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Bc. et RNDr. Ondřej Hotový

Changes in snowmelt and rain-on-snow runoff in mountainous catchments

Změny v tání sněhu a odtoku při událostech deště na sníh v horských povodích

Doctoral thesis

Supervisor: doc. RNDr. Michal Jeníček, Ph.D.

Prague, 2024

Declaration / Prohlášení:

I hereby declare that I have worked independently on the doctoral thesis and reported all the data sources and literature used in the thesis. This thesis has not been submitted to obtain any other academic title.

Prohlašuji, že jsem disertační práci vypracoval samostatně a všechny použité datové a informační zdroje jsem řádně citoval. Tato práce ani její podstatná část nebyla předložena k získání jiného nebo stejného akademického titulu.

August 5, 2024, in Prague

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Bc. et RNDr. Ondřej Hotový

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Abstract

Snowmelt dynamics and the frequency and intensity of rain-on-snow (RoS) events are expected to change in response to climate variations due to changes in precipitation, increase in air temperature and subsequent changes in the snow occurrence. Therefore, there is a need to understand the circumstances under which RoS events produce runoff and how the main drivers affect snowmelt.

This dissertation thesis compiles various types of research at different spatial and temporal scales, including the experimental site study and regional and international multi-catchment research. Mountainous catchments located in Central Europe were selected for the studies. Particular attention was paid to changes in elevation, with a specific focus on areas within the rain-snow transition zones where large changes in snow storage, snow dynamics and RoS occurrence typically occur due to warming climate. Various methodological approaches were used in the research (Papers I-IV). In our experimental study (Paper I), we assessed forest structure as an important parameter that significantly influences the amount of radiation fluxes that consequently affect snowpack energy balance and snowmelt rates. In Papers II-IV, a conceptual hydrological HBV model was used to simulate runoff components. We then identified RoS days/events, evaluated trends and spatial and temporal changes in the RoS occurrence, and assessed the hydrological response resulting from these hydrological events using the data series simulated by the model. We also attributed changes in selected climate variables, particularly air temperature and precipitation, to simulated possible variations in RoS events in the future climate (Paper IV).

This research highlighted the different roles of shortwave and longwave radiation in different forest structures, as well as the influence of other components of the snowpack energy balance. The results presented in Paper I revealed that energy from rain might be very important when assessing snowmelt at daily and shorter temporal resolutions. Notable effects of gradual forest decay on snowmelt processes were also demonstrated in this study, showing a 50% increase in modeled snowmelt rates in the disturbed forest. Our elevation-based methods accounted for the fact that only a part of the catchment contributes to runoff during the specific RoS events due to the strong dependence of snowmelt on air temperature at specific elevations (Paper II). Analyses of the runoff response showed that most of the RoS events (82% in Paper II, 72% in Paper III) did not cause a significant increase in runoff, highlighting the importance of the snowpack which can often prevent extreme runoff even when a large amount of rain occurs (Paper II). Nevertheless, notable climate change-driven RoS changes were identified and were highly variable across regions, elevations, and within the cold season (Papers III and IV). A significant decrease in RoS days (up to 75%) was projected for some lower-elevation sites. An increase in the number of RoS days was limited to higher elevations and the coldest winter months (Papers III and IV). Our projections also suggested that the RoS contribution to annual runoff will be considerably reduced; from the current 10% to 2-4% for the warmest projections in Czechia, and from 18% to 5-9% in Switzerland (Paper IV).

Although the overall impact of RoS on runoff is expected to be lower in the future, extreme hydrological response and flooding triggered by RoS events can still pose a significant flood risk. Therefore, understanding snowmelt processes and RoS behavior is essential for improving snowmelt models, effective water resource management, drought and flood forecasting and risk mitigation, especially in the face of climate change.

Keywords: snowmelt, rain-on-snow events, runoff, rain-snow transition zone, climate change

Abstrakt

Očekává se, že dynamika tání sněhu a četnost a intenzita událostí deště na sníh (*RoS events*) se bude měnit v reakci na změny klimatu, konkrétně v důsledku změn srážek, zvýšení teploty vzduchu a následných změn ve výskytu sněhové pokrývky. I proto je třeba porozumět tomu, jak tyto události generují odtok a jaké jsou hlavní faktory ovlivňují tání sněhu.

Tato disertační práce zahrnuje různé typy výzkumu napříč prostorovými a časovými měřítky, včetně experimentální studie a regionálního a mezinárodního výzkumu na větším počtu povodí. Pro účely výzkumu byla vybrána horská povodí nacházející se v regionu střední Evropy. Zvláštní pozornost byla věnována změnám v různých nadmořských výškách, se zvláštním zaměřením na oblasti v přechodové zóně déšť-sníh, kde v důsledku oteplování klimatu obvykle dochází k výrazným změnám v akumulaci a tání sněhu, ke změnám procesů uvnitř sněhové pokrývky a výskytu RoS. Při výzkumu byly použity různé metodické postupy (články I-IV). V naší experimentální studii (článek I) jsme analyzovali strukturu lesa jako jeden z důležitých parametrů, který významně ovlivňuje intenzitu radiačních toků, jež následně ovlivňují energetickou bilanci sněhové pokrývky a rychlost tání sněhu. V článcích II-IV byl k simulaci komponent odtoku použit koncepční hydrologický model HBV. Následně jsme identifikovali RoS dny/události, vyhodnotili trendy a prostorové a časové změny výskytu RoS a analyzovali hydrologickou odezvu vyvolanou těmito událostmi s použitím dat simulovaných modelem. Dále jsme změny vybraných klimatických proměnných, zejména teploty vzduchu a srážek, vztáhli k možným budoucím změnám událostí RoS (článek IV).

Tento výzkum poukázal na rozdílnou roli krátkovlnného a dlouhovlnného záření v různých strukturách lesa a také na vliv dalších složek energetické bilance sněhové pokrývky. Výsledky prezentované v článku I ukázaly, že energie z deště může být velmi významnou složkou při vyhodnocování tání sněhu v denním a kratším časovém horizontu. V této studii byl také prokázán významný vliv postupného rozpadu lesa na procesy tání sněhu, vykazující 50% nárůst modelované rychlosti tání sněhu v rozpadlém lese. Naše metody zohledňující nadmořskou výšku poukázaly na skutečnost, že během konkrétních událostí RoS přispívá k celkovému odtoku pouze část povodí, a to v důsledku závislosti tání sněhu na teplotě vzduchu v konkrétních nadmořských výškách (článek II). Analýzy odtokové odezvy ukázaly, že většina událostí RoS (82 % v článku II, 72 % v článku III) nezpůsobila významné zvýšení odtoku, což zdůrazňuje význam sněhové pokrývky, která může často zabránit extrémnímu odtoku i při vyšších úhrnech dopadajících srážek (článek II). Přesto byly zjištěny významné změny v událostech RoS vyvolané změnami klimatických parametrů v souvislosti se změnou klimatu. Pozorované změny se významně lišily v závislosti na regionu, nadmořské výšce a období v průběhu zimy (článek III a IV). Naše prognózy také naznačují, že podíl RoS na ročním odtoku se v budoucnosti výrazně sníží; ze současných 10 % na 2-4 % pro nejteplejší projekce v Česku a z 18 % na 5-9 % ve Švýcarsku (článek IV).

Ačkoli se očekává, že celkový dopad RoS na odtok bude v budoucnu nižší, extrémní hydrologická reakce a povodně vyvolané RoS událostmi mohou nadále představovat významné povodňové riziko. Hlubší pochopení procesů tání sněhu a chování RoS je proto nezbytné pro zdokonalení hydrologických modelů, které zohledňují tání sněhu, a tím do budoucna zefektivit management vodních zdrojů, predikce sucha a povodňových stavů a zmírnění povodňového rizika.

Klíčová slova: tání sněhu, události deště na sníh, odtok, přechodová zóna déšť-sníh, klimatická změna

List of publications

The thesis summarizes the results of four papers published in well-recognized international Web-of-Science-indexed journals. All papers in the original journal form are attached in Supplement, overviews of published papers are included in Section 4. Quartiles in the list below are based on the AIS metric.

Paper I (IF 2023 = 2.8, Q1 in Water Resources)

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

Author's contribution (85%): literature research, methodology, data collection, data processing, and analyses, results interpretation, figures, manuscript writing and editing, and correspondence with the journal.

Paper II (IF 2023 = 5.9, Q1 in Water Resources)

Juras R, Blöcher JR, 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: 127002 https://doi.org/10.1016/j.jhydrol.2021.127002

Author's contribution (15%): modeling procedures, manuscript co-writing and editing.

Paper III (IF 2023 = 2.8, Q1 in Water Resources)

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* 68 (4): 572-584 https://doi.org/10.1080/02626667.2023.2177544

Author's contribution (80%): literature research, methodology, data collection, data processing, and analyses, results interpretation, figures, manuscript writing and editing, and correspondence with the journal.

Paper IV (IF 2023 = 5.7, Q1 in Water Resources)

Hotovy O, Nedelcev O, Seibert J, Jenicek M. 2024. Rain-on-snow events in mountainous catchments under climate change. *Hydrology and Earth System Sciences* (under review)

Author's contribution (80%): literature research, methodology, data collection, data processing, and analyses, results interpretation, figures, manuscript writing and editing, and correspondence with the journal.

I, Michal Jeníček, agree with the author's contribution statements above ………………………………

1 Scope of the thesis

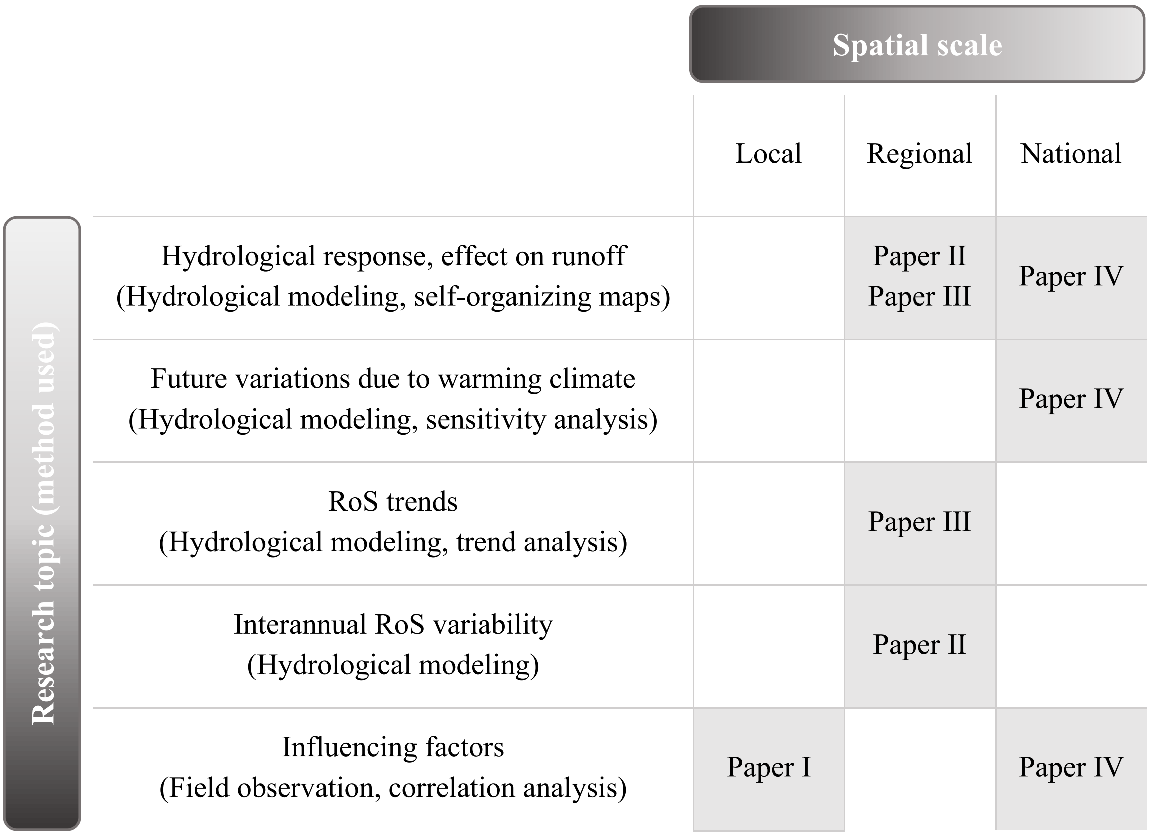
This doctoral thesis assesses changes in mountain snowmelt and rain-on-snow (RoS) runoff in the context of climate change since variations in precipitation, the increase in air temperature and subsequent changes in the snow storage are likely to affect the behavior of extreme hydrological events in the future. Although these snowmelt topics have been widely studied recently, the real impact of changing climate variables on snowmelt processes, RoS frequency and related hydrological implications remain unclear, mainly due to their complex nature.

Four studies included within the thesis represent various types of research at different spatial and temporal scales (Fig. 1). The thesis aims to introduce different methodological approaches that can be applied in the research of mountain snowmelt at various spatial resolutions, from the experimental site study with the high detail on snowmelt processes and influencing factors to more generalized multi-catchment regional and international studies. We were particularly focused on the changes in lower-elevation mountain ranges that represent rain-snow transition areas where large changes in snow storage, snowmelt and RoS occurrence typically occur due to warming climate and landscape changes. Moreover, most European studies have had a limited focus on elevation which significantly influences the precipitation phase and snow cover. Therefore, our focus on differences across elevation zones addressed within the thesis is another important spatial dimension of this research.

The thesis contributes to the understanding of the snowmelt processes, the role of various factors and runoff responses driven by extreme meteorological events within rain-snow transition zones which is essential for effective water resource management, drought and flood prediction and risk mitigation, particularly in the face of climate change, which alters snowfall patterns and the onset and character of snowmelt.

Regarding the scope of the thesis, the **main research objectives** can be drawn as follows:

1) Analyzing main snowmelt drivers and their contribution to runoff
2) Evaluating the frequency and extremity of rain-on-snow events, their spatial and temporal changes and hydrological implications
3) Assessing the role of warming climate and landscape changes on snowmelt processes, runoff and rain-on-snow events



	Spatial scale		
Research topic (method used)	Local	Regional	National
Hydrological response, effect on runoff (Hydrological modeling, self-organizing maps)		Paper II Paper III	Paper IV
Future variations due to warming climate (Hydrological modeling, sensitivity analysis)			Paper IV
RoS trends (Hydrological modeling, trend analysis)		Paper III	
Interannual RoS variability (Hydrological modeling)		Paper II	
Influencing factors (Field observation, correlation analysis)	Paper I		Paper IV

Figure 1: PhD publications sorted by topic and spatial scale.

2 Topic introduction

2.1 Hydrological role of snow

Snow has a profound impact on many dimensions of human life and nature. Seasonal snowpack significantly influences catchment runoff and thus represents an essential component of the hydrological cycle, particularly in mountainous regions in humid climates. Most of the hydrological implications of snowpack are related to its ability to store a substantial amount of water from winter precipitation. Field experiments conducted by Juras *et al.* (2017) showed that snowpack temporarily stored up to 70% of incoming rainwater volume. This stored water is gradually released during the spring and summer as the snow melts. The gradual melting of snow provides a sustained source of water to rivers and streams, which is particularly important in regions that experience dry periods. Snowpack accumulated during the cold season affects groundwater recharge and thus influences spring runoff and summer low flows (Hammond *et al.*, 2018; Jenicek and Ledvinka, 2020; Vlach *et al.*, 2020). The amount of snow accumulated during the winter period together with the character of a subsequent snowmelt process significantly determines the availability of water in many regions, thus affecting agriculture, hydropower generation, water supply management and other related sectors.

Regarding the scope of this thesis, the effects of snow on flood risk are the most relevant to be highlighted here. There are both, positive and negative impacts of snow associated with flood generating – on the one hand, snowpack helps to mitigate the risk of flooding by temporarily storing water that would otherwise contribute to runoff (Würzer *et al.*, 2017; Paper II), on the other hand, rapid snowmelt under certain conditions, especially during rain-on-snow (RoS) events, can lead to increased runoff and potential severe flooding.

Understanding these hazardous events is therefore crucial for flood management and risk mitigation. Given the importance of snow mentioned above, an understanding the snow processes in general, as well as the role of various influencing factors, is essential for effective water resource management, particularly in the face of climate change, which alters snowfall patterns and the onset and character of snowmelt.

2.2 Snow accumulation and snowmelt

Snow accumulation intensity and snowmelt rates directly determine the volume of accumulated snow, and storage of water respectively. At local scales, snow accumulation and ablation are controlled by a number of factors (Fig. 2). These include 1) meteorological conditions (Assaf, 2007), such as air temperature, precipitation rate, air humidity, or wind speed, 2) local topography (Zheng *et al.*, 2016), including elevation, aspect and slope, and 3) canopy structure (Jenicek *et al.*, 2018; Lendzioch *et al.*, 2019; Paper I).

As investigated in several studies (Helgason and Pomeroy, 2012; Lundquist *et al.*, 2013; Broxton *et al.*, 2015; Paper I), the forest significantly influences the amount and distribution of individual energy fluxes and thus the snowpack energy balance (Section 2.2.1), snowpack physical properties and water volume (Musselman and Pomeroy, 2017; Roth and Nolin, 2017). Detailed analysis of the effect of sub-canopy snowmelt was provided in Paper I which concluded the important role of both radiation fluxes (shortwave and longwave radiation) in decreasing snowmelt rates which is consistent with the findings presented by Assaf (2007); Webster *et al.* (2016); Malle *et al.* (2019).

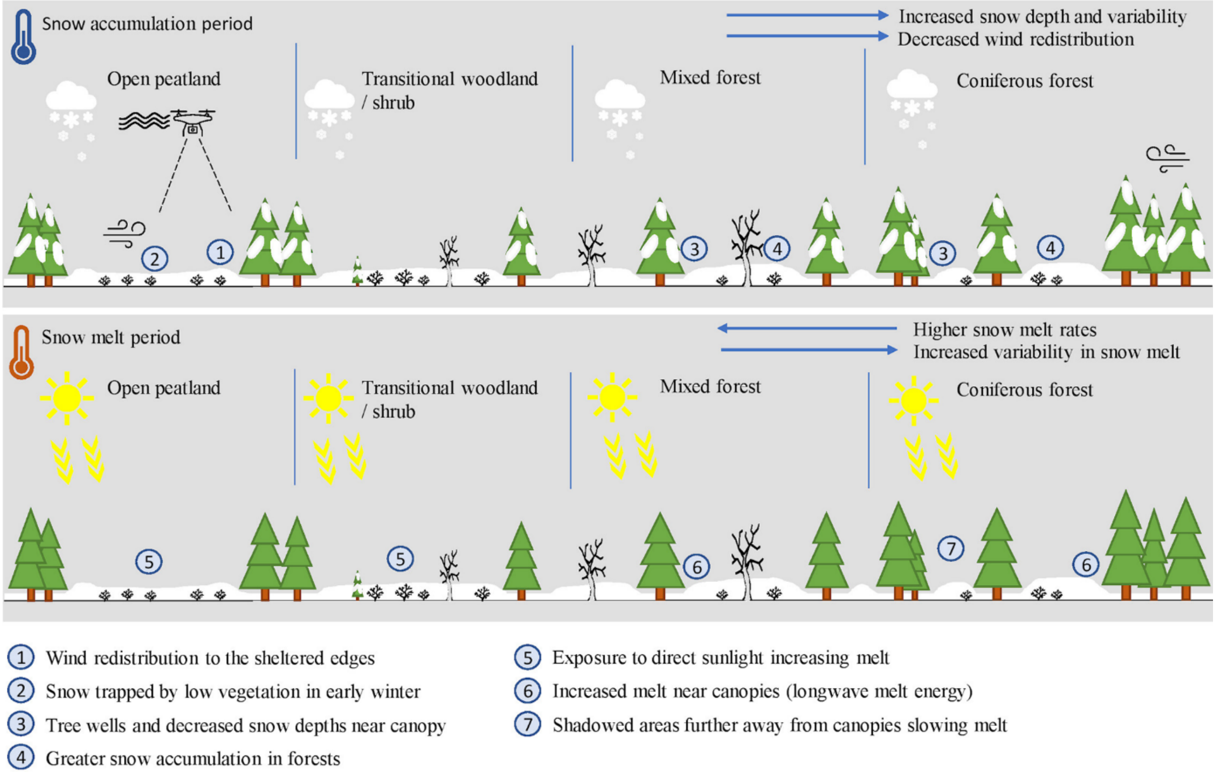


Figure 2: Snow accumulation and snowmelt processes for different land cover types observed by Meriö et al. (2023).

In addition, the canopy structure considerably affects the wind speed (Fig. 2), reducing the intensity of snow redistribution by the wind. Forest density also determines the interception rate which primarily controls the subcanopy snow accumulation. According to Helbig *et al.* (2019), through interception, up to 60% of the cumulative snowfall may be captured by tree crowns in coniferous forests during winter. A high interception rate combined with a reduced redistribution of snow by wind may lead to notable differences in the amount of accumulated snow between forested sites and open areas. This topic was addressed in detail in Paper I since understanding the effect of forests on snowmelt dynamics enables better estimates of snow and water storage and contributes to higher accuracy of spring flood forecasting (Hock, 2003).

There are basically two main methods used for snowmelt rate calculation – the complex snowpack energy balance method and the degree-day-based approach.

2.2.1 Snowpack energy balance method

The snowpack energy balance method is a comprehensive approach to understanding the snowpack behavior, in particular the snowmelt process. This method quantifies heat fluxes, various energy inputs and outputs, at the atmosphere-snow-soil ground interfaces and heat exchange within the snowpack (Singh and Singh, 2001) (Fig. 3). By considering all energy sources, this method allows accurate predictions of snowmelt and its subsequent effects on runoff response. However, the entire energy balance-based calculations require a high demand for detailed meteorological and hydrological data. This physically-based approach was applied in Paper I to calculate the main energy fluxes driving the snowmelt process in different environments (coniferous forest, disturbed coniferous forest, meadow).

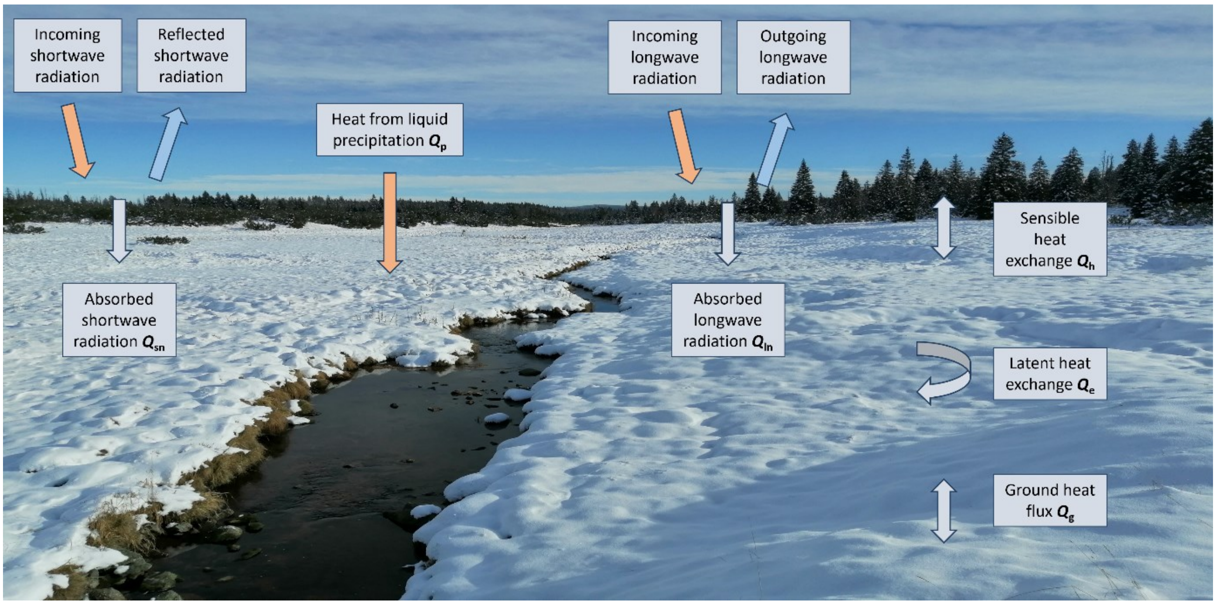


Figure 3: Scheme of individual energy fluxes within the complex snowpack energy balance (photo by author).

Equation (1) expresses the calculation of the total heat Q_m (W.m^{-2}) available for snowmelt and refreezing based on a sum of six components. Positive values of Q_m represent snowpack energy gains resulting in gradual warming of the snowpack (snowmelt occurs when the snowpack temperature reaches 0°C within the entire snow profile). Negative Q_m values signify energy losses, resulting in a decrease of snowpack temperature (no snowmelt):

$$Q_m = Q_{ns} + Q_{nl} + Q_h + Q_e + Q_p + Q_g \tag{1}$$

where Q_{ns} is net shortwave radiation (SWR), including solar radiation that reaches the snow surface. Q_{nl} represents net longwave radiation (LWR) which encompasses the absorbed radiation emitted by the atmosphere and the earth's surface. Q_h is the sensible heat flux, meaning the energy exchange due to temperature differences between the air and the snow surface. Q_e represents the latent heat flux which involves the energy exchange due to phase changes of water. Q_p is the heat supplied by liquid precipitation (investigated in more detail in Paper I) and Q_g is the ground heat flux, attributing energy transfer between the snowpack and the ground beneath it. All components use the same unit (W.m^{-2}).

Since the spatial and temporal variability of key components of the energy balance is important for the timing and intensity of runoff, the topic has been widely studied (Garvelmann *et al.*, 2015; Welch *et al.*, 2016), including the application of energy balance methods into the hydrological modeling (Ellis *et al.*, 2011; Helgason and Pomeroy, 2012; Gouttevin *et al.*, 2015) (Section 3.1.2). Several authors have focused on selected components in their studies, mainly on the role of radiative fluxes; SWR (Courbaud *et al.*, 2003; Reid *et al.*, 2014; Musselman *et al.*, 2015) and LWR (Iziomon *et al.*, 2003; Essery *et al.*, 2008; Webster *et al.*, 2016).

2.2.2 Degree-day approach

The degree-day approach represents the simplified energy balance of the snowpack (DeWalle and Rango, 2008). This approach is based on the principle that the amount of snowmelt is directly related to the accumulated temperature over time, providing a simplified yet effective way to model and predict snowmelt. The basic degree-day calculation is given by Equation (2):

$$M = \mathrm{m_f}(T_a - T_b) \tag{2}$$

where M represents snowmelt volume (mm.d^{-1}), T_a is air temperature, usually daily mean (°C), T_b represents the critical temperature for snowmelt initiation (°C). The critical temperature of 0°C is generally used for melt calculation, however, a wider range can be applied regarding the conditions and of the study area (Hock, 2003). $\mathrm{m_f}$ (alternatively DDF) is a melt factor or degree-day factor (mm.°C^{-1}.d^{-1}) representing the decrease in snow water equivalent (SWE) per day caused by the air temperature (T_a) change by 1°C compared to the critical air temperature (T_b).

A wide range of melt factors can be found in the literature as different variables affect snowmelt. These include meteorological conditions (rainfall intensity, cloudiness, wind, humidity), snowpack properties (snow density, layering, snow surface contamination), site specifics (canopy structure, topography) and other factors (season). Most $\mathrm{m_f}$ values fall between 1 and 8 mm.°C^{-1}.d^{-1}, according to DeWalle and Rango (2008).

The degree-day approach in its simple version was used in many recent studies (Freudiger *et al.*, 2014; Girons Lopez *et al.*, 2020). Jenicek *et al.* (2017) quantified the role of different forest types on snowmelt processes with the $\mathrm{m_f}$ ranging from 2.1 to 3.1 mm.°C^{-1}.d^{-1}. A more complex degree-day calculation was applied in Papers II-IV where the HBV snow routine was used to simulate snow accumulation and snowmelt rates. This model routine uses an extended degree-day approach, that includes potential refreezing of meltwater and snow water holding capacity in its calculation (see Section 3.1.3 for more details).

Despite its limitations, the simplicity and effectiveness of the degree-day method make it an indispensable component of hydrological studies and applications. Temperature-index methods have been widely used in hydrological modeling to approximate snowpack energy exchange rather than using the more data-intensive energy-budget approaches (DeWalle and Rango, 2008).

2.2.3 Energy fluxes in different canopy structures

Specific scientific interest has been put on the contribution of the individual energy balance components regarding the differences in canopy structure (Paper I) as understanding the effects of forest cover on the sub-canopy energy balance is important for improving snowmelt models for accurate prediction of catchment runoff from forested catchments.

Based on the performed research, individual energy fluxes vary significantly among different canopy structures and there are considerable differences between forested sites and open non-forested areas. Thus, potential changes in forest structure, such as forest disturbances, may lead to significant changes in snowmelt dynamics and runoff conditions (Su *et al.*, 2017; Bartik *et al.*, 2019), with expected faster snowmelt (Moeser *et al.*, 2016; Förster *et al.*, 2018, Paper I). These differences can be mainly explained by (a) lower snow interception (Helbig *et al.*, 2019), (b) the increase in incoming SWR due to a lower shading effect of trees after forest disturbance (Pomeroy *et al.*, 2012; Malle *et al.*, 2019) and (c) the decrease in incoming LWR emitted by trees which is an important energy contributor (Essery *et al.*, 2008; Webster *et al.*, 2016; Paper I).

The results of our experimental study (Paper I) showed that SWR was the major energy source at the open site, while, in the dense coniferous forest, net SWR represented only 7% of the amount at the open site due to tree shading (Fig. 4). In contrast, net LWR was the dominant energy contributor at the healthy forest site (on average 41% of all energy fluxes) and thus contributed most to snowmelt.

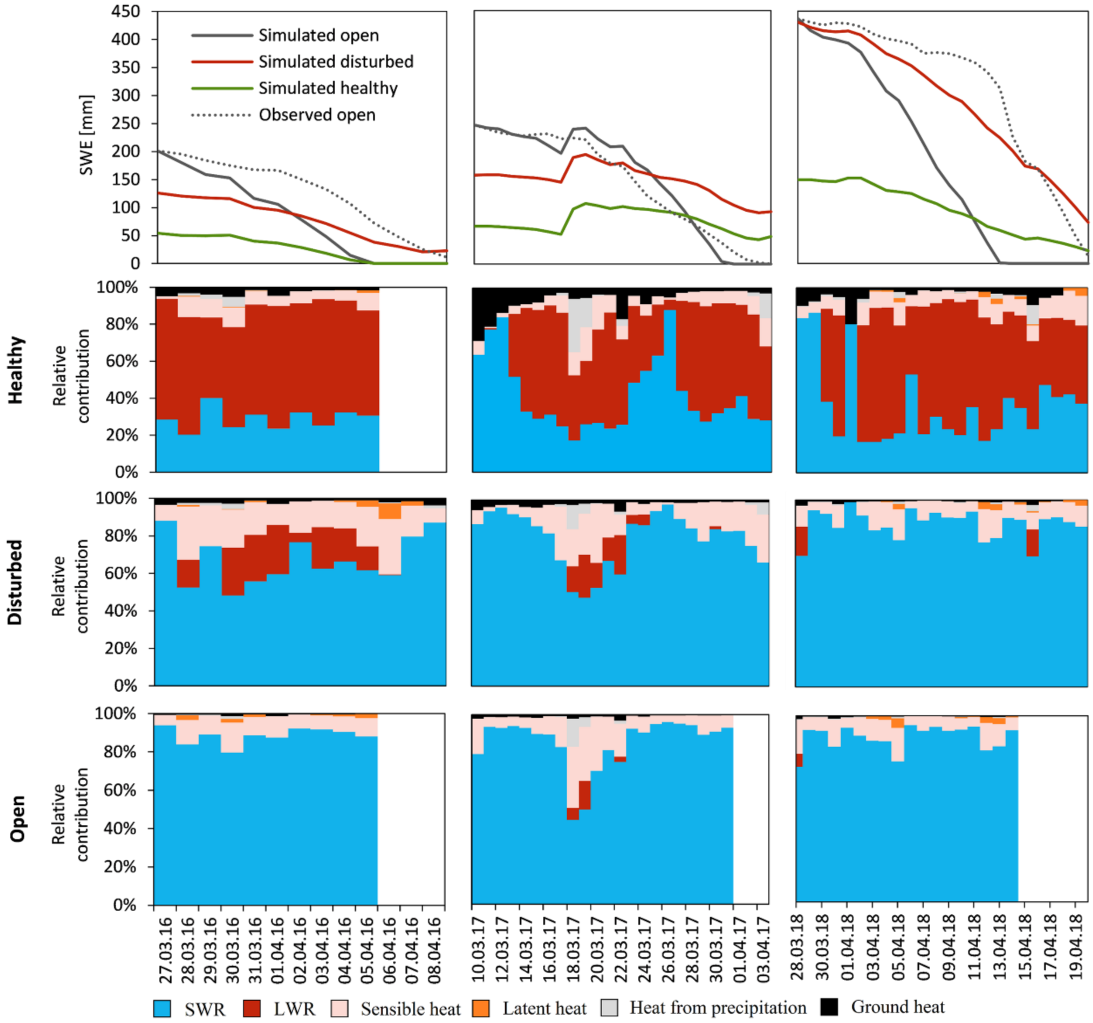


Figure 4: Simulated and observed SWE at individual study sites with different forest structures during the main spring snowmelt periods in seasons 2016, 2017 and 2018 (first line panels). Relative daily contribution of individual energy fluxes to snowmelt rates at the healthy forest site (second line panels), disturbed forest site (third line panels) and open site (fourth line panels) (Paper I).

Notable energy and snowmelt changes were identified in the disturbed forest within the 3 years of gradual forest decay (Fig. 4).

Paper I provided some interesting conclusions related to the turbulent energy exchange since we were specifically interested in the contribution of heat energy from rain. On a seasonal average, rainfall added rather a negligible amount of energy (up to 10%) to the snowpack. This supports the findings of other studies (Mazurkiewicz *et al.*, 2008; Trubilowicz and Moore, 2017; Li *et al.*, 2019). However, the increased importance of heat from the rain to snowmelt was found during the days with heavier precipitation, supporting the fact that energy from rain can be very important when assessing the snowpack energy balance at daily and shorter temporal resolutions (Würzer *et al.*, 2016; Juras *et al.*, 2017). This finding initiated our subsequent interest in rain-on-snow events (Paper II-IV).

2.3 Rain-on-snow events

2.3.1 RoS principles

Rain-on-snow (RoS) events occur when rain falls on snow, intensifying energy fluxes within the snowpack, and can substantially accelerate snowmelt (Garvelmann *et al.*, 2014; Paper I). These events represent an example of multiple meteorological factors acting together, as these meteorological situations are often accompanied by increased air temperature and windy conditions. During RoS events, turbulent (latent and sensible heat) fluxes within the entire snowpack energy balance (Section 2.2.1) are usually dominant (Würzer *et al.*, 2016). Such turbulent energy exchange processes are important when assessing the snowmelt on a daily (event) scale. Heat directly added by rain can contribute more than 25% of the total energy available for snowmelt on days with heavy rainfall (Jennings and Jones, 2015; Paper I). Furthermore, torrential rainfall events are often associated with additional turbulent heat input (Marks *et al.*, 1998; Garvelmann *et al.*, 2014), and longwave radiation that can further accelerate snowmelt (Sezen *et al.*, 2020). On longer (seasonal) scales, the radiation components (shortwave and longwave radiation) become more important (Paper I). The heat directly supplied by rain during RoS events tends to be a minor contributor to snowmelt – typically up to 10% of the total energy balance at longer time scales (Mazurkiewicz *et al.*, 2008; Trubilowicz and Moore, 2017; Li *et al.*, 2019, Paper I).

Moreover, RoS events affect important processes, parameters and mechanisms within the snowpack, including changes in snowpack saturation, an increase in liquid water content, and a decrease in snow albedo, which enhances the energy absorption of the snowpack. These secondary effects can persist for several days after the rainfall event and further accelerate snowmelt (Yang *et al.*, 2023).

2.3.2 RoS-driven hydrological response

Most RoS events do not directly lead to severe flooding because the snowpack, especially fresh snow, can store large amounts of rainwater, resulting in reduced or even zero runoff (Wayand *et al.*, 2015; Paper II). However, under certain conditions, these events can potentially trigger excessive runoff and widespread floods (Berghuijs *et al.*, 2019; Girons Lopez *et al.*, 2020; Brunner and Fischer, 2022). Elevated RoS-driven runoff is often more intense and short-lived compared to the thermally driven types of snowmelt and associated runoff, along with lower groundwater recharge and infiltration rates (Earman *et al.*, 2006).

The interaction of different influencing factors makes it difficult to accurately predict the effect of snow cover on runoff formation for an upcoming RoS event (Würzer *et al.*, 2016). Several studies (Garvelmann *et al.*, 2015; Würzer *et al.*, 2016; Brandt *et al.*, 2022; Paper II) indicated the strong influence of initial snowpack properties on runoff formation during RoS. Therefore, the behavior of rainwater within the snowpack is one of the important issues to be properly understood. Detailed analyses of rainwater behavior were performed by Surfleet and Tullos (2013), Juras *et al.* (2017), or Würzer *et al.* (2017).

2.3.3 RoS occurrence in the current climate

The most vulnerable regions of the world experience more than 10 RoS events per year (Cohen *et al.*, 2015; Suriano, 2022) (Fig. 5). The occurrence and intensity of RoS events have been widely studied in recent years, with the research mainly focused on North American catchments (Grenfell and Putkonen, 2008; Bieniek *et al.*, 2018; Musselman *et al.*, 2018; Crawford *et al.*, 2020), where maximum daily runoff is associated with RoS events 80% of the time between January and May, according to Il Jeong and Sushama (2017). Several other studies have been conducted in Siberia (Bartsch *et al.*, 2010), Scandinavia (Pall *et al.*, 2019; Poschlod *et al.*, 2020; Mooney and Li, 2021), Central Europe (Freudiger *et al.*, 2014; Schirmer *et al.*, 2022; Papers II-IV), high mountain Asia (Yang *et al.*, 2022; Maina and Kumar, 2023), as well as in the terrestrial Arctic (Rennert *et al.*, 2009; Bartsch *et al.*, 2023).

RoS events have been in the focus of hydrologists in recent decades. Although the topic is gaining scientific interest, the complex RoS processes are still on the list of unsolved problems in hydrology proposed by Blöschl *et al.* (2019).

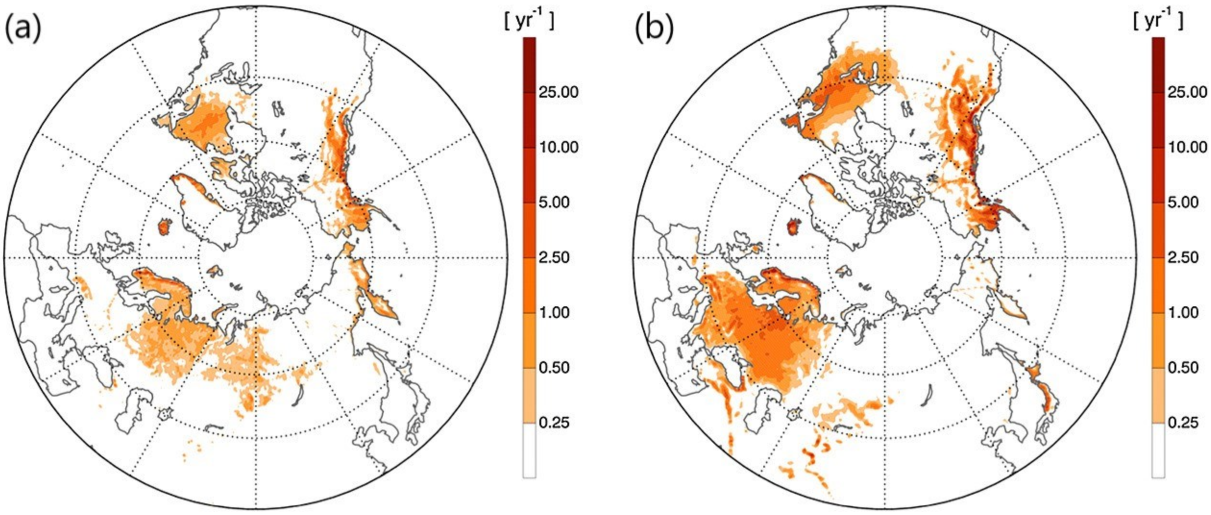


Figure 5: The number of RoS events across the Northern Hemisphere for September-November (a) and December-February (b) for the period 1979/1980 to 2013/2014 (Cohen et al., 2015).

2.4 Changes driven by climate change

2.4.1 Future snow

Projected changes in climate variables will have a strong impact on snow-related hydrometeorological processes, including snow storage and snowmelt dynamics (Jennings *et al.*, 2018; Sezen *et al.*, 2020), variations in precipitation intensity and distribution, as well as a shift from snowfall to rain (Serquet *et al.*, 2011; Musselman *et al.*, 2018; Blahusiakova *et al.*, 2020; Li *et al.*, 2020). As a result, snow cover depth and the number of days with snow on the ground, snow density and snowfall fraction have already shown signs of decreasing trends in many regions of the world (Beniston and Stoffel, 2016; Marty *et al.*, 2017; Li *et al.*, 2020; Notarnicola, 2020; Nedelcev and Jenicek, 2021; Urban *et al.*, 2023) and are expected to be affected by gradual climate warming. Many studies predict a significant decrease in snow storage amounts and durations in the future (Notarnicola, 2020; Jenicek *et al.*, 2021; Nedelcev and Jenicek, 2021; Hale *et al.*, 2023). Snow-related changes are likely to become the main driver of interannual variability in future RoS occurrence (Suriano, 2022).

2.4.2 Future RoS

Since global temperature and precipitation patterns are changing the frequency and spatial distribution of RoS are also changing. Much of the current research focuses on highlighting the changes in RoS and snow conditions regarding ongoing climate change (Paper IV).

Recent studies have shown that the behavior and occurrence of RoS can be strongly determined by its spatial and temporal distribution (López-Moreno *et al.*, 2021). In general, the number of RoS events is expected to decline in low- and mid-latitude areas and low-elevation regions, primarily due to a shortening of the period with the snow on the ground (Mccabe *et al.*, 2007; Surfleet and Tullos, 2013; Musselman *et al.*, 2018; Li *et al.*, 2019; López-Moreno *et al.*, 2021; Mooney and Li, 2021, Paper III). In contrast, RoS events are predicted to occur more frequently in the future due to an increase in the number of days with rain, triggered by increasing air temperature, in both high-latitude and high-elevation regions (Surfleet and Tullos, 2013; Morán-Tejeda *et al.*, 2016; Il Jeong and Sushama, 2017; Trubilowicz and Moore, 2017; Musselman *et al.*, 2018; Li *et al.*, 2019; Sezen *et al.*, 2020, Paper IV).

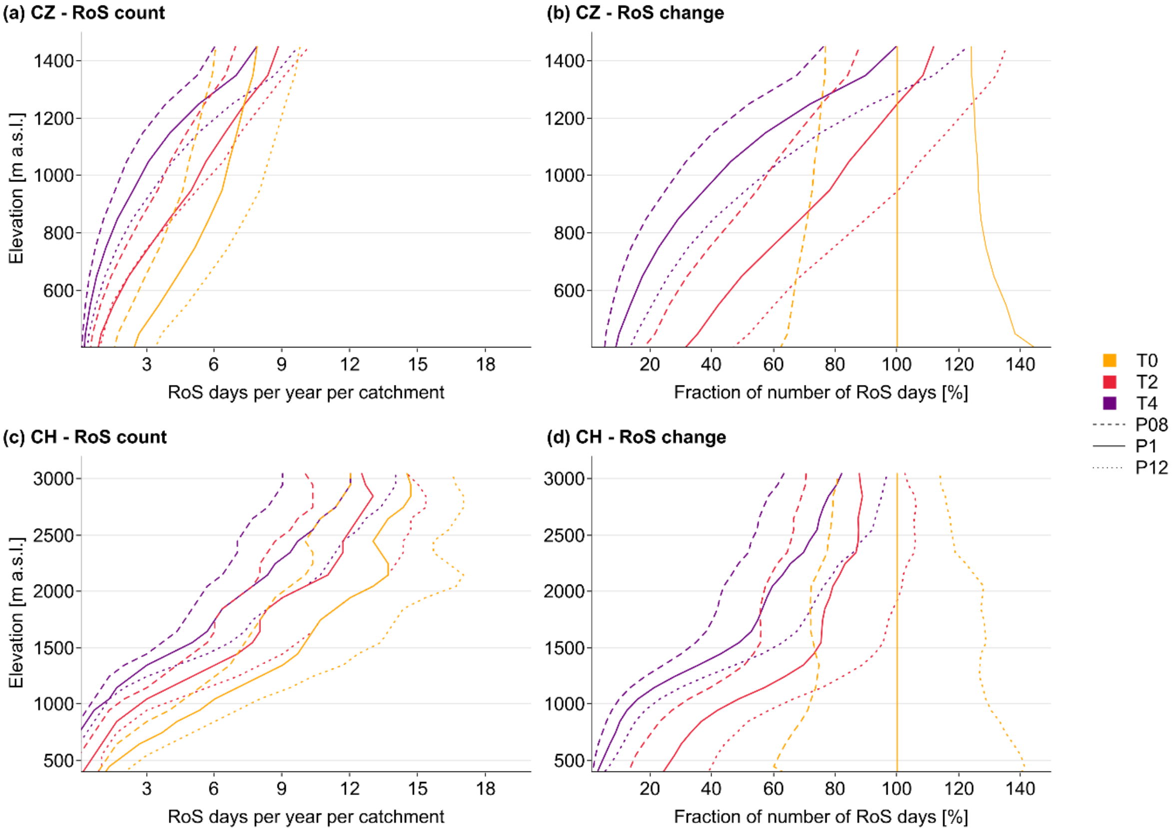


Figure 6: RoS day occurrence (a and c) and a fraction of the number of RoS days for selected projections compared to reference conditions T0_P1 (b and d) for distinct elevation zones in both Czech (a and b) and Swiss (c and d) regions. Line colors and styles represent selected temperature (T) and precipitation (P) projections (Paper IV).

In terms of temporal distribution, future projections for the humid mountain regions suggest an overall increase in RoS in the middle of the winter season (from November to March) as more precipitation will fall as rain rather than snow (Il Jeong and Sushama, 2017). A decrease in the number of RoS is expected in early and late winter due to the shortened period with existing snow cover (Hundecha *et al.*, 2017; Sezen *et al.*, 2020). Similar findings with varying spatial and temporal trends in RoS days for specific months of the winter season at different elevations were found in Papers III and IV.

Despite increasing scientific interest, future climate change-driven changes in RoS are still subject to large uncertainties (López-Moreno *et al.*, 2021; Schirmer *et al.*, 2022) and there is still limited knowledge about the role of different climate variables controlling the RoS behavior, RoS dynamics and RoS-driven runoff responses. The real impact of climate change on RoS events and their associated hydrological consequences remains unclear, mainly due to their complex nature (Sezen *et al.*, 2020; Mooney and Li, 2021; Myers *et al.*, 2023). Moreover, most European studies have had a limited focus on elevation, which significantly influences snow cover and precipitation phase and consequently RoS occurrence.

Papers III and IV addressed the aforementioned research gaps since understanding these specific spatial and temporal changes in RoS, with a particular focus on elevation (Fig. 6), and climate drivers is critical for future water management strategies to mitigate risks and impacts associated with RoS events. A wider area is expected to become vulnerable to RoS-related hazards in the future.

3 Materials and methods

3.1 Study areas

All studies included in the thesis shared the same geographical location within the region of central Europe, including mountainous catchments of various sizes and elevations. These catchments were selected because they are affected by snow, show near-natural runoff regimes and have no glacierized areas. Moreover, most of them represent areas in the rain-snow transition zones where large changes in snow storage and RoS occurrence typically occur. Table 1 summarizes the areas of interest within each paper with selected characteristics. Performed studies covered a range of temporal and spatial scales with different levels of detail, from detailed analyses of snowpack dynamics at the catchment scale to more generic assessments at the national or regional scale involving dozens of catchments.

The first study (Paper I) was carried out in the Ptaci Brook catchment (an experimental catchment of the Charles University, Prague) in the Bohemian Forest (Sumava National Park) in the southwestern part of Czechia. The second study (Paper II) was located in the two highest Czech mountain ranges, Krkonoše and Jeseníky mountains in the Sudetes region (southeastern Czechia). The third study (Paper III) extended this dataset by several other mountain ranges across Czechia. The last study (Paper IV) consisted of 93 mountainous catchments, including several mountain ranges in Czechia, and eastern Germany (located within the same cross-border mountain ranges), and an additional dataset containing catchments in Switzerland (located in three parts of the Alps) (Table 1).

Table 1: Summary of the study areas.

Study	Country	Catchment count	Elevation range [m a.s.l.]	Area range [km^2]	Time period	Spatial scale
Paper I	Czechia	1	1130-1150	4	2016-2018	Local
Paper II	Czechia	15	438-1603	3-181	2004-2014	Regional
Paper III	Czechia	40	295-1489	2-383	1965-2019	Regional
Paper IV	Czechia, Germany, Switzerland	93	269-3269	2-383	1980-2010	National

3.2 Data collecting and analyzing

3.2.1 Field measurements

Field measurements in snow hydrology are essential to accurately assess snowpack properties such as snow depth, snow density, and snow water equivalent (SWE), and to understand snowpack dynamics and snow processes in detail. Field campaigns provide critical data for predicting snowmelt rates and timing which are crucial for effective water resource management, flood forecasting, or agricultural planning. By collecting real-time and historical data, field measurements help to validate and calibrate hydrological models, thereby increasing their reliability (Sections 3.2.2 and 3.2.3).

Complex data collecting with dozens of field measurements over three consecutive winter seasons was the essential part of the research presented in Paper I. Apart from basic manual snow measurements (including snow depth, snow density, and SWE measurements) during the main spring snowmelt periods, the studied experimental catchment (Ptaci Brook) is equipped with the automatic measurements of snow depth and SWE, together with air, snow and soil temperature, precipitation, air moisture and shortwave and longwave radiation. The SWE data are collected directly in the study catchment using a Snow Pack Analyzer (SPA) device (Fig. 7). Three stripes (two placed horizontally, one placed diagonally) measure the electric impedance and provide the aggregate information about the ratio of liquid water, ice and air from the entire snow column.

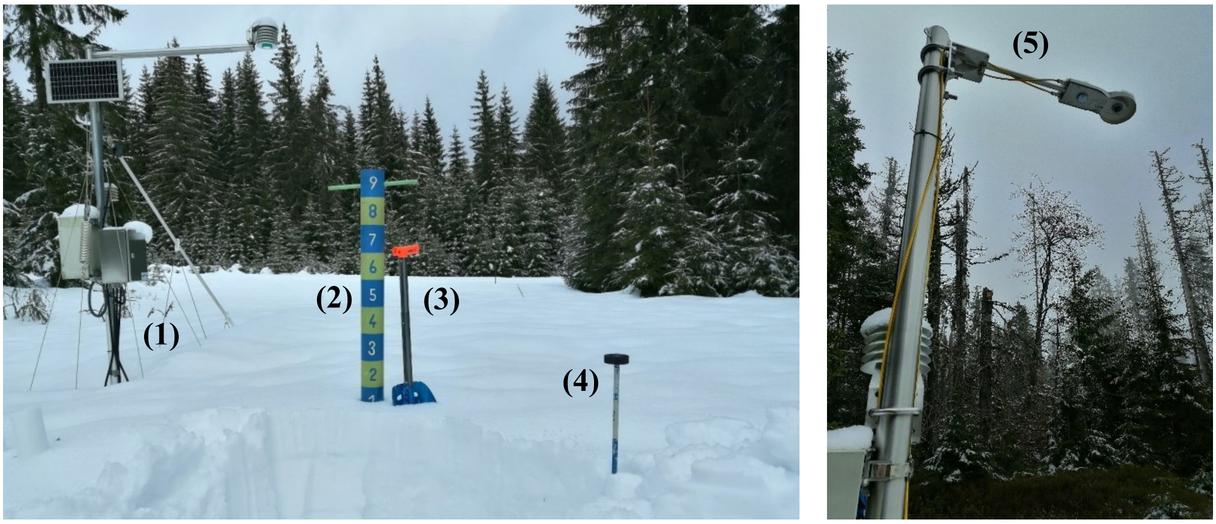


Figure 7: Selected equipment and devices used during the field campaigns in the Ptaci Brook catchment, Sumava National Park: Snow Pack Analyzer (1), snow tube (2), shovel (3), snow measuring stick (4), and radiometer (5) (photos by author).

Regarding the energy balance topic within the scope of Paper I, another specific, not directly snow-related device called the CNR4 Net Radiometer (Fig. 7) was used for the assessment of incoming and reflected shortwave (SWR) and longwave (LWR) radiation at plots with different canopy structures. This device uses pyranometers (for SWR measurements) and pyrgeometers (for LWR measurements), allowing the evaluation of global and reflected radiation, and thus the calculation of albedo, as one of the important parameters affecting snowmelt dynamics.

3.2.2 Modeling approaches

With the development of technology, modeling techniques are now becoming a widely used method in catchment hydrology studies. Hydrological modeling has become an essential tool for understanding, predicting, and managing the complex dynamics of water systems, including snow processes. By integrating diverse data sources and establishing relations, hydrological models can contribute to a better understanding of hydrological variables and their interactions. Snow hydrological models simulate snow accumulation, snowmelt processes, and runoff generation, providing important insights for water resource management, flood forecasting, drought prevention, or more specific hydrological events such as RoS situations. Using climate data and possible future scenarios, snow hydrology models can improve our understanding of how changing climatic conditions affect snow dynamics.

For RoS quantification and the evaluation of RoS changes, modeling techniques are even more important because RoS events generally occur at higher elevations and higher latitudes, which typically have sparse observation networks (Pall *et al.*, 2019). Therefore, many studies have recently employed modeling approaches to detect RoS events or predict climate change-driven RoS changes (Table 2). Individual models use different numbers of inputs and influencing factors that are included in the model calculation, while an increasing model complexity (more parameters included) leads to increasing uncertainty in the model simulation. Therefore, model calibration and validation procedures are being assessed for their ability to achieve as much agreement as possible between observed and simulated values (Section 3.2.3).

Table 2: List of hydrological and meteorological models frequently used in RoS-related studies.

Study	Model used
Paper II-IV	HBV (Hydrologiska Byråns Vattenavdelning)
Schirmer *et al.* (2022)	AWE-GEN-2d
Mooney and Li (2021; Yang *et al.* (2022)	Noah-MP
Sezen *et al.* (2020)	GR6J (Génie Rural à 6 paramètres Journalier), CemaNeige snow modul
Li *et al.* (2019)	VIC (Variable Infiltration Capacity)
Corripio and López-Moreno (2017)	WRD-ARW
Wever *et al.* (2016); Würzer and Jonas (2018)	SNOWPACK
Pomeroy *et al.* (2016)	CRHM (Cold Regions Hydrological Modelling)
Beniston and Stoffel (2016)	snowMAUS
Wayand *et al.* (2015)	DHSVM (Distributed Hydrology Soil Vegetation Model)
Rössler *et al.* (2014)	WaSiM-ETH (Water Flow and Balance Simulation Model)
Pradhanang *et al.* (2013)	SNODAS (Snow Data Assimilation System)
Mazurkiewicz *et al.* (2008)	SNOBAL

A modeling approach was used in all three RoS-related studies (Papers II-IV). For the model simulations, a time series of meteorological (air temperature, precipitation) and hydrological data (discharge, SWE, snow depth) were collected for individual catchments. These datasets were provided by national institutes based on the location of the study.

3.2.3 HBV model

In order to derive individual components of the rainfall-runoff process, and subsequently to detect RoS days/events and assess the hydrological response, a semi-distributed bucket-type HBV model (Lindström *et al.*, 1997; Seibert and Bergström, 2022) in its software implementation "HBV-light" (Seibert and Vis, 2012) was used in Papers II-IV.

The HBV model is composed of four routines (Fig. 8), including a snow routine that simulates snow accumulation and snowmelt using a degree-day approach (Section 2.2.2), taking the potential refreezing of meltwater and snow water holding capacity into account. In addition to the snow routine, a soil moisture routine calculates groundwater recharge and actual evapotranspiration (AET) as a function of the soil moisture. For this, the input data of potential evapotranspiration (PET) was calculated based on air temperature data using the method presented by Oudin *et al.* (2005). Runoff from two groundwater boxes is simulated by a groundwater routine, from which baseflow is calculated directly by the model. A routing routine calculates the propagation of runoff through the catchment using a triangular function.

Each catchment was split into elevation zones of 100 m. This enables some characteristics to be simulated separately for these elevation zones, specifically precipitation, air temperature (using calibrated lapse rates), SWE, snowmelt, soil moisture, AET and groundwater recharge. For details of the model structure and routines, see Seibert and Vis (2012). This approach was applied in all studies where the HBV model was used (Papers II-IV).

In Papers II-IV, the HBV model was automatically calibrated against the observed mean daily runoff and SWE for each study catchment using a genetic algorithm in 100 independent calibration trials.

Since the genetic algorithm contains stochastic elements, each calibration trial will result in different optimized parameter sets, especially if there is significant parameter uncertainty (equifinality) (Beven, 2021). Following a split-sample approach, the period was divided into calibration and validation windows. Table 3 shows calibration and validation periods for individual studies. As an objective function, a weighted mean of the NSE (the Nash-Sutcliffe model efficiency coefficient) based on the logarithmic runoff series, the volume error and the NSE based on the logarithmic SWE were used for the evaluation of the goodness of fit of the model separately in Papers II-IV.

Table 3: Calibration and validation periods used in the modeling procedures.

Study	Calibration	Validation
Paper II	2004-2009	2010-2014
Paper III	1980-1997	1998-2014
Paper IV (Czech catchments)	1981-1997	1998-2014
Paper IV (Swiss catchments)	1981-2000	2001-2020

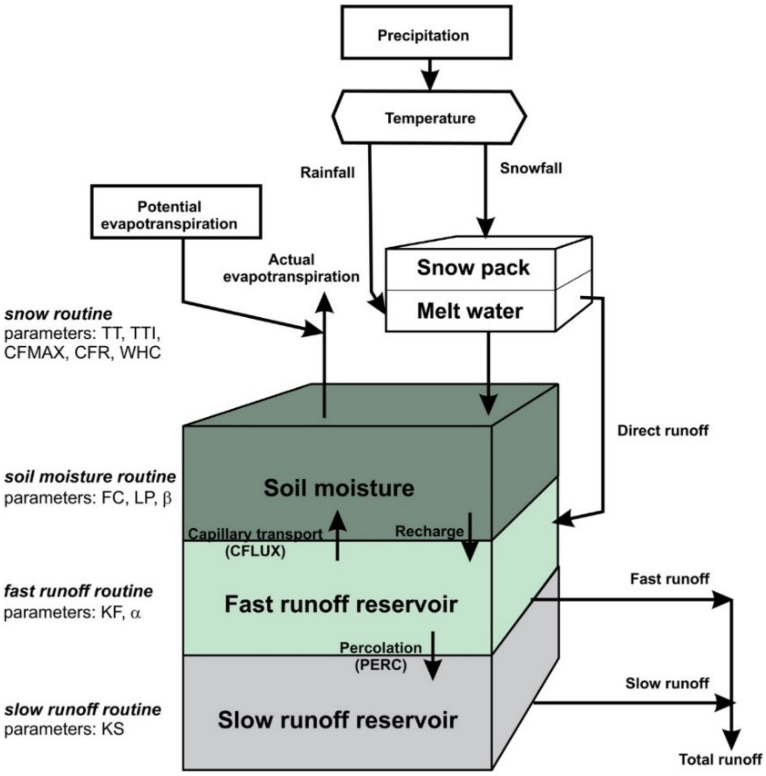


Figure 8: Structure and parameters of the HBV model (Wawrzyniak *et al.*, 2017).

3.3 Identification of RoS events

Although the RoS topic has been a focus for hydrologists over the last several decades, the physical complexity and associated impacts of RoS have led to different definitions and methods used in their assessments (Pall *et al.*, 2019). While variations in the threshold values set to identify individual RoS days/events may significantly affect the total number of recognized situations, a unified RoS definition does not exist in the literature. Different authors use different parameters and thresholds in their studies (Table 4).

For air temperature, several studies (Bieniek et al., 2018; Crawford et al., 2020; Surfleet and Tullos, 2013, Paper III) used the threshold of 0°C for the daily mean air temperature, while numerous recent studies did not specify the temperature threshold for RoS detection (Mooney and Li, 2021; Pall et al., 2019; Schirmer et al., 2022; Yang et al., 2022). In Papers II and IV, the air temperature threshold was calibrated by the model to obtain specific values for each study catchment. Despite the variations in definition, Jennings *et al.* (2018) suggested the temperature range between -0.4 and 2.4°C is valid for 95% of the stations across the Northern Hemisphere.

Table 4: RoS situations defined in selected studies based on several criteria, including air temperature (T), rainfall intensity (P), snow depth (SCE) or snow water equivalent (SWE), snowmelt (M, indicated by a decrease of SCE/SWE) and runoff response (Q_{change}). Q_1 represents 1-year return peak flow, DP is dew point temperature, P_{eq} is a sum of daily rainfall and snowmelt during the RoS event, T_t represents calibrated threshold temperature, +/- indicates whether the value is not defined (-) or defined and not specified (+).

Study	T	P	SCE / SWE	M	Q_{change}
Paper IV	$> T_t$	≥ 5mm/d	SWE ≥ 10 mm	-	-
Paper III	> 0	> 5 mm/d	SWE > 10 mm	-	-
Schirmer *et al.* (2022)	-	> 10 mm/d	SWE > 10 mm	+	-
Yang *et al.* (2022)	-	≥ 5 mm/d	-	≥ 3 mm/d	-
Paper II	$> T_t$	> 0 mm	SWE ≥ 10 mm	-	-
Mooney and Li (2021)	-	≥ 5 mm/d	-	≥ 3 mm/d	-
Sezen *et al.* (2020)	-	-	-	> 0.1 mm/d	+
Crawford *et al.* (2020)	≥ 0°C	≥ 2.54 mm	SCE > 2.54 mm	-	-
Ohba and Kawase (2020)	-	> 10 mm/d	SCE > 10 cm	-	-
Pall *et al.*(2019)	-	≥ 5 mm/d	-	≥ 3 mm/d	-
Bieniek *et al.* (2018)	> 0°C	≥ 0.254 mm/d	SCE > 0 cm	-	-
Würzer and Jonas (2018)	-	≥ 20 mm/d	SCE ≥ 25 cm	-	+
Il Jeong and Sushama (2017)	-	> 1 mm	SWE > 1 mm	-	+
Trubilowicz and Moore (2017)	-	> 0.1 mm/3h; 5 mm/d	SWE > 10 mm	+	-
Guan *et al.* (2016)	-	≥ 10 mm/d	SWE > 0 mm	+	-
Würzer *et al.* (2016)	0.7-1.7°C	≥ 20 mm	SCE ≥ 25 cm	-	+
Cohen *et al.* (2015)	-	≥ 10 mm/d	SCE > 0 cm	-	-
Freudiger *et al.* (2014)	-	≥ 3 mm	SWE ≥ 10 mm	+	20% P_{eq}
Surfleet and Tullos (2013)	> 0°C	> 0 mm	SCE > 0 cm	+	$\geq Q_1$
Mazurkiewicz *et al.* (2008)	> 0.5°C DP	> 0.1 mm/3h	SCE > 0 cm	-	-
McCabe *et al.* (2007)	-	> 0 mm	SCE > 0 cm	+	-

Following the relevant definition of RoS days/events, these hydrological situations were comprehensively analyzed from various points of view (Fig. 1), including interannual variability of RoS (Paper II), RoS trends and climate-driven changes (Papers III and IV), and their effect on runoff (Papers II-IV).

4 Published research overview

This chapter summarizes the results and scopes of all four research papers compiled within the dissertation thesis.

4.1 Paper I

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

This experimental study was performed in a mountainous catchment of the Ptaci Brook in the Bohemian Forest, southwestern Czechia, aiming to understand snowmelt processes in different canopy structures. Investigating the effects of forest cover on the sub-canopy energy balance is important for improving snowmelt models for accurate prediction of catchment runoff from forested mountain catchments (Hock, 2003), especially in the context of land cover changes due to either human activities or climate change.

This study quantified the changes and temporal variations in shortwave (SWR) and longwave (LWR) radiation and their effects on snowmelt at three sites with different canopy structures, including a treeless open area, a forested environment and a site covered by a coniferous forest disturbed by the bark beetle (*Ips typographus*). We benefited from detailed measurements from radiometers placed at all three experimental sites. The sampling design adopted in this study enabled the main components of the energy balance to be analyzed in hourly, daily and seasonal resolution. This research added to earlier studies by focusing on the evolution of both main radiation fluxes (SWR and LWR) during 3 years with gradual forest decay and also by detailed quantification of the relative contribution of other energy fluxes, such as sensible heat, latent heat, ground heat and energy supplied by liquid precipitation (Fig. 9).

Rain contributed from 13 to 29% during the days with heavy rainfall (RoS days) which supported the fact that energy from rain can be very important when assessing the snowpack energy balance at daily and shorter temporal resolutions. Therefore, the topic was further investigated in Papers II-IV. This study concluded that coniferous forest significantly modifies the snowpack energy balance by reducing the total amount of solar SWR and increasing the role of tree-emitted LWR. The results showed that net SWR at the healthy forest site represented only 7% of the amount at the open site due to the shading effect of trees. In contrast, net LWR represented a positive component of the snowpack energy balance at the healthy forest site and thus contributed the most to the snowmelt. The progressive decay of disturbed forest caused decreased LWR and increased SWR, resulting in accelerated snowmelt rates by 50%.

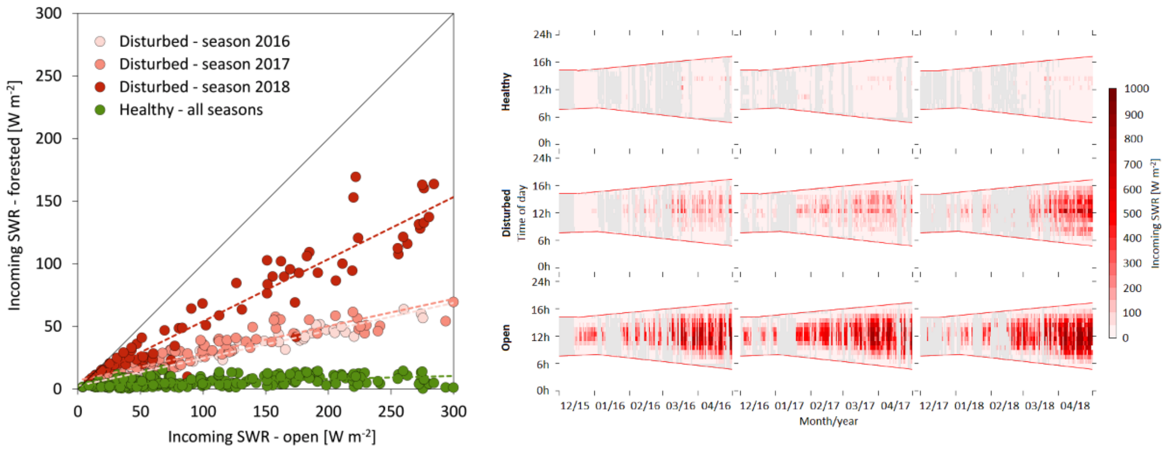


Figure 9: Sample figure from Paper I. Mean daily incoming shortwave radiation (SWR) at the open site compared to forested sites during seasons 2016, 2017 and 2018 (left panel). Mean hourly incoming SWR at the healthy spruce forest site, disturbed forest site and open site during seasons 2016, 2017 and 2018. Red lines represent time of sunrise and sunset. Grey color represents missing data (right panel).

4.2 Paper II

Juras R, Blöcher JR, 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: 127002 https://doi.org/10.1016/j.jhydrol.2021.127002

The RoS-related hydrological response was comprehensively analyzed in this study. Although several studies have focused on modeled runoff response or on single events, empirical analyses of the extended RoS events dataset using measured streamflow at an hourly resolution are rather rare or are even missing in many regions with seasonal snow cover, including European regions outside of the Alps. RoS events are thought to cause severe winter/spring floods, but in most cases, they do not trigger elevated runoff as the snowpack can store a considerable amount of incoming rainwater (Juras *et al.*, 2017). Understanding the hydrological regime of RoS is becoming even more important with the ongoing decline of the snowfall fraction and subsequent changes in snow storage. This study contributed to knowledge of the role of individual climate and snowpack characteristics which control the dynamics of runoff response.

We identified 611 RoS situations which were further analyzed and classified using selected meteorological, snow and runoff indices, based on the observed data and data simulated by the hydrological HBV model. This study benefited from 11 years (10 cold seasons from 2004 to 2014) of hourly climatological and hydrological data for 15 near-natural catchments at different elevations within the highest Czech mountain ranges (Krkonoše and Jeseníky mountains). The focus on elevation was essentially important in this study (Fig. 10). Our methods accounted for the fact that only a part of the catchment contributes to runoff during the specific RoS events due to the strong dependence of snowmelt on air temperature at specific elevations. The analysis of the runoff response revealed that only 5% of RoS events resulted in high runoff exceeding the 1-year return period, but most of the events (82%) did not cause a significant runoff increase. Moreover, we classified these events according to the major driver controlling runoff response using self-organizing maps. This method enabled us to categorize the events and better understand what combination of hydrometeorological characteristics led to various runoff responses. Low snow depth together with high volumes of rain were identified as important factors in the generating of high runoffs. In contrast, higher snow depths affected by rain under lower air temperatures usually resulted in lower runoffs. The results proved the importance of the snowpack in preventing extreme runoff even when a large amount of rainfall occurs.

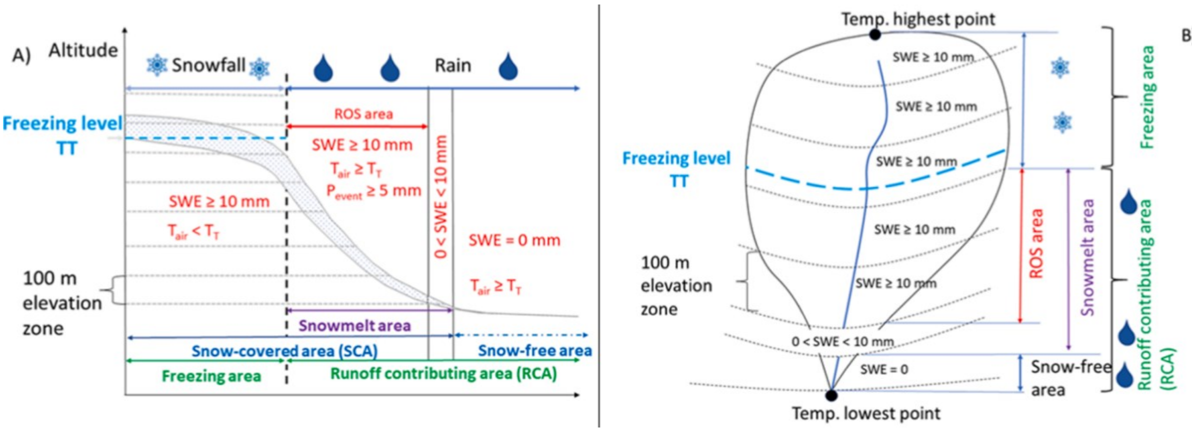


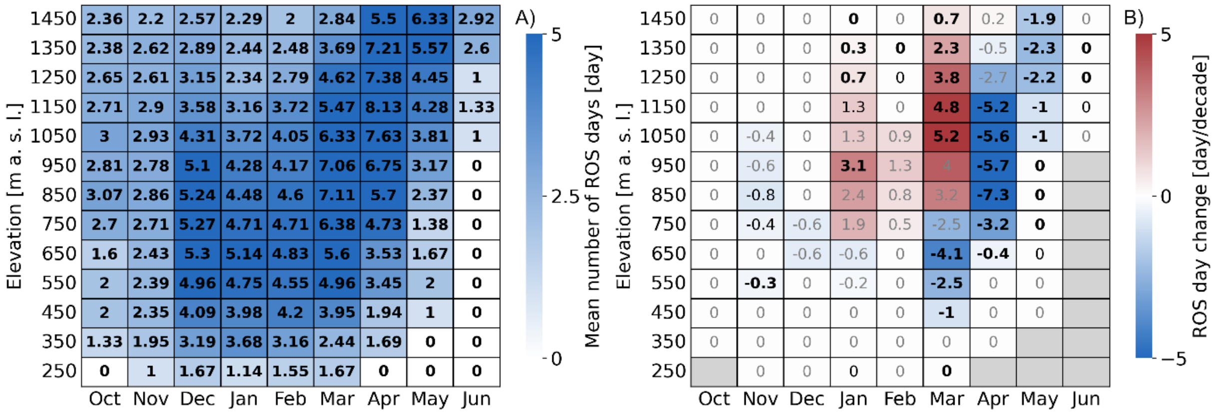
Figure 10: Sample figure from Paper II. The concept of catchment division by elevation zones and area related to snow cover, RoS event, rain-affected area, snow-free area, and runoff area depicted as a a) side and b) plan view. Symbol P_{event} represents hourly rainfall and T_T is the threshold temperature [°C] calibrated for each catchment.

4.3 Paper III

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* 68 (4): 572–584 https://doi.org/10.1080/02626667.2023.2177544

With regards to an expected shift from snowfall to rain and subsequent changes in snow storage and RoS event occurrence due to warming climate in the future, this study was our first attempt to evaluate the frequency, ongoing trends in RoS events and their runoff responses with a focus on RoS behavior at different elevations and the effect of changes in climate variable. Although changes in RoS frequency and intensity have been studied recently, trend analysis of both RoS occurrence and related runoff response was rather scarce, with limited focus on the specifics of different elevations. Similarly to Papers II and IV, this study was unique for its interest in trends in non-Alpine regions within central Europe. We were particularly focused on lower-elevation mountain ranges since they represent rain-snow transition areas with large changes in snow storage affecting ROS occurrence.

The study was performed for 40 near-natural catchments located in five mountain ranges in Czechia. This study benefited from long time series (1965-2019, 55 cold seasons) of daily meteorological and hydrological variables, which enabled us to simulate several components of the water cycle for different elevations using a semi-distributed conceptual HBV model. Using this methodology setup, we identified almost 16,000 RoS days at a catchment scale during the study period. We recognized a typical mean air temperature during the RoS days (2°C), mean daily precipitation (12 mm), mean snowmelt (9 mm) and the mean SWE (111 mm). Generally, values of all four variables increased with elevation. The results showed statistically significant, yet small and not consistent, changes in the number of RoS days in multiple catchments. In contrast, strong, significant trends in RoS days were identified for specific months (March and April) at different elevations (from 700 to 1200 m a.s. l.) (Fig. 11). Regarding the runoff response evaluation, we identified nearly 12,000 RoS events at a catchment scale, showing large temporal and spatial differences. According to our results, RoS event runoff contributed 3-32% to the total direct catchment runoff during the snow season, with the largest relative contribution in January. The long-term changes in RoS event runoff volume were mostly weak and not consistent across individual catchments. The detected trends reflected the changes in climate and snow variables, with an increase in air temperature resulting in the decrease in snowfall fraction and shorter snow cover period. Only about 10% of all assessed RoS events had flood-generation potential and these events occurred mostly in March.



A)

Elevation [m a. s. l.]	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
1450	2.36	2.2	2.57	2.29	2	2.84	5.5	6.33	2.92
1350	2.38	2.62	2.89	2.44	2.48	3.69	7.21	5.57	2.6
1250	2.65	2.61	3.15	2.34	2.79	4.62	7.38	4.45	1
1150	2.71	2.9	3.58	3.16	3.72	5.47	8.13	4.28	1.33
1050	3	2.93	4.31	3.72	4.05	6.33	7.63	3.81	1
950	2.81	2.78	5.1	4.28	4.17	7.06	6.75	3.17	0
850	3.07	2.86	5.24	4.48	4.6	7.11	5.7	2.37	0
750	2.7	2.71	5.27	4.71	4.71	6.38	4.73	1.38	0
650	1.6	2.43	5.3	5.14	4.83	5.6	3.53	1.67	0
550	2	2.39	4.96	4.75	4.55	4.96	3.45	2	0
450	2	2.35	4.09	3.98	4.2	3.95	1.94	1	0
350	1.33	1.95	3.19	3.68	3.16	2.44	1.69	0	0
250	0	1	1.67	1.14	1.55	1.67	0	0	0

B)

Elevation [m a. s. l.]	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
1450	0	0	0	**0**	0	**0.7**	0.2	**-1.9**	0
1350	0	0	0	**0.3**	**0**	**2.3**	-0.5	**-2.3**	**0**
1250	0	0	0	**0.7**	0	**3.8**	-2.7	**-2.2**	**0**
1150	0	0	0	1.3	0	**4.8**	**-5.2**	**-1**	0
1050	0	-0.4	0	1.3	0.9	**5.2**	**-5.6**	**-1**	0
950	0	-0.6	0	**3.1**	1.3	4	**-5.7**	**0**	
850	0	-0.8	0	2.4	0.8	3.2	**-7.3**	**0**	
750	0	-0.4	-0.6	1.9	0.5	-2.5	**-3.2**	**0**	
650	0	0	-0.6	-0.6	0	**-4.1**	**-0.4**	0	
550	0	**-0.3**	0	-0.2	0	**-2.5**	0	0	
450	0	0	0	0	0	**-1**	0	0	
350	0	0	0	0	0	0	0		
250		0	0	0	0	**0**			

Figure 11: Sample figure from Paper III. Mean number of RoS days (a), decadal trends in RoS days (b) from October to June at different elevations for the period 1965-2019. The cell values in panel (a) represent absolute values of RoS days. The cell values in panel (b) represent Theil-Sen's slopes of the regression line. Significant Mann-Kendall trends are highlighted in black bold (p < .05) and in black (p < .1), decreasing trends in shades of blue and increasing trends in shades of red. Grey indicates no trends due to no RoS days.

4.4 Paper IV

Hotovy O, Nedelcev O, Seiber J, Jenicek M. 2024. Rain-on-snow events in mountainous catchments under climate change. *Hydrology and Earth System Sciences* (under review)

In this study, we attributed changes in selected climate variables, particularly air temperature and precipitation, to simulated variations in RoS events, using a sensitivity analysis approach. The occurrence and intensity of RoS events are expected to change in response to climate variations. Changes in precipitation, increase in air temperature and subsequent changes in the snow occurrence will likely affect future RoS behavior and dynamics. However, the real impact of climate change on RoS events and related hydrologic implications remains unclear, mainly due to their complex nature (Sezen *et al.*, 2020; Mooney and Li, 2021; Myers *et al.*, 2023, Papers II and III). Subsequent changes in runoff responses driven by RoS events were also evaluated in this study since there is a lack of studies analyzing both changes in RoS and the related runoff responses. Moreover, most European studies have had a limited focus on elevation, which significantly influences the precipitation phase and snow cover and consequently affects RoS occurrence. Analyzing runoff responses driven by extreme meteorological events within these rain-snow transition zones is a valuable contribution of this paper.

In this study, we present differences between commonly analyzed catchments within the Alpine region and relatively scarce low-elevation locations outside of this mountain range that represent the areas within the transition zones where the largest changes in snow storage typically occur. A selection of 93 mountainous catchments across Central Europe, located in Czechia, Switzerland and Germany, was a substantial extension of the number of catchments analyzed in the previous studies from the same region (Girons Lopez *et al.*, 2020; Nedelcev and Jenicek, 2021; Paper III). Similarly to Papers II and III, a conceptual hydrological HBV model was used to simulate runoff components for 24 climate projections relative to the reference period 1980-2010, along with model testing included in the study.

Results showed that climate change-driven RoS changes were highly variable over regions, across elevations, and during the cold season. The warmest projections (up to 4°C) suggested a significant decrease in RoS days by about 75% for some locations (Fig. 12). An increase in the number of RoS days was limited to higher elevations and the coldest winter months. Our projections also suggested that the RoS contribution to annual runoff will be considerably reduced. However, the RoS contribution to runoff may even increase in winter months, especially for projections leading to an increase in precipitation, demonstrating the joint importance of air temperature and precipitation for future hydrological behavior in snow-dominated catchments.

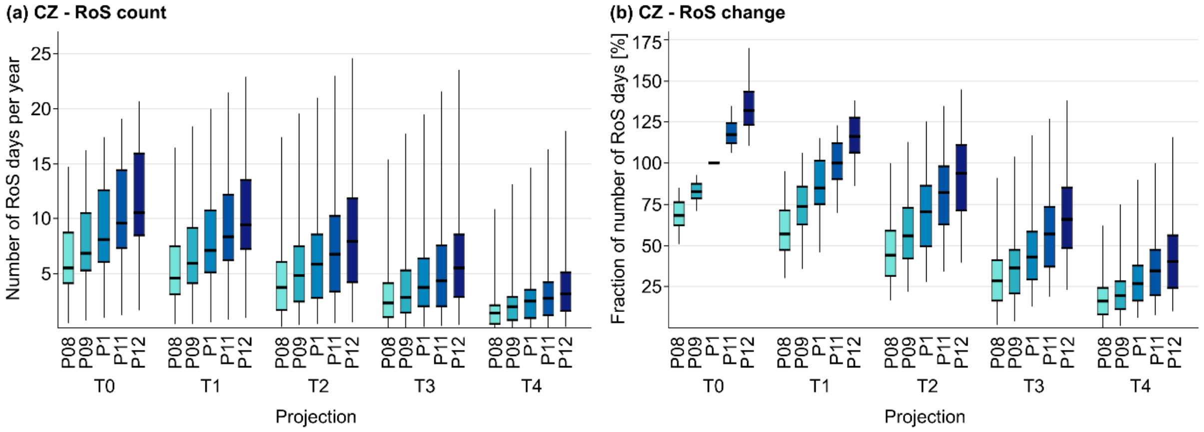


Figure 12: Sample figure from Paper IV. Number of RoS days per year (a) and a fraction of the number of RoS days relative to reference conditions (b) in Czech catchments. Boxplots represent the variation among catchments, with the 25th and 75th percentiles represented by each box, the median as a thick line and the whiskers showing the maximum and minimum values. Boxes are grouped and colored according to the temperature (T) and precipitation (P) projections.

5 Discussion

5.1 Hydrological implications

All papers presented within the dissertation thesis aimed to contribute to the scientific knowledge on the hydrological implications of snowmelt in different environments (Paper I) and RoS-driven runoff (Papers II-IV). Although the model testing showed satisfactory results also for parameters related to runoff (Section 3.2.3), we found some inconsistencies between observed and simulated variables. These uncertainties are likely due to the interaction of different influencing factors which made it difficult to accurately simulate the effect of snow cover on runoff formation during RoS events (Würzer *et al.*, 2016). Several studies (Garvelmann *et al.*, 2015; Juras *et al.*, 2017; Würzer *et al.*, 2017; Brandt *et al.*, 2022) pointed out the strong influence of the initial snowpack properties. Therefore, the behavior of rainwater within the snowpack is one of the important issues to be properly understood.

As a general remark of Paper II, rainfall was the main driver of maximum runoff and runoff in general. However, individual events associated with heavy rainfall were categorized into different runoff groups (based on the self-organizing map method) which supported the expected combined effect of other influencing factors. The temperature was found to play a secondary role, enhancing or attenuating the runoff response depending on the initial snow water equivalent. Apart from the aforementioned hydrometeorological predictors, RoS-related runoff is driven and affected by other individual catchment characteristics such as the type of forest, bedrock, aspect or slope (Li *et al.*, 2019, Paper I). Paper I pointed out that some uncertainties may arise from the calculation of total heat as the energy balance approach requires specific datasets with limited availability (Section 2.2.1). This resulted in high absolute errors between simulated and observed snowmelt rates and consequently runoff responses. Paper I discussed possible errors related to sensor location or the effect of tree composition affecting shading. This study showed that forest disturbance led to important changes in snowmelt processes and runoff conditions, similar to Schelker *et al.* (2013) or Holko *et al.* (2022). Ongoing climate change may further accentuate the effect of these land cover changes on runoff (Langhammer *et al.*, 2015; Blahusiakova *et al.*, 2020). However, faster snowmelt does not necessarily mean that total runoff or flood peaks would be higher, as documented by (Pomeroy *et al.*, 2012).

Our results showed that the majority of RoS events (82% in Paper II, 72% in Paper III) did not cause significant runoff increase which is consistent with previous studies (Merz and Blöschl, 2003; Wayand *et al.*, 2015). Furthermore, the model testing in Paper III showed that 27% of RoS events were overestimated in terms of hydrological response. As the analyses were focused mainly on the relative differences and trends in RoS rather than on absolute values, we still believe that the model provided sufficiently good simulations. Most of the high runoff events were projected to occur in March, probably due to the generally higher air temperature, more intensive spring rainfall and high SWE. Elevated runoff responses during the winter season (December-February) were probably related to the non-ripe snowpack with generally lower snow densities and prevailing preferential flow paths that allowed rainwater to efficiently propagate through the snowpack and thus causing faster and higher runoff (Juras *et al.*, 2017).

5.2 Uncertain climate impacts

In order to limit the uncertainties related to the climatological modeling, a sensitivity analysis was used in Paper IV instead of the complex climatological modeling approach to assess how changes in air temperature and precipitation affect the occurrence and extremity of RoS. In this study, climate variables were altered with respect to the expected future climate variations presented by respected sources (Gutiérrez *et al.*, 2021). Different sources of uncertainty resulting from the modeling approach have been considered in several RoS studies, with natural climate variability being seen as the primary source of uncertainty in RoS projections (Schirmer *et al.*, 2022). A sensitivity analysis approach for RoS-related research was performed by (López-Moreno *et al.*, 2021) who used this method to demonstrate the effects of the warming climate and argued that the hydrological importance of RoS is not expected to decrease, although the overall frequency of RoS will drops.

Our results are consistent with the conclusions presented by Schirmer *et al.* (2022) or Mooney and Li (2021) who found climate change signals towards more intense and frequent RoS events for an RCP 8.5 scenario at high elevations. Many recent studies (Il Jeong and Sushama, 2017; Trubilowicz and Moore, 2017; Musselman *et al.*, 2018; Li *et al.*, 2019; Sezen *et al.*, 2020; Mooney and Li, 2021) evaluating and modeling RoS events for different climate scenarios predict an increase in RoS events, particularly at higher elevations (usually valid for catchments above 1500 m a.s.l.). In contrast, their results showed a general decrease in RoS with lower hydrological extremes at lower elevations (usually for catchments below 1000 m a.s.l.). These broader elevation-based behaviors were investigated in Papers II-IV and appeared to be more pronounced in the Czech catchments. The results also showed seasonal changes in RoS occurrence. Most of the projections in Paper IV suggested a decrease in the number of RoS days towards the end of winter (particularly April and May) which supports the findings presented by Sezen *et al.* (2020). The signals towards more frequent RoS events, which were more pronounced in the Swiss catchments, were detected in the middle of the snow season. The increase in RoS is likely to be driven by changes in precipitation as more precipitation is expected to fall as rain rather than snow (Nedelcev and Jenicek, 2021). Mann-Kendall trend tests performed in Paper III showed a statistically significant change in RoS days in 21 out of 40 Czech catchments. However, the identified trends were rather weak and not consistent across catchments, although some regional patterns can be identified.

The RoS-driven hydrological impacts presented in Papers III and IV are in agreement with the findings by Sikorska-Senoner and Seibert (2020) who found an overall decreasing trend in RoS-related flooding for 27 Swiss catchments between 1980 and 2014, which is consistent with our general results for the Swiss study catchments (Paper IV). In our study, we found that these general trends may not be present for the winter months (January, February and March) due to expected changes in air temperature and precipitation patterns. Beniston and Stoffel (2016) concluded that the frequency of floods triggered by RoS may increase by 50% in Switzerland with a temperature increase of 2-4°C. However, an air temperature increase of more than 4 °C may lead to a decrease in RoS-driven floods due to a decline in snowpack duration.

5.3 RoS identification

In Paper II-IV, we emphasized that variations in the thresholds used to identify RoS days/events can significantly affect the total number of recognized RoS situations identified. However, a unified RoS definition does not exist in the literature which makes the results of different studies hardly comparable (Brandt *et al.*, 2022). Therefore, comparing the occurrence of RoS between different regions can be challenging. This was demonstrated in Paper II where two mountain ranges (Krkonoše and Jeseníky) showed different RoS frequencies despite their close proximity, proving the statement that RoS occurrence is usually limited to specific regions (Li *et al.*, 2019; Yang *et al.*, 2022) since the spatial and temporal distribution of RoS days and events is controlled by current and local weather conditions.

Average temperature, duration of snow cover, and the dominant phase of precipitation are expected to be the main factors explaining the variation in RoS sensitivity to climate warming (López-Moreno et al., 2021).

For air temperature, several studies (Surfleet and Tullos, 2013; Bieniek *et al.*, 2018; Crawford *et al.*, 2020, Paper III) used the threshold of 0°C for the daily mean air temperature, while many recent studies did not specify the temperature threshold for RoS detection (Pall *et al.*, 2019; Mooney and Li, 2021; Schirmer *et al.*, 2022; Yang *et al.*, 2022). In Paper IV, we determined the air temperature threshold as one of the RoS-defining parameters, which was calibrated separately for each of the study catchments. This approach appeared to be a valuable addition to the previous definition used in Paper III where zero was used as the temperature threshold. The varying threshold temperature can buffer local climatic conditions influenced by different catchment characteristics such as elevation range, topography or vegetation, and thus reducing one of the potential sources of error when identifying RoS days and events.

The derived threshold temperatures applied in Paper IV varied from -1.9 to 1.6°C within all study catchments. The mean threshold temperature reached -0.4°C for the study catchments in Paper III. These values were comparable to those presented by Jennings *et al.* (2018), who identified a temperature range between -0.4 and 2.4°C to be valid for 95% of the stations across the Northern Hemisphere, indicating the air temperature at which rain and snowfall occur with equal frequency. Lower temperature thresholds occurred particularly in high-elevation catchments where snowfall is more common than rainfall. The temperature threshold is a challenging criterion used in the model to distinguish the phase of precipitation (Section 3.3). This can be particularly challenging on days when the air temperature fluctuates around the freezing point, making the snowfall fraction even more sensitive to changes in air temperature.

Thresholds defined for rainfall intensity and SWE appear to be less sensitive. A sensitivity analysis conducted partly in the same study area within Paper II showed that RoS characteristics remain similar when different limits for minimum rainfall and SWE are applied.

Regarding the general occurrence of RoS, most of the events analyzed in Papers II-IV occurred between November and May (with rather rare events in October and June at the highest elevations) which is in good agreement with the findings by Freudiger *et al.* (2014). In Paper III, we defined a typical RoS day as a day with a daily mean air temperature ranging from 1.5°C at the lowest elevations to 2.9°C at the highest elevations. This temperature range, as well as typical rainfall intensities and SWEs, do not differ from those reported in other European regions with similar climate (Garvelmann *et al.*, 2015; Würzer *et al.*, 2016; Trubilowicz and Moore, 2017).

5.4 Data complexity in snow hydrology

Discussions about research complexity and level of detail were present throughout the PhD research. These discussions raised further questions about data complexity which is highly dependent on the spatial scale of the research. Mountainous snow hydrology and topics related to RoS events both represent a unique set of challenges and complexities in data collection, analysis, and interpretation, resulting from their complex nature (Sezen *et al.*, 2020). Understanding and managing these complexities is critical for accurate and high quality snow hydrology research.

The scale of observation has a significant impact on the complexity of data in snow hydrology. Data collected at the local scale need to be integrated with macro-scale observations. Bridging the gap between these scales requires multi-scale modeling approaches and downscaling techniques. This dissertation thesis introduces both approaches commonly used in hydrology. An experimental study (Paper I) required various datasets, usually with a higher temporal resolution. This study used site-level energy balance calculations and such approaches are not easily transferable to larger regions. The remaining studies (Paper II-IV) represented large-sample hydrology that generally uses limited data sources with a lower level of detail. The RoS analyses in these studies were performed at a multi-catchment level, using input data from climate stations limited to air temperature and precipitation data, which did not allow the use of the energy balance approach.

Further uncertainties may arise from the fact that the snow cover is inherently heterogeneous, both spatially and temporally. Variations in snow depth, density, and water content at different scales add to the uncertainty. In addition, snow distribution is influenced by numerous factors. Most of these are well-recognized (e.g. air temperature or precipitation), but some can not be easily assessed without appropriate additional data. Several studies have pointed out that the initial properties of the snowpack and its retention capacity are both important factors with a strong influence on snowmelt and runoff formation (Garvelmann *et al.*, 2015; Würzer *et al.*, 2016), as investigated in Paper II. The actual storage potential for the rainwater is controlled by the snow ripeness and the physical properties of the snowpack such as grain size, grain shape (Singh and Singh, 2001), and layering, especially the presence of capillary barriers (Avanzi *et al.*, 2016).

Snow water equivalent (SWE) data appeared to be one of the most important and also challenging parameters for assessing snowmelt processes across scales. The availability of SWE data was crucial for all studies presented within the PhD research. Since the number of stations with long-term daily monitoring of SWE was limited (not the case for the Swiss catchments in Paper IV), the ability of the model to accurately simulate SWE values was repeatedly addressed and discussed (Section 3.2.3). Differences between observed and modeled values may result from the lack of SWE measurements and the representativeness of the measurement location, particularly across the Czech catchments. Furthermore, detailed snowpack data (snow depth, snow water equivalent, etc.) are usually provided at a point scale, which is not necessarily representative of the catchment scale (Würzer and Jonas, 2018).

Although air temperature and precipitation data series are usually available for different temporal and spatial scales, there were some issues in analyzing and processing these primary data. As discussed in all papers where the modeling approach was used (Papers II-IV), the definition of the threshold temperature (T_T), as one of the parameters for RoS identification (Section 3.3) can be difficult using daily data, especially for days with high daily temperature amplitude (warm days and cold nights) resulting in a mean daily temperature around zero despite the fact that precipitation phase may change during the day, or for days with air temperature oscillating near the freezing point. Moreover, T_T can significantly differ among individual catchments with specific influencing factors. Therefore, we addressed this uncertainty by using different methods in Papers III and IV (fixed T_T vs. moving T_T calibrated for individual study catchments).

In addition to the data commonly used to evaluate snow dynamics, we introduced some other complementary methods to increase the complexity of our research. In Paper I, we assessed canopy structure and forest density by calculating Leaf Area Indexes (LAI) for individual study sites from the hemispherical images. We were aware of potential errors from our radiation measurements as these data represented point information and might be affected by the specific fixed position of the sensor.

5.5 Uncertainty in modeling approach

Hydrological models used for the simulations of individual components of the rainfall-runoff process are subject to various uncertainties. These uncertainties stem from model structure, parameter setting and input data quality. In Papers II-IV, a semi-distributed bucket-type HBV model (Lindström *et al.*, 1997; Seibert and Bergström, 2022) in its software implementation “HBV-light” (Seibert and Vis, 2012) was used (Section 3.2.3).

The HBV model uses the modified degree-day approach (Section 2.2.2) within its snow routine (Section 3.2.3) which may raise questions about model simplification. According to Seibert and Bergström (2022), more sophisticated models that use the entire energy balance in their structure perform better at a catchment scale. However, several studies have demonstrated that the degree-day approach is adequately used for snow storage simulation at a catchment scale under a changing climate (Addor *et al.*, 2014; Etter *et al.*, 2017; Jenicek *et al.*, 2021). Although these bucket-type models can generate some limitations, testing of 64 modifications of the HBV snow routine done by Girons Lopez *et al.* (2020) showed that the current snow routine within the HBV model provides satisfactory results at a catchment scale and confirmed that model procedures, setup and derived parameters acceptably represent the actual natural processes, including specifics of RoS events (Freudiger *et al.*, 2014). Authors of this study admitted that some modifications of the routine might represent an interesting alternative. Nevertheless, increased model complexity does not necessarily result in a better model ability to simulate SWE and runoff.

Since the results related to RoS events, as well as RoS identification (presented in Papers II-IV) were both based on modeled SWE, uncertainties arising from the model parametrization needed to be addressed in all three studies. Model calibration, validation and testing were performed in several recent studies using similar datasets (Jenicek and Ledvinka, 2020; Jenicek *et al.*, 2021; Sipek *et al.*, 2021). Consistently with these studies, multi-criteria model calibration and reiterated calibration runs were performed in Paper II-IV to reduce the overall parameter uncertainty. Nash-Sutcliffe efficiency values over 0.7 were reached in Papers II and III, and also for the extended dataset in Paper IV (Fig. 13). This represented one of the acceptable test criteria (Moriasi *et al.*, 2015). However, it might be difficult to agree on specific efficiency benchmarks signalizing a good model performance (Seibert *et al.*, 2018). Thus, model justification required multiple model testing.

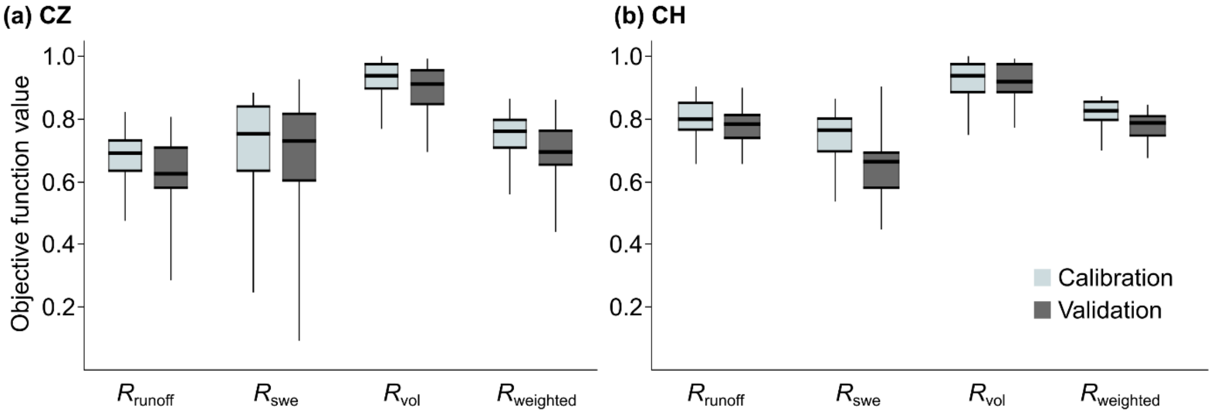


Figure 13: Model performance for all 93 study catchments within both Czech (a) and Swiss (b) regions evaluated by the combination of selected objective criteria, including the logarithmic Nash-Sutcliffe efficiency for runoff (R_{runoff}), Nash-Sutcliffe efficiency for SWE (R_{swe}), and volume error ($Rvol$). These criteria were weighted ($R_{weighted}$) to calculate the overall objective function of the model. Boxplots represent the variation among catchments, with the 25th and 75th percentiles within a box, the median as a thick line and the whiskers represent maximum and minimum values (Paper IV).

The assessment of the model's ability to simulate SWE and thus detect RoS days correctly was investigated in Paper III where we compared counts of observed and simulated RoS days, as well as simulated runoff and SWE during RoS events. We did not find major inconsistencies in the model runs and assumed that the model provided sufficiently good simulations. More detailed testing of SWE simulations for the Czech catchments was carried out by (Jenicek *et al.*, 2021; Nedelcev and Jenicek, 2021). For example, Nedelcev and Jenicek (2021) compared simulated and observed trends in air temperature, precipitation, and SWE, concluding that the model can provide overall reliable simulations of the above variables, which are temporally and spatially consistent with observed data.

6 Outlook and conclusions

This thesis aims to assess the changes in mountain snowmelt and rain-on-snow (RoS) runoff across scales, primarily in the context of climate and landscape changes within the region of central Europe. This research resolves some of the uncertainties associated with the complex snowmelt processes and contributes to the understanding of snowmelt dynamics and their changes during hazardous events in the context of climate change. This cross-scale research is beneficial for a better estimating of snow storages, contributing to a higher accuracy of hydrological modeling, and thus mitigating the risk of drought and flood towards effective water resource management in the future. We performed various types of research at different spatial and temporal scales, from the experimental site study to regional and international multi-catchment research. We were particularly focused on the changes across elevations that include the areas within the rain-snow transition zones where large changes in snow storage, snow dynamics and RoS occurrence typically occur due to climate warming. Individual studies applied various methodological approaches and addressed different topics related to snowmelt and subsequent hydrological implications, with the specific focus on changes of the frequency and intensity of RoS events.

The effects of forest cover on the sub-canopy energy balance and snowmelt processes were explored in Paper I. This study helped to understand the detailed mechanisms of snowmelt dynamics related to the heat fluxes within the snowpack energy balance and demonstrated what are the differences between the sites with different canopy structures. This study supported the fact that energy from rain can be important when assessing snowmelt at daily and shorter temporal resolutions, which initiated research questions for subsequent studies (Papers II-IV). Paper I highlighted the role of shortwave radiation (SWR), which was the major energy contributor to snowmelt at the open (treeless) site. In the healthy forested site, SWR represented only 7% of the amount at the open site due to tree shading. In contrast, longwave radiation (LWR) was the dominant energy component, representing 41% of all energy fluxes, and thus contributed most to snowmelt. Notable effects of gradual forest decay on snowmelt processes were also shown in Paper I.

Changes in the occurrence of RoS days/events and the associated hydrological implications were the main topics of the dissertation thesis and were investigated in Papers II-IV, primarily in the context of climate change. At the multi-catchment scale, we assessed thousands of RoS days/events, and contributed to the understanding of the temporal and spatial variability of this hydrological phenomenon. We found the most frequent RoS occurrences in the elevation range from 1000 to 2000 m a.s.l. Distinct catchments saw the average RoS occurrence at different times of the year from mid-January to mid-May (Paper IV). The results showed that climate change-driven RoS changes are highly variable across regions and sub-regions, across elevations, and within the cold season (Papers II-IV). These changes were rather small and inconsistent at the catchment scale but were more pronounced (strong and significant trends) at higher resolution - for specific months at different elevations (Paper III). The largest decrease was detected at elevations between 700 and 1200 m a.s. l. during April, most likely caused by a shortening of the period with existing snow cover on the ground due to increasing air temperature. The largest increase was recorded at elevations above 1000 m a.s.l. in March which was associated with more frequent rainfall.

In general, RoS days are expected to occur less frequently with further warming, particularly at lower elevations (Paper III and IV). The warmest projections defined in Paper IV suggested a significant decrease in RoS days by about 75% for some locations. An increase in the number of RoS days was limited to higher elevations and the coldest winter months. Our projections also suggested that the RoS contribution to annual runoff is likely to decrease significantly. However, the RoS contribution to runoff may even increase in the winter months, especially for projections that lead to an increase in precipitation, demonstrating the joint importance of air temperature and precipitation for future hydrological behavior in snow-dominated catchments.

Moreover, the effect of various seasonal climate and snow characteristics that may control RoS behavior was investigated in Paper IV, concluding that the RoS occurrence was identified as more sensitive to changes in snowfall in the Czech catchments, whereas seasonal precipitation totals (regardless of snowfall or rainfall) appeared to be the primary driver in Switzerland. Surprisingly, the correlation between RoS and air temperature was relatively weak in both regions.

Focusing on the hydrological implications of changes in snowmelt processes and RoS events is important and our findings (Papers I-IV) contribute to improve the process understanding, which is further important for improving snowmelt and catchment runoff models. Although the methods of experimental study presented in Paper I are rather limited to the specific study area and may not be easily generalized, the results proved that changes in individual energy balance components after forest disturbance have important consequences on snowmelt rates which may further affect the seasonal distribution of spring runoff. The highest simulated snowmelt rates were observed at the open site (median snowmelt rate 13.5 $mm.d^{-1}$). The modeled snowmelt was significantly slower at the disturbed forest site (5.9 $mm.d^{-1}$) and at the healthy forest site (3.3 $mm.d^{-1}$).

Analyzing runoff responses driven by extreme meteorological events such as RoS within transition zones is a valuable contribution of Papers II-IV. We concluded that only about 10% of all RoS events have flood-generation potential and most of the events (up to 82%) did not cause a significant runoff increase. Within the catchments in Czechia, RoS event runoff contributed 3-32% to the total direct catchment runoff during the snow season, with the largest relative contribution in January (Paper III). Paper IV suggested that RoS contribution to annual runoff is likely to decrease due to changes in climate variables from the current 10% to 2-4% for the warmest projections in Czechia, and from 18% to 5-9% in Switzerland. However, the RoS contribution to runoff may increase in winter months in Switzerland, for almost all projections with the same or higher amount of precipitation, regardless of air temperature increase. With more frequent RoS events expected during these months, Swiss catchments, particularly those at higher elevations, may face more extreme RoS-related flood events in the future. For Czech catchments, the increase in winter runoff is expected only for wet projections with a relatively small air temperature increase. Despite the expectations that the overall RoS impact on runoff will be lower in the future, extreme hydrological response and flooding triggered by RoS events may still represent a significant flood risk.

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8 Supplements

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