Charles University, Faculty of Science

Department of Physical Geography and Geoecology

Mountain snowpack and its importance for catchment storage and runoff

Habilitation thesis

Michal Jeníček

Prague, 2023

Content

Acknowledgements

The research presented in this thesis is based on long-term investigations over the past 10 years, and I have certainly not been the only person involved. Therefore, my thanks go to my colleagues at the Department of Physical Geography and Geoecology, especially to several PhD, Master and Bachelor students, who have contributed significantly to the results and publications. I would also like to thank my colleagues in the Hydrology and Climate Group at the University of Zurich, where I spent two wonderful years as a postdoc. This experience has significantly influenced my further career by initiating new collaborations and will continue within the new collaborative research project we have recently received.

Publication included in this habilitation thesis

Section 1

1. Hotovy, O., Nedelcev, O., Jenicek, M. (2023). Changes in rain-on-snow events in mountain catchments in the rain-snow transition zone. Hydrological Sciences Journal. Published online first. https://doi.org/10.1080/02626667.2023.2177544.
2. Juras, R., Blöcher, J.R., Jenicek, M., Hotovy, O., Markonis, Y. (2021). What affects the hydrological response of rain-on-snow events in low-altitude mountain ranges in Central Europe? Journal of Hydrology, 603(C), 127002. https://doi.org/10.1016/j.jhydrol.2021.127002.
3. Šípek, V., Jenicek, M., Hnilica, J., Zelíková, N. (2021). Catchment storage and its influence on summer low flows in central European mountainous catchments. Water Resources Management, 35, 2829–2843. https://doi.org/10.1007/s11269-021-02871-x.
4. Jenicek, M., Ledvinka, O. (2020). Importance of snowmelt contribution to seasonal runoff and summer low flows in Czechia. Hydrology and Earth System Sciences, 24 (7), 3475–3491. https://doi.org/10.5194/hess-24-3475-2020.
5. Parajka, J., Bezak, N., Burkhart, J., Hauksson, B., Holko, L., Hundecha, Y., Jenicek, M., Krajčí, P., Mangini, W., Molnar, P., Riboust, P., Rizzi, J., Sensoy, A., Thirel, G., Viglione, A. (2019). MODIS snowline elevation changes during snowmelt runoff events in Europe. Journal of Hydrology and Hydromechanics, 67 (1), 101-109. https://doi.org/10.2478/johh-2018-0011.
6. Jenicek, M., Seibert, J., Zappa, M., Staudinger, M., and Jonas, T. (2016). Importance of maximum snow accumulation for summer low flows in humid catchments. Hydrology and Earth System Sciences, 20, 859-874. https://doi.org/10.5194/hess-20-859-2016.

Section 2

7. Jenicek, M., Hnilica, J., Nedelcev, O., Sipek, V. (2021). Future changes in snowpack will impact seasonal runoff and low flows in Czechia. Journal of Hydrology: Regional Studies, 37, 100899. https://doi.org/10.1016/j.ejrh.2021.100899.
8. Nedelcev O., Jenicek, M. (2021). Trends in seasonal snowpack and their relation to climate variables in mountain catchments in Czechia, Hydrological Sciences Journal, 66 (16), 2340-2356. https://doi.org/10.1080/02626667.2021.1990298.
9. Blahusiakova, A., Matouskova, M., Jenicek, M., Ledvinka, O., Kliment, Z., Podolinska, J., Snopkova, Z. (2020). Snow and climate trends and their impact on seasonal runoff and hydrological drought types in selected mountain catchments in Central Europe. Hydrological Sciences Journal, 65(1-2), 2083-2096. https://doi.org/10.1080/02626667.2020.1784900.
10. Girons Lopez M., Vis, M.J.P., Jenicek, M., Griessinger, N., Seibert, J. (2020). Assessing the degree of detail of temperature-based snow routines for runoff modelling in mountainous areas in central Europe. Hydrology and Earth System Sciences, 24, 4441–4461. https://doi.org/10.5194/hess-24-4441-2020.

11. Jenicek, M., Seibert, J., Staudinger, M. (2018). Modeling of future changes in seasonal snowpack and impacts on summer low flows in Alpine catchments, Water Resources Research, 54(1), 538-556. https://doi.org/10.1002/2017WR021648.

Section 3

12. Hotovy, O., Jenicek, M. (2020). The impact of changing subcanopy radiation on snowmelt in a disturbed coniferous forest. Hydrological Processes, 34(26), 5298-5314. https://doi.org/10.1002/hyp.13936.
13. Lendzioch, T., Langhammer, J., Jenicek, M. (2019). Estimating Snow Depth and Leaf Area Index Based on UAV Digital Photogrammetry. Sensors, 19(5), 1027. https://doi.org/10.3390/s19051027.
14. Jenicek, M., Pevna, H., Matejka, O. (2018). Canopy structure and topography effects on snow distribution at a catchment scale: Application of multivariate approaches. Journal of Hydrology and Hydromechanics, 66 (1), 43-54. https://doi.org/10.1515/johh-2017-0027.
15. Jenicek M, Hotovy O, Matejka O. (2017). Snow accumulation and ablation in different canopy structures at a plot scale: using degree-day approach and measured shortwave radiation. AUC Geographica 52 (1): 61–72. https://doi.org/10.14712/23361980.2017.5.
16. Kucerova D, Jenicek M. (2014). Comparison of selected methods used for the calculation of the snowpack spatial distribution, Bystřice River basin, Czechia. Geografie 119 (3), 199–217. https://doi.org/10.37040/geografie2014119030199.

1 Hydrological significance of mountains

Mountain regions cover about 39% of the world's land area and provide fresh water for a large part of the world's population living in the adjacent lowlands. They are often referred to as water towers because they store a lot of water due to typically high precipitation and low evapotranspiration (Immerzeel et al., 2020). About 44% of mountain areas are important for lowland water resources (Viviroli et al., 2007). About 1.8 billion people (39% of the world's lowland population in 2010) are critically dependent on mountain water, and this number is projected to increase to 2.5 billion people by the mid-21st century (Viviroli et al., 2020). Mountain water is essential especially in arid and semi-arid regions which are highly vulnerable to water scarcity due to climate changes.

A significant proportion of mountain water is stored in the form of perennial or seasonal snowpack or glaciers. Snowpack water doesn't contribute immediately to runoff, but it is released with a considerable delay during the snowmelt period, typically in spring or early summer in humid climates (Seibert et al., 2021). Therefore, the seasonal snowpack strongly alters the temporal distribution of water during the hydrological year, with maximum runoff in spring and early summer and minimum runoff in winter. The seasonal water distribution is strongly influenced by melting glaciers in glaciated catchments by further shifting the seasonal runoff maximum to the summer months (Huss and Hock, 2018).

Snow cover is generally very sensitive to changes in air temperature, although its variability additionally depends also on other climate variables, such as precipitation. Therefore, with the recent increase in air temperature, more precipitation falls as rain rather than snow leading to a decrease in snow storage in most parts of the world's mountainous regions (Beniston, 2012; Marty et al., 2017b; **Nedelcev and Jenicek, 2021**; Stähli et al., 2021). In addition, spring snowmelt has also shifted to occur earlier in the year (Klein et al., 2016; Musselman et al., 2017a). The above sensitivity of snow to changes in climate variables suggests that snow will continue to decrease in the future due to projected changes in climate, as shown by recent studies (Fyfe et al., 2017; **Jenicek et al., 2018b**; Marty et al., 2017a). However, the changes in snow amount and duration are highly variable both regionally and at different elevations. In general, the largest changes in snow cover occur in the rain-snow transition zone, i.e. in areas where the seasonal air temperature is close to 0°C, and thus small changes in air temperature lead to large changes in precipitation patterns, and thus in the amount of snow (Harpold et al., 2017).

The role of the mountain snowpack in the hydrological cycle is crucial since snow cover influences the runoff distribution throughout the year. In many mountainous regions of the world, snow and ice melt is a major contributor to annual streamflow (Immerzeel et al., 2020) (Fig. 1). As precipitation falls as snow in winter, the runoff occurs with a delay in spring and summer, depending on the region and elevation, and may be further influenced by mountain glaciers. Thus, snow and glacier melt often contribute to runoff in periods when it is most needed, and are therefore important for adjacent lowlands that may be at water deficit due to lower precipitation and high evapotranspiration. Mountain water is therefore very important both for the natural environment (landscape, ecosystems) and for society (drinking water supply, irrigation, hydropower etc.). In addition, snowmelt is more effective for groundwater recharge compared to rain, which contributes to runoff during low flow periods. Furthermore, catchments with higher snowfall fractions (the proportion of snowfall to total annual precipitation) produce higher long-term mean streamflow compared to catchments with lower snowfall fractions (Berghuijs et al., 2014).

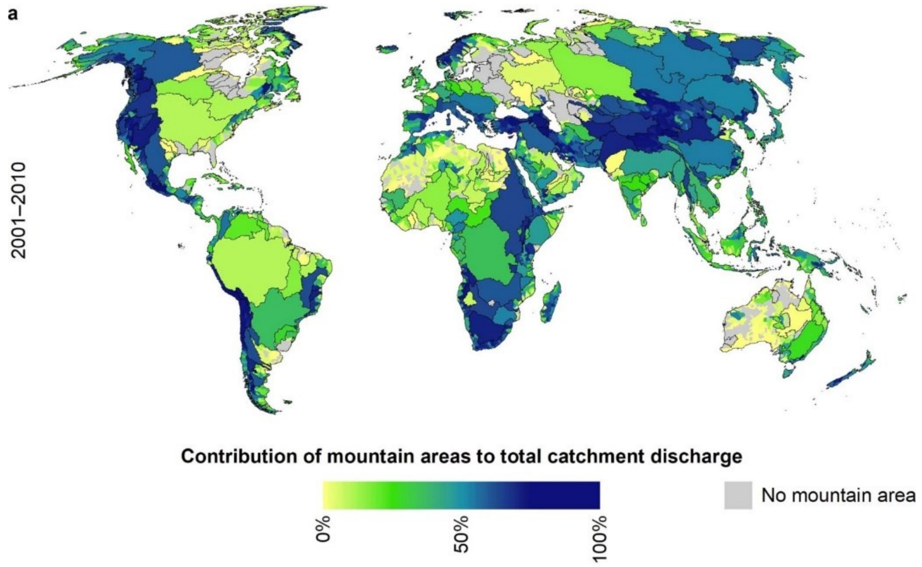

Fig. 1. Contribution of mountains to total catchment discharge 2001–2010. 100% means that all discharge in a basin originates in its mountain area, and 0% that all discharge originates in its lowland area (modified from Viviroli et al., 2020)

Despite many studies demonstrating the importance of snow in the hydrological cycle, still little is known about the mutual interactions of individual factors affecting the water storage and release at a catchment scale at different elevations. For example, some studies have shown a disproportion between the snowmelt runoff contribution and the snowfall fraction (Hammond et al., 2019; Li et al., 2017) suggesting that snow is more effective in generating runoff compared to rainfall. Additionally, several studies have also shown that most of the runoff in the specific season comes from opposite season's precipitation, highlighting the importance of catchment water storage and transit times (Barnhart et al., 2016; Kirchner and Allen, 2020). Therefore, streamflow generation and deep groundwater recharge may be vulnerable to loss of snow, making it important to quantify how snowmelt is partitioned between soil storage, groundwater recharge, evapotranspiration, and runoff. This is particularly relevant for areas in the rain-snow transition zone, such as central Europe, i.e., areas where large changes in snow storage occur. The need to explain the mechanism leading to spatial and temporal variability and change in runoff has been identified by the hydrological community as one of the major unsolved problems in hydrology (Blöschl et al., 2019).

For the research presented in this thesis, the following questions were important:

1) How does a shift from snow to rain affect snow storage, groundwater recharge and runoff dynamics? This is of particular interest for regions in the rain-snow transition zone, such as central Europe.

2) How does snowmelt affect catchment storage and how long does snowmelt continue to contribute to runoff after melt-out? An important follow-up question is whether the snow originating from winter precipitation can influence the other season (summer) runoff, especially during low flow periods.
3) How will future snow changes influence snowmelt runoff, groundwater recharge and catchment storage, considering a wide range of hydrological responses to different climate projections?
4) How important are catchment attributes for snow distribution and snowmelt? Specifically, what is the role of forests in snow accumulation and melting?

The above questions further shaped the objectives defined in individual studies presented in this habilitation thesis.

2 Main methodological aspects

2.1 Working at different spatial scales: From in-situ monitoring to large-sample hydrology

The role of snow in seasonal catchment runoff, summer low flows and water supply is frequently quantified at a site and catchment levels based on field investigations or using hydrological models. Field investigations allow for the assessment of more detailed interactions, such as the effect of forests on snowpack energy balance, snowmelt, and runoff **(Hotovy and Jenicek, 2020**). Field investigations also improve our understanding of topography and forest effects on snow distribution and snowmelt by using accurate measurements of snow distribution (e.g., using UAVs), forest structure and site-specific meteorological variables **(Jenicek et al., 2018a; Lendzioch et al., 2019**).

In contrast, modelling approaches allow the assessment of catchment response and help to answer questions, such as what are the trends in snow storage, how does snow respond to climate variability or how long does snow influence runoff after snowmelt **(Jenicek and Ledvinka, 2020; Nedelcev and Jenicek, 2021**). Moreover, modelling approaches enable to quantify the impact of future snow changes on spring and summer runoff including low flows based on climate projections (**Jenicek et al., 2021**).

From the above, it is clear that both field and modelling approaches are needed to better understand catchment hydrological responses to climate variability (not only) in mountain areas. As modelling and field approaches provide complementary information at different scales, it is important to combine both in order to transfer accurate, but site-specific field information to catchment and regional scales (Blume et al., 2016).

Modelling approaches applied to multi-catchment datasets are often referred to as large-sample hydrology. Large data samples of diverse catchments with different characteristics allow a comprehensive analysis of the hydrological regime and thus enable the assessment of hydrological variability and changes in space and time (Addor et al., 2020). It therefore provides a better insight into hydrological processes that are shaped by environmental factors and climate and allows robust conclusions to be drawn. Such comparative hydrology also enables us to learn more about the differences and similarities between catchments, enabling their classifications and regionalization.

In the studies presented in Sections 3.1 and 3.2, modelling approaches were applied to a multi-catchment dataset (~80 catchments in Czechia and Switzerland), enabling the results to be generalized to a regional scale and for different elevations from high-alpine catchments to catchments in the rain-snow transition zone (Fig. 2). This is important because changes in hydrological storage and fluxes are expected to differ substantially between climate regimes and elevations. The modelling approach also allowed for simulating the effect of predicted climate change on snow and catchment storage and consequent runoff. In contrast, Section 3.3 presents studies that were mostly carried out at the site level using detailed field survey and monitoring with further transferring the acquired site information to the catchment level.

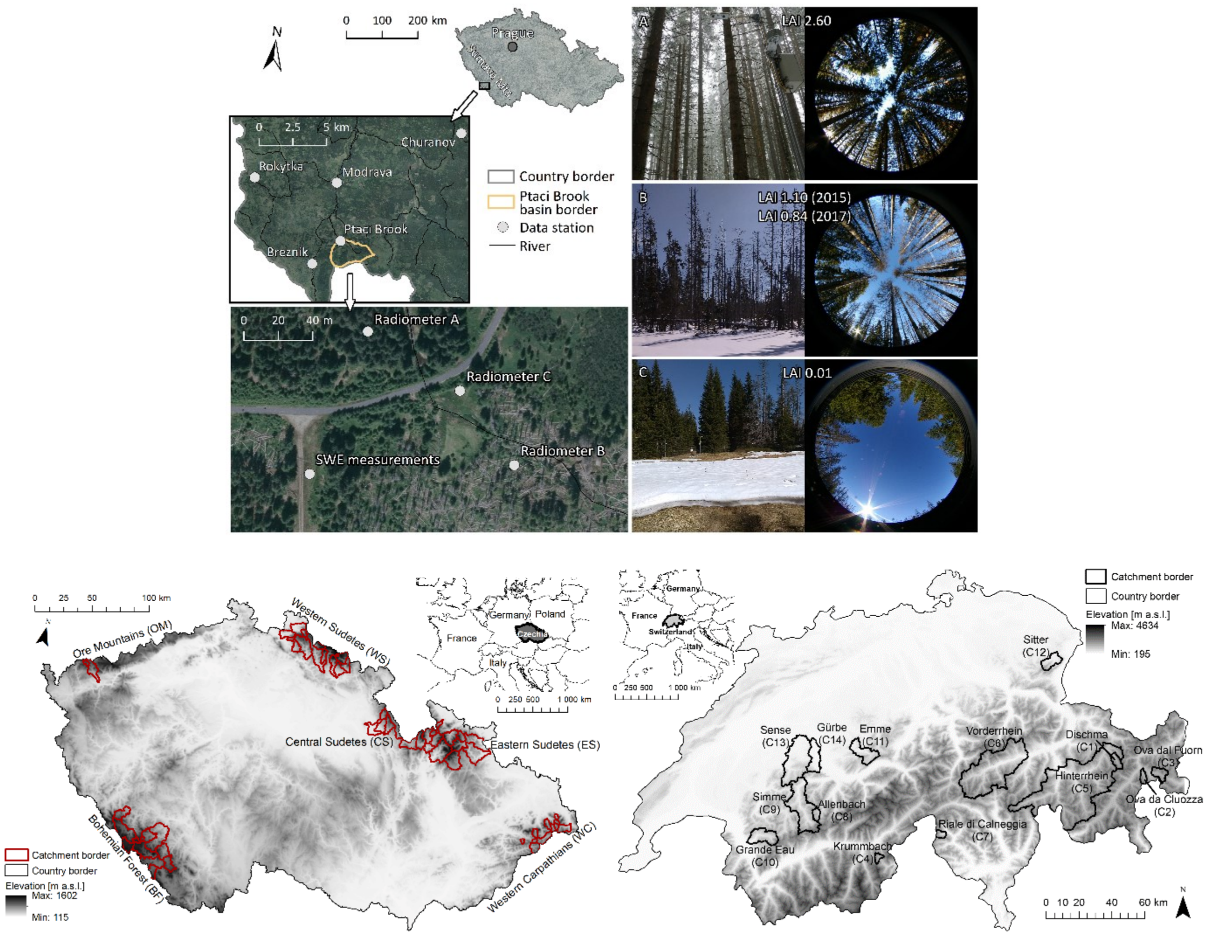

Fig. 2. Working at different spatial scales: Field research at experimental sites (Hotovy and Jenicek, 2020) versus working with large samples of diver catchments (Jenicek et al., 2021, 2018b)

2.2 Hydrological models as a tool for quantifying the runoff regime

For the assessment of runoff generation in snow-dominated mountain catchments, both in-situ investigations and modelling approaches are essential. For climate change impact assessment, conceptual, bucket-type models are frequently used, which separates the entire precipitation-runoff process to several, mutually related components. For each component, different equations are used, which require a sort of input data (e.g., precipitation or evapotranspiration) and produces a sort of output simulations (snowmelt, soil moisture, groundwater storage etc.). For the studies presented in this thesis, the snow accumulation and snowmelt components represent the most important component influencing the spatial and temporal distribution of surface water inputs.

The temporal evolution of snowpack and its melting is governed by the budget of individual energy fluxes acting at the atmosphere-snow-soil interfaces and inside the snowpack. The basic approach to modelling snowmelt summarizes all these energy fluxes, namely shortwave and longwave radiations, sensible and latent heats, ground heat, heat from liquid precipitation and heat exchanges inside the snowpack. Based on the availability of input data, a wide range of approximations to these energy balance equations can be used. The advantage of the energy balance approach is its pure physical basis and thus general applicability to different regions and climates. The main disadvantage is that this approach is demanding on data needed for the parameterisation, calibration and validation of such a model.

The above shortcoming of the energy-based approach is overcome by the so-called degree-day methods. These methods calculate snowmelt using an easily measurable variable, such as air temperature, which can be directly related to the energy balance thanks to its strong correlation with snow (and glacier) melt. Therefore, this method is known as the temperature index method or the degree-day method.

The original degree-day method can be modified with a number of other parameters to better capture varying conditions leading to snowmelt. For example, the amount of liquid water stored in the snowpack before melting can be taken into account. More specifically, the model assumes that a certain amount of water melts at the beginning of the melt, which does not cause runoff, but the water is stored in the snowpack. When the snow temperature drops, this liquid water can freeze (so called refreezing). Different structures of the degree-day approach were tested in one study presented in this thesis (**Girons Lopez et al., 2020**). The question was how complex the snow accumulation and snowmelt components should be to sufficiently represent the whole process. The testing of degree of detail of the snow component therefore brings a useful information on model quality.

Some of the studies presented in this thesis assessed the snow accumulation and snowmelt at a local (site) spatial scale using both energy balance and degree-day approaches without direct quantification of runoff (**Hotovy and Jenicek, 2020**; **Jenicek et al., 2018a, 2017**). In contrast, some studies used models simulating the entire runoff process of which the snowmelt component is only a part (e.g., **Girons Lopez et al., 2020; Jenicek et al., 2018b, 2016; Jenicek and Ledvinka, 2020**). In these cases, the conceptual, bucket-type catchment model HBV was used (Hydrologiska Byråns Vattenbalansavdelning; Lindström et al., 1997; Seibert and Vis, 2012).

The HBV simulates the entire runoff process at a catchment scale using four basic routines (Fig. 3); 1) the snow routine, which applies a degree-day method described above, 2) the soil routine, which quantifies actual evaporation and groundwater recharge, 3) the response routine, which calculates the runoff volume distributed over upper and lower groundwater boxes, and 4) the routing routine, which propagates the runoff to the catchment outlet using a triangular weighting function. The main model inputs are daily precipitation, daily air temperature, and monthly potential evapotranspiration. The catchments were also divided into elevation zones (100-200 m) to better simulate the snow accumulation and snowmelt at different elevations.

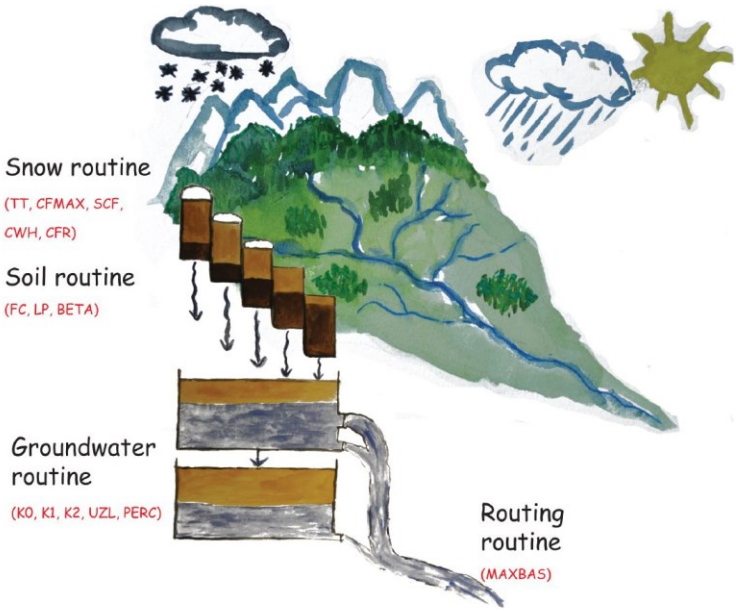

Fig. 3. Schematic structure of the HBV model (Seibert and Vis, 2012)

Conceptual catchment models are usually calibrated against observed runoff. In most of our studies which applied the HBV model, the model was additionally calibrated against observed snow water equivalent (SWE), which improved overall model performance especially in catchments at highest elevations with dominated snowmelt runoff. For the automatic calibration, we used a genetic algorithm which generates different values of parameters for each calibration run (Seibert, 2000). The reason for this is that the optimized set of parameters is found by consecutive evolution of parameter sets using selection and recombination. Therefore, we calibrated model 100 times, resulting in 100 optimized parameter sets and runoff simulations **(Jenicek et al., 2018b**; **Jenicek and Ledvinka, 2020**). In this way, the uncertainty in the model parametrization was considered and the robustness of the model was increased.

One of the important model results is the simulated snowmelt contribution. For this, we used an "effect tracking" algorithm which aims to track the effects of individual water sources through the system, such as rain, snow and glacier contribution to total runoff, rather than tracking of individual water particles (Weiler et al., 2018). This approach assumes complete mixing of the water in the individual water storages. In this way, we were able to assess both the inter-annual variability of runoff components **(Jenicek and Ledvinka, 2020**) and their potential changes due to past and future changes in climate (**Jenicek et al., 2021, 2018b**).

2.3 Climate variability and change impact assessment

For the climate impact assessment, considering a wide range of hydrological responses to a wide range of climate projections is essential. Specifically, climate projections are based on a variety of regional climate models (RCMs) driven by a set of global circulation models (GCMs), resulting in a lot of unique combinations of hydrological projections. GCMs and RCMs differ mainly in the equations describing physical atmospheric processes, as well as in the spatial domain and resolution. RCMs driven by different GCMs are typically run for a variety of greenhouse gasses scenarios (emissions, concentrations or shared socio-economic pathways).

For the results presented in **Jenicek et al. (2018b)**, we used simulations prepared within the ENSEMBLES project (van der Linden and Mitchell, 2009). Downscaled and bias-corrected data of changes in air temperature and precipitation were prepared by the CH2011 Swiss Climate Scenarios Initiative (CH2011, 2011) for the moderate A1B emissions scenario which assumes peak of global CO_2 emissions around 2050 and decline thereafter (Gobiet et al., 2014; IPCC, 2007).

The study by **Jenicek et al. (2021)** is based on results from the European domain of the Coordinated Regional Downscaling Experiment (EURO-CORDEX; https://www.euro-cordex.net/), which is based on the CMIP5 family of GCM models. This experiment assumes different representative concentration pathways (RCPs), whereas three of them were used in study by **Jenicek et al. (2021)**; 1) RCP2.6 which assumes start of CO_2 emissions decline by 2020 and go to zero by 2100 resulting in temperature increase less than 2°C, 2) RCP4.5 which is considered as a "moderate" scenario assuming a peak of emissions around 2040 and a decline thereafter, and 3) RCP8.5 assuming the rice of emissions throughout the 21st century (IPCC, 2014). In total, 17 combinations of GCMs and RCMs were used in the study which were further bias-corrected on observations using the multivariate approach of Piani and Haerter (2012).

For the studies presented in this habitation thesis, analyses of projected changes in snow and its runoff response were done for three future periods from the present to the end of the 21st century (near future, middle future and far future) relative to the defined reference period (typically 1980-2010). Changes in the hydrological behaviour of catchments were often shown for several snow, climate, and runoff signatures, such as annual maximum SWE, snow cover duration, snowfall fraction, mean annual or seasonal air temperature and precipitation, groundwater recharge, snowmelt contribution to runoff, baseflow, minimum streamflow and deficit volumes. Using the above signatures, the potential influence of snow on catchment runoff, including runoff extremes was analysed. Trends in the data series were determined using the Mann-Kendall test together with Theil-Sen's slope estimator to quantify the slope of the monotonic trend. In this way, we were able to quantify the sensitivity of different catchments, for example how sensitive summer low flows are to interannual variation in snow storage, or how this sensitivity changes with the overall decrease in snow storages and earlier snowmelt onset. This climate elasticity is a useful indicator of the changing streamflow sensitivity to changes in climate variables (Andréassian et al., 2016).

3 Results

3.1 From snow to catchment runoff under climate variability

3.1.1 Impact of climate and snow variability on groundwater recharge and snowmelt runoff

Mountain snowpack significantly influences the spatial and temporal distribution of runoff since solid precipitation is temporarily stored in the catchment in the form of snowpack and this water contributes to runoff with a significant delay. Moreover, snowpack from different elevations contributes to runoff at different times due to changes in snowline elevation during snowmelt events (**Parajka et al., 2019**). All these aspects mean that mountainous areas contribute to streamflow even in lower parts of the basins partly also during low precipitation periods. However, the whole process of snowmelt runoff generation is relatively complex and influenced by many variables and feedbacks. Snowmelt occurred during higher air temperature results in a higher proportion of water that evaporates (Barnhart et al., 2016). In contrast, earlier snowmelt means that vegetation is less active and thus uses less water for root uptake. Similarly, earlier snowmelt can also lead to slower snowmelt due to less available solar energy (Musselman et al., 2017a). Both earlier and slower snowmelt may lead to the fact that higher fraction of the snowmelt water produces groundwater recharge and fill the groundwater storages contributing to more stable streamflow during warm and dry periods (Carroll et al., 2019; Cochand et al., 2019). Additionally, slower snowmelt may also cause lower streamflow since soils are less often on their maximum retention capacity thus larger water fractions recharge to groundwaters which further dictates baseflow during the warmer part of the year.

The above set of drivers and feedbacks affecting the snowmelt ability to generate runoff leads to disproportions between the snowfall fraction and the snowmelt runoff fraction (the proportion of snowmelt contribution to runoff to total annual runoff). For example, in Czech mountainous catchments 26% of annual runoff originates as snowmelt despite the fact that only 20% of precipitation falls as snow (**Jenicek and Ledvinka, 2020**). This difference increases with increasing elevation and thus with increasing snowfall fraction. Similar results were achieved also by (Li et al., 2017) for the western United States confirming the overall importance of snow-dominated catchments in generating runoff (Berghuijs et al., 2014) which can be additionally characterized by higher catchment storage (**Šípek et al., 2021**; Staudinger et al., 2017). The above contrast between the snowfall fraction and snowmelt runoff fractions may be important for the future shift from snowfall to rain, especially in rain-snow transition catchments (Harpold et al., 2017; **Jenicek and Ledvinka, 2020)**.

The role of snow in runoff generation can be assessed using data from recent decades separately for years with above average snow storage (snow-rich years) compared to years with below average snow storage (snow-poor years). For mountainous catchments in Czechia, snow-poor years produced considerably lower snowmelt runoff compared to snow-rich years, especially during April and May **(Jenicek and Ledvinka, 2020**). Groundwater recharge during the cold part of the year was also lower, although it increased for the December to February period due to more frequent snowmelt associated with often warmer winters, but decreased sharply for the

March to May period due to earlier and smaller snowmelt. Additionally, the annual runoff was lower, and the difference between snow-poor and snow-rich years was larger for catchments at higher elevations with overall larger snow storage. The influence of snow-poor and snow-rich years on summer (June-August) baseflow is not evident for catchments with generally less snow and lower baseflow, but is clearer for catchments with more snow or higher baseflow (**Jenicek and Ledvinka, 2020**). The increasing sensitivity of summer baseflow (low flows) to previous winter snow storage with elevation was also shown by **Jenicek et al. (2016**) for Swiss alpine catchments.

3.1.2 Importance of snow for summer low flows

An important question often discussed in the scientific community is to which degree snow affects summer runoff during drought periods. This is because snowmelt effectively contributes to groundwater recharge and thus fills the groundwater storage. Therefore, snowmelt is more effective to generate runoff compared to rainfall (**Jenicek and Ledvinka, 2020**). Several studies have shown that a significant part of the runoff in a given season originates as other season's precipitation (Kirchner and Allen, 2020). This indicates the seasonally varying importance of snow, soil and groundwater storages to contribute to runoff **(Šípek et al., 2021**). Additionally, the importance of catchment storage varies with different topography, geology and soils.

The effect of snow on summer runoff is well described especially for low flows (Dierauer et al., 2018; **Jenicek et al., 2016**; **Jenicek and Ledvinka, 2020**). Larger snow storage and later snowmelt period and melt-out considerable contribute to summer baseflow and thus prolong the period when water from melting snow contributes to streamflow (Hammond et al., 2018). Not surprisingly, the greatest importance of snow in summer low flows is documented for climates with an uneven seasonal distribution of precipitation, such as the western United States (e.g., the Sierra Nevada Mountain range). Most of the precipitation falls in the winter forming the seasonal snowpack in the mountains. This seasonal snowpack contributes to runoff during summer and reduces droughts by increasing low flows (Godsey et al., 2014). The above study found significant correlations not only between summer low flows and the previous winter's snow storage, but also with the snow storage in previous year. This implies long water transit times and the overall importance of mountain snowpack. In climates with high precipitation seasonality, the snowpack also influences river intermittency, e.g., by later cessation of mountain streams for years with later melt-out day of the snowpack (Kiewiet et al., 2022).

The relationship between snow and summer low flows is more complex in most of the parts of Europe where precipitation is more equally distributed during the year. Therefore, liquid precipitation is usually the main driver to control summer low flows (Floriancic et al., 2019). However, the lack of snow storage causes even lower low flows for years when this low snowpack is supported by low summer rainfall (**Jenicek et al., 2016**). The "memory effect" of snow to influence runoff generally decreases from spring to autumn. Towards later day of year, the rainfall contribution to mean streamflow increases and groundwater contribution decreases. However, for low flows, its duration and deficit volume, the relative contribution of groundwater storage increases from summer to autumn, suggesting the importance of groundwater storage (influenced by previous winter snowpack) to control runoff during low flow periods (**Šípek et al., 2021**). Additionally, the total catchment storage increases with elevation, mainly due to a strong correlation of elevation and snow storage (**Šípek et al., 2021**; Staudinger et al., 2017). Besides climate variables, low flows and the time needed to catchment recovery after groundwater drought are driven by the hydrogeological conditions (Hellwig et al., 2021).

The varying relative contributions of snowmelt and rainfall to summer runoff can be identified when studying years with below-average and above-average snowpack. For example, lower summer baseflow is associated not only with years with lower summer rainfall, but also with below-average winter snowpack, which causes lower and often earlier snowmelt **(Jenicek and Ledvinka, 2020**) (Fig. 4). Moreover, years with below-average snowpack also produced lower annual runoff, suggesting future lower runoff if more precipitation falls as rain rather than snow. Additionally, above-average snow storage often means a later snowmelt season and melt-out postponing the period with low flows (**Jenicek et al., 2016**). In high alpine catchments, annual maximum snowpack may be used as a useful predictor of summer low flows not only for highly seasonal climates (Godsey et al., 2014), but also for high alpine catchments in Europe (**Jenicek et al., 2016**; Jörg-Hess et al., 2014), although in the latter case, the snow cannot be used as the only predictor. Based on our results presented in **Jenicek et al. (2016)**, **Jenicek and Ledvinka (2020)** and **Šípek et al. (2021)**, snow storage considerable affects minimum streamflow from May to September, with decreasing importance in high elevation catchments in the Swiss Alps. This also implies a high vulnerability of these catchments to future snow loss, which may contribute to more extreme drought events.

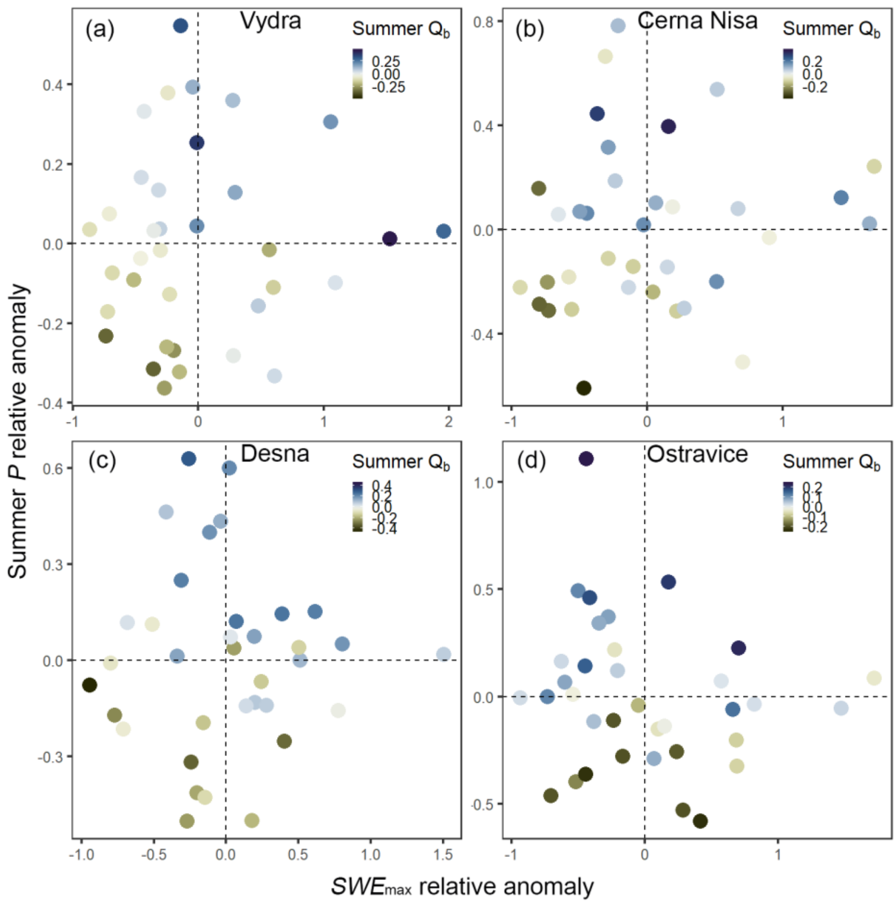

Fig. 4. Dependence of summer baseflow (Q_b) relative anomalies on annual maximum SWE (SWE_{max}) and summer (JJA) precipitation relative anomalies at four selected catchments. (a) Vydra (Bohemian Forest), (b) Cerna Nisa (Western Sudetes), (c) Desna (Eastern Sudetes), (d) Ostravice (Western Carpathians). The lowest summer baseflow seems to be associated with both the lowest summer precipitation and SWE_{max} (dark-brown points are mostly located in the bottom-left quadrants) suggesting that summer low flows are partly influenced by previous winter snowpack (Jenicek and Ledvinka, 2020).

3.1.3 Runoff during rain-on-snow

Changes in snow cover influence not only the runoff seasonality and low flows as presented above, but also high flows, including extreme runoff from rain-on-snow events. Rain-on-snow (ROS) events represent the runoff response to weather situations when rain falls on the snowpack causing its physical properties changes, followed by snowmelt and runoff. In fact, ROS events represent the only natural mechanism of higher runoff volume than precipitation causing the runoff, because of additional snowmelt. Therefore, the event runoff coefficient, i.e. the ratio of runoff volume to event precipitation, can be higher than one. In mountainous areas with humid climates, most of the runoff peaks during the snow-covered season are caused by rain-on-snow (Il Jeong and Sushama, 2018), and the seasonal runoff fraction from rain-on-snow may represent an important part of total seasonal runoff. For Czech mountain catchments, this fraction has been quantified as 3-32% in individual months (with highest contribution in January), and 10% of rain-on-snow events had flood-generation potential over the last five decades, mostly associated with wet and warm winters (**Hotovy et al., 2023**). In contrast, most of the weather situations leading to rain-on-snow generated no or a very little runoff suggesting a large variability in runoff responses that is largely controlled by snowpack properties **(Hotovy**

et al., 2023; Juras et al., 2021; Trubilowicz and Moore, 2017). Increasing air temperature causes more winter precipitation to fall as rain rather than snow, changing the frequency of rain-on-snow situations. Therefore, an important question is whether the frequency and extremity of ROS events have changed in recent decades and how they will change in the future due to climate changes. This question is particularly relevant for rain-snow transition zone, such as central Europe, i.e. for regions, where the winter air temperature is close to zero, which changes the precipitation phase already with small warming.

The physical mechanism of snowmelt during rain-on-snow is driven by the snowpack energy balance. Turbulent heat fluxes (sensible heat and latent heat) play the dominant role, while radiative forcing is rather small (Würzer et al., 2016a). This is because rain-on-snow mostly occurs during overcast days with rain, and the turbulent heat exchange above the snow surface is often supported by wind. Additional heat brings the rain itself (rain temperature is higher than snow temperature). An important heat also represents the latent heat released when rain freezes in below-zero temperature snowpack. The heat from warmer rain together with the latent heat release in the frozen snowpack is usually not very important on longer (seasonal) time scales. However, the relative contribution of the above heat exchanges to the total heat exchange strongly increases in days when rain-on-snow occurs **(Hotovy and Jenicek, 2020**) and therefore represents an important heat source for snowmelt with flood generation potential (Freudiger et al., 2014; **Hotovy et al., 2023**; **Juras et al., 2021**).

Recent studies have shown that rain-on-snow events may increase in certain regions because the decrease in the snowfall fraction and the resulting rainfall increase **(Blahušiaková et al., 2020; Hotovy et al., 2023**; Musselman et al., 2018). However, the changes are strongly related to elevation as both the precipitation phase and snow storage depend on air temperature and thus elevation (**Hotovy et al., 2023**) (Fig. 5). It leads not only to changes in precipitation phase, but it also influences the snowpack occurrence at different elevations and its changes during snowmelt events resulting in changes in regional snowline elevation (**Parajka et al., 2019**). In Czech mountain catchments (and in central Europe in general), there is a clear trend of increasing rain-on-snow events at middle and high elevations during winter and early March over the last decades due to the shift from snowfall to rainfall (Freudiger et al., 2014; **Hotovy et al., 2023**). In contrast, rain-on-snow events have decreased in late spring at higher elevations due to an overall decrease in snowpack and earlier melt-out. However, the changes in Czechia are not regionally consistent at the catchment level showing the decrease in rain-on-snow events mostly in the Bohemian Forest and Western Sudetes, while changes in other mountain ranges are mostly insignificant, although significant at certain elevations (**Hotovy et al., 2023**).

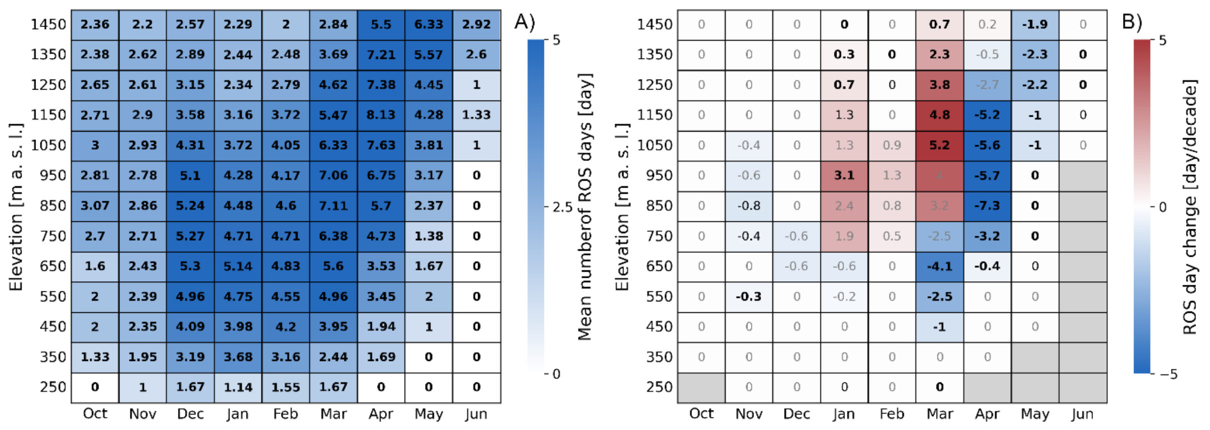

Fig. 5. Mean number of ROS days (A), decadal trends in ROS days (B) from October to June at different elevations for the period 1965-2019. Significant Mann-Kendall trends in panel (B) are highlighted in black bold (p < 0.05) and in black (p < 0.1), decreasing trends in shades of blue and increasing trends in shades of red. Grey indicates no trends due to no ROS days. The monthly and elevation dependent decreases in ROS days were caused by the shortening of the period with existing snow cover on the ground as a response to increasing air temperature (Hotovy et al., 2023).

As air temperature continues to increase, the spatial and temporal changes in the occurrence of rain-on-snow events also affect the runoff response, including high flows. Nevertheless, several studies have highlighted the role of the snowpack physical properties which substantially influence the runoff response dynamics, because the snowpack can store a considerable amount of water, causing a delay in the resulting runoff response (Juras et al., 2017; Wever et al., 2014). This is particularly the case for large snowpacks with large storage potential, reducing the runoff even during high-rainfall events (**Juras et al., 2021**). However, this storage potential may decrease in the future due to the predicted decrease in snow storages (see e.g. **Jenicek et al., 2021, 2018**). As shown by **Juras et al. (2021)**, the runoff response is typically higher for shallow snowpacks compared to high snowpacks assuming the same amount of rain. Additionally, the water flow through the snowpack is influenced by snowpack ripeness controlling the nature of the water movement, such as matrix or preferential (vertical, lateral) flow (Juras et al., 2017; Würzer et al., 2017).

3.2 Past and future changes in snow and impacts on seasonal runoff and low flows

3.2.1 Past and future changes in snow storages

Mountain snowpack is highly sensitive to changes in air temperature which controls both the phase of precipitation and the timing of snowmelt. Several studies have documented that snowfall fraction decreased in many areas of the world over the last decades (**Jenicek et al., 2021, 2018b**; Knowles et al., 2006; **Nedelcev and Jenicek, 2021**). This decrease has led to a decrease in snow storage and snow cover duration in many worlds regions in humid climates, although the former is not always significant and depends on regions and climate (**Blahušiaková et al., 2020**; Cooper et al., 2016; Fyfe et al., 2017; Marty et al., 2017b; **Nedelcev and Jenicek, 2021**).

In Czechia, the largest decreases in both annual and maximum SWE were found at elevations around 800 m a.s.l. for the period 1965-2019. However, changes in maximum and mean SWE were not significant in most of the mountain ranges despite the fact that air temperature in the period November-April increased significantly by 0.1-0.3°C per decade causing the decrease in snowfall fraction (**Nedelcev and Jenicek, 2021**). The often missing trends in SWE can be explained by the mutual interaction of other climate variables (e.g. precipitation) that compensate the effect of increasing air temperature (Marty et al., 2017b; Mote et al., 2018). In general, some trends in snow storage occurred in the western parts of Czechia, while no trends were detected in the eastern part of Czechia suggesting the different climatology of the two regions (including the continentality effect). In contrast to weak trends in SWE, significant strong trends in snow cover duration were documented, which decrease on average by 5.5 days per decade (**Nedelcev and Jenicek, 2021**). Additionally, the above results showed that snow at high elevations is more sensitive compared to lower elevations. Important implications may result from the fact, that the main snowmelt season was shifted from May to April at high elevations and from April to March at low elevations indicating the potential changes in runoff seasonality (**Blahušiaková et al., 2020**). Interestingly, the snow cover season was shortened due to earlier melt-out, while the snow onset did not changed significantly (Klein et al., 2016; **Nedelcev and Jenicek, 2021**).

Changes in snow storage are primarily controlled by climate variables, mainly air temperature and precipitation. Therefore, the response of seasonal snow to inter-annual changes in climate variables is often not straightforward. For example, the effect of increasing air temperatures causing the decrease in snow storage may be partially compensated by an increase in precipitation (**Jenicek et al., 2021**). Another effect is represented by the increase in the number of extreme snowfall events (Lute et al., 2015; Marshall et al., 2020). As a result, snow responds differently to climate variables across elevations which makes it possible to identify threshold elevations, below which the snow characteristics are mainly controlled by changes in air temperature, and above which precipitation is the dominant driver of snow storage. In mountainous catchments in Czechia, 900 m a.s.l. has been identified as the elevation with dominant temperature influence on snow, while above 1200 m a.s.l., snow is controlled dominantly by precipitation **(Nedelcev and Jenicek, 2021**). Nevertheless, the changing role of different climate variables to influence several snow-related signatures, such as annual maximum SWE, snow cover duration or the day of the year of melt-out are changing greatly with elevation as documented both by our studies **(Blahušiaková et al., 2020; Nedelcev and Jenicek, 2021**) and studies from other world regions with similar climate (Marty et al., 2017b; Morán-Tejeda et al., 2013; Sospedra-Alfonso et al., 2015).

While only some significant changes in central European snowpack has been documented over the last five decades, substantial changes in all snow-related variables are expected for the future based on the current family of global circulation and regional climate models (Jenicek et al., 2021, 2018b; Marty et al., 2017a). For mountain ranges in central Europe, the decrease in annual maximum SWE by 30-75% is expected by the end of the 21st century. However, the decrease differs with elevation. Largest decrease is expected for elevations below 2200 m a.s.l.

for the Swiss Alps (**Jenicek et al., 2018b**; Marty et al., 2017a) (Fig. 6) and approximately below 1200 m a.s.l. for Czechia (**Jenicek et al., 2021**) while snowmelt losses are projected to be relatively smaller above these elevations. A similar range of snow losses is also projected for other regions with humid climate, such as the United States (Fyfe et al., 2017; Musselman et al., 2017b).

Dramatic future changes are also expected for other snow-related variables, such as the snow cover duration, which will be shorter, especially due to an earlier onset of the melt season and thus melt-out (the day when snow melts in a catchment). In general, the melt-out day is projected to occur by 30-60 days earlier by the end of the century compared to current conditions. Similar to the maximum SWE, this characteristic depends on elevation, with major changes at elevations 2000-2500 m a.s.l. in the Swiss Alps (**Jenicek et al., 2018b**) and at elevations 800-1300 m a.s.l. in Czechia (**Jenicek et al., 2021**).

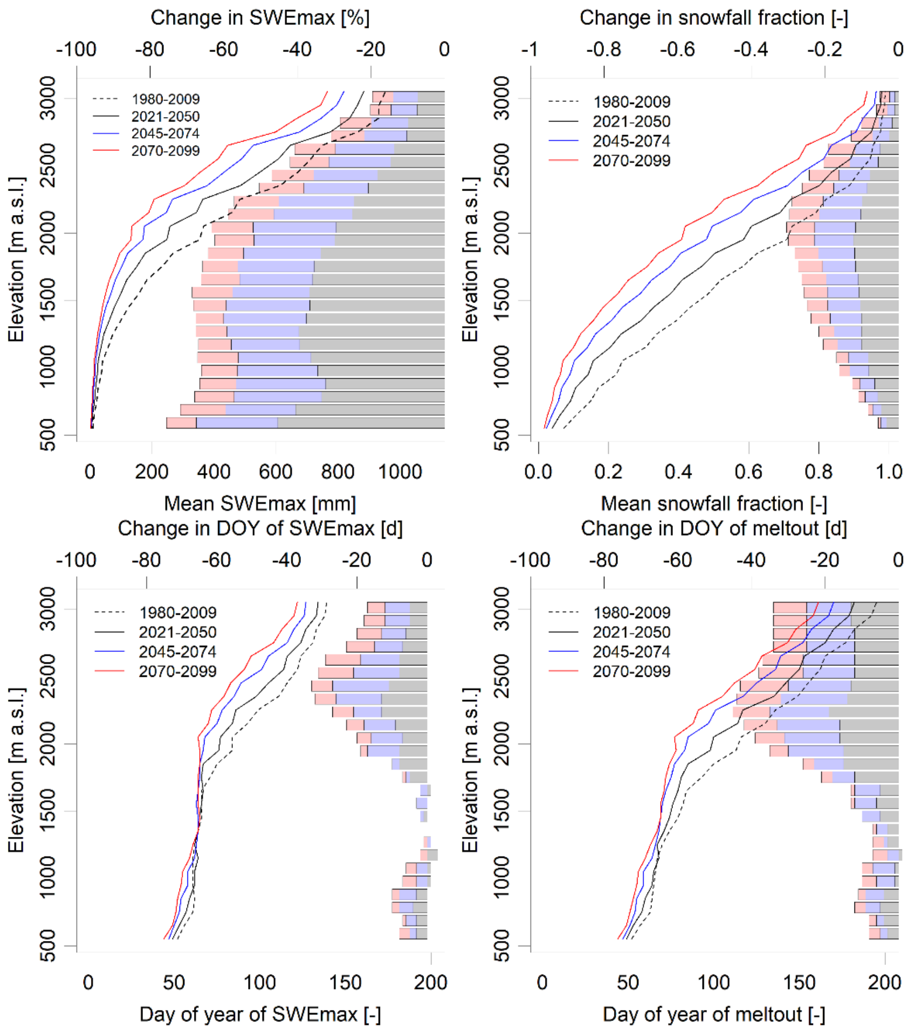

Fig. 6. Mean annual maximum SWE (SWE_{max}) (top left), mean snowfall fraction (top right), the day of the year (DOY) of SWE_{max} (bottom left) and DOY of melt-out (bottom right) at different elevations for the reference period and three future periods for 14 alpine catchments in Switzerland. Lines represent real values (bottom x-axis), horizontal bars represent relative differences from the reference period (top x-axis). The largest absolute decrease in SWE_{max} is predicted for elevations from 2000 to 2700 m a.s.l, while the largest relative decrease is predicted for elevations below 2200 m a.s.l. (up to 80% for the period 2070–2099). Additionally, the snow will melt by 40-50 days earlier at elevations around 2000 m a.s.l. by the end of the 21st century (Jenicek et al., 2018b).

3.2.2 Impact of snow changes on seasonal runoff and low flows

Seasonal snow is not only important for spring runoff, but it also affects runoff during the rest of the year, including summer low flows and drought periods (Van Loon, 2015). However, the relative importance of snow in influencing summer low flows varies across different climates and elevations, as it is usually not a dominant factor, at least in humid climates. The main effect of snow changes on runoff represents changes in runoff seasonality. Based on data from previous decades, a shift in the snowmelt season was detected in many world's regions since snow starts to melt earlier and thus contributes to runoff earlier in the water year (Birsan et al., 2005; **Blahušiaková et al., 2020**). The above effect has also been shown by studies assessing the inter-annual variability of runoff during snow-poor and snow-rich winters (Dirauer et al., 2018; **Jenicek et al., 2016**). Also well documented is the increase in winter runoff across central Europe and the United States due to the increase in winter air temperature, and thus the decreasing snowfall fraction which causes the shift from snowfall to rainfall. As a result, precipitation contributes to runoff with a shorter delay, which together with winter snowmelt leads to higher winter streamflow (Birsan et al., 2005; **Blahušiaková et al., 2020**; Muelchi et al., 2021). However, the effect of changes in winter and spring runoff is regionally different and is also highly related to catchment elevation.

As described in the previous chapter, previous winter snow storage is correlated with spring and summer low flows, suggesting a significant memory effect of the snowpack to influence baseflow and low flows much later after snow melt-out **(Jenicek et al., 2016; Jenicek and Ledvinka, 2020**). Therefore, due to the shift of the snowmelt season in the last decades **(Nedelcev and Jenicek, 2021**), the trends of decreasing low flows for May to August period (non-alpine catchments in central Europe) and for June to August period (alpine catchments) were detected (**Blahušiaková et al., 2020**). The above study showed that summer hydrological droughts in mountainous catchments of central Europe are controlled not only by summer precipitation and evaporation, but also by previous winter snowpack. This may indicate an intensification of summer droughts in mountainous regions in the future.

Both the overall decrease and shift in spring snowmelt runoff (decrease in late spring, increase in early spring) and the increase in winter runoff are expected to continue and intensify in the future (**Jenicek et al., 2021**; Muelchi et al., 2021) (Fig. 7), although the reduced snow will cause a lower contribution of snowmelt runoff to total runoff. Therefore, the effect of snow will decrease especially at lower elevations which will result in a shift of catchment runoff regimes from nival to nival-pluvial and fully pluvial. Earlier snowmelt onset leading to earlier melt-out in the future, will result in a shorter period during which snowmelt contributes to summer baseflow, which is further important for summer streamflow (**Jenicek et al., 2018b**).

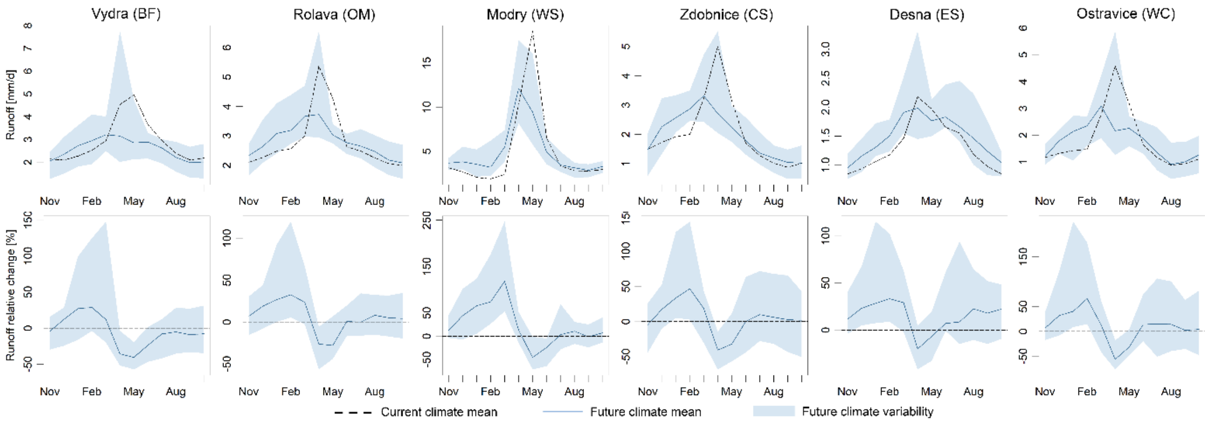

Fig. 7. Monthly runoff in six selected catchments for the reference period and for the future period 2070-2099 (top panels), and relative changes in monthly runoff for the future period 2070-2099 compared to the reference period (bottom panels). Black dashed line indicates reference period, blue line represents future period 2070-2099, light blue area indicates the range of individual future climate chains. Note the different scales used for the y-axis. The period of highest streamflow will occur on average a month earlier due to earlier snowmelt, and the seasonal runoff volume will decrease due to less snowmelt water. Additionally, an increase in winter runoff is projected (Jenicek et al., 2021).

3.2.3 Climate projections and modelling uncertainty

As described above in Section 2.3, any climate impact assessment requires considering an ensemble of climate projections. The reason is not only in a variety of climate models themselves, but also due to potential variations in hydrological responses. Uncertainties in climate impact modelling arise mainly from emission scenarios, climate and hydrological model structures, and the natural variability (Addor et al., 2014). The most important is usually uncertainty in emissions scenarios and climate models, while uncertainty in hydrological model structure is smaller, although it increases for catchments with significant influence of snow on runoff generation (Addor et al., 2014).

Climate projections are typically based on a wide range of regional climate models (RCMs) which are driven by a wide range of global circulation models (GCMs). Individual GCMs and RCMs differ in the way they describe physical atmospheric processes. Besides, they are often run for different spatial domain using different spatial resolution and for different emissions scenarios (IPCC, 2021). This results in a variety of unique hydrological projections. Therefore, a range of climate projections were used for our future climate impact studies depending on their availability in the time of study processing. The study by **Jenicek et al. (2018b)** used simulations prepared within the ENSEMBLES project (van der Linden and Mitchell, 2009) using daily bias-corrected data prepared by the CH2011 Swiss Climate Scenarios Initiative (CH2011, 2011) for moderate A1B emissions (Gobiet et al., 2014; IPCC, 2007). The study by **Jenicek et al. (2021)** used bias-corrected data based on the CMIP5 family of GCM models prepared within EURO-CORDEX experiment (see Section 2.3 for details). The latter study used a total of 17 combinations of GCMs and RCMs, which enables to make a variety in hydrological projections.

Due to the complexity of the precipitation-runoff processes, the responses of hydrological variables such as snow storage, seasonal runoff or baseflow to changing climate conditions may be much larger than the changes in climate variables resulting from climate projections.

Therefore, the hydrological response of catchments may not be straightforward and thus may be surprising and unexpected. This is especially relevant for mountain snow-dominated catchments, where a relatively small change in air temperature may result in a large change in snow storage and its dynamics, since air temperature controls the phase of precipitation and the snowmelt timing (**Jenicek et al., 2021**). While the above may be less pronounced in high-elevation or high-latitude catchments, the changes in the rain-snow transition zone where air temperature fluctuates near freezing point, are usually substantial. However, current climate projections for central Europe are still uncertain in terms of predicting of the precipitation amount and its seasonality. Some of climate projections suggests precipitation increase, while others suggest a decrease. Therefore, the increase in air temperature, causing a decrease in snowfall could by partly compensated by the winter precipitation increase predicted by some of the climate models (Fig. 8). For example, individual model chains projected decrease in maximum snow storage for Czechia by 25–50% for RCP4.5 and by 50–80% for RCP8.5 (**Jenicek et al., 2021**).

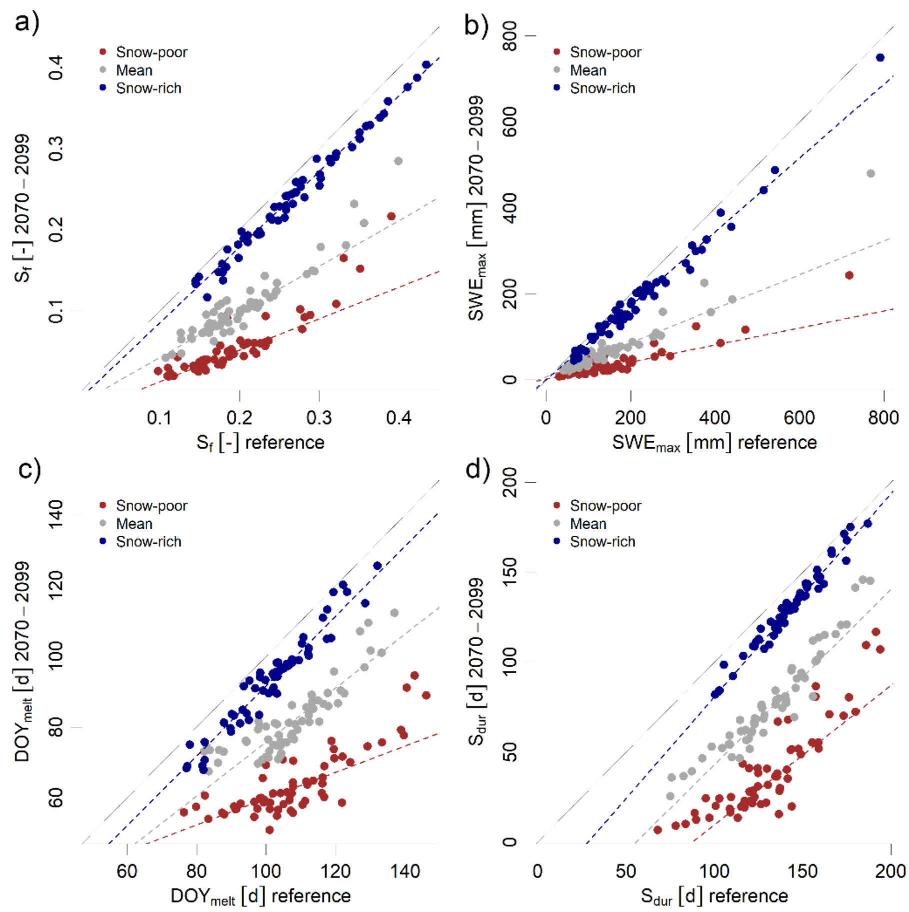

Fig. 8. (a) Changes in mean snowfall fraction (S_f), (b) mean annual SWE maximum (SWE_{max}), (c) mean DOY of melt-out (DOY_{melt}) and (4) mean snow cover duration (S_{dur}) in 59 mountain catchments in Czechia for three selected climate chains leading to 1) snow-poor (brown points) and 2) snow-rich (blue points) conditions and for the 3) mean conditions (grey points) for the future period 2070-2099 compared to the reference period. Dashed lines represent Theil-Sen regressions. The results showed that despite the large future decrease in all variables, the differences between the two border conditions are relatively large due to uncertainty in climate projections (Jenicek et al., 2021).

An important uncertainty in both past and future hydrological projections represents hydrological model structure and its calibration and validation using observed data. For mountain catchments, correct simulation of snow storage is essential. Physically, snow processes are controlled by energy balance, while the typical approach to simulate snow component in conceptual, bucket-type models is represented by a relatively simple degree-day approach (Seibert and Vis, 2012). The question is how complex the snow components need to be to correctly represent snow accumulation and snowmelt. The testing the level of detail of the snow component therefore provides a useful insight into the model quality, which is particularly important for snow-dominated or glaciated catchments. However, recent studies have shown that increasing level of detail does not necessarily mean the improvement of the model performance (**Girons Lopez et al., 2020**). Although there may be a few improvements in model structure, such as non-linear snowmelt functions or seasonally different melt factors, leading to overall better results, the differences are rather minor (**Girons Lopez et al., 2020**).

In addition to snow storage modelling, a general issue in hydrological modelling is whether real natural processes can be described by using model parameters. For example, conceptual models frequently apply a factor correcting snowfall undercatch due to wind when using traditional measurement of precipitation with rain gauge (Freudiger et al., 2017; Seibert and Vis, 2012). However, the factor can generally compensate for processes not included in the model structure, such as snow interception, or sublimation (**Jenicek and Ledvinka, 2020**). Similarly, the threshold temperature is often used both to differentiate between snow and rain and for the snowmelt onset. All of the above parameter issues may have an important impact on runoff components simulations and should therefore be considered for climate impact assessment.

3.3 Forest effects on snow distribution, snowmelt, and runoff

3.3.1 Forest effects on snow distribution

Over the large areas, the main factors affecting snow accumulation and distribution are air temperature and precipitation amount. Air temperature mainly determines the precipitation phase, i.e., whether it is rainfall, snowfall, or sleet (Harpold et al., 2017). At temperatures around 0 °C, the humidity is also important for the precipitation phase. However, at smaller spatial scales, vegetation and topography significantly influence the snowpack distribution and melting (**Jenicek et al., 2018a**; **Kucerova and Jenicek, 2014**; López-Moreno et al., 2013). Forest influences snowpack accumulation mainly through its canopy which influences local meteorological conditions. Forest also substantially alters the snowpack energy balance, which affects the snowpack evolution and snowmelt (Welch et al., 2015). Therefore, understanding the forest effects on snowpack distribution and snowmelt is essential for investigating and modelling of catchment runoff.

The influence of forests on snow accumulation is mainly through snow interception, i.e., the temporal storage of the snowfall on the tree canopy (Förster et al., 2018; Helbig et al., 2019; Moeser et al., 2015). Interception is generally higher for snowfall than for rainfall. For example, a healthy spruce forest can intercept up to 70% of the cumulative seasonal snowfall (Helbig et al., 2020; Míka, 2021). This intercepted precipitation is usually sublimated into the atmosphere and thus does not participate in subsequent melting and runoff. Some of the intercepted precipitation reaches the ground surface from the tree branches due to wind and melting. As a result of interception processes together with modified heat transfer under the forest canopy, the snow water equivalent in the dense coniferous forest can be by 30-50% lower compared to adjacent open area (**Jenicek et al., 2018a**; Stähli and Gustafsson, 2006). Therefore, coniferous forests significantly affect the water balance by reducing the fraction of precipitation reaching the earth surface resulting in reducing snowmelt runoff.

The snowpack evolution depends mainly on the energy (heat) balance at the atmosphere-snow and snow-earth surface interfaces. The main energy flux influenced by vegetation is shortwave (solar) radiation. For example, a dense coniferous forest reduces up to 95% of the total solar radiation (**Hotovy and Jenicek, 2020**; **Jenicek et al., 2017**). However, the amount of solar radiation reaching the snow cover in a forest varies considerably, and depends, for example, on the species composition of the forest; coniferous forest reduces solar radiation more than deciduous forest, which is leafless in winter. Another important factor is the forest structure, i.e., the density of the tree canopy (**Lendzioch et al., 2019**; López-Moreno and Stähli, 2008; Musselman et al., 2015).

Forest vegetation also significantly influences the amount of longwave radiation. For example, during sunny days, tree trunks warm up and accumulate heat, which is then emitted and causes the snowpack warming (Musselman and Pomeroy, 2017). Longwave radiation thus contributes to a faster melting in the forest than in the adjacent open area. On average, longwave radiation in the open area contributes negatively to the snowpack energy balance causing its cooling (longwave radiation of the snowpack dominates over the longwave heat input from the atmosphere), whereas the balance of longwave radiation in the forest is positive, causing its warming or melting (**Hotovy and Jenicek, 2020**). In general, however, the heat gain from longwave radiation in the forest is lower than the heat loss due to lower solar radiation. Therefore, the snowpack melts slower in the forest than in the adjacent open area.

As mentioned above, the snowpack radiation balance under the forest canopy depends on its structure. This can be defined, for example, in terms of species composition or in terms of categories, such as coniferous, mixed and deciduous forest. A common method is to describe it using vegetation indicators such as the Leaf Area Index, Canopy Closure or Potential Irradiation all of which are directly correlated with snow depth, SWE, and snowmelt at the site. For example, LAI is usually a better predictor of SWE during the accumulation period, while potential irradiance dominates during snowmelt period (**Jenicek et al., 2018a**) (Fig. 9). Together with topographic characteristics, it is possible to establish a suitable statistical model of SWE distribution in the whole catchment (**Kucerova and Jenicek, 2014**). The above indicators can be determined, for example, by analysing hemispherical images of vegetation, measuring radiation attenuation under the forest canopy, UAV-based imaginary or using laser scanning (either terrestrial or airborne placed on UAV or aircraft). In particular, the UAV-based methods are now widely used (Bühler et al., 2016; Koutantou et al., 2022), due to their high spatial accuracy, although their use is limited to relatively small scales (site level). Promising results were also achieved by the combination of UAV-based forest structure and snow-depth mapping tested by (**Lendzioch et al., 2019**) which showed a good accuracy in both snow depth and forest structure measurements and thus demonstrating an interesting added value for studies assessing the snowpack distribution and snowmelt at small scales.

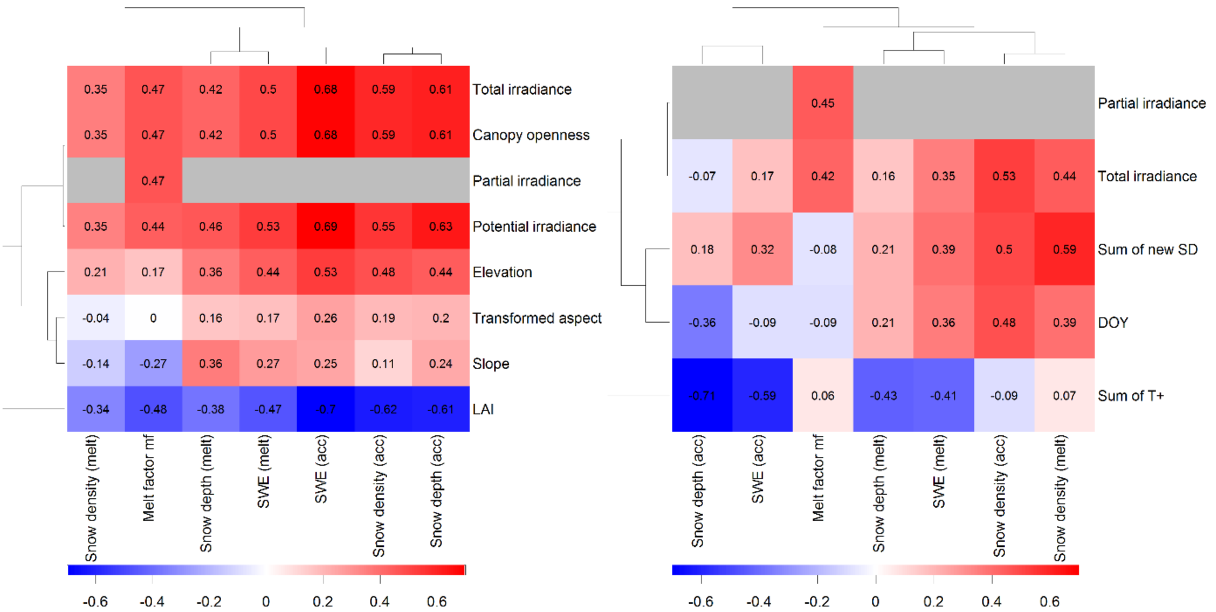

Fig. 9. Spearman correlation coefficients for selected predictors (rows) and response variables (columns) varying for 1) different measurement sites (left) and 2) during the winter season (right). Hierarchical cluster analysis and Euclidean distance were used to show the similarity of individual predictors and response variables. Grey colour used for NA values. For example high correlations of melt factors with variables related to canopy structure was detected. Vegetation structure is also strongly correlated with snow depth and SWE during both accumulation and melt periods (Jenicek et al., 2018a).

3.3.2 Forest effects on snowmelt runoff

Local conditions such as vegetation cover and topography have a significant impact on snowmelt runoff from catchments, fundamentally influencing both the amount and the time at which snowmelt water leaves the snowpack and enters the soil and stream. Since the snow melts slower in forests than in open areas, the snowmelt runoff is distributed over a longer period, increasing the efficiency of water infiltration and groundwater recharge.

The differences in energy exchange between forested and open environments described above are one of the causes of differences in snowmelt onset, snowmelt rates and melt-out, which additionally lead to differences in snow cover duration (Cristea et al., 2014; **Hotovy and Jenicek, 2020; Jenicek et al., 2018a**; Pomeroy et al., 2012; Winkler et al., 2015). Both shortwave and longwave radiation may represent up to 80% of the total energy available for snowmelt despite the fact that this contribution varies both spatially (site characteristics) and temporally (from sub-daily to seasonal scales). Specific meteorological conditions are also important, since radiative forcing is mostly important during clear sky conditions, while turbulent fluxes (sensible and latent heats) dominate, for example, during snowmelt caused by rain-on-snow events (Würzer et al., 2016b). Nevertheless, radiative heat transfers dominate on seasonal time scales in most of the climates, contributing mainly to snowmelt runoff. This also causes more than doubled snowmelt rates in open areas compared to forests, as investigated in the Vydra catchment, an experimental research catchment of the Department of Physical Geography and Geoecology of the Charles University (**Hotovy and Jenicek, 2020**; **Jenicek et al., 2017**).

Although the forest influenced snowpack energy balance is a dominant control of snowmelt, the forest effect on runoff generation during snowmelt is more complex and influenced by other factors, such as meteorological conditions during snowmelt and snowpack properties (Jennings et al., 2018). Therefore, higher snow storage at open areas may not necessarily result in a corresponding increase in runoff as documented, for example by Pomeroy et al. (2012) in Canada and Schelker et al. (2013) in Sweden. Both studies showed that year-to-year variations in snowmelt in forests and open areas depend on year-to-year variations in meteorological conditions.

Ongoing and future climate changes are causing dramatic changes in snow storage, timing of snowmelt and consequent winter and spring runoff in mountainous catchments (Fyfe et al., 2017; **Jenicek et al., 2018b**; Marty et al., 2017a). These changes may further underline runoff changes caused by changes in land cover. Therefore, understanding the forest effects on snowmelt runoff generation is important for accurate prediction of runoff in forested catchments with dominant snowmelt runoff regime. Several models use simplified degree-day approaches where the representation of snowmelt relies on air temperature and melt factor which only marginally reflect the site-to-site differences in snowmelt in forested areas. This puts a pressure on the hydrological community to improve models of runoff from melting snow.

3.3.3 Impact of forest disturbances on snow accumulation and melt

Forest disturbances are in the focus of current hydrological research since they represent an important impact on catchment runoff variability and change, especially at smaller scales. Although forests affect all components of the hydrological cycle, they have important implications for regions with seasonal or perennial snow cover. Specifically, forest change leads to significant changes in the snowpack energy balance, such as changes in shortwave and longwave radiation. Moreover, forest change also influences the amount of intercept snowfall, affecting the total water balance of catchments.

Forest disturbances, such as forest decay due to windstorms or caused by insect outbreaks (e.g., bark beetle; *Ips typographus* or mountain pine beetle; *Dendroctonus ponderosae*), have a major impact on the canopy structure causing the decrease in snow interception (Bartík et al., 2019; Boon, 2012). Depending on the forest type, interception can represent up to 70% of the total winter precipitation (Förster et al., 2018; Helbig et al., 2019; Míka, 2021). This means that a significant part of this amount, which sublimates to the atmosphere in a healthy coniferous forest, becomes ground snowpack after forest decay. This change in water partitioning leads to an increase in seasonal runoff after forest decay (Schelker et al., 2013; Winkler et al., 2015). However, the effectiveness of interception (the fraction of precipitation captured by the canopy) is influenced by the specific climatic conditions during the winter season. For example, the difference in interception effectivity between healthy and disturbed forests may be less important in snow-rich years compared to snow-poor years, because large snowfall events often exceed the interception capacity of individual tree species (Boon, 2012).

Forest disturbances lead to considerable changes in the snowpack energy balance and consequent snowmelt (Bartík et al., 2019; **Hotovy and Jenicek, 2020; Jenicek et al., 2017**).

One of the most important changes is a successive increase in solar radiation starting from the initial stage of a tree decay after bark beetle attack (red stage) until the tree fall. The increased solar radiation accelerates snowmelt rates (**Hotovy and Jenicek, 2020**; Pomeroy et al., 2012) (Fig. 10). Another effect is the change in longwave radiation flux which turns over from heat gain in the forest to heat loss in deforested areas (Klos and Link, 2018; Webster et al., 2016). A common explanation for this turnover is that the heat emitted by trees in the forest to the snowpack is typically higher than the snowpack cooling during clear sky conditions. This may be particularly important during clear sky nights when the outgoing longwave radiation from the snowpack considerable exceeds the incoming longwave radiation from the atmosphere which results in a negative budget of the longwave radiation that cause the snowpack cooling in open or deforested areas (**Hotovy and Jenicek, 2020**).

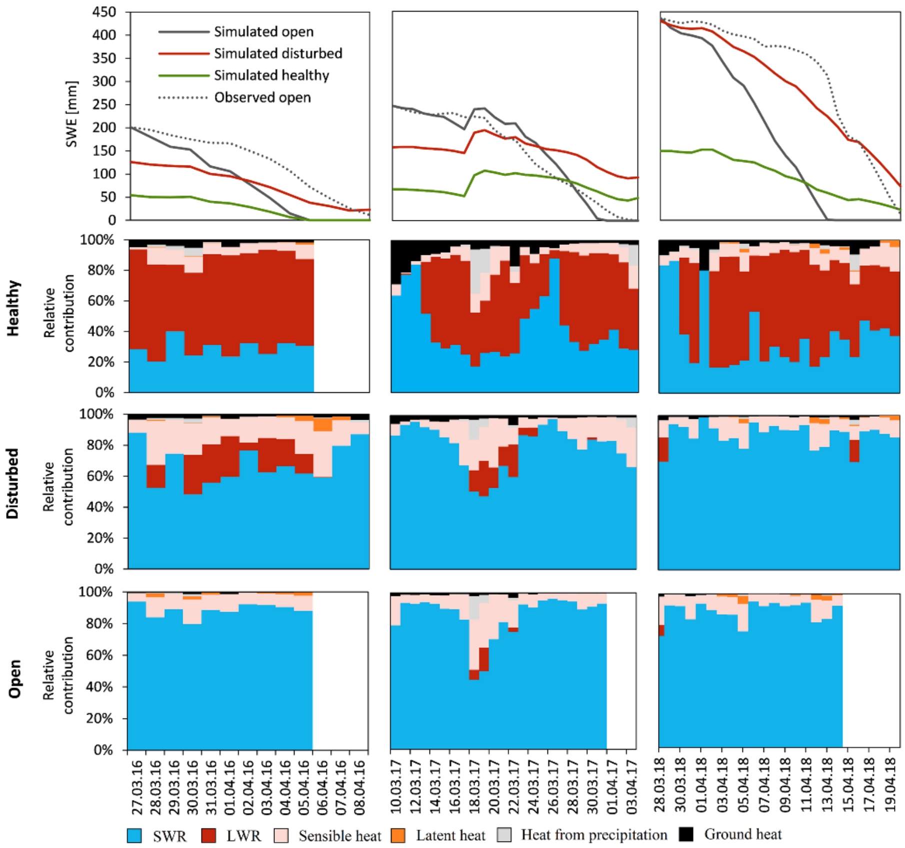

Fig. 10. Simulated SWE at three study sites and observed SWE at a nearby open meadow during the main spring snowmelt periods in seasons 2016, 2017 and 2018 (first line panels). Relative daily contribution of individual energy fluxes to snowmelt rates at the healthy forest site (second line panels), disturbed forest site (third line panels) and open site (fourth line panels). On average, shortwave radiation (SWR) and turbulent fluxes together represented 99% of the total contribution to snowmelt at the open site. In contrast, SWR and longwave radiation (LWR) represented 37 and 48% of the total snowmelt contribution in healthy forest. In the disturbed forest, SWR increased from 67% in season 2016 to 87% in 2018 (Hotovy and Jenicek, 2020).

Although trees decay following insect attack, wildfires or windstorms may cause the considerable increase in snowmelt volume, the spring runoff increase may be much lower. For example, Pomeroy et al. (2012) documented increase in snowmelt volume by 45% at Marmot Creek in Canada in case of forest wildfire and logging while respective increase in spring and summer runoff volume reached only 10%. However, the above deforestation influenced more peak flows in the Marmot Creek study area which was also documented by Langhammer et al. (2015) in the Sumava Mts.

Bark beetle outbreaks occurred over the last three decades in the Sumava Mts. (Bavarian Forest) in Czechia, Germany and Austria and widely affected large areas of Norway spruce (*Picea abies*) at the highest elevations. Together with windstorms, they represent the major cause of natural forest changes in the region affecting also hydrological processes, such as evapotranspiration, interception, snow and soil storages and consequent runoff (see e.g., **Hotovy and Jenicek, 2020; Jenicek et al., 2018a**; Kliment et al., 2011; Langhammer and Bernsteinová, 2020; Su et al., 2017).

The investigations of how forest disturbances impact snow accumulation and melt are often carried out using either field observations or modelling approaches. The use of field measurements allows an accurate description of the physical process at very small scales, however, it is usually time-consuming and costly (see e.g., **Hotovy and Jenicek, 2020; Jenicek et al., 2018a, 2017**; Jost et al., 2009; Lundquist et al., 2015). Therefore, the modelling approaches are often use that enable to generalize the processes to the catchment scale, although usually with lower accuracy and necessary simplifications (Essery et al., 2013; Jost et al., 2012). However, field data are needed to bridge the gap between the real physical process and its mathematical conceptualization applied in snowmelt models.

4 Conclusions and future perspectives

Snow cover is generally very sensitive to changes in air temperature. With climate changes, the snow amounts, its duration and the snowmelt timing have changed in recent decades. Lower snowfall fractions and hence snow storage reduced spring and early summer runoff, which now occurs earlier. In contrast, winter runoff has increased due to more rain than snow in the winter. Air temperature is dominant control for snow storage at lower and middle elevations, while precipitation controls the snow storage at the highest elevations in the central European mountains. However, with increasing air temperature, its dominant role increases as well even at high elevations. The results presented in Sections 3.1 and 3.2 of this habilitation thesis also showed that changes in snow cover affect hydrological extremes, such as rain-on-snow floods or summer low flows. The latter suggests that catchments may have a long memory effect, as snow is important for groundwater recharge and thus affects runoff even after it has melted.

Although climate change impacts on snowmelt have been widely studied, the role of changes in precipitation phase on groundwater recharge and catchment storage is not yet fully understood. Streamflow generation and deep groundwater recharge may be vulnerable to loss of snow, making it important to quantify how snowmelt is partitioned between soil storage, groundwater recharge, evapotranspiration, and runoff. This is particularly important for assessing how changes in snow storage affect the seasonal runoff distribution and whether they may also affect catchment storage and the annual water balance. In the studies presented in this thesis (Sections 3.1 and 3.2), we have partially addressed this issue with modelling approaches using a large sample of diverse catchments. However, modelling approaches did not allow us to go into the detailed description of the runoff generation process since the applied model treated catchments as a single unit separated into elevation zones. Therefore, field investigations on the mechanism of snowmelt runoff generation are needed, e.g. using stable water isotopes and other biogeochemical indicators. As groundwater levels tent to response more slowly to changes in precipitation compared to direct runoff, it is important to determine the memory effect of individual catchments, which may also help to explain multi-year effects in runoff response.

Field investigations can also better reflect specific catchment conditions, such as topography and forest. As the results in Section 3.3 show, forest has an important effect both during snow accumulation through the interception and during snowmelt, as it substantially modifies the snowpack energy balance. On the one hand, forests attenuate solar radiation causing slower snowmelt, while they increase the role of longwave radiation emitted by trees on the other hand. These energy effects change significantly as the forest declines due to various disturbances, such as bark beetle attacks or windstorms.

Related to the above, an open issue is still the coupling of results from field investigations with conceptual hydrological models to transfer the field information to catchment and regional scales and thus to improve our understanding of the catchment hydrological responses to climate variations. For example, conceptual models often calculate the snowmelt contribution to runoff with an effect tracking algorithm that aims to track the effect of individual water sources through the system rather than the individual water particles, which is the case of most of field approaches, such as stable water isotope sampling (Weiler et al., 2018). These two fundamental approaches to water tracking can also lead to different calculations of catchment storage, water transit times and runoff response.

Future projections of snow cover are consistent both in terms of snow amount decrease and earlier snowmelt (results in Section 3.2). Changes in mountain snowpack will further alter spring and summer runoff, including low flows. Although snow is not a dominant driver of summer low flows in the humid climate of central Europe, its decrease and earlier melt may contribute to more extreme droughts in the future due to less water coming from mountains to the adjacent lowlands. The above changes are associated with a wide range of impacts not only on natural ecosystems, but also have important socio-economic consequences, such as the water availability for drinking, hydropower, agriculture, irrigation, industry, and tourism.

However, simulations of the future changes in snow signatures and their impact on runoff response showed a range of projected snow storages related to associated with climate projections (results in Section 3.2). The reason for this is that the overall decrease in snow storage due to the increase in air temperature is partly compensated by the increase in precipitation suggested by some of the climate projections for the region of central Europe (while others simulate its decrease). This particular result suggests a large variability in hydrological responses depending on different climate projections especially in snow dominated catchments. The variability in climate projections could be important not only for snow storage, but also for the associated runoff response and thus for catchment storage. Therefore, this issue deserves further investigation since it is important to correctly set climate change adaptation strategies.

In the studies presented in sections 3.1 and 3.2, we used modelling approaches using a large sample of diverse catchments focusing on how snow changes affect runoff generation. However, we did not systematically focus on the role of catchment attributes, i.e. what are the similarities or differences between catchments and why do they differ. Our results showed differences in the behaviour of individual catchments, suggesting the role of partly different climates between individual regions, and also of different physio-geographical characteristics, such as topography or geology, which may affect the runoff response and water transit times. Similarly, the role of vegetation is important since it significantly affects the snowpack energy balance as shown by the studies presented in Section 3.3. Understanding the role of catchment attributes in catchment storage can also help to quantify the ”worst case scenario” for some extreme events, such as low flows. Such stress tests can also be useful in estimating the time required for the catchment to recover from such extreme events (Hellwig et al., 2021; Stoelzle et al., 2020).

5 References

Addor, N., Do, H.X., Alvarez-Garreton, C., Coxon, G., Fowler, K., Mendoza, P.A., 2020. Large-sample hydrology: recent progress, guidelines for new datasets and grand challenges. Hydrol. Sci. J. 65, 712–725. https://doi.org/10.1080/02626667.2019.1683182

Addor, N., Rössler, O., Köplin, N., Huss, M., Weingartner, R., Seibert, J., 2014. Robust changes and sources of uncertainty in the projected hydrological regimes of Swiss catchments. Water Resour. Res. 50, 7541–7562. https://doi.org/10.1002/2014WR015549

Andréassian, V., Coron, L., Lerat, J., Le Moine, N., 2016. Climate elasticity of streamflow revisited – an elasticity index based on long-term hydrometeorological records. Hydrol. Earth Syst. Sci. 20, 4503–4524. https://doi.org/10.5194/hess-20-4503-2016

Barnhart, T.B., Molotch, N.P., Livneh, B., Harpold, A.A., Knowles, J.F., Schneider, D., 2016. Snowmelt rate dictates streamflow. Geophys. Res. Lett. 43, 8006–8016. https://doi.org/10.1002/2016GL069690

Bartík, M., Holko, L., Jančo, M., Škvarenina, J., Danko, M., Kostka, Z., 2019. Influence of Mountain Spruce Forest Dieback on Snow Accumulation and Melt. J. Hydrol. Hydromechanics 67, 59–69. https://doi.org/10.2478/johh-2018-0022

Beniston, M., 2012. Is snow in the Alps receding or disappearing? Wiley Interdiscip. Rev. Clim. Chang. 3, 349–358. https://doi.org/10.1002/wcc.179

Berghuijs, W.R., Woods, R.A., Hrachowitz, M., 2014. A precipitation shift from snow towards rain leads to a decrease in streamflow. Nat. Clim. Chang. 4, 583–586. https://doi.org/10.1038/NCLIMATE2246

Birsan, M.V., Molnar, P., Burlando, P., Pfaundler, M., 2005. Streamflow trends in Switzerland. J. Hydrol. 314, 312–329. https://doi.org/10.1016/j.jhydrol.2005.06.008

Blahušiaková, A., Matoušková, M., Jenicek, M., Ledvinka, O., Kliment, Z., Podolinská, J., Snopková, Z., 2020. Snow and climate trends and their impact on seasonal runoff and hydrological drought types in selected mountain catchments in Central Europe. Hydrol. Sci. J. 65, 2083–2096. https://doi.org/10.1080/02626667.2020.1784900

Blöschl, G., Bierkens, M.F.P., Chambel, A., Cudennec, C., Destouni, G., Fiori, A., Kirchner, J.W., McDonnell, J.J., Savenije, H.H.G., Sivapalan, M., Stumpp, C., Toth, E., Volpi, E., Carr, G., Lupton, C., Salinas, J., Széles, B., Viglione, A., Aksoy, H., Allen, S.T., Amin, A., Andréassian, V., Arheimer, B., Aryal, S.K., Baker, V., Bardsley, E., Barendrecht, M.H., Bartosova, A., Batelaan, O., Berghuijs, W.R., Beven, K., Blume, T., Bogaard, T., Borges de Amorim, P., Böttcher, M.E., Boulet, G., Breinl, K., Brilly, M., Brocca, L., Buytaert, W., Castellarin, A., Castelletti, A., Chen, X., Chen, Yangbo, Chen, Yuanfang, Chifflard, P., Claps, P., Clark, M.P., Collins, A.L., Croke, B., Dathe, A., David, P.C., de Barros, F.P.J., de Rooij, G., Di Baldassarre, G., Driscoll, J.M., Duethmann, D., Dwivedi, R., Eris, E., Farmer, W.H., Feiccabrino, J., Ferguson, G., Ferrari, E., Ferraris, S., Fersch, B., Finger, D., Foglia, L., Fowler, K., Gartsman, B., Gascoin, S., Gaume, E., Gelfan, A., Geris, J., Gharari, S., Gleeson, T., Glendell, M., Gonzalez Bevacqua, A., González-Dugo, M.P., Grimaldi, S., Gupta, A.B., Guse, B., Han, D., Hannah, D., Harpold, A., Haun, S., Heal, K., Helfricht, K., Herrnegger, M., Hipsey, M., Hlaváčiková, H., Hohmann, C., Holko, L., Hopkinson, C., Hrachowitz, M., Illangasekare, T.H., Inam, A., Innocente, C., Istanbulluoglu, E., Jarihani, B., Kalantari, Z., Kalvans, A., Khanal, S., Khatami, S., Kiesel, J., Kirkby, M., Knoben, W., Kochanek, K., Kohnová, S., Kolechkina, A., Krause, S., Kreamer, D., Kreibich, H., Kunstmann, H., Lange, H., Liberato, M.L.R., Lindquist, E., Link, T., Liu, J., Loucks, D.P., Luce, C., Mahé, G., Makarieva, O., Malard, J., Mashtayeva, S., Maskey, S., Mas-Pla, J., Mavrova-Guirguinova, M., Mazzoleni, M., Mernild, S., Misstear, B.D., Montanari, A., Müller-Thomy, H., Nabizadeh, A., Nardi, F., Neale, C., Nesterova, N., Nurtaev, B., Odongo, V.O., Panda, S., Pande, S., Pang, Z., Papacharalampous, G., Perrin, C., Pfister, L., Pimentel, R., Polo, M.J., Post, D., Prieto Sierra, C., Ramos, M.-H., Renner, M., Reynolds, J.E., Ridolfi, E., Rigon, R., Riva, M., Robertson, D.E., Rosso, R., Roy, T., Sá, J.H.M., Salvadori, G., Sandells, M., Schaefli, B., Schumann, A., Scolobig, A., Seibert, J., Servat, E., Shafiei, M., Sharma, A., Sidibe, M., Sidle, R.C., Skaugen, T., Smith, H., Spiessl, S.M., Stein, L., Steinsland, I., Strasser, U., Su, B., Szolgay, J., Tarboton, D., Tauro, F., Thirel, G., Tian, F., Tong, R., Tussupova, K., Tyralis, H., Uijlenhoet, R., van Beek, R., van der Ent, R.J., van der Ploeg, M., Van Loon, A.F., van Meerveld, I., van Nooijen, R., van Oel, P.R., Vidal, J.-P., von Freyberg, J., Vorogushyn, S., Wachniew, P., Wade, A.J., Ward, P., Westerberg, I.K., White, C., Wood, E.F., Woods, R., Xu, Z., Yilmaz, K.K., Zhang, Y., 2019. Twenty-three unsolved problems in hydrology (UPH) – a community perspective. Hydrol. Sci. J. 64, 1141–1158. https://doi.org/10.1080/02626667.2019.1620507

Blume, T., van Meerveld, I., Weiler, M., 2016. The role of experimental work in hydrological sciences – insights from a community survey. Hydrol. Sci. J. 1–4. https://doi.org/10.1080/02626667.2016.1230675

Boon, S., 2012. Snow accumulation following forest disturbance. Ecohydrology 5, 279–285. https://doi.org/10.1002/eco.212

Bühler, Y., Adams, M.S., Bösch, R., Stoffel, A., 2016. Mapping snow depth in alpine terrain with unmanned aerial systems (UASs): potential and limitations. Cryosph. 10, 1075–1088. https://doi.org/10.5194/tc-10-1075-2016

Carroll, R.W.H., Deems, J.S., Niswonger, R., Schumer, R., Williams, K.H., 2019. The Importance of Interflow to Groundwater Recharge in a Snowmelt-Dominated Headwater Basin. Geophys. Res. Lett. 46, 5899–5908. https://doi.org/10.1029/2019GL082447

CH2011, 2011. Swiss Climate Change Scenarios 2011. C2SM, MeteoSwiss, ETH, NCCR Climate, and OcCC, Zurich.

Cochand, M., Christe, P., Ornstein, P., Hunkeler, D., 2019. Groundwater Storage in High Alpine Catchments and Its Contribution to Streamflow. Water Resour. Res. 55, 2613–2630. https://doi.org/10.1029/2018WR022989

Cooper, M.G., Nolin, A.W., Safeeq, M., 2016. Testing the recent snow drought as an analog for climate warming sensitivity of Cascades snowpacks. Environ. Res. Lett. 11, 084009. https://doi.org/10.1088/1748-9326/11/8/084009

Cristea, N.C., Lundquist, J.D., Loheide, S.P., Lowry, C.S., Moore, C.E., 2014. Modelling how vegetation cover affects climate change impacts on streamflow timing and magnitude in the snowmelt-dominated upper Tuolumne Basin, Sierra Nevada. Hydrol. Process. 28, 3896–3918. https://doi.org/10.1002/hyp.9909

Dierauer, J.R., Whitfield, P.H., Allen, D.M., 2018. Climate Controls on Runoff and Low Flows in Mountain Catchments of Western North America. Water Resour. Res. 54, 7495–7510. https://doi.org/10.1029/2018WR023087

Essery, R., Morin, S., Lejeune, Y., B Ménard, C., 2013. A comparison of 1701 snow models using observations from an alpine site. Adv. Water Resour. 55, 131–148. https://doi.org/10.1016/j.advwatres.2012.07.013

Floriancic, M.G., Berghuijs, W.R., Kirchner, J.W., Molnar, P., 2019. The effects of climatic anomalies on low flows in Switzerland. Hydrol. Earth Syst. Sci. Discuss. 1–18. https://doi.org/10.5194/hess-2019-448

Förster, K., Garvelmann, J., Meißl, G., Strasser, U., 2018. Modelling forest snow processes with a new version of WaSiM. Hydrol. Sci. J. 63, 1540–1557. https://doi.org/10.1080/02626667.2018.1518626

Freudiger, D., Kohn, I., Seibert, J., Stahl, K., Weiler, M., 2017. Snow redistribution for the hydrological modeling of alpine catchments. WIREs Water e1232. https://doi.org/10.1002/wat2.1232

Freudiger, D., Kohn, I., Stahl, K., Weiler, M., 2014. Large-scale analysis of changing frequencies of rain-on-snow events with flood-generation potential. Hydrol. Earth Syst. Sci. 18, 2695–2709. https://doi.org/10.5194/hess-18-2695-2014

Fyfe, J.C., Derksen, C., Mudryk, L., Flato, G.M., Santer, B.D., Swart, N.C., Molotch, N.P., Zhang, X., Wan, H., Arora, V.K., Scinocca, J., Jiao, Y., 2017. Large near-term projected snowpack loss over the western United States. Nat. Commun. 8, 14996. https://doi.org/10.1038/ncomms14996

Girons Lopez, M., Vis, M.J.P., Jenicek, M., Griessinger, N., Seibert, J., 2020. Assessing the degree of detail of temperature-based snow routines for runoff modelling in mountainous areas in central Europe. Hydrol. Earth Syst. Sci. 24, 4441–4461. https://doi.org/10.5194/hess-24-4441-2020

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., Stoffel, M., 2014. 21st century climate change in the European Alps—A review. Sci. Total Environ. 493, 1138–1151. https://doi.org/10.1016/j.scitotenv.2013.07.050

Godsey, S.E., Kirchner, J.W., Tague, C.L., 2014. Effects of changes in winter snowpacks on summer low flows: case studies in the Sierra Nevada, California, USA. Hydrol. Process. 28, 5048–5064. https://doi.org/10.1002/hyp.9943

Hammond, J.C., Harpold, A.A., Weiss, S., Kampf, S.K., 2019. Partitioning snowmelt and rainfall in the critical zone: effects of climate type and soil properties. Hydrol. Earth Syst. Sci. 23, 3553–3570. https://doi.org/10.5194/hess-23-3553-2019

Hammond, J.C., Saavedra, F.A., Kampf, S.K., 2018. How Does Snow Persistence Relate to Annual Streamflow in Mountain Watersheds of the Western U.S. With Wet Maritime and Dry Continental Climates? Water Resour. Res. 54, 2605–2623. https://doi.org/10.1002/2017WR021899

Harpold, A., Kaplan, M.L., Klos, P.Z., Link, T., McNamara, J.P., Rajagopal, S., Schumer, R., Steele, C.M., 2017. Rain or snow: hydrologic processes, observations, prediction, and research needs. Hydrol. Earth Syst. Sci. 21, 1–22. https://doi.org/10.5194/hess-21-1-2017

Helbig, N., Moeser, D., Teich, M., Vincent, L., Lejeune, Y., Sicart, J.-E., Monnet, J.-M., 2020. Snow processes in mountain forests: interception modeling for coarse-scale applications. Hydrol. Earth Syst. Sci. 24, 2545–2560. https://doi.org/10.5194/hess-24-2545-2020

Helbig, N., Moeser, D., Teich, M., Vincent, L., Lejeune, Y., Sicart, J.-E., Monnet, J.-M., 2019. Snow processes in mountain forests: Interception modeling for coarse-scale applications. Hydrol. Earth Syst. Sci. Discuss. 1–24. https://doi.org/10.5194/hess-2019-348

Hellwig, J., Stoelzle, M., Stahl, K., 2021. Groundwater and baseflow drought responses to synthetic recharge stress tests. Hydrol. Earth Syst. Sci. 25, 1053–1068. https://doi.org/10.5194/hess-25-1053-2021

Hotovy, O., Jenicek, M., 2020. The impact of changing subcanopy radiation on snowmelt in a disturbed coniferous forest. Hydrol. Process. 34, 5298–5314. https://doi.org/10.1002/hyp.13936

Hotovy, O., Nedelcev, O., Jenicek, M., 2023. Changes in rain-on-snow events in mountain catchments in the rain-snow transition zone. Hydrol. Sci. J. Online fir. https://doi.org/10.1080/02626667.2023.2177544

Huss, M., Hock, R., 2018. Global-scale hydrological response to future glacier mass loss. Nat. Clim. Chang. 8, 135–140. https://doi.org/10.1038/s41558-017-0049-x

Il Jeong, D., Sushama, L., 2018. Rain-on-snow events over North America based on two Canadian regional climate models. Clim. Dyn. 50, 303–316. https://doi.org/10.1007/s00382-017-3609-x

Immerzeel, W.W., Lutz, A.F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B.J., Elmore, A.C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J.S., Koppes, M., Kraaijenbrink, P.D.A., Kulkarni, A. V., Mayewski, P.A., Nepal, S., Pacheco, P., Painter, T.H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A.B., Viviroli, D., Wada, Y., Xiao, C., Yao, T., Baillie, J.E.M., 2020. Importance and vulnerability of the world's water towers. Nature 577, 364–369. https://doi.org/10.1038/s41586-019-1822-y

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernm Climate Changeental Panel on. Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1017/9781009157896

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland.

IPCC, 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland.

Jenicek, M., Hnilica, J., Nedelcev, O., Sipek, V., 2021. Future changes in snowpack will impact seasonal runoff and low flows in Czechia. J. Hydrol. Reg. Stud. 37, 100899. https://doi.org/10.1016/j.ejrh.2021.100899

Jenicek, M., Hotovy, O., Matejka, O., 2017. Snow accumulation and ablation in different canopy structures at a plot scale: using degree-day approach and measured shortwave radiation. AUC Geogr. 52, 61–72. https://doi.org/10.14712/23361980.2017.5

Jenicek, M., Ledvinka, O., 2020. Importance of snowmelt contribution to seasonal runoff and summer low flows in Czechia. Hydrol. Earth Syst. Sci. 24, 3475–3491. https://doi.org/10.5194/hess-24-3475-2020

Jenicek, M., Pevna, H., Matejka, O., 2018a. Canopy structure and topography effects on snow distribution at a catchment scale: Application of multivariate approaches. J. Hydrol. Hydromechanics 66, 43–54. https://doi.org/10.1515/johh-2017-0027

Jenicek, M., Seibert, J., Staudinger, M., 2018b. Modeling of Future Changes in Seasonal Snowpack and Impacts on Summer Low Flows in Alpine Catchments. Water Resour. Res. 54, 538–556. https://doi.org/10.1002/2017WR021648

Jenicek, M., Seibert, J., Zappa, M., Staudinger, M., Jonas, T., 2016. Importance of maximum snow accumulation for summer low flows in humid catchments. Hydrol. Earth Syst. Sci. 20, 859–874. https://doi.org/10.5194/hess-20-859-2016

Jennings, K.S., Kittel, T.G.F., Molotch, N.P., 2018. Observations and simulations of the seasonal evolution of snowpack cold content and its relation to snowmelt and the snowpack energy budget. Cryosph. 12, 1595–1614. https://doi.org/10.5194/tc-12-1595-2018

Jörg-Hess, S., Fundel, F., Jonas, T., Zappa, M., 2014. Homogenisation of a gridded snow water equivalent climatology for Alpine terrain: methodology and applications. Cryosph. 8, 471–485. https://doi.org/10.5194/tc-8-471-2014

Jost, G., Dan Moore, R., Smith, R., Gluns, D.R., 2012. Distributed temperature-index snowmelt modelling for forested catchments. J. Hydrol. 420, 87–101.

Jost, G., Dan Moore, R., Weiler, M., Gluns, D.R., Alila, Y., 2009. Use of distributed snow measurements to test and improve a snowmelt model for predicting the effect of forest clear-cutting. J. Hydrol. 376, 94–106. https://doi.org/10.1016/j.jhydrol.2009.07.017

Juras, R., Blöcher, J.R., Jenicek, M., Hotovy, O., Markonis, Y., 2021. What affects the hydrological response of rain-on-snow events in low-altitude mountain ranges in Central Europe? J. Hydrol. 603, 127002. https://doi.org/10.1016/j.jhydrol.2021.127002

Juras, R., Würzer, S., Pavlásek, J., Vitvar, T., Jonas, T., 2017. Rainwater propagation through snowpack during rain-on-snow sprinkling experiments under different snow conditions. Hydrol. Earth Syst. Sci. 21, 4973–4987. https://doi.org/10.5194/hess-21-4973-2017

Kiewiet, L., Trujillo, E., Hedrick, A., Havens, S., Hale, K., Seyfried, M., Kampf, S., Godsey, S.E., 2022. Effects of spatial and temporal variability in surface water inputs on streamflow generation and cessation in the rain-snow transition zone. Hydrol. Earth Syst. Sci. 26, 2779–2796. https://doi.org/10.5194/HESS-26-2779-2022

Kirchner, J.W., Allen, S.T., 2020. Seasonal partitioning of precipitation between streamflow and evapotranspiration, inferred from end-member splitting analysis. Hydrol. Earth Syst. Sci. 24, 17–39. https://doi.org/10.5194/hess-24-17-2020

Klein, G., Vitasse, Y., Rixen, C., Marty, C., Rebetez, M., 2016. Shorter snow cover duration since 1970 in the Swiss Alps due to earlier snowmelt more than to later snow onset. Clim. Change 139, 637–649. https://doi.org/10.1007/s10584-016-1806-y

Kliment, Z., Matouskova, M., Ledvinka, O., Kralovec, V., 2011. Trend Analysis of Rainfall-Runoff Regimes in Selected Headwater Areas of the Czech Republic. J. Hydrol. Hydromechanics 59, 36–50. https://doi.org/DOI 10.2478/v10098-011-0003-y

Klos, P.Z., Link, T.E., 2018. Quantifying shortwave and longwave radiation inputs to headwater streams under differing canopy structures. For. Ecol. Manage. 407, 116–124. https://doi.org/10.1016/j.foreco.2017.10.046

Knowles, N., Dettinger, M.D., Cayan, D.R., 2006. Trends in snowfall versus rainfall in theWestern United States. J. Clim. 19, 4545–4559.

Koutantou, K., Mazzotti, G., Brunner, P., Webster, C., Jonas, T., 2022. Exploring snow distribution dynamics in steep forested slopes with UAV-borne LiDAR. Cold Reg. Sci. Technol. 200, 103587. https://doi.org/10.1016/j.coldregions.2022.103587

Kucerova, D., Jenicek, M., 2014. Comparison of selected methods used for the calculation of the snowpack spatial distribution, Bystřice River basin, Czechia. Geografie 119, 199–217.

Langhammer, J., Bernsteinová, J., 2020. Which Aspects of Hydrological Regime in Mid-Latitude Montane Basins Are Affected by Climate Change? Water 12, 2279. https://doi.org/10.3390/w12082279

Langhammer, J., Su, Y., Bernsteinová, J., 2015. Runoff Response to Climate Warming and Forest Disturbance in a Mid-Mountain Basin. Water 7, 3320–3342. https://doi.org/10.3390/w7073320

Lendzioch, T., Langhammer, J., Jenicek, M., 2019. Estimating Snow Depth and Leaf Area Index Based on UAV Digital Photogrammetry. Sensors 19, 1027. https://doi.org/10.3390/s19051027

Li, D., Wrzesien, M.L., Durand, M., Adam, J., Lettenmaier, D.P., 2017. How much runoff originates as snow in the western United States, and how will that change in the future? Geophys. Res. Lett. 44, 6163–6172. https://doi.org/10.1002/2017GL073551

Lindström, G., Johansson, B., Persson, M., Gardelin, M., Bergström, S., 1997. Development and test of the distributed HBV-96 hydrological model. J. Hydrol. 201, 272–288. https://doi.org/10.1016/S0022-1694(97)00041-3

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. https://doi.org/10.1016/j.advwatres.2012.08.010

López-Moreno, J.I., Stähli, M., 2008. Statistical analysis of the snow cover variability in a subalpine watershed: Assessing the role of topography and forest interactions. J. Hydrol. 348, 379–394. https://doi.org/10.1016/j.jhydrol.2007.10.018

Lundquist, J.D., Wayand, N.E., Massmann, A., Clark, M.P., Lott, F., Cristea, N.C., 2015. Diagnosis of insidious data disasters. Water Resour. Res. 51, 3815–3827. https://doi.org/10.1002/2014WR016585

Lute, A.C., Abatzoglou, J.T., Hegewisch, K.C., 2015. Projected changes in snowfall extremes and interannual variability of snowfall in the western United States. Water Resour. Res. 51, 960–972. https://doi.org/10.1002/2014WR016267

Marshall, A.M., Link, T.E., Robinson, A.P., Abatzoglou, J.T., 2020. Higher Snowfall Intensity is Associated with Reduced Impacts of Warming Upon Winter Snow Ablation. Geophys. Res. Lett. 47. https://doi.org/10.1029/2019GL086409

Marty, C., Schlögl, S., Bavay, M., Lehning, M., 2017a. How much can we save? Impact of different emission scenarios on future snow cover in the Alps. Cryosph. 11, 517–529. https://doi.org/10.5194/tc-11-517-2017

Marty, C., Tilg, A.-M., Jonas, T., 2017b. Recent Evidence of Large-Scale Receding Snow Water Equivalents in the European Alps. J. Hydrometeorol. 18, 1021–1031. https://doi.org/10.1175/JHM-D-16-0188.1

Míka, D., 2021. Modelling of snow interception in the spruce forest in the Ptačí Brook basin, Šumava Mts. Master thesis (in Czech). Charles University.

Moeser, D., Stähli, M., Jonas, T., 2015. Improved snow interception modeling using canopy parameters derived from airborne LiDAR data. Water Resour. Res. 51, 5041–5059. https://doi.org/10.1002/2014WR016724

Morán-Tejeda, E., López-Moreno, J.I., Beniston, M., 2013. The changing roles of temperature and precipitation on snowpack variability in Switzerland as a function of altitude. Geophys. Res. Lett. 40, 2131–2136. https://doi.org/10.1002/grl.50463

Mote, P.W., Li, S., Lettenmaier, D.P., Xiao, M., Engel, R., 2018. Dramatic declines in snowpack in the western US. npj Clim. Atmos. Sci. 1, 2. https://doi.org/10.1038/s41612-018-0012-1

Muelchi, R., Rössler, O., Schwanbeck, J., Weingartner, R., Martius, O., 2021. River runoff in Switzerland in a changing climate – runoff regime changes and their time of emergence. Hydrol. Earth Syst. Sci. 25, 3071–3086. https://doi.org/10.5194/hess-25-3071-2021

Musselman, K.N., Clark, M.P., Liu, C., Ikeda, K., Rasmussen, R., 2017a. Slower snowmelt in a warmer world. Nat. Clim. Chang. 7, 214–219. https://doi.org/10.1038/nclimate3225

Musselman, K.N., Lehner, F., Ikeda, K., Clark, M.P., Prein, A.F., Liu, C., Barlage, M., Rasmussen, R., 2018. Projected increases and shifts in rain-on-snow flood risk over western North America. Nat. Clim. Chang. 8, 808–812. https://doi.org/10.1038/s41558-018-0236-4

Musselman, K.N., Molotch, N.P., Margulis, S.A., 2017b. Snowmelt response to simulated warming across a large elevation gradient, southern Sierra Nevada, California. Cryosph. 11, 2847–2866. https://doi.org/10.5194/tc-11-2847-2017

Musselman, K.N., Pomeroy, J.W., 2017. Estimation of Needleleaf Canopy and Trunk Temperatures and Longwave Contribution to Melting Snow. J. Hydrometeorol. 18, 555–572. https://doi.org/10.1175/jhm-d-16-0111.1

Musselman, K.N., Pomeroy, J.W., Link, T.E., 2015. Variability in shortwave irradiance caused by forest gaps: Measurements, modelling, and implications for snow energetics. Agric. For. Meteorol. 207, 69–82. https://doi.org/10.1016/j.agrformet.2015.03.014

Nedelcev, O., Jenicek, M., 2021. Trends in seasonal snowpack and their relation to climate variables in mountain catchments in Czechia. Hydrol. Sci. J. 66, 2340–2356. https://doi.org/10.1080/02626667.2021.1990298

Parajka, J., Bezak, N., Burkhart, J., Bjarki, H., Holko, L., Hundecha, Y., Jenicek, M., Krajčí, P., Manginy, W., Molnar, P., Riboust, P., Rizzi, J., Sensoy, A., Thirel, G., Viglione, A., 2019. MODIS snowline elevation changes during snowmelt runoff events in Europe. J. Hydrol. hydromechanics 67, 101–109. https://doi.org/10.2478/johh-2018-0011

Piani, C., Haerter, J.O., 2012. Two dimensional bias correction of temperature and precipitation copulas in climate models. Geophys. Res. Lett. 39, 2012GL053839. https://doi.org/10.1029/2012GL053839

Pomeroy, J., Fang, X., Ellis, C., 2012. Sensitivity of snowmelt hydrology in Marmot Creek, Alberta, to forest cover disturbance. Hydrol. Process. 26, 1891–1904. https://doi.org/10.1002/hyp.9248

Schelker, J., Kuglerová, L., Eklöf, K., Bishop, K., Laudon, H., 2013. Hydrological effects of clear-cutting in a boreal forest – Snowpack dynamics, snowmelt and streamflow responses. J. Hydrol. 484, 105–114. https://doi.org/10.1016/j.jhydrol.2013.01.015

Seibert, J., 2000. Multi-criteria calibration of a conceptual runoff model using a genetic algorithm. Hydrol. Earth Syst. Sci. 4, 215–224. https://doi.org/10.5194/hess-4-215-2000

Seibert, J., Jenicek, M., Huss, M., Ewen, T., Viviroli, D., 2021. Snow and ice in the hydrosphere, in: Haeberli, W., Whiteman, C. (Eds.), Snow and Ice-Related Hazards, Risks, and Disasters. Elsevier, pp. 93–135. https://doi.org/10.1016/B978-0-12-817129-5.00010-X

Seibert, J., Vis, M.J.P., 2012. Teaching hydrological modeling with a user-friendly catchment-runoff-model software package. Hydrol. Earth Syst. Sci. 16, 3315–3325. https://doi.org/10.5194/hess-16-3315-2012

Šípek, V., Jenicek, M., Hnilica, J., Zelíková, N., 2021. Catchment Storage and its Influence on Summer Low Flows in Central European Mountainous Catchments. Water Resour. Manag. 35, 2829–2843. https://doi.org/10.1007/s11269-021-02871-x

Sospedra-Alfonso, R., Melton, J.R., Merryfield, W.J., 2015. Effects of temperature and precipitation on snowpack variability in the Central Rocky Mountains as a function of elevation. Geophys. Res. Lett. 42, 4429–4438. https://doi.org/10.1002/2015GL063898

Stähli, M., Gustafsson, D., 2006. Long-term investigations of the snow cover in a subalpine semi-forested catchment. Hydrol. Process. 20, 411–428. https://doi.org/10.1002/hyp.6058

Stähli, M., Seibert, J., Kirchner, J.W., von Freyberg, J., van Meerveld, I., 2021. Hydrological trends and the evolution of catchment research in the Alptal valley, central Switzerland. Hydrol. Process. 35, e14113. https://doi.org/10.1002/hyp.14113

Staudinger, M., Stoelzle, M., Seeger, S., Seibert, J., Weiler, M., Stahl, K., 2017. Catchment water storage variation with elevation. Hydrol. Process. 31, 2000–2015. https://doi.org/10.1002/hyp.11158

Stoelzle, M., Staudinger, M., Stahl, K., Weiler, M., 2020. Stress testing as complement to climate scenarios: recharge scenarios to quantify streamflow drought sensitivity. Proc. Int. Assoc. Hydrol. Sci. 383, 43–50. https://doi.org/10.5194/piahs-383-43-2020

Su, Y., Langhammer, J., Jarsjö, J., 2017. Geochemical responses of forested catchments to bark beetle infestation: Evidence from high frequency in-stream electrical conductivity monitoring. J. Hydrol. 550, 635–649. https://doi.org/10.1016/j.jhydrol.2017.05.035

Trubilowicz, J.W., Moore, R.D., 2017. Quantifying the role of the snowpack in generating water available for run-off during rain-on-snow events from snow pillow records. Hydrol. Process. 31, 4136–4150. https://doi.org/10.1002/hyp.11310

van der Linden, P., Mitchell, J.F.B., 2009. ENSEMBLES: climate change and its impacts: summary of research and results from the ENSEMBLES project.

Van Loon, A.F., 2015. Hydrological drought explained. Wiley Interdiscip. Rev. Water 2, 359–392. https://doi.org/10.1002/wat2.1085

Viviroli, D., Dürr, H.H., Messerli, B., Meybeck, M., Weingartner, R., 2007. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. Water Resour. Res. 43. https://doi.org/10.1029/2006WR005653

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., Wada, Y., 2020. Increasing dependence of lowland populations on mountain water resources. Nat. Sustain. 3, 917–928. https://doi.org/10.1038/s41893-020-0559-9

Webster, C., Rutter, N., Zahner, F., Jonas, T., 2016. Modeling subcanopy incoming longwave radiation to seasonal snow using air and tree trunk temperatures. J. Geophys. Res. Atmos. 121, 1220–1235. https://doi.org/10.1002/2015JD024099

Weiler, M., Seibert, J., Stahl, K., 2018. Magic components-why quantifying rain, snowmelt, and icemelt in river discharge is not easy. Hydrol. Process. 32, 160–166. https://doi.org/10.1002/hyp.11361

Welch, C.M., Stoy, P.C., Rains, F.A., Johnson, A. V., McGlynn, B.L., 2015. The impacts of mountain pine beetle disturbance on the energy balance of snow during the melt period. Hydrol. Process. 30, n/a-n/a. https://doi.org/10.1002/hyp.10638

Wever, N., Jonas, T., Fierz, C., Lehning, M., 2014. Model simulations of the modulating effect of the snow cover in a rain-on-snow event. Hydrol. Earth Syst. Sci. 18, 4657–4669. https://doi.org/10.5194/hess-18-4657-2014

Winkler, R., Spittlehouse, D., Boon, S., Zimonick, B., 2015. Forest disturbance effects on snow and water yield in interior British Columbia. Hydrol. Res. 46, 521–532. https://doi.org/10.2166/nh.2014.016

Würzer, S., Jonas, T., Wever, N., Lehning, M., 2016a. Influence of Initial Snowpack Properties on Runoff Formation during Rain-on-Snow Events. J. Hydrometeorol. 17, 1801–1815. https://doi.org/10.1175/JHM-D-15-0181.1

Würzer, S., Jonas, T., Wever, N., Lehning, M., 2016b. Influence of Initial Snowpack Properties on Runoff Formation during Rain-on-Snow Events. J. Hydrometeorol. 17, 1801–1815. https://doi.org/10.1175/JHM-D-15-0181.1

Würzer, S., Wever, N., Juras, R., Lehning, M., Jonas, T., 2017. Modelling liquid water transport in snow under rain-on-snow conditions – considering preferential flow. Hydrol. Earth Syst. Sci. 21, 1741–1756. https://doi.org/10.5194/hess-21-1741-2017

6 Attached publications

1. Hotovy, O., Nedelcev, O., Jenicek, M. (2023). Changes in rain-on-snow events in mountain catchments in the rain-snow transition zone. Hydrological Sciences Journal. Published online first.
2. Juras, R., Blöcher, J.R., Jenicek, M., Hotovy, O., Markonis, Y. (2021). What affects the hydrological response of rain-on-snow events in low-altitude mountain ranges in Central Europe? Journal of Hydrology, 603(C), 127002.
3. Šípek, V., Jenicek, M., Hnilica, J., Zelíková, N. (2021). Catchment storage and its influence on summer low flows in central European mountainous catchments. Water Resources Management, 35, 2829–2843.
4. Jenicek, M., Ledvinka, O. (2020). Importance of snowmelt contribution to seasonal runoff and summer low flows in Czechia. Hydrology and Earth System Sciences, 24 (7), 3475–3491.
5. Parajka, J., Bezak, N., Burkhart, J., Hauksson, B., Holko, L., Hundecha, Y., Jenicek, M., Krajčí, P., Mangini, W., Molnar, P., Riboust, P., Rizzi, J., Sensoy, A., Thirel, G., Viglione, A. (2019). MODIS snowline elevation changes during snowmelt runoff events in Europe. Journal of Hydrology and Hydromechanics, 67 (1), 101-109.
6. Jenicek, M., Seibert, J., Zappa, M., Staudinger, M., and Jonas, T. (2016). Importance of maximum snow accumulation for summer low flows in humid catchments. Hydrology and Earth System Sciences, 20, 859-874.
7. Jenicek, M., Hnilica, J., Nedelcev, O., Sipek, V. (2021). Future changes in snowpack will impact seasonal runoff and low flows in Czechia. Journal of Hydrology: Regional Studies, 37, 100899.
8. Nedelcev O., Jenicek, M. (2021). Trends in seasonal snowpack and their relation to climate variables in mountain catchments in Czechia, Hydrological Sciences Journal, 66 (16), 2340-2356.
9. Blahusiakova, A., Matouskova, M., Jenicek, M., Ledvinka, O., Kliment, Z., Podolinska, J., Snopkova, Z. (2020). Snow and climate trends and their impact on seasonal runoff and hydrological drought types in selected mountain catchments in Central Europe. Hydrological Sciences Journal, 65(1-2), 2083-2096.
10. Girons Lopez M., Vis, M.J.P., Jenicek, M., Griessinger, N., Seibert, J. (2020). Assessing the degree of detail of temperature-based snow routines for runoff modelling in mountainous areas in central Europe. Hydrology and Earth System Sciences, 24, 4441–4461.
11. Jenicek, M., Seibert, J., Staudinger, M. (2018). Modeling of future changes in seasonal snowpack and impacts on summer low flows in Alpine catchments, Water Resources Research, 54(1), 538-556.
12. Hotovy, O., Jenicek, M. (2020). The impact of changing subcanopy radiation on snowmelt in a disturbed coniferous forest. Hydrological Processes, 34(26), 5298-5314.
13. Lendzioch, T., Langhammer, J., Jenicek, M. (2019). Estimating Snow Depth and Leaf Area Index Based on UAV Digital Photogrammetry. Sensors, 19(5), 1027.

14. Jenicek, M., Pevna, H., Matejka, O. (2018). Canopy structure and topography effects on snow distribution at a catchment scale: Application of multivariate approaches. Journal of Hydrology and Hydromechanics, 66 (1), 43-54.
15. Jenicek M, Hotovy O, Matejka O. (2017). Snow accumulation and ablation in different canopy structures at a plot scale: using degree-day approach and measured shortwave radiation. AUC Geographica 52 (1): 61–72.
16. Kucerova D, Jenicek M. (2014). Comparison of selected methods used for the calculation of the snowpack spatial distribution, Bystřice River basin, Czechia. Geografie 119 (3), 199–217.