Snow cover is naturally spatially variable and GIS is a useful solution and powerful management tool used for snow data management, analyzing and displaying spatial data. CHMI regularly releases many snow products during the winter season, like snow depth and snow water equivalent maps. Detailed information of the snow water equivalent is also an essential part of improving input data for modelling flow forecasts throughout the winter season, including flood situations. GIS helps hydrologists and climatologists to inform public better about snow problematic using the highest sophisticated tools.

KEYWORDS: Geographical Information System, Snow data management, Spatial interpolation, Snow water supplies, Automatic snow stations.

1. INTRODUCTION

Snow characteristics measurement and monitoring in the Czech Republic has a long tradition. Historical data have been available for some localities since the second half of the 19th century. These data are useful in the issue e.g. of climate change. Nowadays there is a push for operational use of data. Snow measurements provide mainly a basis for hydrological snowmelt runoff in daily hydrological forecast routine during the winter season. The evaluation of water reserves in a snow cover is an important service for the state-owned water supply companies, for which this information is essential for the handling of waterworks.

They are important source of information for winter tourism or for the Mountain Rescue Service, because the more accurate information the rescue members have, the better they can prepare not only avalanche forecasts, but also generally carry out all their activities in the mountains.

During the winter season, CHMI also publishes many snow products including snow depth (SD) or snow water equivalent (SWE) maps. These maps are generated using GIS and spatial interpolation techniques based on point measurement.

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SD is measured daily at more than 700 stations in the Czech Republic (see Figure 1). Most of them are conventional observation stations and beside weather information, new snow and SD measurements are observed and recorded on a daily basis. SWE equivalent once a week. 70 automatic snow stations provide data with a 10-minutes interval. Such volumes of data need to be processed efficiently to be usable in other products.

2. SNOW DATA MANAGEMENT - METHODS AND SYSTEMS

Every assessment of climate or hydrological characteristics starts with data collection. CHMI has a sophisticated system based on manual station measurements of volunteer and professional observers, automatic stations and in recent years in some cases on crowd funding.

Historical climatological data together with data outputs from automatic meteorological stations generate a large volume of data and other climatological information.

Modern climate applications include measurement and station information, so-called metadata, data part, products, allow direct connections to other applications (such as GIS) and various outputs (e.g. NOAA 2024, Copernicus 2024). CHMI has developed climate database application CLIDATA to work with metadata and to processing of climate data since 1996 (CLIDATA 2024). The CLIDATA application is the main climatological database, which is also used for operational meteorology and air quality (Tolasz 2007). And, of course, for snow data management.

Snow characteristics are measured either manually or automatically. In recent years, it is necessary to extend these methods and allow data sharing from the field and letting them be usable for further evaluation and control. Regular snow measurements held on Mondays at various altitudes are used to determine the basic characteristics. Snow surveys at the assumed maximum water snow value are used to refine hydrological models and to climate assessment of the winter season.

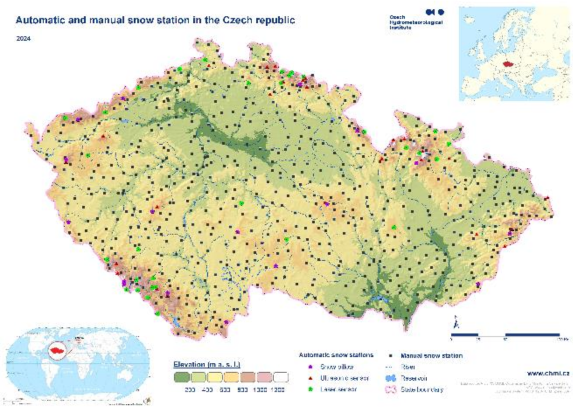

Figure 1: Automatic and manual snow stations in the Czech Republic.

2.1 Snow data collecting

We collect data from three types of stations or measurements.

1. Climatological stations with observer - professional or volunteer

- New snow – snow plate
- Snow depth – snow pole
- Snow water equivalent – rain gauge cylinder or snow tube

Manually measured parameters of snow cover can be written by the observer in several ways: i. by filling in a paper monthly form and sending it to the branch after the end of the month, ii. by filling in a special web form available to the observer from any computer, tablet or even smartphone with internet access. The advantage is that the data is stored in the database immediately after sending it from this form and can be used in the operation.

2. Automatic snow stations

- Automatic climatological stations with laser snow depth measurement
- Automatic snow stations with ultrasonic snow depth measurement
- Automatic stations with ultrasonic snow depth measurement and pillow pressure sensor snow water equivalent measurement

Data from automatic snow stations are transmitted to the data center, checked and stored in the database, and are also widely used in operations and other related applications.

But of course, this also applies to data collected manually in the field, if we can quickly transfer and process it.

3. Snow measurement in the mountainous areas and snow surveys

- Snow depth and snow water equivalent measurements held on Mondays
- Snow depth and snow water equivalent snow surveys at the peak season

During the field measurements, the observers store their route using GPS. The measured data are then recorded via the ArcGIS Survey 123 application (ESRI 2020b) directly online via smartphone. This application allows data collection even offline without an internet connection. The application also allows you to save photos or make audio recordings. In case of bad weather or signal problems, the observer then writes the values into a paper form and sends them under conditions that are more suitable. Data taken in the ArcGIS Survey123 application are immediately available on the ArcGIS platform. This allows you to optimize your fieldwork, understand your data, share the results with others and continue to use the data through, for example, ArcGISOnline (see Figure 2).

At the end of every survey, the data are distributed with some extended information about snow conditions to the CHMI National forecast center and to other users such as Mountain Rescue Service, National parks, meteorologist on TV etc.

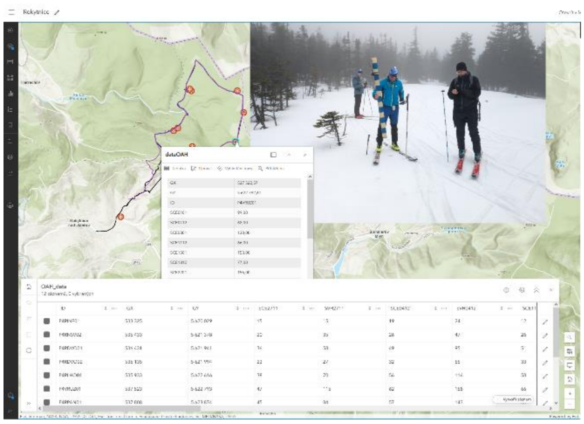

Figure 2: Route and measuring points with measured values of snow depth and snow water equivalent in ArcGISOnline (Study area - Krkonose Mountains).

2.2 Snow data evaluating and controlling

Snow data controls, as well as checks of all term data, routinely work at all levels (formal, logical and spatial). Logical and spatial control of data is performed using the CLIDATA database and partially GIS.

The total SD of the snow cover from both manual and automatic measurements is marked SCE (cm) in the CLIDATA database. The SWE is marked SVH - manual or SVHa (mm) - automatic.

Depending on availability, data from selected stations with manual measurement are checked on a daily basis. If the observer inserts them via the web form into the CLIDATA database, the data are available every morning from the regular measurement at 7:00 CET.

Data from automatic snow stations, transmitted to the CHMI data center, have a large volume and it is generally not possible to check them by the same methods and methodology as the data from manual measurements. They require special tools that have been developed within the CLIDATA application (see Figure 3). Each station has its own ID and the measurement interval of these data is 10 minutes.

When imported into the database, the SD and SWE data are subject to an automatic type of control. This means that the data are evaluated and then imported only if they do not exceed the set limit. For example, these limits are for SD <0–350> cm and SWE <0–2000> mm. The missing values are interpolated over an interval of < 12 hours. In this case, the application uses IDW interpolation, the weighted inverse distance method. For ultrasonic sensors, the condition is set for snow height < 2,4 cm, then both SD and SWE are set to zero. The suspicious value alert occurs at so-called interterm differences. For example, if the difference between two consecutive values (in the above mentioned 10-minute interval) of SD is > 7 cm or water equivalent > 10 mm (Walder et al. 2021)

In the period of expected no snow, the import condition is set that each imported value (SCE) is equal to 0. To determine this period, automatic snow stations were divided into three groups according to altitude: 1st group of stations above 1100 m a. s. l. (period with the expected snow cover from Sep 1 to May 31.), 2nd group of stations between 675 and 1100 m a. s. l. (Oct 1 – May 15.) and 3rd group of stations below 675 m a. s. l. (Oct 15 – Apr 4).

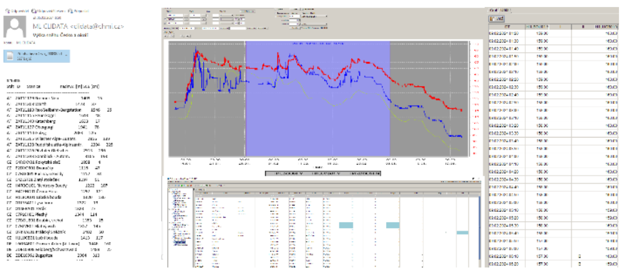

Figure 3: Data checking and correcting tools within the CLIDATA database application.

Data from automatic snow stations at 7:00 CET are the average of the previous six values in the 10-minute interval from 6:10 to 7:00. Manual control of these data is then carried out at the CHMI by members of the working group "Snow", who check and correct data from automatic snow stations every day (Sustkova et al. 2023). The check form is part of the CLIDATA application, where are all automatic snow stations and data for the last 3 days (Walder et al. 2021).

Another important control for the manual and automatic measurements of SWE is the expert estimation of the likely range of snow cover density (the ratio of SWE to SD). We call it the Snow Density Bulletin. Every Monday, hydrologists publish bulletin of density intervals, which are determined for three different altitude areas: 100–600 m a. s. l., 601–900 m a. s. l. and 901–1600 m a. s. l. In problematic situations, snow density intervals are also determined for specific regions of the country or for individual mountain ranges. In the Czech Republic, the influence of continentality and oceanicity is also slightly manifested, although the width of the territory from west to east is only 500 km. The western part, which is closer to the ocean, may be slightly wetter and the snow density may be slightly higher than in areas at the same altitude on the eastern edge of the territory. However, orography has a greater influence on snow density in the Czech Republic.

In addition to the mentioned density intervals, the Snow Density Bulletin also contains information on the past week's weather in mountain, hill and lowland areas. The weather outlook for the coming week is also an important part of the bulletin. The snow density bulletin has become an important part of snow data control, especially SWE, over the last ten years.

Another important element of the data control is the calculated snow water equivalent (SWEC). Theoretical values of SWEC are calculated using an empirical formula for all meteorological and climatological stations in a daily step.

2.3 <u>Snow data sharing</u>

After the completion of the whole controlling process, each day an email is sent to selected CHMI internal users with values of snow cover heights. Selected stations from neighboring countries (Slovakia, Poland, Germany, Austria) have been included in the station list as part of the international data exchange (see Figure 3).

For the public, the revised snow data are subsequently displayed in a daily step on the website of the Flood Warning and Forecasting Service (CHMI 2024a). This simple and quick tabular form information is regularly extended on CHMI social networks such as FB or X (CHMU 2024). All map and other outputs are based on the CLIDATA database and supplemented with comments and pictures from the field.

For some Institutions, such as the Mountain Rescue Service of the Czech Republic, we also provide access to data in a 10-minute interval.

Most of the snow water storage estimation outputs are published on the CHMI website Flood Warning and Forecasting Service (there are maps, tables, graphs and texts, CHMI 2024b) and on the drought impact website HAMR (Hydrology, Agriculture, Meteorology and Retention). The presentation of the results on the HAMR website includes a mapping application where maps of SD and SWE equivalent are stored in weekly steps (HAMR 2019).

A specific product is the evaluation of the snow water reserves, when these are calculated once a week from Monday's measured data (see the chapter 3.3 for more information).

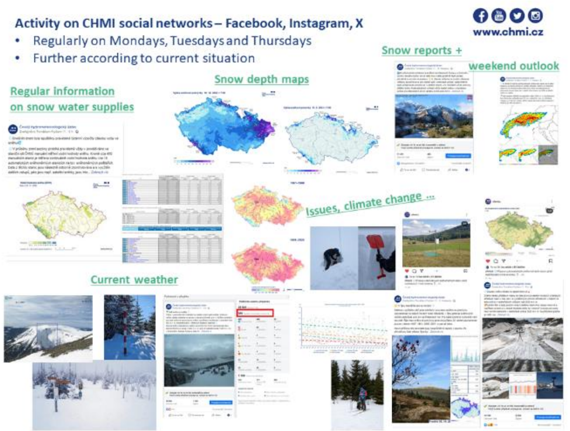

Figure 4: Example of outputs on CHMI social network FB and X.

3. SPATIAL AND STATISTICAL ANALYSIS OF SNOW DATA

3.1 *CHMI snow station network*

Meteorological stations provide data about a given phenomenon or element through a number of point data. To visualize the spatial distribution we use GIS and specific interpolation methods that help us to estimate the value in places where measurements have not been made, but also in the above-mentioned spatial visualization. Estimating the distribution and amount of snow is very challenging due to its large spatial variability. One way to refine these is to thicken the network of measuring stations or the other one is to use appropriate interpolation tools.

The density of the network of snow stations in the Czech Republic is quite high. The depth of snow is measured at more than 700 locations, the water equivalent is then measured at about 470 locations. Manual measurement predominates, but automation continues and there are 70 snow automatic stations in operation.

Currently, on average, there is one station per about 112 km^2. At altitudes above 800 m a. s. l., where conditions are most favorable for the formation of snow cover during the winter season, the density of the network is even higher, about 1 station per 58 km^2 (see Figure 1). In some areas, the density of stations is sufficient. But in highlands and mountains with a dynamic relief, and especially in the foothills the interpolation is still problematic and it is an effort of GIS specialists to improve this (see Figure 5).

3.2 *Using snow data and GIS in Climatology*

Climatological data can be displayed in GIS in various formats (Chapman, Thornes 2003). We most often process data from point measurements at CHMI and with the help of GIS, we create spatial information from them. Than we perform other selected analyses.

We use the desktop version of the ArcGIS system from ESRI (ESRI 2024a). We also use the open source SAGA GIS (SAGA GIS 2024) and QGIS (QGIS 2024).

There is a special extension for ESRI GIS program ArcGIS CLIDATA GIS for ArcGIS version 10. This extension allow to connect GIS program to climatological database CLIDATA, creating GIS layers from data store in database, text files (CSV), interpolate point (station's) data into surface, calculate area statistics and so on (Striz 2024).

Special interpolation methods have been developed at CHMI. These are the Orographic interpolation method (Sercl 2008a, Sercl 2008b), CLIDATA-DEM and LLR (local linear regression) (Striz 2011). Both basic methods are based on local linear regression and take into account the influence of altitude (or other elements such as slope orientation and inclination or land cover) on the interpolated variable and retain the original measured value at a known point.

The GIS terrain layer is chosen according to the size of the area being processed and the density of the network of available stations. For detailed maps of mountain areas, we use SRTM 1 Arc-Second Global, created by the US National Geospatial-Intelligence Agency (NGA) the US National Aeronautics and Space Administration (NASA) (USGS 2018). This digital elevation model (DEM) is chosen for more detailed analyses because it offers a high resolution input grid (raster) for spatial analyses and the size of individual cells (pixels) captures the desired detail as well as possible. DEM has a resolution of 38x38 m. At each point, an estimate of the SD (or SWE) is calculated using a local regression analysis, based on the surrounding stations. The stations are selected on the basis of a pre-selected distance in kilometers and a minimum number of stations. The advantage of this DEM is the availability for the whole Europe in the WGS-84 coordinate system and the possibility of spatial analysis beyond the borders of the Czech Republic (USGS 2022).

A minor disadvantage with high resolution DEM is the time-consuming calculation. For daily issued maps of the whole territory of the Czech Republic due to the above-mentioned facts, we usually use DEM with a resolution of 100x100 m or 500x500 m.

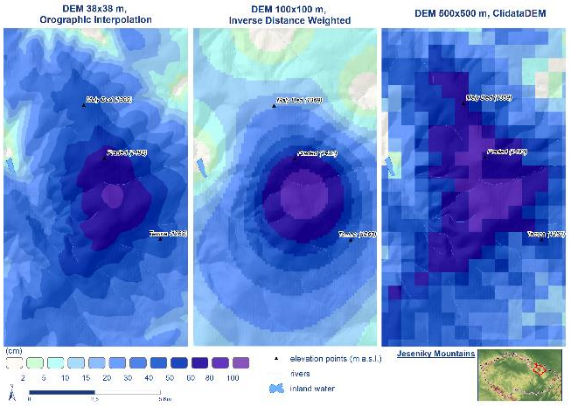

Figure 5: Example of spatial distribution of SD - various interpolation methods and DEM.

Thanks to the CLIDATA database, we also have historical data from the Czech Republic dating back to the mid-19th century. We also use the GIS when collecting and checking these historical data. Spatial data control allows the detection of suspicious or incorrect values. These historical data are then used in analyses of climate change.

The PERUN project - Prediction, evaluation and research of the sensitivity of selected systems, impact of drought and climate change in the Czech Republic (PERUN 2022) is dedicated to the study of potential climate change in the Czech Republic.

Thanks to the climate version of the forecast model Aladin-CLIMATE/CZ, specifically its configuration called ALARO (Brozkova et al. 2019), which was created within the PERUN project, we have data for the development of basic meteorological elements for the following period up to 2100 for selected SSP - socio-economic scenarios (IPCC 2018) in a spatial resolution of 2,3x2,3 km. We discussed in detail the impacts of climate change on snow cover in the Czech Republic in our last year's ISSW2023 paper (Sustkova et al. 2023). Map outputs for individual 20-year-olds and for emission scenarios SSP2-4.5 and SSP5-8.5 are available for download in the format jpg, csv and asc (Perun 2023) or in the online web viewer ArcGISOnline (see Figure 6, PERUN 2024).

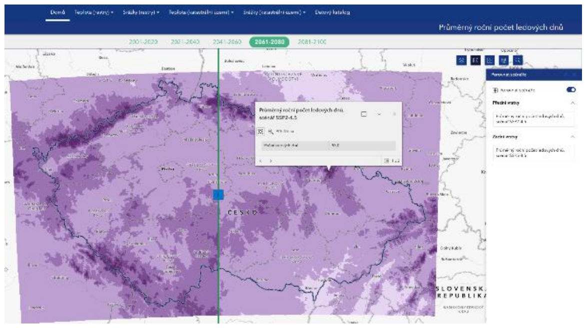

Figure 6: Map viewer of the PERUN project in ArcGIS Online - number of Ice days in 2061–2080 (PERUN 2024).

3.3 The evaluation of water reserves in the snow cover using GIS

There are still numbers of reasons why emphasis is placed on continuously improving the evaluation of water reserves in the snow cover in the Czech Republic. Due to the risk of long-term droughts and in general due to the climate change in Central Europe, there is a growing demand for more accurate water storage calculations for the state water companies. Because of the increasing frequency of melting periods in all altitudinal zones during the whole winter season, the staff of the state-owned water supply companies need to have the most accurate information available and also as soon as possible. The Flood Warning and Forecasting Service of the CHMI has similar requirements for more accurate water supply calculations which can refine flow forecasts in problematic regions especially during periods of melting (CHMI 2024b).

Methodology for obtaining input data to improve interpolation

The snow water storage is calculated in a weekly step on Monday during the whole winter season from the beginning of November until the end of April. The weekly calculation step is due to the fact that the SWE is measured at manual weather stations only every Monday. The calculation of water storage is performed using a special interpolation method Clidata-DEM (Striz 2009, 2011, 2024).

In recent years, the number of stations entering the calculation has stabilized at a total of 600. This number consists of 430 selected verified manual stations, 70 automatic snow stations and about 100 auxiliary stations. An auxiliary station in this case is a station where the snow cover parameters are measured only a few times per winter season and the remaining Monday values are calculated according to an established empirical relationship with the nearest surrounding regularly measured stations. Auxiliary stations are mainly located in places with insufficient density of regular measuring stations or in areas where interpolation of SWE is problematic due to their specific relief.

The measurement of SWE can sometimes be difficult due to the specific density and structure of the snow layer and due to low SD, so the accuracy of manual measurements may be affected. Similarly, the accuracy of automatic snow station measurements is in some cases affected by natural, technical and physical factors. For these reasons, data from all mentioned stations are checked in detail before starting the interpolation. To check the measured SWE data, it is necessary to use the values of snow density intervals given in Regular Weekly Snow Density Bulletin (see the chapter 2.2 for more information about snow data controlling).

Using satellite imagery and ground observations to define the extent of snow cover

For a good interpolation of SWE data it is also necessary to determine the zero isochion (snow line with zero value) for individual regions of the Czech Republic as accurately as possible. For the calculation of snow water reserves the territory of the Czech Republic is divided into 9 main regions, in case of problematic situations 27 regions are used. For each region, a zero snow line value is determined to avoid erroneous interpolations where the SWE was calculated even in areas where snow cover did not occur. Several sources are used to determine the zero isochion. Firstly, data are obtained from the NSIDC (National Snow and Ice Data Center - University of Colorado) portal, where images from daily MODIS satellite flybys over central Europe are archived (NSIDC 2024). The selection of satellite images for snowline position analysis is based mainly on the date of acquisition and the amount of cloud cover. One representative image is selected for each week of the observation period. Suitable images are selected due to the Monday ground measurements of the CHMI either on the same day or at the earliest possible previous date. The transformed image is then imported into the ArcGIS as a classified raster, from which the classes "snow cover", "area without snow cover" and "cloud cover" are essential for the purpose of zero isochion. Unfortunately, the accuracy of images depends on the level of cloud cover. Other important sources for determining zero isochion are webcams (cameras of the CHMI, commercial cameras, cameras of amateur meteorologists, etc.) and, of course, records of snow cover measurements at meteorological stations and, last but not least, observations of amateur meteorologists.

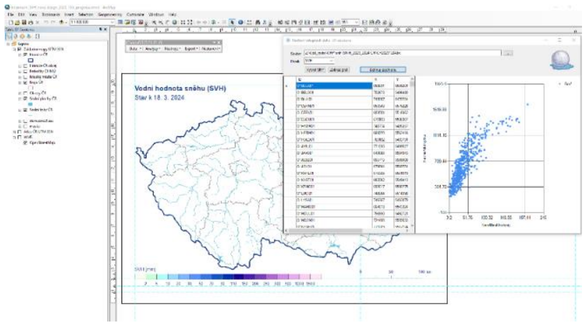

Figure 7: Example of the calculation environment in ArcGIS - Clidata GIS including a graph expressing the ratio of altitude to SWE.

Main outputs of the water storage in the snow cover evaluation

The checked data from manual, automatic and auxiliary stations and the zero isochion data in each region are the input database of weekly GIS calculation whose main purpose is to evaluate the water storage in snow cover as efficiently as possible, especially for flood protection, modeling flow forecasts and water management purposes. The current water storage is evaluated in the GIS for the whole country (see Figures 8, 9), individual 14 administrative regions and 6 main altitude zones, but also for nearly 80 selected catchments and waterworks.

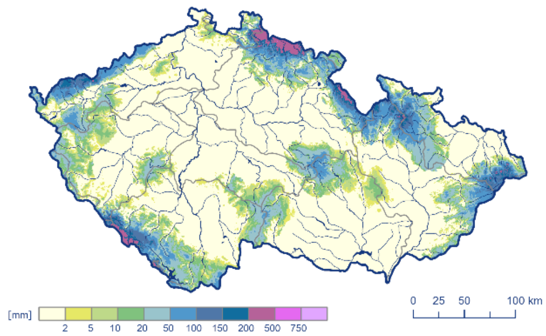

Figure 8: Snow water equivalent map February 7 2022.

Most of the outputs of the snow water storage estimation are published on the CHMI website "Flood Reporting and Forecasting Service" where are stored maps, tables, graphs and texts from the last ten years (CHMI 2024b). Another output is a comparison of the current water storage with other winter seasons since 1970, or with the maximum, average and minimum storage volumes in a particular week of the season in selected basins of the country.

Another important source of information is the drought impact website HAMR (abbreviation of Hydrology, Agriculture, Meteorology and Retention). The presentation of the results on the HAMR website includes a mapping application where maps of SD and SWE are stored in weekly steps (see Figure 9, HAMR 2019).

Currently, the presentation of snow data, including water supplies, is being prepared in ArcGIS Online, where the data should be presented in the form of an interactive map with a number of important metadata.

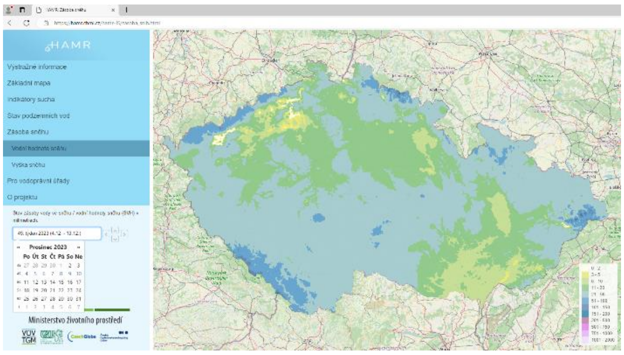

Figure 9: Snow water equivalent interactive map December 4 2023 (HAMR 2019).

Other efforts of the SWE calculation are moving toward daily-step of evaluation. With more frequent floods or mid-week precipitation episodes, it is important for water management to have accurate information at the day step. Research in this area focuses on model calculations based on measurements of meteorological elements (air temperature and humidity, precipitation, speed and direction of wind). The model calculations can be checked by automatic snow stations. There is an assumption that the number of automatic snow stations will increase constantly in the future.

4. CONCLUSION

The Czech Hydrometeorological Institute is a special institute for meteorology, climatology, hydrology and air quality. To meet his responsibilities and monitor the natural environment nationwide for those subjects, he manages an extensive station network. In relation to snow hydrology and climatology, long-term cooperation between field workers, GIS specialists and forecast centre is necessary.

Modern and efficient tools are extremely useful in order to manage, record, process and control data, their availability, protection and use in operational and other downstream applications. There is a long-standing effort to give accurate, important and interesting information about snow cover.

In recent years, the use of GIS in a variety of applications involving the processing of climatological, meteorological and hydrological data has expanded at CHMI, making the manipulation of spatial data easier and more efficient. Add to that the expansion of the data connection in the field leads to real-time bespoke solution for many end-users.

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