Complexity and performance of temperature-based snow routines for runoff modelling in mountainous areas in Central Europe

Marc Girons Lopez[1,2], Marc J. P. Vis[1], Michal Jenicek[3], Nena Griessinger[4], Jan Seibert[1]

[1]Department of Geography, University of Zurich, Zurich, CH-8006, Switzerland
5 [2]Swedish Meteorological and Hydrological Institute, Norrköping, SE-60176, Sweden
[3]Department of Physical Geography and Geoecology, Charles University, Prague, CZ-11636, Czechia
[4]WSL Institute for Snow and Avalanche Research SLF, Davos, CH-7260, Switzerland

Correspondence to: Marc Girons Lopez (marc.girons@smhi.se)

Abstract. Snow processes are a key component of the water cycle in mountainous areas as well as in many areas of the mid-
10 and high latitudes of the Earth. The complexity of these processes, coupled with the limited data available on them, has led
to the development of different modelling approaches to improve their understanding and support management practices.
Physically-based approaches, such as the energy balance method, provide the best representation of these processes but at
the expense of high data requirements. Data limitations, in most situations, constrain the use of these methods in favour of
more simple approaches. The temperature-index method is the most widely-used modelling approach of the snowpack
15 processes for hydrological modelling, with many variants implemented in different models. However, in many cases, the
decisions on the most suitable complexity of these conceptualisations are not adequately assessed for a given model
structure, application, or decision-making support tool.

In this study, we assessed model structure choices of the HBV model, a popular semi-distributed, bucket-type hydrological
model, for its application in mountainous areas in Central Europe. To this end, we reviewed the most widely-used choices to
20 different components of the snow routine in different hydrological models and proposed a series of modifications to the
structure of HBV. We constrained the choice of modifications to those that are aligned with HBV's modelling approach of
keeping processes as simple as possible to constrain model complexity. We analysed a total of 64 alternative snow routine
structures over 54 catchments using a split-sample test. We found that using (a) an exponential snowmelt function coupled
with no refreezing instead of a linear function for both processes and (b) a seasonally-variable degree-day factor instead of a
25 constant one were, overall, the most valuable modifications to the model. Additionally, we found that increasing model
complexity does not necessarily lead to improved model performance per se. Instead, we found that a thorough analysis of
the different processes included in the model and their optimal degree of realism for a given application is a preferable
alternative. While the results may not be transferrable to other modelling purposes or geographical domains, the
methodology presented here may be used to assess the suitability of model design choices.

1 Introduction

30

Snow is an essential aspect of the seasonal hydrological variations in Alpine areas as well as in many other regions of the mid and high latitudes of the Earth. Unlike rainfall, which contributes directly to groundwater recharge and stream runoff, snowfall accumulates on the ground creating a temporary freshwater reservoir. This accumulated water is then gradually released through melting, often triggered by raising temperatures, and ultimately contributes to runoff. The snow

35 accumulated on the ground (i.e. snowpack) is not only crucial for ecological reasons (Hannah et al., 2007), but also for many human activities such as hydropower, agriculture, or tourism (Barnett et al., 2005). At the same time, snow processes can also lead to risks for society. For instance, the accumulation of snow on steep slopes may, under the right conditions, cause avalanches (Schweizer et al., 2003) and the sudden melt of large amounts of snow, such as during rain-on-snow events (Sui and Koehler, 2001) or after rapid increases of air temperature, may lead to widespread flooding either directly (Merz and

40 Blöschl, 2003) or indirectly (e.g. dam failure accidents) (Rico et al., 2008).

Society´s dependence on the freshwater stored in the snowpack and its vulnerability to its associated risks raises the need to understand its dynamics and evolution (Fang et al., 2014; Jamieson and Stethem, 2002). Nevertheless, even if knowledge on snow hydrology has broadly advanced over the last decades, the limitations of data availability on catchment hydrology – and especially on snow processes – pose a challenge to properly monitoring these processes as well as implementing

45 adequate management policies and practices. Furthermore, the evolution of snow water resources in the future cannot be estimated through direct observation, but is essential in the context of global climate change (Berghuijs et al., 2014; Jenicek and Ledvinka, 2020).

Consequently, different modelling strategies have been developed to overcome the data limitations and to study the evolution of the snowpack and its impact on water resources. The most common modelling approaches are based either on

50 the physically-based energy budget model or on the temperature-index distribution function method (Verdhen et al., 2014). While energy budget models are the most accurate alternative to represent snowpack processes, in order to be reliable they usually require data that are often not available in conventional meteorological stations (Avanzi et al., 2016). These models attempt to estimate the snow contribution to runoff in a distributed way by solving the energy balance of the snowpack, which requires detailed data on topography, temperature, wind speed and direction, cloud cover fraction, snow density, etc.

55 Conversely, temperature-based models tend to have low data requirements and offer a balance between simplicity and realism, which makes them successful in many different contexts and applications, even in cases with limited data availability (Hock, 2003). Hybrid methods have also been developed, such as including a radiation component in the temperature-based models (Hock, 1999). These approaches are especially relevant for high elevation, often glacierised areas in which temperature seldom gets above the freezing point (Gabbi et al., 2014; Pellicciotti et al., 2005).

60 The temperature-index model – also referred to as degree-day method – is based on the observation that the rate of snowmelt is proportional to the temperature above the freezing point per unit time through a proportionality constant commonly named degree-day factor (Collins, 1934; Martinec, 1960). Many distribution function hydrological models use variations of this

method to simulate snowpack processes. For instance, while some models use the freezing point as reference temperature (Walter et al., 2005), others include a calibrated threshold temperature parameter (Viviroli et al., 2007). Regarding the

65 proportionality constant, some applications define it as time-independent (Valéry et al., 2014), while others establish it as being seasonally-variable (Hottelet et al., 1994). Moreover, connecting with energy budget models, some applications use two proportionality constants: one for temperature and another for net radiation (Kane et al., 1997). Nevertheless, regardless of the preferred approach, the inherent simplifications made in semi-distributed temperature-index models leave out some critical aspects of the snowpack processes that may be significant in some circumstances. For instance, the disregard of

70 lateral transport processes may lead to the development of unreasonable accumulations of snow over long periods of time (i.e., snow towers) in high mountainous areas (Freudiger et al., 2017; Frey and Holzmann, 2015).

The different implementations of the temperature-index method may relate to differences in model philosophy, scope, desired resolution, or available computing power, among others. Nevertheless, these choices are not always adequately tested to ensure that they provide the best possible alternative for a given model design and application (Harpold et al.,

75 2017). For instance, some studies have found that a more realistic representation of hydrological processes does not always translate into improved model performance (Orth et al., 2015). For a long time, limitations in computing power hindered the systematic testing of different alternative model structures over a large number of catchments. In recent years, however, the increase in computing power has made these tests not only feasible but also desirable in order to ensure that model structures are adequate and robust for their intended applications (Günther et al., 2019).

80 In this study, we evaluated the design choices made in the snow routine of the HBV hydrological model (Bergström, 1995), a typical bucket-type model with a temperature-based snow routine, for its application in mountainous central-European catchments. We implemented and tested a number of modifications to the snow routine of the model based on common practices in similar hydrological models, and investigated whether it is possible to identify model structure alternatives which generally result in improved model performance. With this, we aimed to provide a basis to decide on useful

85 modifications to the model while avoiding adding unnecessary complexity and additional parameters. To ensure that the results are representative we explored different levels of added complexity, from single modifications to combinations of multiple modifications, to a large dataset of catchments covering a wide range of climatological and hydrological conditions of the area of interest.

2 Materials and Methods

90 The HBV model is a bucket-type rainfall-runoff model, with a number of boxes (routines) including the main components of the terrestrial phase of the water cycle, i.e., snow routine, soil routine, groundwater (response) routine, and routing function. In this study, we focus solely on the snow routine of the model. We use the HBV-light software, which follows the general structure of other implementation of the HBV model and includes some additional functionalities such as Monte Carlo runs and a genetic algorithm for automated optimisation (Seibert and Vis, 2012). Henceforth we use the term 'HBV model' when

Hydrology and
Earth System
Sciences
Discussions
EGU
Open Access

95   referring to our simulations using the HBV-light software. With 'HBV model' we mean the 'standard HBV', i.e., the HBV model with the snow routine as described in Lindström et al. (1997) or Seibert & Vis (2012).

2.1 HBV's Snow Routine

The snow routine of the HBV model is based on well-established conceptualisations of the relevant snow processes for hydrological applications. It represents the processes regarding two aspects of snow hydrology: the phase of the precipitation
100   (snow or rain), and the accumulation and melt of the snowpack.

Regarding the precipitation phase, HBV uses a threshold temperature parameter, T_T [°C], above which all precipitation, P [mm/Δt], is considered to fall as rain, P_R [mm/Δt] (Eq. 1). This threshold can be adjusted to account for local conditions. Below the threshold, all snow is considered to fall as snow, P_S [mm/Δt] (Eq. 2). The combined effect of snowfall undercatch and interception of snowfall by the vegetation is represented by a snowfall correction factor, C_{SF} [-].

105    $$P_R = P, \quad \&T > T_T ,\tag{1}$$

$$P_S = P \cdot C_{SF}, \quad \&T \leq T_T ,\tag{2}$$

As previously mentioned, the HBV model uses a simple approach based on the temperature-index method to simulate the evolution of the snowpack. This way, snowmelt, M [mm/Δt], is assumed to be proportional to the air temperature, T [°C], above a predefined threshold temperature, T_T [°C], through a proportionality coefficient, also called degree-day factor,
110   C_0 [mm/Δt°C] (Eq. 3). The physical motivation of this approach is that the energy available for snowmelt is generally proportional to the air temperature (Ohmura, 2001). The model allows for a certain volume of melted water to remain within the snowpack, given as a fraction of the corresponding snow water equivalent of the snowpack, C_{WH} [-]. Finally, the refreezing of melted water, F [mm/Δt], takes place when the air temperature is below T_T, and its magnitude is modulated through an additional proportionality parameter, C_F [-] (Eq. 4).

115    $$M = C_0(T - T_T) ,\tag{3}$$

$$F = C_F \cdot C_0(T_T - T) ,\tag{4}$$

HBV allows for a limited representation of catchment characteristics through the specification of different elevation and vegetation zones. This way, the parameters controlling the different processes included in the snow routine can be modified for individual vegetation zones. The combination of elevation and vegetation zones (also known as Elevation Vegetation
120   Units, EVUs) is the equivalent of the Hydrologic Response Units (HRUs) used in other distribution function models (Flügel, 1995). Both precipitation and temperature are corrected for elevation using two parameters for the precipitation and temperature lapse rate.

2.2 Proposed Modifications to Snow Routine Components

Here we review the individual components of the snow routine structure of the HBV model as well as functions that are
125   directly related to it (e.g. input data correction with elevation) and describe the proposed modifications. Each of these
modifications requires one to three parameters (Table 1).

Table 1 Description of the proposed modifications to the snow routine of the HBV model. The default component structures of the HBV model are marked with a * symbol.

Snow routine component	Structure	Abbreviation	Number of Parameters
Temperature lapse rate	Constant*	Γ_c	1
	Seasonally-variable	Γ_s	2
Precipitation phase partition	Abrupt transition*	ΔP_a	1
	Partition defined by a linear function	ΔP_l	2
	Partition defined by a sine function	ΔP_s	2
	Partition defined by an exponential function	ΔP_e	2
Threshold temperature	One threshold for both precipitation and snowmelt*	T_T	1
	Different thresholds for precipitation and snowmelt	$T_{P,M}$	2
Degree-day factor	Constant*	$C_{0,c}$	1
	Seasonally-variable	$C_{0,s}$	2
Snowmelt and refreezing	Linear snowmelt and refreezing magnitude with temperature*	M_l	3
	Exponential snowmelt magnitude with temperature. No refreezing.	M_e	3

130

2.2.1 Temperature Lapse Rate

When different elevation zones are used, the temperature for each zone is generally computed from some catchment-average
value and a lapse rate. In HBV, usually a constant temperature lapse rate is used. Alternatively, if the available data allows, it
is also possible to provide an estimation of the daily temperature lapse rate. However, if no data on the altitude dependence
135   of temperature is available, setting a constant value throughout the year might be an oversimplification. Indeed, in an
experimental study on several locations across the Alps, Rolland (2002) found that the seasonal variability of the temperature
lapse rate follows approximately a sine curve with a minimum at the winter solstice. Following these results, we

implemented a seasonally variable computation of the temperature lapse rate using a sine function (Eq. 5). This way, the temperature lapse rate for a given day of the year, Γ_n *[°C/100 m]* (where *n* is the day of the year, a sequential day number starting with day 1 on the 1st of January), depends on two parameters, namely the annual temperature lapse rate average, Γ_0 *[°C/100 m]*, and amplitude, Γ_i *[°C/100 m]*.

$$\Gamma_n = \Gamma_0 + \frac{1}{2}\Gamma_i \sin\frac{2\pi(n-81)}{365} , \tag{5}$$

Precipitation lapse rates could not be related to a seasonal or other types of systematic variations as they are strongly dependent on the synoptic meteorological conditions and therefore highly variable. Therefore, we decided to keep the default approach of calibrating the model using an average precipitation lapse rate parameter.

2.2.2 Precipitation Phase Partition

The determination of the precipitation phase is crucial as it controls whether water accumulates in the snowpack or contributes directly to recharge and runoff. In the HBV model the distinction between rainfall and snowfall is based on the assumption that precipitation falls either as rain or as snow, depending on a threshold temperature. However, in reality, this transition is less sharp, as there are mixed events with both rain and snow and, depending on other factors such as humidity and atmosphere stratification, the shift from rain to snow can occur at different temperatures (Dai, 2008; Magnusson et al., 2014; Sims and Liu, 2015). Therefore, the single threshold temperature may not adequately represent the snow accumulation, especially in areas or periods with temperatures close to zero degrees Celsius. Different approaches have been suggested to describe the snow fraction of precipitation, S *[-]*, as a function of temperature (Froidurot et al., 2014; Magnusson et al., 2014; Viviroli et al., 2007). In this study, we considered three different conceptualisations of snowfall fraction of precipitation, (Eq. 6 – 7): (i) a linear function (Eq. 8), (ii) a sine function (Eq. 9), and (iii) an exponential function (Eq. 10). Both the T_A *[°C]* and M_P *[°C]* parameters control the range of temperatures for mixed precipitation.

$$P_S = P \cdot S \cdot C_{SF} , \tag{6}$$

$$P_R = P \cdot (1 - S) , \tag{7}$$

$$S = \begin{cases} 1, & T \leq T_T - \frac{T_A}{2} \\ \frac{1}{2} + \frac{T_T - T}{T_A}, & T_T - \frac{T_A}{2} < T \leq T_T + \frac{T_A}{2}, \\ 0, & T > T_T + \frac{T_A}{2} \end{cases} \tag{8}$$

$$S = \begin{cases} 1, & T \leq T_T - \frac{T_A}{2} \\ \frac{1}{2} - \frac{1}{2}\sin\left(\pi \frac{T_T - T}{T_A}\right), & T_T - \frac{T_A}{2} < T \leq T_T + \frac{T_A}{2}, \\ 0, & T > T_T + \frac{T_A}{2} \end{cases} \tag{9}$$

$$S = \frac{1}{1 + e^{\frac{T - T_T}{M_P}}} ,$$

(10)

2.2.3 Snowmelt Threshold Temperature

In addition to determining the precipitation phase, a temperature threshold is also needed to determine when snowmelt starts.
165 The most straightforward approach, as used in the HBV model, is to use the same threshold temperature parameter for both snowfall and snowmelt. However, as these two transitions are related to different processes happening at different environmental conditions, a single parameter might not adequately describe both transitions. A more realistic approach would be to consider two separate parameters for these processes: a threshold temperature parameter for precipitation phase differentiation, T_P [°C], and another one for snowmelt processes, T_M [°C] (Debele et al., 2010). We implemented this
170 modification using one additional parameter.

2.2.4 Degree-day factor

The degree-day factor is an empirical factor that relates the rate of snowmelt to air temperature (Ohmura, 2001). In the HBV model a single proportionality coefficient to estimate the magnitude of the snowmelt is used. This coefficient, multiplied by a constant (usually set to 0.05 in HBV), is also used to compute refreezing rates. However, while the degree-day factor is
175 often assumed to be constant over time, there are good reasons to assume temporal variations due to changes such as snow albedo and solar inclination. A simple way to represent this variability is to consider the degree-day factor to be seasonally variable following a sine function defined by a yearly average degree-day factor parameter, C_0 [mm/Δt°C], and an amplitude parameter, $C_{0,a}$ [mm/Δt°C], defining the amplitude of the seasonal variation (Eq. 11) (Braun and Renner, 1992). By establishing a seasonally-variable degree-day factor instead of a constant value for this parameter, potential snowmelt rates
180 are smaller during the winter months, while increasing during spring.

$$C_{0,n} = C_0 + \frac{1}{2} C_{0,a} \sin \frac{2\pi(n-81)}{365} ,$$

(11)

2.2.5 Snowmelt and Refreezing

Snowmelt water does not leave the snowpack directly; a certain amount of liquid water may be stored in the snow. This is important as it delays the outflow of water from the snowpack, and besides that, the liquid water can potentially refreeze if
185 temperatures decrease again. In the HBV model, both the storage of liquid water and refreezing processes are considered. However, since the magnitude of refreezing meltwater is generally tiny compared to other fluxes, some models disregard this process entirely as it adds complexity to the model without adding any value to it (Magnusson et al., 2014). Here we follow the approach by Magnusson et al. (2014) which, besides disregarding the refreezing process, describes snowmelt using an exponential function (Eq. 12). This conceptualisation if somewhat more realistic than the one used in HBV but requires the
190 use of an additional parameter to control for the smoothness of the snowmelt transition, M_M [°C]. This way, and contrary to

the formulation used in HBV, snowmelt occurs even below the freezing point, but at negligible amounts. The impact of increasing temperatures on snowmelt is also higher for this conceptualisation.

$$M = C_0 \cdot M_M \left(\frac{T-T_T}{M_M} + \ln\left(1 + e^{-\frac{T-T_T}{M_M}}\right)\right),$$ (11)

2.3 Study Domain and Data

195 We selected two sets of catchments in two different geographical domains to test the proposed modifications to the individual components of the snow routine of the model (Table 2, Figure 1). The first set, composed of Swiss catchments, contains a range of catchments from high altitude, steep catchments in the central Alps to lower catchments in the Pre-Alps and Jura mountains. The second set, composed of Czech catchments, is representative of mountain catchments at lower elevations compared to the Swiss catchments.
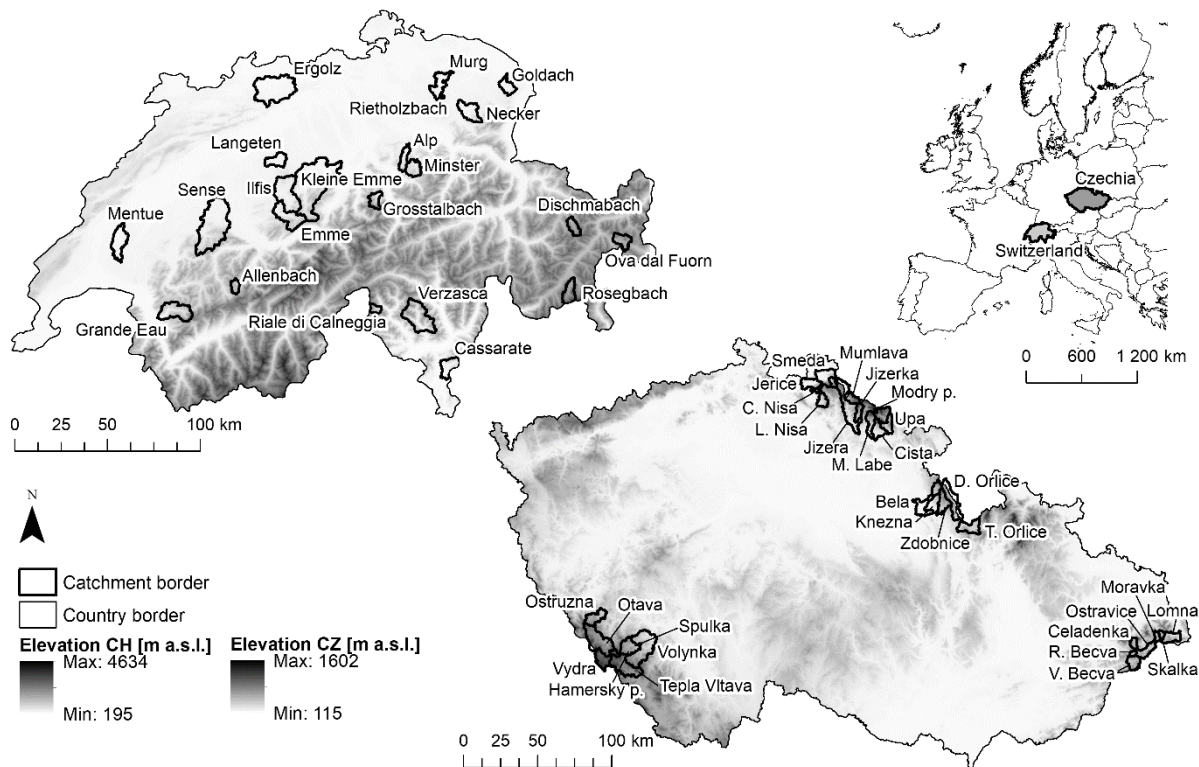
200

Figure 1 Geographical location of the catchments used in this study. We used a total of 54 catchments; 22 located in Switzerland and 32 in Czechia.

205 **Table 2 Relevant physical characteristics of the catchments included in the study. Each catchment is given an identification code in the following way: country (CH – Switzerland, CZ – Czechia), geographical location (Switzerland: 100 – Jura and Swiss Plateau, 200 – Central Alps, 300 – Southern Alps; Czechia: 100 – Bohemian Forest, 200 – Western Sudetes, 300 – Central Sudetes, 400 – Carpathians), and a sequential number for increasingly snow-dominated catchments within each geographical setting. The official hydrometric station IDs from FOEN and CHMI are also provided.**

ID	Catchment	Station	Station ID	Area [km²]	Mean elevation [m a.s.l.]	Elevation range [m a.s.l.]	Snowmelt contribution to runoff [%]
CH-101	Ergolz	Liestal	2202	261.2	604	305 – 1087	5
CH-102	Mentue	Yvonand	2369	105.3	690	469 – 915	5
CH-103	Murg	Wängi	2126	80.1	657	469 – 930	7
CH-104	Langeten	Huttwil	2343	59.9	770	632 – 1032	8
CH-105	Goldach	Goldach	2308	50.4	825	401 – 1178	14
CH-106	Rietholzbach	Mosnang	2414	3.2	774	697 – 868	9
CH-107	Sense	Thörishaus	2179	351.2	1091	551 – 2096	12
CH-108	Emme	Eggiwil	2409	124.4	1308	770 – 2022	22
CH-109	Ilfis	Langnau	2603	187.4	1060	699 – 1973	14
CH-110	Alp	Einsiedeln	2609	46.7	1173	878 – 1577	19
CH-111	Kleine Emme	Emmen	2634	478.3	1080	440 – 2261	16
CH-112	Necker	Mogelsberg	2374	88.1	970	649 – 1372	16
CH-113	Minster	Euthal	2300	59.1	1362	891 – 1994	26
CH-201	Grande Eau	Aigle	2203	131.6	1624	427 – 3154	26
CH-202	Ova dal Fuorn	Zernez	2304	55.2	2359	1797 – 3032	36
CH-203	Grosstalbach	Isenthal	2276	43.9	1880	781 – 2700	28
CH-204	Allenbach	Adelboden	2232	28.8	1930	1321 – 2587	38
CH-205	Dischmabach	Davos	2327	42.9	2434	1657 – 3024	52
CH-206	Rosegbach	Pontresina	2256	66.6	2772	1771 – 3793	62
CH-301	Riale di Calneggia	Cavergno	2356	23.9	2079	881 – 2827	42
CH-302	Verzasca	Lavertezzo	2605	185.1	1723	546 – 2679	27
CH-303	Cassarate	Pregassona	2321	75.8	1017	286 – 1904	4
CZ-101	Vydra	Modrava	135000	89.8	1140	983 – 1345	34
CZ-102	Otava	Rejstejn	137000	333.6	1017	598 – 1345	29
CZ-103	Hamersky potok	Antygl	136000	20.4	1098	978 – 1213	26
CZ-104	Ostruzna	Kolinec	139000	92.0	755	541 – 1165	17
CZ-105	Spulka	Bohumilice	141700	104.6	804	558 – 1131	19
CZ-106	Volynka	Nemetice	143000	383.4	722	430 – 1302	17

CZ-107	Tepla Vltava	Lenora	106000	176.0	1010	765 – 1314	20
CZ-201	Jerice	Chrastava	319000	76.0	493	295 – 862	14
CZ-202	Cerna Nisa	Straz nad Nisou	317000	18.3	672	368 – 850	13
CZ-203	Luzicka Nisa	Prosec	314000	53.8	611	419 – 835	22
CZ-204	Smeda	Bily potok	322000	26.5	817	412 – 1090	26
CZ-205	Smeda	Frydlant	323000	132.7	588	297 – 1113	18
CZ-206	Jizera	Dolni Sytová	086000	321.8	771	399 – 1404	26
CZ-207	Mumlava	Janov-Harrachov	083000	51.3	970	625 – 1404	34
CZ-208	Jizerka	Dolni Stepanice	086000	44.2	842	490 – 1379	29
CZ-209	Malé Labe	Prosecne	003000	72.8	731	376 – 1378	25
CZ-210	Cista	Hostinne	004000	77.4	594	358 – 1322	19
CZ-211	Modry potok	Modry dul	008000	2.6	1297	1076 – 1489	38
CZ-212	Upa	Horni Marsov	013000	82.0	1030	581 – 1495	28
CZ-213	Upa	Horni Stare Mesto	014000	144.8	902	452 – 1495	25
CZ-301	Bela	Castolovice	031000	214.1	491	269 – 1104	25
CZ-302	Knezna	Rychnov nad Kneznou	030000	75.4	502	305 – 861	25
CZ-303	Zdobnice	Slatina nad Zdobnici	027000	84.1	721	395 – 1092	24
CZ-304	Divoka Orlice	Klasterec nad Orlici	024000	153.6	728	505 – 1078	22
CZ-305	Ticha Orlice	Sobkovice	032000	98.5	622	459 – 965	22
CZ-401	Vsetinska Becva	Velke Karlovice	370000	68.3	749	524 – 1042	22
CZ-402	Roznovska Becva	Horni Becva	383000	14.1	745	568 – 966	24
CZ-403	Celadenka	Celadna	279000	31.0	803	536 – 1187	30
CZ-404	Ostravice	Stare Hamry	275300	73.3	707	542 – 922	32
CZ-405	Moravka	Uspolka	281000	22.2	763	560 – 1104	30
CZ-406	Skalka	Uspolka	282000	18.9	785	571 – 1029	24
CZ-407	Lomna	Jablunkov	298000	69.9	667	390 – 1011	25

210

2.3.1 Switzerland

We selected 22 catchments in Switzerland covering a wide range of elevations and areas in the three main hydro-geographical domains of the country, i.e. the Jura and Swiss Plateau, the Central Alps, and the Southern Alps (Weingartner and Aschwanden, 1989). The choice of catchments was constrained by our intention to avoid catchments with significant

215 karst or glacierised areas, as well as catchments with substantial human influence on runoff. This decision allowed us to observe the signal of snow processes, without including noise or added complexity from other processes, but limited the number of catchments in high altitudes, which are the ones with largest snowmelt contribution to runoff, and therefore those that would potentially benefit the most from an increased realism of the snow routine of the model. The resulting set of

catchments has mean elevations between 600 and 2800 m a.s.l. with elevation gradients of up to 2000 m and catchment areas

220   between 3 and 500 km^2 (Figure 2). There is a great variability in the yearly snowmelt contribution to runoff ranging from 5 % to 60 % as the catchments range between pluvial to glacio-nival regimes.

We obtained the necessary meteorological data for running the HBV model from the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss). More specifically, we used pre-processed gridded data products to obtain catchment-average precipitation (Frei et al., 2006; Frei and Schär, 1998), and temperature (Frei, 2014). These gridded data products are

225   available from 1961, have a daily temporal resolution, and a spatial resolution of 1.25 degree minutes covering the entire country.

We used both stream runoff and snow water equivalent data for model calibration and validation. We obtained daily stream runoff data from the Swiss Federal Office for the Environment (FOEN, 2017). Regarding snow water equivalent, we used 18 years of gridded daily snow water equivalent data at 1 km^2 resolution derived from a temperature index snow model with

230   integrated three-dimensional sequential assimilation of observed snow data from 338 stations of the snow monitoring networks of MeteoSwiss and the Swiss Institute for Snow and Avalanche Research (SLF) (Griessinger et al., 2016; Magnusson et al., 2014). Finally, we obtained the catchment areas and topography from a digital elevation model with a resolution of 25 m from the Swiss Federal Office of Topography (swisstopo).

2.3.2 Czechia

235   The second set composed of Czech catchments includes 32 mountain catchments with catchment areas ranging from 3 to 383 km^2 (Figure 2). We selected near-natural catchments with no major human influences such as big dams or water transfers. The resulting catchments are at relatively lower elevations and present lower elevation ranges compared to most of the selected Swiss catchments. Additionally, they are located in the transient zone between oceanic and continental climate with lower mean annual precipitation compared to Swiss catchments. The mean annual snow water equivalent maximum for the

240   period 1980 – 2014 ranges from 35 mm to 742 mm depending on catchment elevation, resulting in 13 % to 39 % of the annual runoff coming from spring snowmelt.

We obtained daily precipitation, daily mean air temperature, and daily mean runoff time series from the Czech Hydrometeorological Institute (CHMI). Additionally, we obtained weekly snow water equivalent data from CHMI (measured each Monday at 7 CET). Since no gridded data of precipitation, air temperature, or snow water equivalent are

245   available for Czechia, station data were used for HBV model parametrization. We used stations located within individual catchments when available. When no such station was available, we selected the nearest station representing similar catchment conditions (e.g., stations situated at a similar elevation). Finally, we used a digital elevation model with a vertical resolution of 5 m from the Czech Office for Surveying, Mapping and Cadastre to obtain catchment areas and topography.
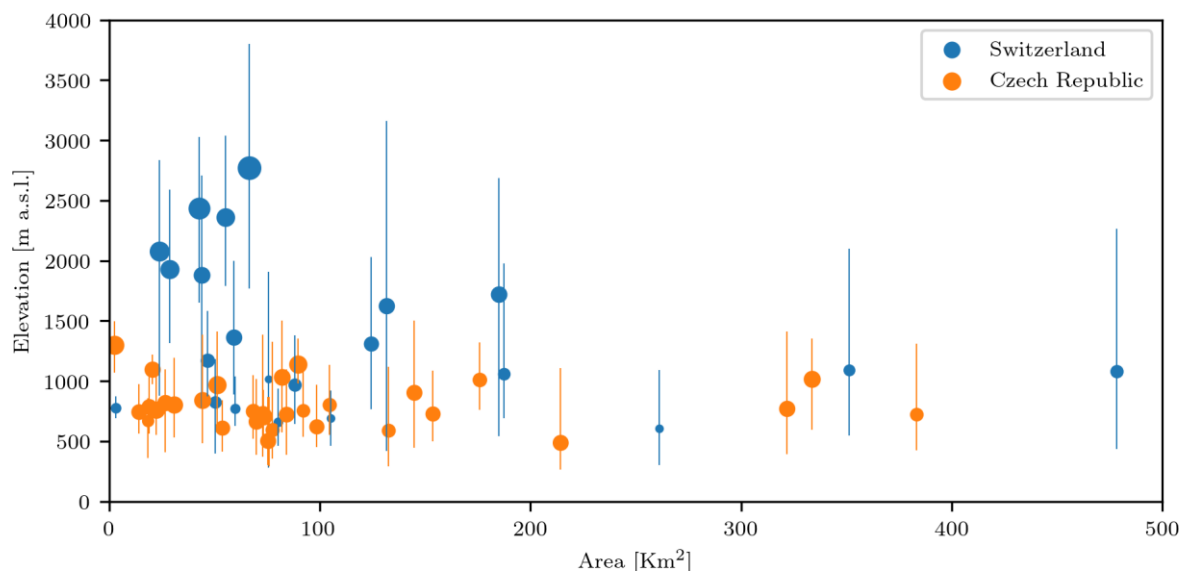
Figure 2 Distribution of the catchments used in this study regarding their area (x-axis), elevation mean value and range (y-axis), and snowmelt contribution to runoff (marker size). The catchments are coloured according to their respective geographical domain: blue (Switzerland), and orange (Czechia).

2.4 Experimental Setup

Even if sub-daily data were available for most variables for the Swiss catchments, we considered that daily data was suitable for this study, as using sub-daily temporal resolutions would have required taking into account the diurnal variability of some of the variables, thus requiring a higher model complexity (Wever et al., 2014). For instance, radiation and temperature fluctuations along the day would require similarly variable degree-day factor values (Hock, 2005). Other factors such as travel times between the sources of snowmelt and the streams would also become significant issues at sub-daily time scales (Magnusson et al., 2015). In order to keep the model simple but able to represent the elevation-dependent snow processes, we used a single vegetation zone per catchment but divided the catchment area into 100 m elevation zones.

When evaluating the performance of hydrological models to simulate snow dynamics, this evaluation is sometimes done solely looking at the simulated runoff by the model, as this variable is the main output of hydrological models (Riboust et al., 2019; Watson and Putz, 2014). Nevertheless, this analysis alone is incomplete as the performance of the model to reproduce runoff is the result of the interaction between the different components of the model, also those that are not directly related to snow processes. For this reason, here we evaluated the existing model structure as well as the proposed modifications to it based on their ability to represent (i) the snow water equivalent of the snowpack, and (ii) stream runoff at the catchment outlet.

To evaluate the performance of the different model structures to reproduce the snow water equivalent of the snowpack we used a modified version of the Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) where the model performance, R_W, is

270 given by the fraction of the sum of quadratic differences between snow water equivalent observations, W_O, and simulations, W_S, and between observations and the mean observed value, $\overline{W_o}$ (Eq. 12).

$$R_W = 1 - \frac{\Sigma(W_o - W_S)^2}{\Sigma(W_o - \overline{W_o})^2},$$ (12)

Due to the substantial differences in snow water equivalent data availability between the two datasets (gridded data in Switzerland vs point data in Czechia), we had to adapt the model calibration and evaluation procedure to each case. We

275 evaluated the model against the mean snow water equivalent value for each elevation zone for the Swiss catchments, and against the measured values at a given elevation for the Czech ones.

Regarding the evaluation of the stream runoff estimation, we deemed that the standard Nash-Sutcliffe efficiency measure was not suitable for our case study as it is skewed towards high flows (Schaefli and Gupta, 2007). Snow processes are dominant both in periods of high flows (e.g. spring flood) and low flows (e.g. winter conditions), which are equally

280 important to estimate correctly. For this reason, we decided to evaluate the estimation of stream runoff by using the natural logarithm of runoff instead (Eq. 13).

$$R_{\ln Q} = 1 - \frac{\Sigma(\ln Q_o - \ln Q_S)^2}{\Sigma(\ln Q_o - \overline{\ln Q_o})^2},$$ (13)

Some studies focusing on snow hydrology establish specific calibration periods for each catchment based on, for instance, the snowmelt season (Griessinger et al., 2016). In this study, however, we decided to constrain the calibration and evaluation

285 periods in a consistent and automated manner for all catchments. For this reason, we defined the model calibration and evaluation periods as comprising days with significant snow cover on the catchment (>25% of the catchment covered by snow). We also considered a full week after the occurrence of snowmelt in order to account for runoff delay. We obtained the value of 25% through empirical tests on the number of days with specific snow coverage values and their corresponding snow water equivalent values. We found that below this value the total snow water equivalent in the studied catchments

290 becomes negligible.

We calibrated the model for all the catchments in the study using a split-sample approach. We selected this approach because it allowed us to assess both the best possible efficiency for each model alternative (calibration period), and a realistic model application scenario (validation period), helping us to distinguish between real model improvement and overfitting. In our case, the simulation period was limited by the input data with the shortest temporal availability, which in this case was the

295 snow water equivalent data for the Swiss catchments. In total 20 years were available, which we divided into two equally long 9-year periods plus 2 years for model warm-up. We calibrated the model for both periods and cross-validated the simulations for the remaining periods. For the Swiss catchments, we considered the period between 1st of September 1998 and 31st August 2016, while for the Czech catchments we considered the period between 1st November 1996 and 31st October 2014. The different start dates for simulation periods in the Swiss and Czech catchments correspond to the different

300 timing for the onset of snow conditions in the different areas. Additionally, the different years included in each study domain

correspond to data limitations in each area. Since both areas are geographically separated, we considered that it was more important to have the same period length for simulation in both domains rather than using the exact same years, as the meteorological conditions are different in the two study domains anyway.

Overall, we calibrated the model for all possible combinations of the single modifications to individual components of the
305   snow routine of the HBV model described in Section 0 (n = 64), catchments (n = 54), simulation periods (n = 2), and objective functions (n = 2) using a genetic algorithm (Seibert, 2000). Every calibration effort consisted of 3500 model runs with parameter ranges based on previous studies (Seibert, 1999; Vis et al., 2015). We performed 10 independent calibrations for each setup in order to capture the uncertainty of the model. In total we performed around 500 million model simulations.

3 Results

310   The large number of catchments and model variations considered in this study make it difficult to grasp the detailed results when looking at the entire dataset. Therefore, we first describe the results for one single catchment to explore the implications of individual model modifications and then we progressively add more elements into the analysis. Additionally, even if we calibrated (and validated) the model for both periods defined in the split-sample test, here we only present the results for the calibration effort in period 1 and corresponding model validation in period 2, as they are representative for the
315   entire analysis. As an example catchment, we selected one of the high altitude, snow-dominated catchments in the set, the Allenbach catchment at Adelboden (CH-204), as it allows us to describe some of the general trends observed across the study domain.

The performance of HBV for this catchment is very high for both objective functions (~0.90). Looking at all the single modifications to the snow routine structure of the HBV model that we evaluated in this study, using a seasonally varying
320   degree-day factor ($C_{0,s}$) has the most substantial impact on the model performance to represent snow water equivalent and, to a lesser extent, stream runoff (Figure 3). Apart from these modifications, only the use of an exponential function to define the precipitation partition between rain and snow (ΔP_e) produces significant changes in the model performance against both objective functions. In this case, however, this modification impacts the model performance in different ways depending on the objective function, even leading to decreased model performance when calibrating against stream runoff. Finally, if we
325   look at the model, we observe that model uncertainty, as given by the performance ranges obtained when aggregating the different calibration efforts, is small compared to the performance differences between the different model structures.
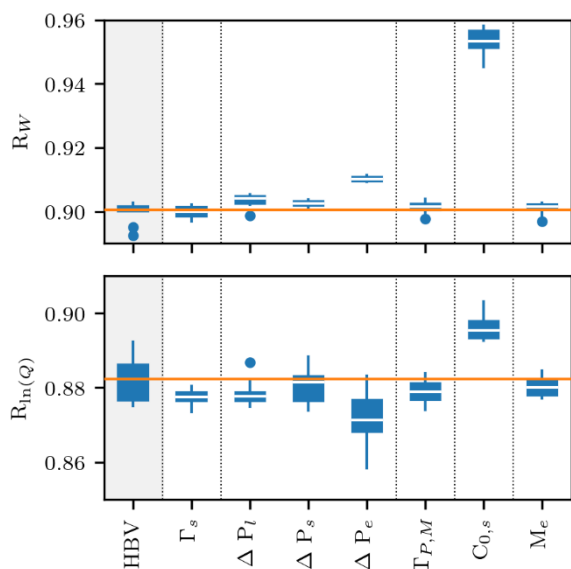
Figure 3 Model calibration performance for the 10 calibration efforts against the two objective functions (top: snow water equivalent; bottom: logarithmic stream runoff) for each of the modifications to individual components of the snow routine of the HBV model for the Allenbach catchment at Adelboden (CH-204). The modifications include a seasonally-variable temperature lapse rate (Γ_s), a linear, sinusoidal, and exponential function for the precipitation phase partition (ΔP_l, ΔP_s, and ΔP_e respectively), different thresholds for precipitation phase and snowmelt ($T_{P,M}$), a seasonally variable degree-day factor ($C_{0,s}$), and an exponential snowmelt with no refreezing (M_e). The median efficiency of HBV is represented with an orange horizontal line.

If we look at an example year within the calibration period, we can get a grasp of how the simulated values of snow water equivalent and stream runoff, including the model uncertainty, compared with the observed values (Figure 3). While capturing the general evolution of the snowpack, the HBV model tends to underestimate the snow water equivalent amounts, except for the spring snowmelt period. The model alternative using a seasonal degree-day factor ($C_{0,s}$), which, as we have already seen, is the best possible model structure modification for model calibration against snow water equivalent for this catchment, exhibits the same behaviour but is more accurate than the HBV model structure. Regarding the calibration against stream runoff, both model alternatives perform well for low flow periods, but they miss or underestimate some of the peaks. Model uncertainty is comparable for both model alternatives and is not significant when compared to the simulated values.
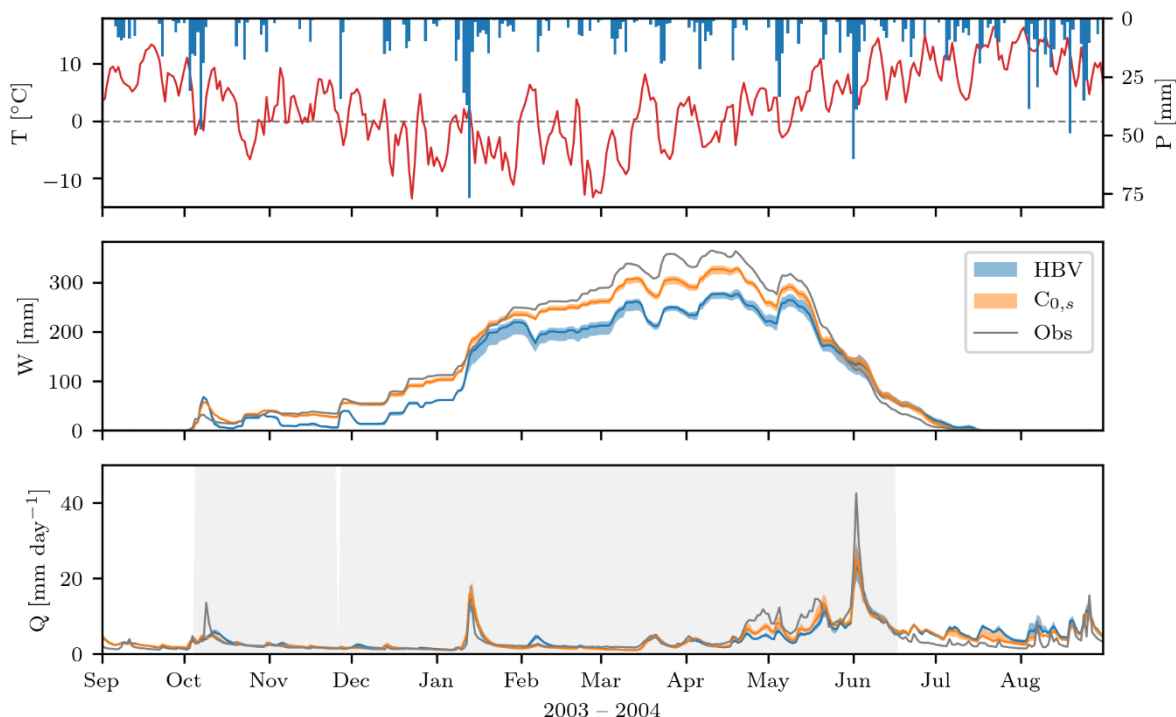
15

Figure 4 Example time series (September 2003 – August 2004) from the Allenbach catchment at Adelboden (CH-204) within the calibration period. Top: daily mean air temperature and total precipitation. Middle: catchment-average observed (grey line) and simulated snow water equivalent (HBV in blue and the model structure modification including a seasonally-varying degree-day factor, $C_{0,s}$ in orange). Bottom: observed (grey line) and simulated stream runoff (HBV in blue and the model structure modification including a seasonal degree-day factor in orange). The grey field represents the period used when calibrating the model against the logarithmic stream runoff. The uncertainty fields for model simulation cover the 10th – 90th percentiles range while the solid line represents the median value.

Zooming out to the entire set of catchments we can observe that, for the calibration period, the impact of the different modifications on the model performance is generally more pronounced for R_W than for $R_{\ln(Q)}$ across all of the considered catchments (Figure 5). For most catchments, most performance improvements when calibrating against snow water equivalent were achieved by using a seasonally variable degree-day factor ($C_{0,s}$). Using different thresholds for precipitation phase partition and snowmelt ($T_{P,M}$) and using an exponential function for precipitation phase partition (ΔP_e) also convey significant improvements in some of the catchments. Nevertheless, this last modification performs almost equal to the HBV model when calibrating against stream runoff, and for some catchments even slightly worse. Using an exponential function to define the precipitation partition between rain and snow consistently penalises the model performance when calibrating the HBV model against stream runoff, whereas using an exponential function for snowmelt (M_e) is the best alternative when looking at this objective function. Overall, most modifications convey slight improvements in model performance with respect to snow water equivalent for most of the catchments in the dataset. Nevertheless, the modifications on the precipitation phase partition tend to penalise most Czech catchments when calibrating against snow water equivalent. We did

not observe any significant connection between model performance and catchment characteristics such as mean catchment

elevation, catchment area, or yearly snowmelt contribution to runoff.
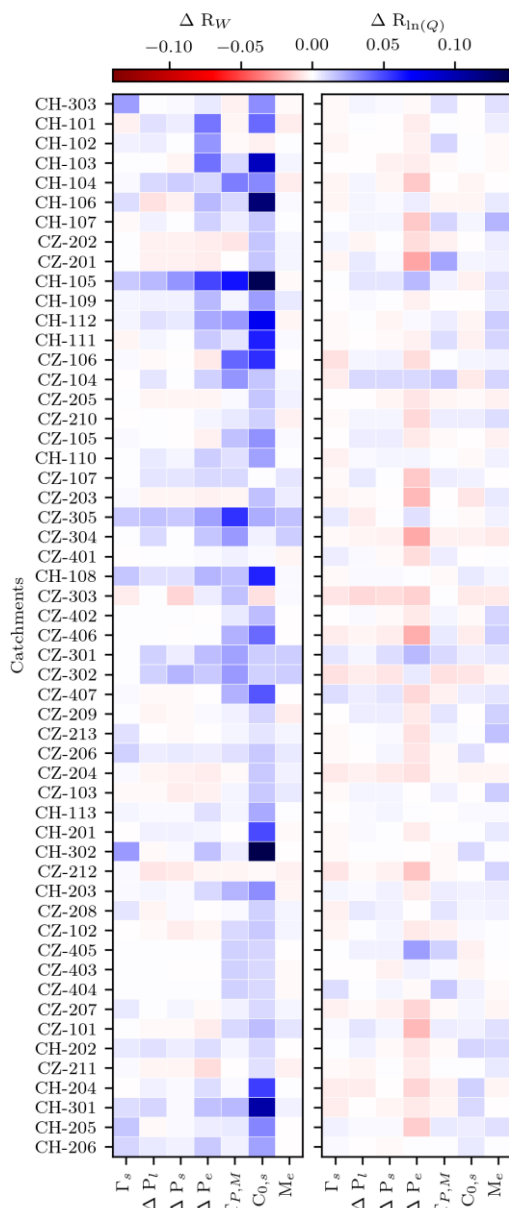
Figure 5 Median relative model calibration performance for alternative HBV model structures, including modifications to single components of the snow routine with respect to HBV. The modifications include a seasonally-variable temperature lapse rate (Γ_s), a linear, sinusoidal, and exponential function for the precipitation phase partition (ΔP_l, ΔP_s, and ΔP_e respectively), different thresholds for precipitation phase and snowmelt ($T_{P,M}$), a seasonally variable degree-day factor ($C_{0,s}$), and an exponential snowmelt with no refreezing (M_e). Left: model calibration against snow water equivalent; right: model calibration against logarithmic stream runoff. The catchments are ordered by mean yearly snowmelt contribution to runoff in downwards increasing order.

365

370

So far, we have seen that while some modifications have a clear and consistent impact on model calibration performance in all catchments, most of them have less pronounced, catchment-dependent impact. It is therefore difficult to decide which modifications are better than others (including the default HBV structure) for most of the catchments. Furthermore, until this point, we have only looked at the calibration efficiencies. To better understand the usefulness of the different modifications in real applications, we need to take into account which of the modifications perform best with respect to the validation period (Figure 6). As already observed in Figure 5, using a seasonal degree-day factor ($C_{0,s}$) is the best modification for calibrating the model against snow water equivalent for the vast majority of the catchments. Nevertheless, this modification ranks relatively low for model validation against the same objective function. Looking at stream runoff, using an exponential function for snowmelt simulation while disregarding the refreezing process (M_e) is the best-ranking modification for both model calibration and validation while the HBV model structure ranks higher than several of the considered modifications. Using an exponential function to define the precipitation partition between rain and snow (ΔP_e) is the worst alternative for calibrating it against stream runoff. For model calibration, there is a diagonal pattern from the top left to the bottom right (Figure 6), indicating that different modifications have the same rank in most catchments (notice that the ranking of modifications is different when looking at snow water equivalent with respect to stream runoff). Such a pattern is not present for model validation, suggesting that there is no clear answer to which modifications convey most value to the model.
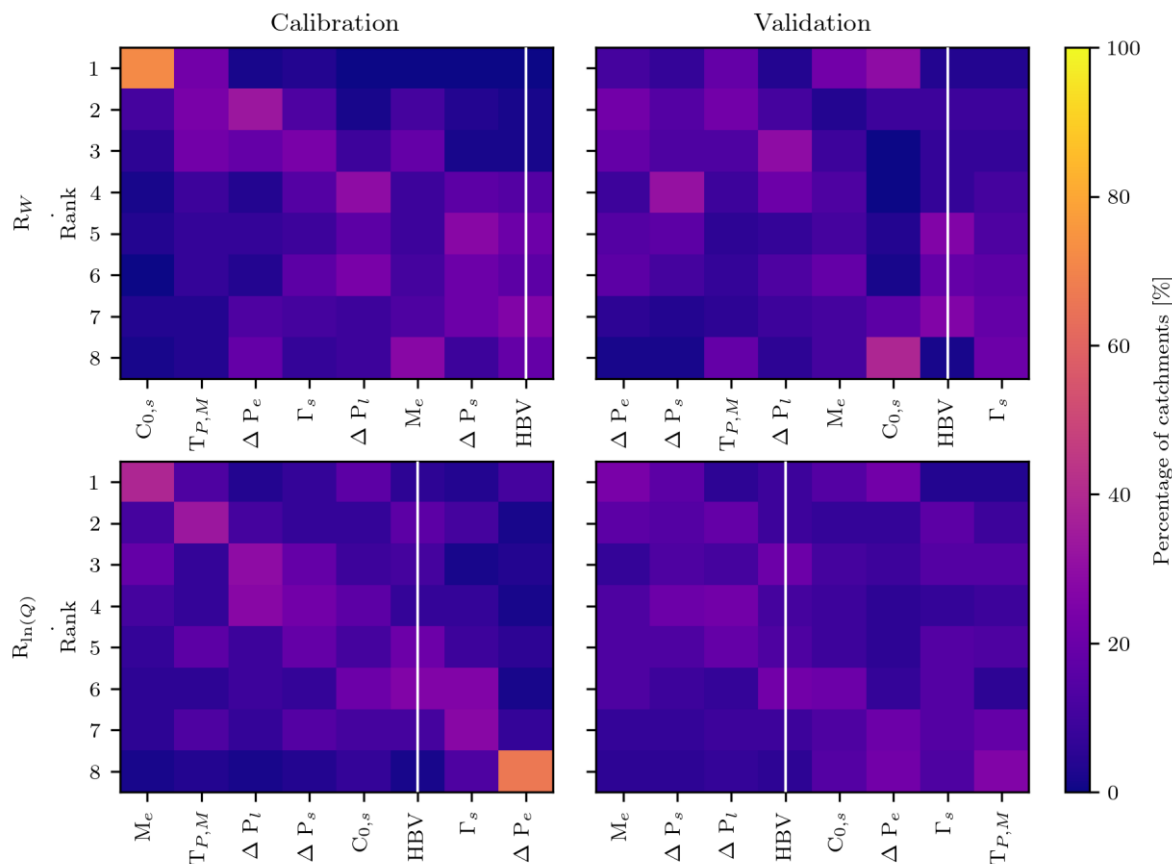
Figure 6 Rank matrices for each of the model simulation scenarios. Top: model calibration (left) and validation (right) against snow water equivalent; bottom: model calibration (left) and validation (right) against logarithmic stream runoff. Each rank matrix shows the rank distribution of each modification to single components of the snow structure of the HBV model for all the catchments included in this study. The modifications are ordered from highest to lowest average ranking (left to right) and include a seasonally-variable temperature lapse rate (Γ_s), a linear, sinusoidal, and exponential function for the precipitation phase partition (ΔP_l, ΔP_s, and ΔP_e respectively), different thresholds for precipitation phase and snowmelt ($T_{P,M}$), a seasonally variable degree-day factor ($C_{0,s}$), and an exponential snowmelt with no refreezing (M_e). The HBV model structure is highlighted with a white vertical line.

As we have seen, even if some model modifications clearly improve the performance of the model for model calibration, most modifications have at most minimal impact. A reason for this might be that the actual differences compared to the standard HBV model formulation are minimal. For this reason, we next explore whether the same trends persist when increasing the model complexity through incorporating an increasing amount of modifications simultaneously. The number of model alternatives for each number of modifications to the model structure is presented in Table 3.

19

Hydrology and
Earth System
Sciences
Discussions

Open Access

EGU

Table 3 Number of model structure alternatives containing a given number of snow routine modifications.

Number of modifications	Number of alternatives
1	7
2	18
3	22
4	13
5	3
	n = 63

For instance, in the case of introducing 5 modifications to the snow routine of the model, the only available alternative
405 representation for the lapse rate (i.e. $\varGamma_s$), the threshold temperature (i.e. $T_{P,M}$), the degree-day factor (i.e. $C_{0,s}$), and snowmelt and refreezing (i.e. M_e) are used, in combination with one of the three alternative representations for the precipitation phase partition (i.e. $\varDelta P_l$, $\varDelta P_s$ or $\varDelta P_e$).

Figure 7 shows the median relative efficiency of each of the 64 possible model structure alternatives for all catchments relative to the standard HBV model performance, sorted by the number of components being modified. We can see that,
410 when calibrating the model against snow water equivalent, model efficiency clearly increases for all of the model structure alternatives. The impact is more modest for model validation with a significant percentage of alternative structures performing worse than HBV. Regarding model calibration against stream runoff, the effect of an increasing number of components being modified is minimal but mostly positive. The range of efficiencies is also significantly smaller than when looking at snow water equivalent, which is due to the fact that, for most catchments, the snow routine has a limited weight
415 over the entire HBV model. For model validation we observe a similar trend, but with broader efficiency ranges. Also, the fact that performance ranges vary significantly across the number of components being modified is in part due to the differences in the number of model alternatives for each of them.
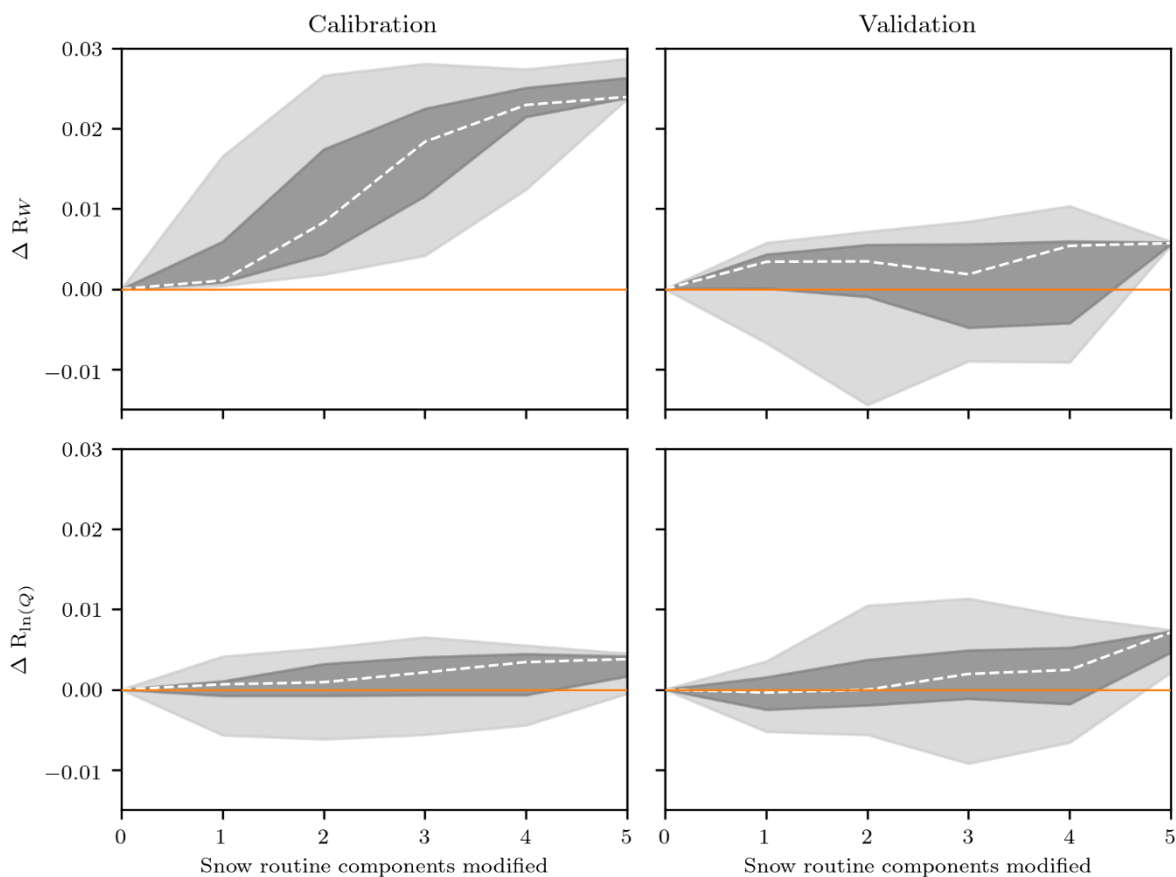
Figure 7 Median relative model efficiency with respect to HBV across all catchments for the 64 considered snow routine structures sorted by an increasing number of modifications. Model simulations against snow water equivalent are presented in the top row, while those against logarithmic stream runoff are shown in the bottom row. Model calibration is presented in the left column and model validation in the right one. The dashed line represents the median value across all catchments while the grey fields represent the minimum to maximum (light grey) and 25th to 75th percentiles (dark grey). The relative efficiency of HBV is highlighted with a solid orange line.

In general, there is an increase of model efficiency for all cases. However, with the exception of model calibration against snow water equivalent, there is no clear indication that an increasing model structure complexity leads to significantly improved model performance. Indeed, the range of performances among the different model structures is larger than the median net increase. This might be an indication that choosing the right modifications (or combinations of modifications) is more relevant than increasing model complexity. This way, we attempted to determine if there are some modifications that convey model performance gain across all model structures for the four simulation scenarios. We ranked all model structures for model calibration and validation against the two objective functions and looked at the cumulative distribution of each of the individual model modifications (Figure 8). Some of the patterns remain the same as those observed for single modifications only (Figure 6). For instance, when looking at model calibration against snow water equivalent, all top-ranking model structures use a seasonally variable degree-day factor ($C_{0,s}$). Similarly, when looking at model calibration

435 against stream runoff, all bottom-ranking model structures use an exponential function for precipitation phase partition (ΔP_e). Other patterns that could not be clearly observed when only looking at single modifications emerge here as well. Indeed, even if a seasonal degree-day factor performs above average for most cases, this particular modification is included in all bottom-ranking model structures for model validation against snow water equivalent. Also, structures including an exponential function for snowmelt (M_e) perform above average for all cases, even in almost all the top-ranking ones.
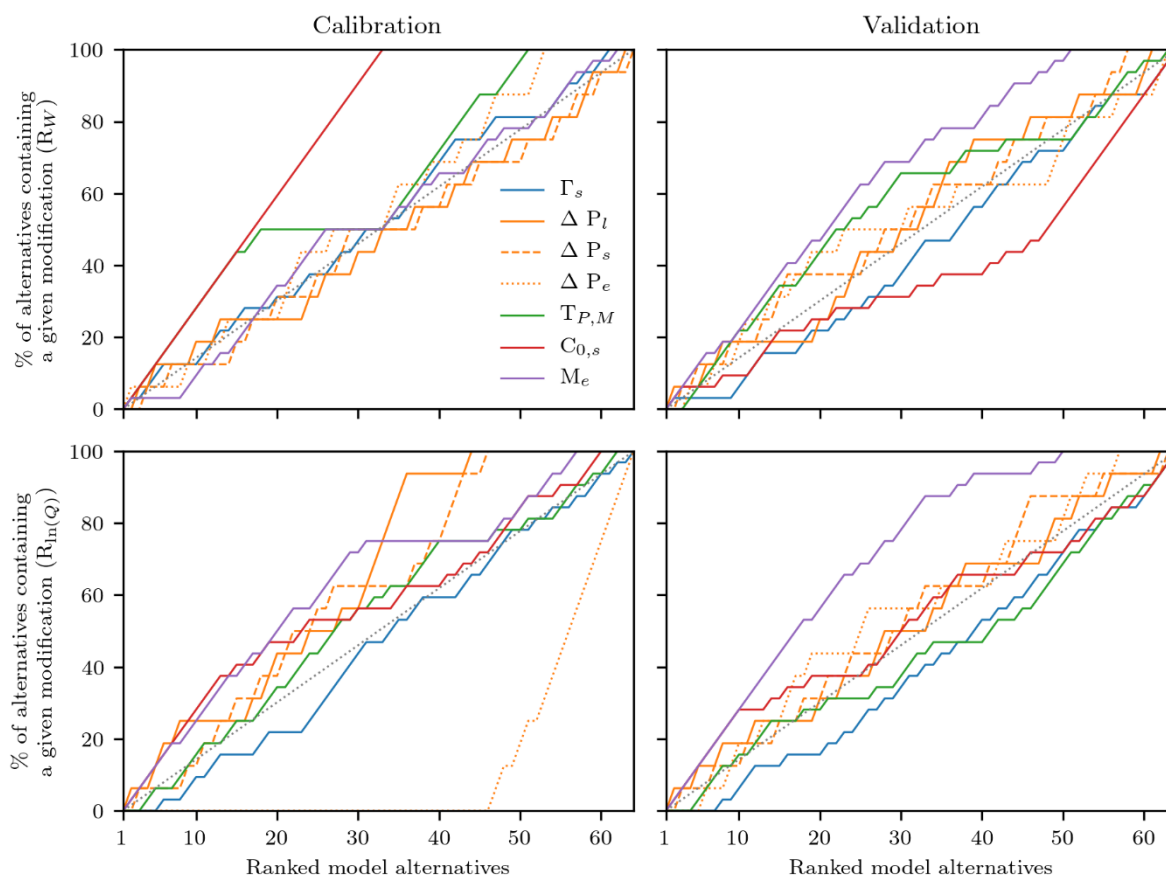
Figure 8 Cummulative plots for each of the 7 individual modifications to the snow routine of the HBV model as a function of the ranked 64 model structures arising from all the possible combinations of modifications. The modifications are a seasonally-variable temperature lapse rate (Γ_s), a linear, sinusoidal, and exponential function for the precipitation phase partition (ΔP_l, ΔP_s, and ΔP_e respectively), different thresholds for precipitation phase and snowmelt ($T_{P,M}$), a seasonally variable degree-day factor ($C_{0,s}$), and an exponential snowmelt with no refreezing (M_e). Model simulations against snow water equivalent are presented in the top row, while those against logarithmic stream runoff are presented in the bottom row. Model calibration is presented in the lleft column and model validation in the right one. Model modifications plotting above the 1:1 line (gray dotted line) tend to be included in high-ranking model structures, while those plotting below the 1:1 line tend to be included in low ranking structures.

Indeed, looking at the ranked alternative model structures and the modifications contained in each of them, some model
450 modifications have proven to be dominant, even when combined with a number of other modifications. Nevertheless, these dominant modifications impact the model structure performance in different ways, depending on the modelling scenario.

Ideally, the modifications we are considering to the HBV model should convey an improved representation of snow water equivalent but also have a positive impact on stream runoff, both for model calibration and validation.

455 To achieve an improved representation of both snow water equivalent and stream runoff we should only consider model alternatives that have a positive impact for each of the four modelling scenarios (i.e. calibration and validation efforts against both objective functions). This way, we selected and ranked all model alternatives that have positive median relative efficiency values with respect to HBV and examine which modifications are dominant (Figure 9). All of the selected alternative model structures contain an exponential function for snowmelt (M_e), and none of them includes an exponential function for precipitation phase partition (ΔP_e). Most model structures are the result of the combination of three or four 460 different modifications (seven alternatives each). Four alternatives contain two model modifications and two alternatives include five modifications. Perhaps most interesting, two of the model alternatives only include a single modification: an exponential snowmelt function, and a sine function for precipitation phase partition (ΔP_s). Nevertheless, these alternatives have the lowest ranking among the selection. Overall, the top-ranking alternatives contain a seasonally varying degree-day factor ($C_{0,s}$) and an exponential snowmelt function, while other modifications resulted in more variable performances.
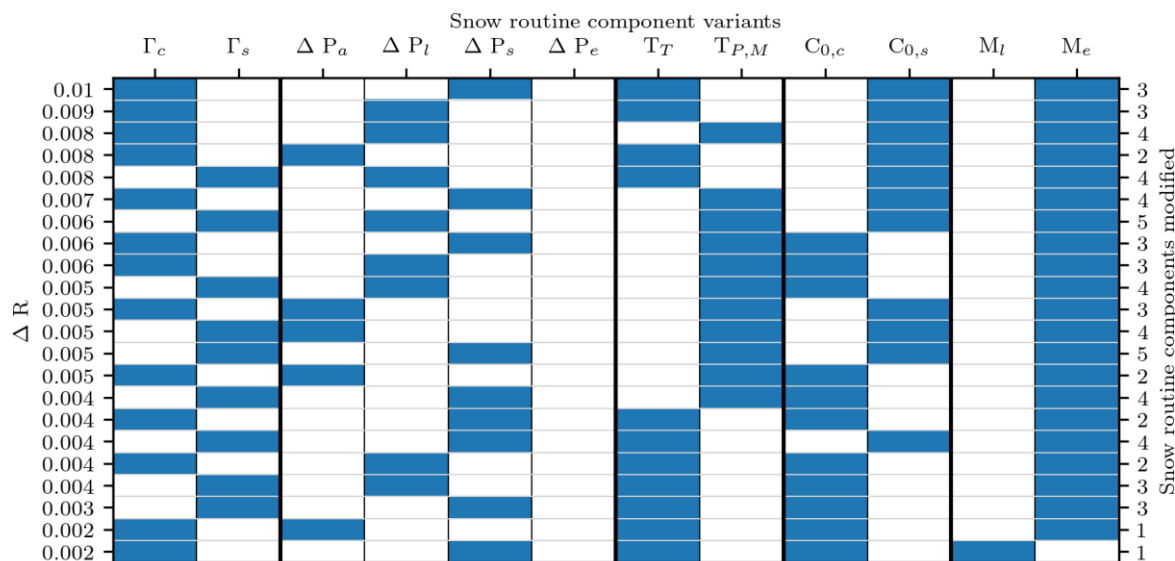
465

Figure 9 Ranked alternative structures to the snow routine of HBV that present positive relative efficiency values with respect to HBV for model calibration and validation against snow water equivalent and stream runoff disaggregated by snow routine component variants. The alternatives for each of the considered model components are a linear and a seasonally-variable degree-day factor (Γ_c and Γ_s respectively); an abrupt, linear, sinusoidal, and exponential precipitation phase partition (ΔP_a, ΔP_l, ΔP_s, and 470 **ΔP_e respectively); a common and individualised threshold temperature for precipitation phase partition and snowmelt (T_T and $T_{P,M}$ respectively); a constant and seasonally-variable degree-day factor ($C_{0,c}$ and $C_{0,s}$ respectively); and a linear and exponential (with no refreezing) melt function (M_l and M_e respectively). Every row contains one model structure with the selected variant for each of the components highlighted in blue. The median relative efficiency for all modelling scenarios is given on the left y-axis while the number of model modifications in each alternative is provided in the right y-axis.**

4 Discussion

From the results obtained in this study we can conclude that it is difficult to improve existing hydrological models and especially those that, like HBV, have proven capable of reproducing the hydrological behaviour of catchments over an extensive range of environmental and geographical conditions (Bergström, 2006). That being said, some of the proposed modifications to the snow routine of the HBV model that we tested in this study showed a generally positive impact on the model performance for simulating both snow water equivalent and stream runoff, albeit to different extents. The most valuable single model modifications for modelling mountainous catchments in Central Europe are the use of an exponential snowmelt function and, to a lesser extent, a seasonally-varying degree-day factor. Another modification, using different thresholds for snowfall and snowmelt instead of a single threshold, produces significant improvements towards snow water equivalent, but does not convey any advantage for simulating stream runoff.

Continuing on the impact of model modifications on the different objective functions we considered in this study, we have seen that there are large differences between them. In general, the impact is more evident when simulating snow water equivalent, as the simulated stream runoff is modulated and smoothened out by the other routines of the model (i.e. soil, groundwater, and routing routines), which partially compensate and mask any modifications made on the snow routine (Clark and Vrugt, 2006). Additionally, some of the modifications that improve the performance of the model to simulate snow water equivalent, such as the use of an exponential function to define the solid and liquid phases of precipitation, clearly penalise the stream runoff simulations.

Unlike most modifications considered in this study, which are simplifications of complex processes, the use of an exponential function to describe precipitation phase partition and the use of a seasonally varying temperature lapse rate are both modifications derived from empirical evidence (Magnusson et al., 2014; Rolland, 2002). Nevertheless, as we have previously discussed, neither of these modifications translate into an improvement of model performance for any of the objective functions. This might be due to the fact that, since the models are based on simplifications and generalisations of the processes that occur in reality, these accurate measurements of the processes do not align well with other simplifications made in the model structure and/or behaviour or the chosen spatio-temporal resolution (Harder and Pomeroy, 2014; Magnusson et al., 2015).

Other modifications are relatively similar to each other, such as the case of using linear and sine functions to describe precipitation phase partition. Both these conceptualisations require only one additional parameter, and perform almost identical. Indeed, precipitation partition between rain and snow is exactly the same for both conceptualisations for most of the transition temperature range. The only divergence is in the tails, which are abrupt for the linear case and smooth for the sine one. Provided that the smooth transition is a more accurate description of the physical process which, in addition, avoids the introduction of discontinuities into the objectives functions, which might complicate model calibration (Kavetski and Kuczera, 2007), and that both modifications include the same degree of complexity and perform nearly identical, we should

24

Hydrology and
Earth System
Sciences
Discussions
Open Access
EGU

favour the most accurate description. Nevertheless, some models, including HBV, continue to use the linear conceptualisation with the argument of simplicity.

We observe differences in model performance among the two geographical domains included in this study. Most notably, the
510 modifications on precipitation phase partition penalised the model performance on most Czech catchments for simulating snow water equivalent, while having the opposite impact for Swiss catchments. The Czech catchments have a narrower elevation range compared to the Swiss catchments, in addition to an earlier and shorter snowmelt period. These characteristics may favour the simplification of an abrupt transition between rain and snow, while using gradual transitions between rain and snow favours the more extended melt season and larger elevation ranges of the Swiss catchments. Another
515 factor that may impact the results is the significant differences in model driving and validation data availability for each of the geographical domains (Günther et al., 2019; Meeks et al., 2017). Indeed, while in Czechia there are a limited number of meteorological stations providing temperature, precipitation and snow water equivalent data, the Swiss catchments benefit from distributed data for the different catchment elevations, allowing for more accurate calibration of snow-related parameters.

520 Nevertheless, even with the large differences in hydrological regime, catchment morphology, and data availability between the two geographical domains, the impact of the different modifications to model performance was in general comparable among them. This is a relevant point because HBV aims to be a general-purpose hydrological model that is applicable to a range of geographical domains and both in areas with data wealth and scarcity. Achieving comparable model performances under these different conditions is an indication of the suitability and strength of the HBV model for such goals.

525 Regarding model complexity and uncertainty, we found that increasing the complexity, and thus the number of parameters of the model, generally translated into a broader range of model performances, indicating that the uncertainty related to the model structure was also increased. This is a well-known problem of hydrological models, and the focus of many studies (Essery et al., 2013; Strasser et al., 2002). Additionally, we found that, for most cases, the median model performance increase with increasing model complexity was not significant with respect to the performance range. This means that an
530 increasing model complexity does not necessarily translate into better model performance, which is consistent with other studies (Orth et al., 2015). This fact highlights the importance of carefully choosing the degree of complexity of the model based on the objectives to be achieved and the available data (Hock, 2003; Magnusson et al., 2015).

Even if model complexity is not desirable by itself if implemented in a sensible way, it can improve the performance of hydrological models. Indeed, 22 of the 63 model structure alternatives that we tested in this study (all of them conveying an
535 increase of model complexity) convey and increase in model performance with respect to HBV for all cases. Furthermore, out of these 22 alternatives, only two of them consist of a single modification, while most have 3 or 4 modifications. Nevertheless, all of these alternatives share common traits such as using an exponential snowmelt function with no refreezing. Indeed, almost all model structures that do not have this particular modification perform worse than HBV in at least one simulation scenario.

540 Considering these results, it is reasonable to state that, while the increased realism arising from the interplay among the different modifications in these model structure alternatives play a role in improving the model performance, this is mainly the result of a few dominant modifications. This way, the use of an exponential snowmelt function is the most valuable single modification with a median performance increase of 0.002 with respect to HBV for all simulations (with individual performance increases over 0.1). However, when we combine it with a seasonal degree-day factor, we achieve a median

545 performance increase of 0.008, almost the highest performance increase amongst all model alternatives. Adding further complexity to the model does not convey significant improvements with respect to this model structure. Consequently, if we were to implement any modifications to the model, they would be to substitute the linear snowmelt and refreezing conceptualisation by an exponential snowmelt function, and replacing the constant degree-day factor by a seasonally varying one, in that order.

550 Finally, it is important to mention that these results are only valid for the selected study areas and cannot be extrapolated to all the different alpine and snow-covered areas around the world. The different processes involved in different settings are likely to favour different conceptualisations of the snow processes. So, while the proposed modifications might be useful to tailor the model to Central-European alpine catchments, we still consider the default model structure of HBV as a very capable general purpose model that can be used in a variety of settings and for different purposes.

555 **5 Conclusions**

We evaluated the performance of the snow routine of the HBV model and explored possible modifications to make it more realistic and relevant for hydrological modelling in Alpine areas in Central Europe. We tested a number of modifications to all of the different components of the snow routine over a large number of catchments covering a range of geographical settings, and different data availability conditions on their ability to reproduce both snow water equivalent and stream runoff.

560 We found that the results differ greatly across the different catchments, objective functions, and simulation type (calibration/validation). However, the results allow drawing the following general conclusions regarding the value of the different model modifications for the performance in mountainous catchments in Central Europe:

- The comparatively simple default structure of the HBV model performs well when simulating snow-related processes and their impact to stream runoff in most of the examined catchments.

565 - An increased model complexity does not by itself add any value to the ability of the model to reproduce snow water equivalent and stream runoff. A careful examination of the design choices of the model for the given application, data availability and objective is a significantly better approach.

- An exponential snowmelt function with no refreezing is the single most valuable overall modification to the snow routine structure, followed by a seasonally variable degree-day factor. Adding further complexity to the model does

570 not necessarily translate in significant performance improvements.

Hydrology and
Earth System
Sciences
Discussions

These results are not transferrable to other geographical domains or purposes, but the methodology presented here may be used to assess the suitability of model design choices.

6 Data availability

575 Meteorological and hydrological data to calibrate the HBV model were obtained from the Swiss Federal Office of Meteorology and Climatology, the Swiss Federal Office for the Environment, and the Czech Hydrometeorological Institute. The HBV model outputs are available from the first author upon request.

7 Author contribution

JS initiated the study. MGL developed the methodology and performed all analyses. MGL, NG, and MJ prepared the input meteorological and hydrological data used to calibrate the HBV model. MJPV performed all the necessary modifications to 580 the source code of the HBV model. MGL prepared the manuscript with contributions from all co-authors.

8 Competing interests

The authors declare that they have no conflict of interest.

9 Acknowledgements

References

Avanzi, F., De Michele, C., Morin, S., Carmagnola, C. M., Ghezzi, A. and Lejeune, Y.: Model complexity and data requirements in snow hydrology: seeking a balance in practical applications, Hydrol. Process., 30(13), 2106–2118, doi:10.1002/hyp.10782, 2016.

590 Barnett, T. P., Adam, J. C. and Lettenmaier, D. P.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438(7066), 303–309, doi:10.1038/nature04141, 2005.

Berghuijs, W. R., Woods, R. A. and Hrachowitz, M.: A precipitation shift from snow towards rain leads to a decrease in streamflow-supplement, Nat. Clim. Chang., 4(7), 583–586, doi:10.1038/NCLIMATE2246, 2014.

Bergström, S.: The HBV Model, in Computer Models of Watershed Hydrology, edited by V. P. Singh, pp. 443–476, Water 595 Resources Publications, Highlands Ranch, CO., 1995.

Hydrology and
Earth System
Sciences
Discussions

Open Access

EGU

Bergström, S.: Experience from applications of the HBV hydrological model from the perspective of prediction in ungauged basins, IAHS Publ., 307, 97–107, 2006.

Braun, J. N. and Renner, C. B.: Application of a conceptual runoff model in different physiographic regions of Switzerland, Hydrol. Sci. J., 37(3), 217–231, doi:10.1080/02626669209492583, 1992.

600   Clark, M. P. and Vrugt, J. A.: Unraveling uncertainties in hydrologic model calibration: Addressing the problem of compensatory parameters, Geophys. Res. Lett., 33(6), 1–5, doi:10.1029/2005GL025604, 2006.

Collins, E. H.: Relationship of Degree-Days above Freezing to Runoff, Eos, Trans. Am. Geophys. Union, 15(2), 624–629, 1934.

Dai, A.: Temperature and pressure dependence of the rain-snow phase transition over land and ocean, Geophys. Res. Lett.,
605   35(12), 1–7, doi:10.1029/2008GL033295, 2008.

Debele, B., Srinivasan, R. and Gosain, A. K.: Comparison of process-based and temperature-index snowmelt modeling in SWAT, Water Resour. Manag., 24(6), 1065–1088, doi:10.1007/s11269-009-9486-2, 2010.

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

610   Fang, S., Xu, L., Pei, H., Liu, Y., Liu, Z., Zhu, Y., Yan, J. and Zhang, H.: An Integrated Approach to Snowmelt Flood Forecasting in Water Resource Management, IEEE Trans. Ind. Informatics, 10(1), 548–558, doi:10.1109/TII.2013.2257807, 2014.

Flügel, W.-A.: Hydrological response units (HRUs) to preserve basin heterogeneity in hydrological modelling using PRMS/MMS - case study in the Bröl basin, Germany, in Modelling and Management of Sustainable Basin-scale Water
615   Resource Systems, vol. 231, pp. 79–87, International Association of Hydrological Sciences (IAHS), Boulder, CO., 1995.

FOEN: Observed Discharge Time Series of Swiss Rivers, 2017.

Frei, C.: Interpolation of temperature in a mountainous region using nonlinear profiles and non-Euclidean distances, Int. J. Climatol., 34, 1585–1605, doi:10.1002/joc.3786, 2014.

Frei, C. and Schär, C.: A precipitation climatology of the Alps from high-resolution rain-gauge observations, Int. J.
620   Climatol., 18, 873–900, doi:10.1002/(SICI)1097-0088(19980630)18:8<873::AID-JOC255>3.0.CO;2-9, 1998.

Frei, C., Schöll, R., Fukutome, S., Schmidli, J. and Vidale, P. L.: Future change of precipitation extremes in Europe: Intercomparison of scenarios from regional climate models, J. Geophys. Res., 111, doi:10.1029/2005JD005965, 2006.

Freudiger, D., Kohn, I., Seibert, J., Stahl, K. and Weiler, M.: Snow redistribution for the hydrological modeling of alpine catchments, Wiley Interdiscip. Rev. Water, 4(5), e1232, doi:10.1002/wat2.1232, 2017.

625   Frey, S. and Holzmann, H.: A conceptual, distributed snow redistribution model, Hydrol. Earth Syst. Sci., 19(11), 4517–4530, doi:10.5194/hess-19-4517-2015, 2015.

Froidurot, S., Zin, I., Hingray, B. and Gautheron, A.: Sensitivity of Precipitation Phase over the Swiss Alps to Different Meteorological Variables, J. Hydrometeorol., 15(2), 685–696, doi:doi:10.1175/JHM-D-13-073.1, 2014.

Gabbi, J., Carenzo, M., Pellicciotti, F., Bauder, A. and Funk, M.: A comparison of empirical and physically based glacier

630 surface melt models for long-term simulations of glacier response, J. Glaciol., 60(224), 1199–1207, doi:10.3189/2014JoG14J011, 2014.

Griessinger, N., Seibert, J., Magnusson, J. and Jonas, T.: Assessing the benefit of snow data assimilation for runoff modeling in Alpine catchments, Hydrol. Earth Syst. Sci., 20(9), 3895–3905, doi:10.5194/hess-20-3895-2016, 2016.

Günther, D., Marke, T., Essery, R. and Strasser, U.: Uncertainties in Snowpack Simulations—Assessing the Impact of Model

635 Structure, Parameter Choice, and Forcing Data Error on Point-Scale Energy Balance Snow Model Performance, Water Resour. Res., 55(4), 2779–2800, doi:10.1029/2018WR023403, 2019.

Hannah, D. M., Brown, L. E., Milner, A. M., Gurnell, A. M., McGregor, G. R., Petts, G. E., Smith, B. P. G. and Snook, D. L.: Integrating climate-hydrology-ecology for alpine river systems, Aquat. Conserv. Mar. Freshw. Ecosyst., 17, 636–656, doi:10.1002/aqc.800, 2007.

640 Harder, P. and Pomeroy, J. W.: Hydrological model uncertainty due to precipitation-phase partitioning methods, Hydrol. Process., 28(14), 4311–4327, doi:10.1002/hyp.10214, 2014.

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

645 Hock, R.: A distributed temperature-index ice- and snowmelt model including potential direct solar radiation, J. Glaciol., 45(149), 101–111, doi:10.1017/S0022143000003087, 1999.

Hock, R.: Temperature index melt modelling in mountain areas, J. Hydrol., 282(1–4), 104–115, doi:10.1016/S0022-1694(03)00257-9, 2003.

Hock, R.: Glacier melt: a review of processes and their modelling, Prog. Phys. Geogr., 29(3), 362–391,

650 doi:10.1191/0309133305pp453ra, 2005.

Hottelet, C., Blažková, Š. and Bičík, M.: Application of the ETH Snow Model to Three Basins of Different Character in Central Europe, Nord. Hydrol., 25(1–2), 113–128, 1994.

Jamieson, B. and Stethem, C.: Snow avalanche hazards and management in Canada: Challenges and progress, Nat. Hazards, 26(1), 35–53, doi:10.1023/A:1015212626232, 2002.

655 Jenicek, M. and Ledvinka, O.: Importance of snowmelt contribution to seasonal runoff and summer low flows in Czechia, Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2019-611, 2020.

Kane, D. L., Gieck, R. E. and Hinzman, L. D.: Snowmelt Modeling at Small Alaskan Arctic Watershed, J. Hydrol. Eng., 2(4), 204–210, doi:10.1061/(ASCE)1084-0699(1997)2:4(204), 1997.

Kavetski, D. and Kuczera, G.: Model smoothing strategies to remove microscale discontinuities and spurious secondary

660 optima im objective functions in hydrological calibration, Water Resour. Res., 43(3), 1–9, doi:10.1029/2006WR005195, 2007.

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

Magnusson, J., Gustafsson, D., Hüsler, F. and Jonas, T.: Assimilation of point SWE data into a distributed snow cover model
665   comparing two contrasting methods, Water Resour. Res., 50, 7816–7835, doi:10.1002/ 2014WR015302, 2014.

Magnusson, J., Wever, N., Essery, R., Helbig, N., Winstral, A. and Jonas, T.: Evaluating snow models with varying process
representations for hydrological applications, Water Resour. Res., 51(4), 2707–2723, doi:10.1002/2014WR016498, 2015.

Martinec, J.: The degree–day factor for snowmelt runoff forecasting, in IUGG General Assembly of Helsinki, vol. 51, pp.
468–477, IAHS Commission of Surface Waters, Helsinki, Finland., 1960.

670   Meeks, J., Moeck, C., Brunner, P. and Hunkeler, D.: Infiltration under snow cover: Modeling approaches and predictive
uncertainty, J. Hydrol., 546, 16–27, doi:10.1016/j.jhydrol.2016.12.042, 2017.

Merz, R. and Blöschl, G.: A process typology of regional floods, Water Resour. Res., 39(12), 1–20,
doi:10.1029/2002WR001952, 2003.

Nash, J. E. and Sutcliffe, J. V.: River flow forecasting through conceptual models part I: A discussion of principles, J.
675   Hydrol., 10, 282–290, doi:10.1016/0022-1694(70)90255-6, 1970.

Ohmura, A.: Physical Basis for the Temperature-Based Melt-Index Method, J. Appl. Meteorol., 40(4), 753–761,
doi:10.1175/1520-0450(2001)040<0753:PBFTTB>2.0.CO;2, 2001.

Orth, R., Staudinger, M., Seneviratne, S. I., Seibert, J. and Zappa, M.: Does model performance improve with complexity? A
case study with three hydrological models, J. Hydrol., 523, 147–159, doi:10.1016/j.jhydrol.2015.01.044, 2015.

680   Pellicciotti, F., Brock, B., Strasser, U., Burlando, P., Funk, M. and Corripio, J.: An enhanced temperature-index glacier melt
model including the shortwave radiation balance: development and testing for Haut Glacier d'Arolla, Switzerland, J.
Glaciol., 51, doi:10.3189/172756505781829124, 2005.

Riboust, P., Thirel, G., Moine, N. Le and Ribstein, P.: Revisiting a simple degree-day model for integrating satellite data:
implementation of swe-sca hystereses, J. Hydrol. Hydromechanics, 67(1), 70–81, doi:10.2478/johh-2018-0004, 2019.

685   Rico, M., Benito, G., Salgueiro, A. R., Díez-Herrero, A. and Pereira, H. G.: Reported tailings dam failures. A review of the
European incidents in the worldwide context, J. Hazard. Mater., 152(2), 846–852, doi:10.1016/j.jhazmat.2007.07.050, 2008.

Rolland, C.: Spatial and Seasonal Variations of Air Temperature Lapse Rates in Alpine Regions, J. Clim., 16, 1032–1046,
doi:10.1175/1520-0442(2003)016<1032:SASVOA>2.0.CO;2, 2002.

Schaefli, B. and Gupta, H. V.: Do Nash values have value?, Hydrol. Process., 21, 2075–2080, doi:10.1002/hyp.6825, 2007.

690   Schweizer, J., Jamieson, J. B. and Schneebeli, M.: Snow avalanche formation, Rev. Geophys., 41(4),
doi:10.1029/2002RG000123, 2003.

Seibert, J.: Regionalisation of parameters for a conceptual rainfall-runoff model, Agric. For. Meteorol., 98–99, 279–293,
doi:10.1016/S0168-1923(99)00105-7, 1999.

Seibert, J.: Multi-criteria calibration of a conceptual runoff model using a genetic algorithm, Hydrol. Earth Syst. Sci., 4(5),
695   215–224, 2000.

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

Hydrology and
Earth System
Sciences
Discussions
EGU
Open Access

Sims, E. M. and Liu, G.: A Parameterization of the Probability of Snow–Rain Transition, J. Hydrometeorol., 16(4), 1466–1477, doi:10.1175/JHM-D-14-0211.1, 2015.

700   Strasser, U., Etchevers, P. and Lejeune, Y.: Inter-comparison of two snow models with different complexity using data from an alpine site, Nord. Hydrol., 33(1), 15–26, doi:10.2166/nh.2002.0002, 2002.

Sui, J. and Koehler, G.: Rain-on-snow induced flood events in southern Germany, J. Hydrol., 252(1–4), 205–220, doi:10.1016/S0022-1694(01)00460-7, 2001.

Valéry, A., Andréassian, V. and Perrin, C.: "As simple as possible but not simpler": What is useful in a temperature-based

705   snow-accounting routine? Part 1 - Comparison of six snow accounting routines on 380 catchments, J. Hydrol., 517, 1166–1175, doi:10.1016/j.jhydrol.2014.04.059, 2014.

Verdhen, A., Chahar, B. R. and Sharma, O. P.: Snowmelt modelling approaches in watershed models: Computation and comparison of efficiencies under varying climatic conditions, Water Resour. Manag., 28(11), 3439–3453, doi:10.1007/s11269-014-0662-7, 2014.

710   Vis, M., Knight, R., Pool, S., Wolfe, W. and Seibert, J.: Model calibration criteria for estimating ecological flow characteristics, Water, 7(5), 2358–2381, doi:10.3390/w7052358, 2015.

Viviroli, D., Gurtz, J. and Zappa, M.: The hydrological modelling system PREVAH, edited by S. Steiner, Geographica Bernensia P40, Berne, Switzerland., 2007.

Walter, M. T., Brooks, E. S., McCool, D. K., King, L. G., Molnau, M. and Boll, J.: Process-based snowmelt modeling: does

715   it require more input data than temperature-index modeling?, J. Hydrol., 300(1–4), 65–75, doi:10.1016/j.jhydrol.2004.05.002, 2005.

Watson, B. M. and Putz, G.: Comparison of Temperature-Index Snowmelt Models for Use within an Operational Water Quality Model, J. Environ. Qual., 43(1), 199–207, doi:10.2134/jeq2011.0369, 2014.

Weingartner, R. and Aschwanden, H.: Discharge Regime - the Basis for the Estimation of Average Flows, Plate 5.2, in

720   Hydrological Atlas of Switzerland, edited by R. Weingartner and S. M., Swiss Federal Office for Water and Geology, Bern, Switzerland., 1989.

Wever, N., Fierz, C., Mitterer, C., Hirashima, H. and Lehning, M.: Solving Richards Equation for snow improves snowpack meltwater runoff estimations in detailed multi-layer snowpack model, Cryosphere, 8(1), 257–274, doi:10.5194/tc-8-257-2014, 2014.

725