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'As simple as possible but not simpler': What is useful in a temperature-based snow-accounting routine? Part 2 – Sensitivity analysis of the Cemaneige snow accounting routine on 380 catchments

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SUMMARY

This paper investigates the degree of complexity required in a snow accounting routine to ultimately simulate flows at the catchment outlet. We present a simple, parsimonious and general snow accounting routine (SAR), called Cemaneige, that can be associated with any precipitation-runoff model to simulate discharge at the catchment scale. To get results of general applicability, this SAR was tested on a large set of 380 catchments from four countries (France, Switzerland, Sweden and Canada) and combined with four different hydrological models.

Our results show that five basic features provide a good reliability and robustness to the SAR, namely considering: (1) a transition range of temperature for the determination of the solid fraction of precipitation; (2) five altitudinal bands of equal area for snow accumulation; (3) the cold-content of the snowpack (with a parameter controlling snowpack inertia); (4) a degree-day factor controlling snowmelt; (5) uneven snow distribution in each band. This general SAR includes two internal states (the snowpack and its cold-content). Results also indicate that only two free parameters (snowmelt factor and cold-content factor) are warranted in a SAR at the daily time step and that further complexity is not supported by improvements in flow simulation efficiency.

To justify the reasons for considering the five features above, a sensitivity analysis comparing Cemaneige with other SAR versions is performed. It analyses the snow processes which should be selected or not to bring significant improvement in model performances.

Compared with the six existing SARs presented in the companion article (Valéry et al., 2014) on the 380 catchments set, Cemaneige shows better performance on average than five of these six SARs. It provides performance similar to the sixth SAR (MORD4) but with only half its number of free parameters. However, CemaNeige still appears perfectible on mountainous catchments (France and Switzerland) where the lumped SAR, MORD4, outperforms Cemaneige.

Cemaneige can easily be adapted for simulation on ungauged catchments: fixing its two parameters to default values much less degrades performances than the other best performing SAR. This may partly due to the Cemaneige parsimony.

1. Introduction

1.1. Context

In a companion paper (Valéry et al., 2014), we presented a comparison of six existing snow accounting routines (SARs). The SAR were combined with two lumped precipitation-runoff models and tested on a set of 380 catchments spread in four countries (France, Switzerland, Sweden and Canada) with various levels of snow influence. Our analysis focused on understanding the overall behaviour of the SARs as well as identifying the reasons for differences in performance. Results suggested that complexity in SAR is not a guarantee for better efficiency and that the representation of all processes of the snow dynamics does not seem equally useful for simulating flows. Although a single SAR could not be identified as best performing on all catchments, it appeared that simple SARs could be considered as reliable in a wide range of conditions.

To better identify the necessary components of a SAR and its warranted level of complexity, we propose here to build upon

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the lessons learnt in the comparison study and to carry out a general sensitivity analysis on the structure of SARs.

1.2. How much complexity is warranted in a hydrological snow accounting routing?

Our search for a snow accounting routine that would be 'As simple as possible but not simpler' – according to Albert Einstein's recommendation – led us to investigate a large number of ways to combine the different mathematical representations of the snow accumulation and melt processes. We chose as starting point the simplest SAR found in the literature, which we progressively made more complex. This gradual increase in complexity makes the interpretation of results easier to interpret than if we had started from a complex structure that we had tried to simplify (see e.g. Bergström, 1991). This process spanned over several years; relating it in a paper would be extremely lengthy and frankly unreadable. We preferred to start from the end: present the resulting structure, and analyze the sensitivity of streamflow simulation results to each of its components.

For the sake of generality, we based our research on the same dataset of 380 catchments used in the companion paper. And for the same reasons of data-availability, this work is restricted to temperature-based snow accounting routines. Aside their limited data requirements (precipitation and air temperature), these SARs are easily usable in operational applications. Energy-balance methods are not considered here. The reader may refer to the work by Etchevers et al. (2004) for further discussion on this type of approach.

1.3. Questions needing an answer to identify a general snow accounting routine

The analysis carried out in the companion paper resulted in identifying the four basic questions, which must be addressed before starting any precipitation-runoff modelling on a snow-affected catchment:

– *About precipitation inputs:* how should the precipitation phase be determined: using a fixed or calibrated temperature threshold, or considering a fixed or calibrated temperature interval with a mix of liquid and solid precipitations? Moreover, is it possible to correct snowfall underestimation?
– *About snowmelt and the degree-day approach:* should a constant or a seasonal snowmelt factor be considered? Which melt temperature should we use: a fixed, seasonally-varying or calibrated value?
– *About spatial resolution subdivision:* should the catchment be divided into elevation zones? If yes, which kind of subdivision and how many zones should be considered? Should the number of zones be adapted for each catchment? Should a snow-covered area component be taken into account to consider the snowpack areal distribution within a zone?
– *About additional elements in the snowmelt process:* what improvement can be expected from the use of minimal and maximal daily air temperatures? Is it useful to introduce the snowpack temperature as an internal state? The water retention capacity of the snowpack? The rain on snow events? The snowmelt at the snowpack–ground interface?

These questions will seem quite obvious for those working on snow modelling. They have been addressed in the hydrologic literature (see among others Braun et al. (1994), Leavesley and Stannard (1995) on precipitation inputs, Brubaker et al. (1996), Ferguson (1999) on the degree-day approach, WMO (1986), Blöschl et al. (1991) on the spatial subdivision and Bergström (1995), DHI (2009) on the additional elements). But to the knowledge of the authors, no clear diagnostic on these questions has been published so far in the literature on a set of catchments that would be large enough to include a wide range of conditions and levels of snow influence: too often, the conclusions have been catchment specific, and our aim in this paper was to identify a generic trend.

1.4. Scope of the paper

This article presents the end result of an exhaustive and systematic evaluation process, in which a large number of modeling options were tested to account for snow at the catchment scale with the objective of flow simulation. It led to a snow accounting routine which was named CemaNeige (Valéry, 2010), and is our answer to the title question of this paper: a routine 'as simple as possible but not simpler'. We consider it simple and general enough to be easily applied to a large variety of catchments influenced by snow. If needed, it can be easily complexified to fit specific environments.

Section 2 will detail the evaluation methodology, and Section 3 will then present CemaNeige's structure. Then, we will evaluate the relevance of each of its components by conducting a systematic sensitivity analysis (Section 4). Section 5 will briefly compare CemaNeige on alternative structures, and finally, a few general conclusions will be drawn.

We would like to underline that this work did not deal with all possible approaches for a snow accounting routine. Only degree-day approaches are tested, because of the limitations in availability of input data implied by a large dataset, which did not allow us to deal with energy balance approaches.

2. Methodology for evaluating alternative routines

To assess the various tested versions, we needed of course to judge of their efficiency. Since no snow measurements were available as independent validation measures in this study, we only focused on streamflow as reference while intercomparing snow accounting routines. As we were looking for a general SAR, the various versions were tested on a large set of catchments (the 380 catchments presented in the companion article). Moreover, since we wanted to avoid the risk of obtaining a SAR dependent on a specific hydrological model, we repeated the evaluations in combination with different lumped hydrological models.

The efficiency of each alternative version was evaluated following a split-sample test scheme (Klemeš, 1986) on the available data record for each catchment: two subperiods of almost equal length were used alternatively for calibration and validation. Only efficiency in validation was considered. From 6 to 11 years of data were available on each catchment. To quantify the efficiency, three criteria based on a bounded formulation of the Nash and Sutcliffe (1970) criterion were used. Each of them evaluates performances on specific periods within the year (see Table 1). More details on the evaluation procedure are provided in the companion paper (Valéry et al., 2014).

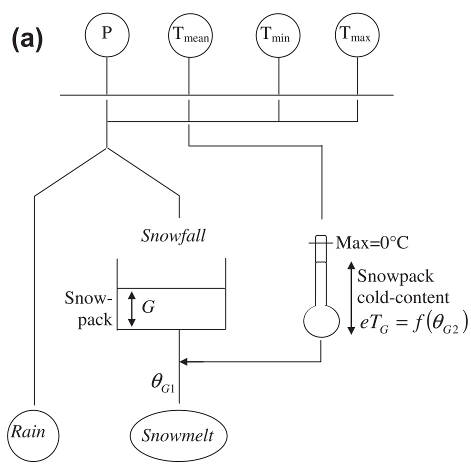
3. Presentation of the CemaNeige snow accounting routine

CemaNeige (see conceptual scheme in Fig. 1) is a two-parameter semi-distributed SAR. It has five main functions summarized in Table 2. It was developed at the daily time step.

CemaNeige only requires as inputs the daily liquid equivalent water depth of total precipitations (P) and the daily air temperature (either the mean T_{mean}, or minimum $T_{\min}$ and maximum $T_{\max}$ temperatures). To be applied at the catchment's scale, the first step

Table 1
Details on the three criteria used to assess SAR performances.

Criterion	Computation period in the year	Evaluation objectives
C_{year}	Whole year	Overall performance
C_{snow}	6-Month period from December to May	Performance during snow accumulation and melt
C_{melt}	2-Month period: for moderately snow-affected catchments, February and March, and for largely snow-affected catchments, April and May	Performance during snowmelt only (often considered as the most critical period of simulation)



(b)

• Determination of solid fraction of precipitation

If $Z_{median\ catchment} < 1500m$, $SolidFraction = f(T_{min}, T_{max})$

If $Z_{median\ catchment} \geq 1500m$, $SolidFraction = f([-1;+3°C])$

$Snowfall = P \times SolidFraction$ and $Rain = P - Snowfall$

• Snow accumulation

$G = G + Snowfall$

$eT_G = \theta_{G2} \times eT_G + (1 - \theta_{G2}) \times T_{mean}$

• Potential snowmelt computation

If $eT_G = 0$ et $T_{mean} > 0$, $Potential\ Snowmelt = \theta_{G1} \times T_{mean}$

If $Potential\ Snowmelt > G$, $Potential\ Snowmelt = G$

• Snow-covered area computation

If $G < G_{threshold}$, $Snow\ covered\ area = G / G_{threshold}$,

Otherwise, $Snow\ covered\ area = 1$

• Actual snowmelt computation

$Snowmelt = f(Snow\ covered\ area) \times Potential\ snowmelt$

• Snowpack updating

$G = G - Snowmelt$

• Total water quantity feeding the hydrological model

$Total\ water\ quantity = Rain + Snowmelt$

Fig. 1. (a) Conceptual scheme and (b) equations of the CemaNeige snow accounting routine.

is to divide the catchment into 5 elevation zones of equal area. Inputs (P, T_{mean}, T_{min} and T_{max}) are extrapolated to mean altitude of every elevation zone using:

- A multiplicative altitudinal gradient for precipitation (one constant value for the year, see Valéry et al. (2010)).
- Monthly additive altitudinal gradients for air temperatures, separately calibrated for T_{mean}, T_{min} and T_{max} (see Valéry et al. 2010).

On each elevation band, the five functions of CemaNeige described in Table 2 are applied with a unique set of calibrated parameters (θ_{G1}, θ_{G2}). Internal states (snowpack quantity, G and its cold-content, eT_G) vary independently on each elevation zone according to the differences in input values.

On every elevation zone, at every time step, two outputs are computed: rain and snowmelt, which are added together. To estimate the total liquid output of CemaNeige at the catchment scale, the five outputs of every band are averaged (with an equal weight, since each band corresponds to one fifth of the catchment). Finally, Cemaneige's output is used as input to the combined hydrological model.

4. Sensitivity analysis: questioning the essential features of the CemaNeige SAR

As it would be too long to present all the tests performed during the development of CemaNeige, we preferred to present results on a systematic sensitivity analysis for the main components which we did or did not include in our snow accounting routine. In the following sections, the sensitivity analysis of the CemaNeige routine is presented as the answer to seven questions. Each time, we compare the final version of CemaNeige with an alternative version. When relevant, we present an example from our dataset, and then we give the overall result over the entire dataset. All results shown were obtained in validation.

All the efficiency results of the different SAR versions presented in this article are summarized in Table 3. Note that the efficiency of the SARs is only evaluated based on streamflow simulations. Although we only present the results for SARs associated with the GR4J hydrological model (Perrin et al., 2003) for the sake of brevity, we also systematically tested all the variants with three other rainfall-runoff models to ensure independence between the structures of the SAR and the hydrological model.

4.1. Question 1: does a SAR require a subdivision of the catchment into elevation zones?

A snow accounting routine can be lumped, distributed or semi-distributed. A very common and intuitive choice is to divide catchments into several elevation zones to take into account the close dependency between the snow occurrence and altitude at the catchment scale. Four out of the six SARs presented in the companion article (Valéry et al., 2014) chose this approach with altitudinal subdivisions: CEQUeau (Morin, 2002), HBV-SAR (Bergström, 1975; Lindström et al., 1997), NAM (DHI, 2009) and M_SNE (Paquet, 2004).

Fig. 2 illustrates the differences in simulations obtained by a lumped version of Cemaneige (on the left) and by the final version with five elevation bands (on the right) on the Arve river at Arthaz. This catchment of 1664 km^2 is located in the French Alps, with altitudes between 780 and 4800 m a.s.l. In February 1999, the lumped version considered that all the precipitation is in solid form and simulated an important period of accumulation without any simulated runoff at the basin outlet. This behaviour does not fit with streamflow observations (see circled part in Fig. 2). But the semi-distributed CemaNeige interpreted precipitation as snowfall in the highest elevation bands only: precipitation was interpreted

Table 2
The five main features of CemaNeige's structure.

	Function	Description	Internal state involved	Free parameter
1	Determination of the solid fraction of precipitation	Two options available • When catchment mean altitude is below 1500 m a.s.l., T_{min} and T_{max} are used (as in Leavesley and Stannard, 1995; Turcotte et al., 2007) • When catchment mean altitude is above 1500 m a.s.l., a fixed temperature interval equal to [−1; 3]°C is considered (as in L'Hôte et al., 2005; US Army Corps of Engineers, 1956)		
2	Snow accumulation	The solid part of precipitation is added to the snowpack	G: snowpack water equivalent	
3	Updating of the snowpack cold-content	This function depends on the daily mean temperature and previous time-steps	eT_G. snowpack cold content	θ_{G2}: cold content factor
4	Potential snowmelt computation	A degree-day approach is used Snowmelt can only occur when the snowpack cold-content is equal to 0 °C		θ_{G1}: snowmelt factor
5	Actual snowmelt computation	The actual snowmelt quantity is then moderated according to the remaining snow quantity in the snowpack An empirical threshold fixed to 90% of the mean yearly snowfall of a given catchment	G: snowpack water equivalent	

Table 3
Mean validation efficiency of tested SARs on the set of 380 catchments with the GR4J model.

#	Versions	Number of free parameters	Mean C_{year}	Mean C_{snow}	Mean C_{melt}	
0	**CemaNeige**	**2**	**0.72**	**0.68**	**0.63**	
1.1	Lumped	2	0.70	0.66	0.59	Single zone (lumped approach)
1.2	10 Elevation zones	2	0.72	0.68	0.63	Subdivision in 10 elevation zones of equal area
1.3	5 Zones (identical ΔZ)	2	0.71	0.68	0.62	Subdivision in 5 elevation zones of equal range of altitude
2.1	$T_{treshold} = 0$	2	0.71	0.67	0.61	Single threshold temperature equal to 0 °C
2.2	$T_s + \Delta T$	3	0.72	0.69	0.63	Fixed range of temperature (4 °C) around a threshold temperature (parameter to be calibrated)
2.3	[−1, +3] °C	2	0.70	0.66	0.61	Mixed rain and snow between −1 °C and +3 °C
2.4	$F(T_{min}, T_{max})$	2	0.72	0.68	0.62	Use of daily extrema of temperature
3	No eT_G	1	0.71	0.67	0.61	No cold-content (heat-content) for the snowpack
4	Uniform snowcover	2	0.71	0.67	0.60	Snow cover assumed uniform on a given zone
5	Seasonal θ_{G1}	3	0.72	0.68	0.63	Seasonally varying melt factor
6.1	eT_G control	4	0.72	0.68	0.63	Liquid water retention and refreezing controlled by the cold-content
6.2	T control	4	0.72	0.68	0.63	Liquid water retention and refreezing controlled by the air temperature
7	Basis snowmelt	3	0.72	0.68	0.63	Snowmelt at the ground interface with a free parameter
8	Uncalibrated CemaNeige	0	0.69	0.65	0.58	CemaNeige with a unique set of fixed values for θ_{G1} and θ_{G2}
9	No snow accounting routine	0	0.42	0.29	0.16	GR4J run without any snow accounting routine

The bold identifies the option which yielded the best performance.

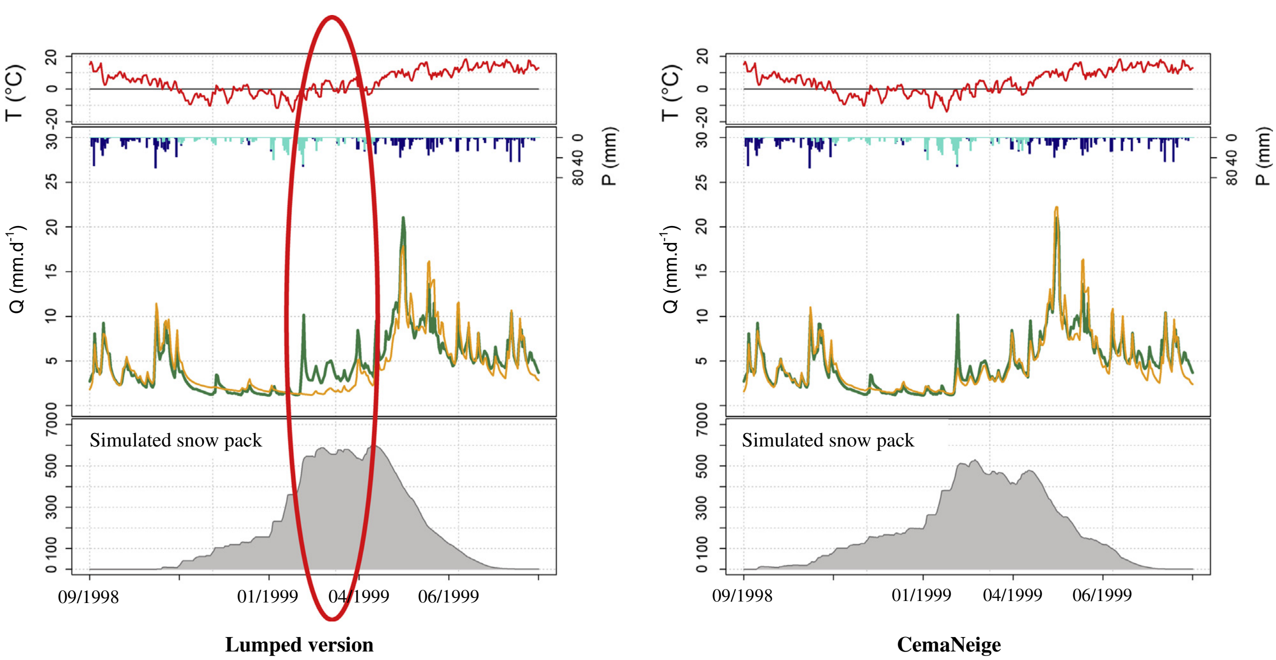


Fig. 2. Comparison of simulations produced by lumped and semi-distributed versions of Cemaneige on the Arve river at Arthaz (France) for 1998–1999. Mean temperature is on the top graph, precipitation in blue histogram, observed runoff in green, simulated runoff in orange and simulated snowpack on the bottom graph. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

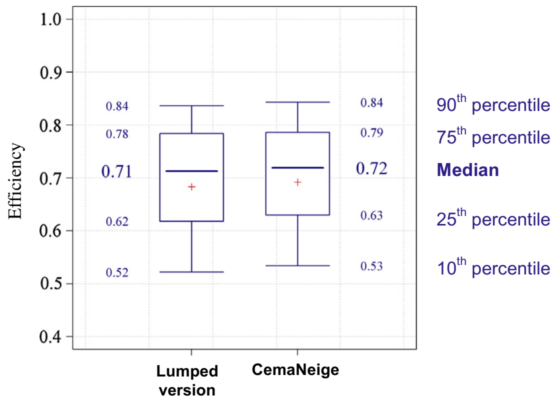


Fig. 3. Boxplots of C_{year} criteria obtained by the lumped and semi-distributed versions of CemaNeige in validation with the GR4J model on 380 basins.

as rainfall in the lowest elevation bands, and generated a runoff response very close to the observed one.

As we are interested in general conclusions, we compared the two SARs efficiency distributions on the 380 catchments. Fig. 3 shows results with the GR4J model in validation over the whole period (C_{year}). Without increasing the complexity of the SAR (no additional free parameter in CemaNeige compared to the lumped approach), CemaNeige presents a slightly better efficiency distribution on the whole catchment set.

This is why we retained for CemaNeige a distribution into elevation zones for the SAR to better account for the specific relation of snow with altitude, especially in mountainous areas. We tested different numbers of elevation zones, including the possibility to optimize the number of zones for each catchment. Five elevation bands for all catchments appeared as a good trade-off: the efficiency improved steadily when increasing the number of zones from one to five, and then levelled off. Note that bands with equal area were preferred to bands with equal altitudinal range (version 1.3 in Table 3) because of the risk to create artificial interannual snowpack on the highest zones with the second option (Valéry, 2010).

4.2. Question 2: should the SAR structure account for the uneven snow distribution (in each altitude zone)?

The snowpack depth variability is strongly correlated with elevation at the catchment scale, which justifies the choice of catchment subdivision into altitudinal bands in a SAR. Moreover, at a finer spatial scale (typically on each elevation band), snowpack depth can significantly vary because of non-uniform snow unloading by forest canopy, wind redistribution, aspect, etc.

Some existing SARs such as NAM and MORD4 (Garçon, 1999) already consider in their structure an uneven snow distribution component. This allows the SAR to distribute the snowpack differently at the catchment or at the elevation band scale: this uneven distribution reduces the melt rate. In CemaNeige there is a specific predefined threshold above which all the area is considered covered by snow. This threshold is equal to 90% of the mean annual snowfall on the studied catchment. Below this, the snow-covered area decreases as a linear function of snowpack quantity.

Fig. 4 compares simulations obtained by CemaNeige and a simplified version with uniform snowpack repartition (version 4 in Table 3) on the Swedish catchment of the Röran River at Ytterholmer (1012 km^2). The simplified SAR version simulated an anticipated streamflow peak: with the first temperature increase at the beginning of April 2003, almost all the snowpack melted which resulted in poorly modelled flows. Conversely, CemaNeige provides a very good fit between observed and simulated streamflow showing a first small increase in April, and a second larger event in late April and May 2003, resulting from two successive snowmelt periods.

Fig. 5 compares the performance of the two options on the whole dataset: performances with CemaNeige are slightly better than with the simplified SAR version. Moreover, this process is implemented without increasing the SAR structure complexity: the threshold is set empirically, based on a climatological catchment feature.

4.3. Question 3: how to decide of the form of precipitation?

During the development phase, we searched for the most efficient function to determine the form (rain or snow) of precipita-

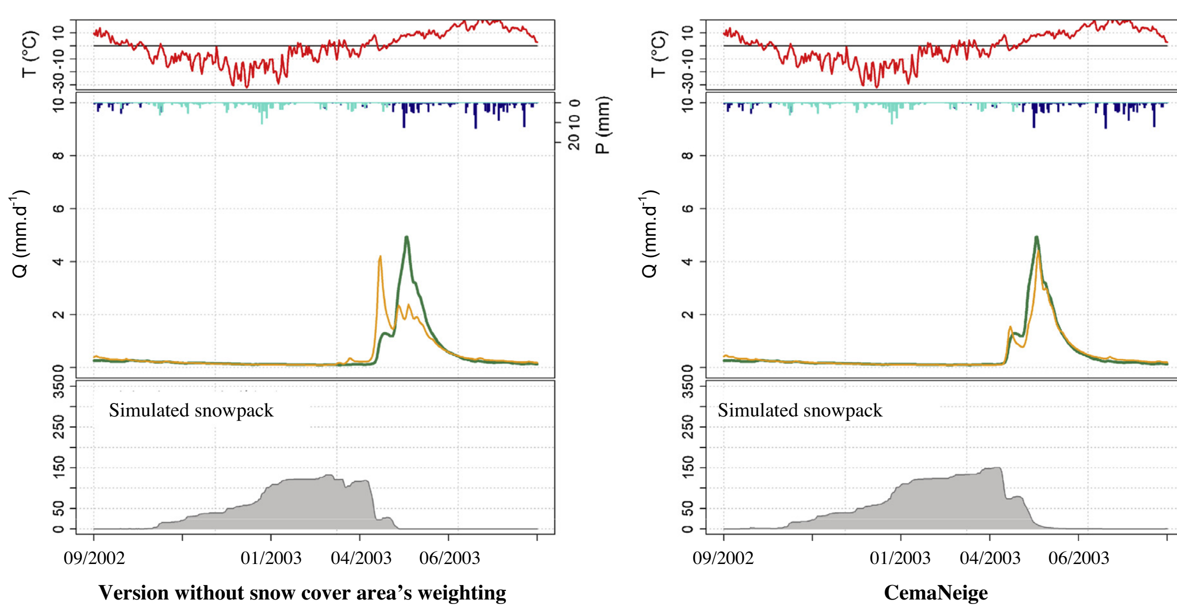


Fig. 4. Comparison of two SARs' simulation on the Röran river at Ytterholmer (Sweden) for 2002–2003. Mean temperature is on the top graph, precipitation in blue histogram, observed runoff in green, simulated runoff in orange and simulated snowpack on the bottom graph. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

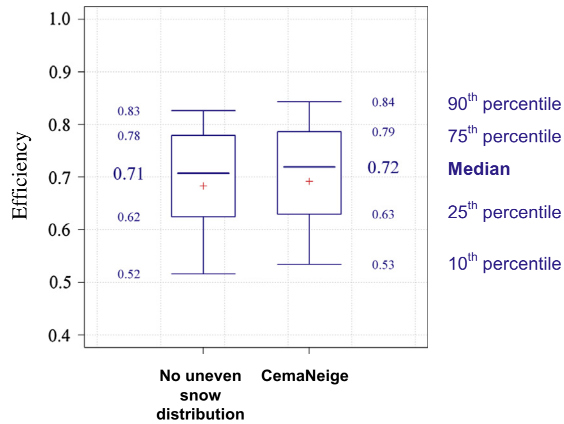


Fig. 5. Boxplots of C_{year} criteria obtained by the version without taking into account the uneven snow distribution and CemaNeige in validation with GR4J model on 380 catchments.

tion. Various possibilities exist from a simple threshold temperature like in MOHYSE (Fortin and Turcotte, 2007) and NAM (DHI, 2009) to more complex functions: fixed range of temperature (Bergström, 1975; Garçon, 1999; Morin, 2002; Paquet, 2004; US Army Corps of Engineers, 1956), use of daily extrema of temperature (Leavesley and Stannard, 1995; Turcotte et al., 2007), etc. In this section, CemaNeige is compared with several versions which consider different functions detailed in Table 3 (versions 2.1–2.4) to discriminate between rain and snow.

Fig. 6 illustrates the differences in simulations obtained with either a very simple version of the snow accounting routine with a fixed threshold equal to 0 °C (on the left and version 2.1 in Table 3), or the CemaNeige final version (on the right) on the Guil river at Montdauphin. This catchment of 725 km^2 is located in the French Alps with altitudes between 900 and 3170 m a.s.l. In November 2002, the simplified version considered that all precipitation was rain and simulated a lot of runoff and then, did not represent well the snowmelt peak in April 2003. This too simplistic approach had a double negative effect: first, a bad accumulation simulation, and then a wrong induced snowmelt simulation (circled periods in Fig. 6).

Fig. 7 presents general results on the whole catchment set in validation mode with the GR4J model. There is no difference in model complexity between the two tested versions (no additional free parameter in CemaNeige compared to the simplified version). Nevertheless, CemaNeige shows a slightly better efficiency distribution than the simplified version. This is why the more elaborated function to discriminate rain and snow is retained.

In addition, our tests showed that it was interesting to keep in CemaNeige two options to discriminate snow and rain in precipitation input, depending on the mean altitude of the catchment: using either daily extrema or a fixed range of temperature ([−1; +3] °C). Fig. 8 plots the performances difference between the two possible options as a function of the mean altitude on four subsets of the whole set of 380 catchments. A positive value indicated that using daily extrema temperature to discriminate rain and snow (version 2.4 in Table 3) is more efficient than using the fixed interval [−1; +3] °C (version 2.3 in Table 3). A negative value means the opposite.

Fig. 8 clearly illustrates the difference in results on the French and the Swiss subsets: all simulations on the most mountainous catchments (with Z_{mean} above 1500 m a.s.l.) present better performances using a fixed temperature interval. In the contrary, simulation efficiency on catchments with mean altitude below 1500 m a.s.l. is mostly better considering T_{min} and T_{max} data when available. A possible explanation can be the increase in temperature extrapolation's uncertainties on the highest catchments: extrapolation uncertainties (required to assess inputs at each elevation zone) are lower for the daily average.

4.4. Question 4: should an additional state variable be introduced to account for snowpack cold-content?

During the development stage, a structure considering the snowpack cold-content was tested. Since this option appeared efficient, it was included in the CemaNeige final structure. This process takes into account the snowpack inertia, delaying the beginning of snowmelt with the introduction of an additional

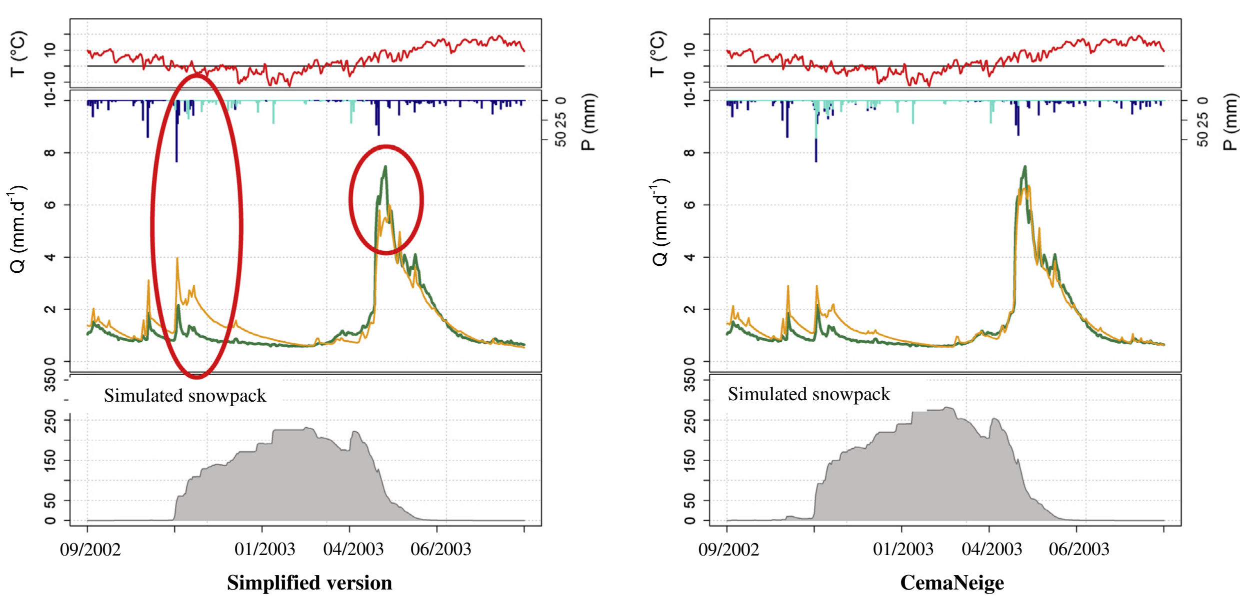


Fig. 6. Comparison of simulations produced by two versions of Cemaneige with different snow/rainfall separation on the Guil river at Montdauphin (France) for 2002–2003. Mean temperature is on the top graph, precipitation in blue histogram, observed runoff in green, simulated runoff in orange and simulated snowpack on the bottom graph. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

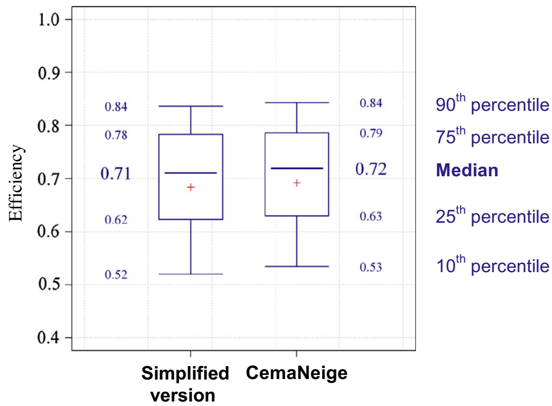


Fig. 7. Boxplots of C_{year} criteria obtained by the simplified and final versions of CemaNeige in validation with GR4J model on 380 catchments.

internal state (G) and an additional free parameter (θ_{G2}) requiring calibration.

Fig. 9 compares simulations with CemaNeige and a simpler SAR version without the snowpack cold-content process (version 3 in Table 3) on the Raneälven River at Niemisel. This Swedish catchment has an area of 3780 km^2 and is located in the Northern part of the country, between 28 m and 593 m a.s.l. Without any snowpack cold-content process in the SAR, simulations on the period 2001–2002 showed two anticipated snowmelt events in December 2001 and April 2002 due to the temporary rise of air temperature above 0 °C. Subsequently, the simulated streamflow peak corresponding to the spring snowmelt was underestimated. Conversely, simulations with CemaNeige fitted very well to streamflow observations on both snow-accumulation and snowmelt periods as the snowpack inertia did not produce any snowmelt response before the end of April 2002.

General results on the whole dataset (Fig. 10) shows higher performances distribution for CemaNeige compared to the simplified SAR (version 3 in Table 3): in particular, the median value is 0.02 higher with CemaNeige.

This significant improvement of performances validated the choice to keep the snowpack cold-content process in the CemaNeige final structure.

4.5. Question 5: should the melt factor depend on the season?

Some existing SARs chose to adopt a melt factor varying with the season (Anderson, 1973; Franz, 2006; Obled and Rosse, 1975). Physical reasons exist for advocating a lower value of the melt factor during winter and a higher value in spring (because of longer sunshine duration, lower snow surface albedo in the spring). Thus, during the development stage, a seasonal variation of θ_{G1} was tested with a sinusoidal approach, which required an additional free parameter to determine the variation interval: θ_{G1} had a minimum value on December 21st and a maximum value on June 21st.

Comparing this modified SAR version (version 5 in Table 3) with CemaNeige on the whole dataset, both SARs presented very similar performances distribution (Fig. 11). This result did not mean that the seasonal variation of the melt factor was not an efficient process: it could be useful on specific conditions or catchments. Nevertheless, it did not appear essential to the SAR. Thus, this option was not retained for the final CemaNeige structure because of lack of performance improvement.

4.6. Question 6: should a water retention capacity in the snowpack be considered?

Additional processes can be considered in a SAR in order to simulate the snowpack evolution. Indeed, snowpack can retain a

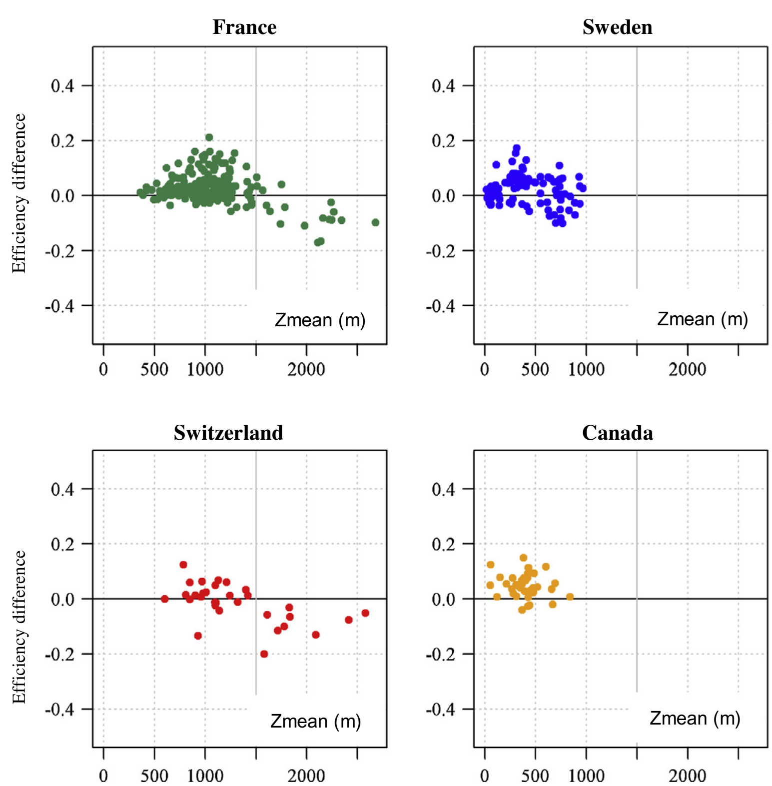


Fig. 8. Difference in efficiency (C_{year}) between two options to determine precipitation form as a function of the mean catchment altitude on four subsets.

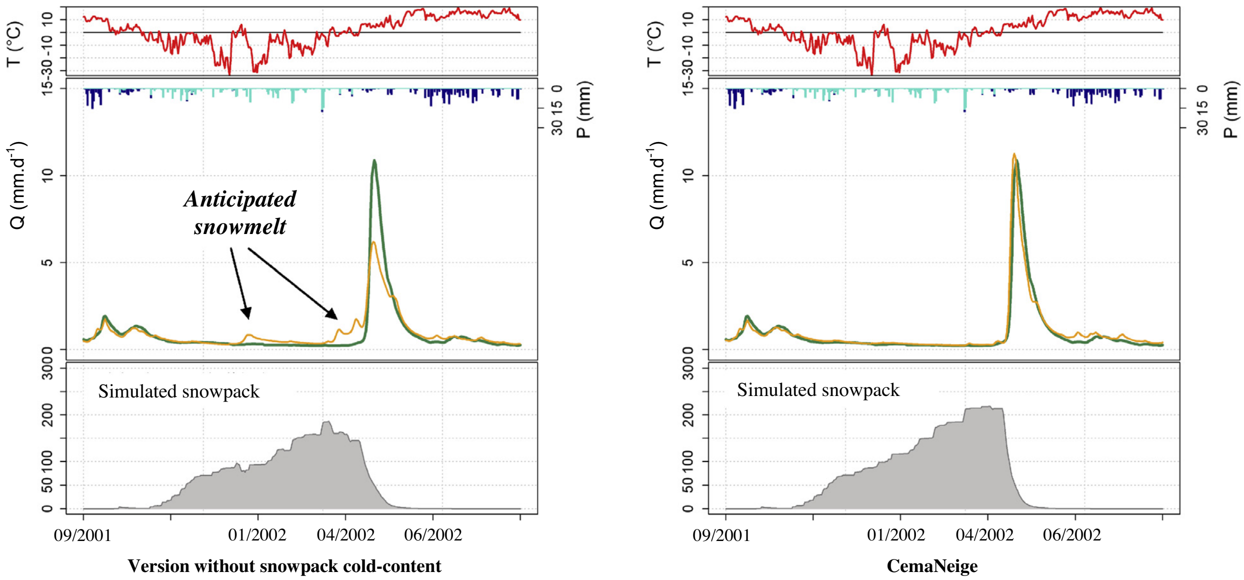


Fig. 9. Comparison of simulations obtained using Cemaneige, with (right) and without (left) cold-content process included on the Raneälven river at Niemisel (Sweden) for 2001–2002. Mean temperature is on the top graph, precipitation in blue histogram, observed runoff in green, simulated runoff in orange and simulated snowpack on the bottom graph. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

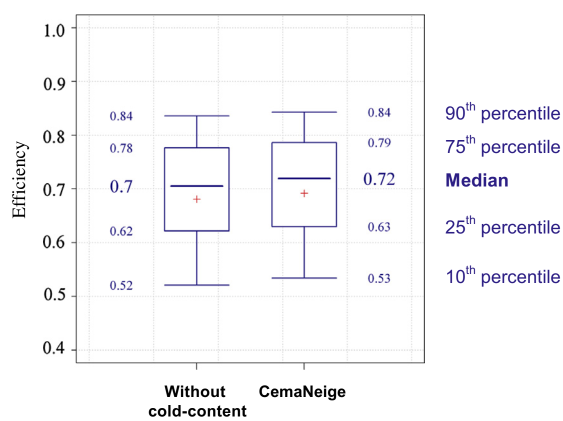


Fig. 10. Boxplots of C_{year} criteria obtained by the version without snowpack cold-content and CemaNeige in validation with the GR4J model on 380 catchments.

certain quantity of liquid water until reaching a given percentage of its total volume. This process is usually called snowpack water retention capacity (Bergström, 1975; DHI, 2009; Paquet, 2004). In the same time, according to the climatic conditions affecting the snowpack and its cold-content, this liquid water can be either evacuated in the case of temperature increase, or refrozen in the case of temperature decrease in the snowpack. Three SARs among the six presented in the companion article (Valéry et al., 2014) include these processes in their structure: HBV-SAR (Bergström, 1975), M_SNE (Paquet, 2004) and NAM (DHI, 2009).

Various options can be implemented to consider liquid water retention and refreezing into the snowpack. The performances of two of them are reported in Table 3:

– Version 6.1 (eT_G control) considers that the snowpack cold-content controls the liquid water phase in the snowpack (smoothing effect).
– Version 6.2 (T control) considers that the air temperature controls this phase. There is no smoothing effect.

Both options introduced two additional free parameters: a threshold temperature (eT_G or T) to control melt and refreezing, and an additional melt and refreezing factor which controls the rate of transformation from solid to liquid and inversely. The versions were tested considering that the two factors are exactly the opposite, i.e. the same rate of transformation, positive for melt and negative for refreezing.

Finally, the two versions presented in Table 3 shows no better performance efficiency compared to CemaNeige, despite their two additional free parameters. Different interpretations can be given: (i) First, the tested approaches may be too simple to correctly represent the water retention capacity and refreezing of the snowpack (also, additional local information may be required to adequately represent this process); (ii) second, these processes may be relevant at the plot scale, and not at the catchment scale (remember that since we focus on streamflow, we can only detect those effects which propagate themselves until the outlet).

Because of the lack of efficiency improvement on the whole dataset, these processes were not included in the CemaNeige final structure.

4.7. Question 7: is snowmelt at the ground-snowpack interface a significant process?

It may appear interesting to allow snowmelt at the ground-snowpack interface as a consequence of Earth's long-wave radiation transfer. MORD4 (Garçon, 1999) and M-SNE (Paquet, 2004) integrate this process in their structure. This option allows producing a small meltwater amount even during the snow-accumulation period.

A modified SAR structure (version 7 in Table 3) was implemented and compared to CemaNeige. This SAR had a third free parameter which was a "ground melt-factor" to control the snowmelt at the ground-snowpack interface specifically, i.e. independently from the classical snowmelt process.

Introducing this process with an additional free parameter (version 7 in Table 3) did not improve performance distribution compared to CemaNeige on the 380 catchments dataset. Although

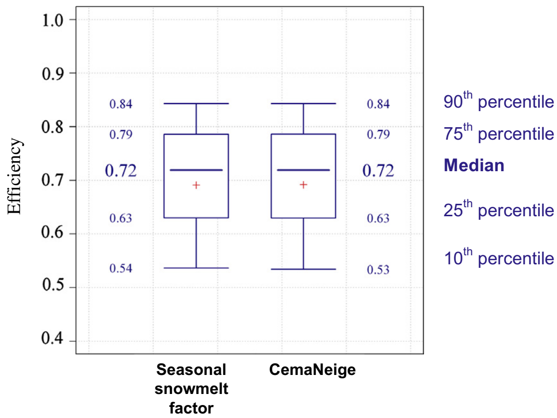


Fig. 11. Percentiles of C_{year} obtained by the version with a calibrated seasonal snowmelt factor and CemaNeige in validation with GR4J model on 380 cathcments.

this option may appear justified on a given catchment and/or under specified climatic conditions, it did not appear as a main and general process for a SAR structure. This is why it was not adopted in the final structure of CemaNeige.

4.8. Synthesis

Table 3 summarizes performances of all the options tested for the sensitivity analysis of the CemaNeige snow accounting routine, used in conjunction with the GR4J rainfall-runoff model. We also added the performances of two references:

- A SAR used with fixed parameters (the same for all catchments θ_{G1} = 3.74 mm d^{-1} and θ_{G2} = 0.25 which are the median values of these two parameters, calibrated on the whole dataset).
- GR4J used without any SAR.

5. Comparison of performances with existing SARs

5.1. Overall comparison

In the companion paper (Valéry et al., 2014), we compared six existing SARs. We now analyze how CemaNeige performs compared to these routines. Fig. 12a compares the efficiency distribution of C_{year} for CemaNeige, for the six selected SARs associated with the GR4J model, and for GR4J without any SAR, on the whole catchment set. Fig. 12b presents the same comparison using a different hydrological model, for more generality of our results. Here, we use the HBV9 structure, already presented in the companion paper. Table 4 summarizes mean efficiency values of the three criteria and with the two hydrological models.

In general, CemaNeige is the best or among the best performing SARs, the difference being more visible when we concentrate on the two criteria which focus on the snow influenced periods. It is especially true for the snowmelt criteria. More detailed comparisons indicate that:

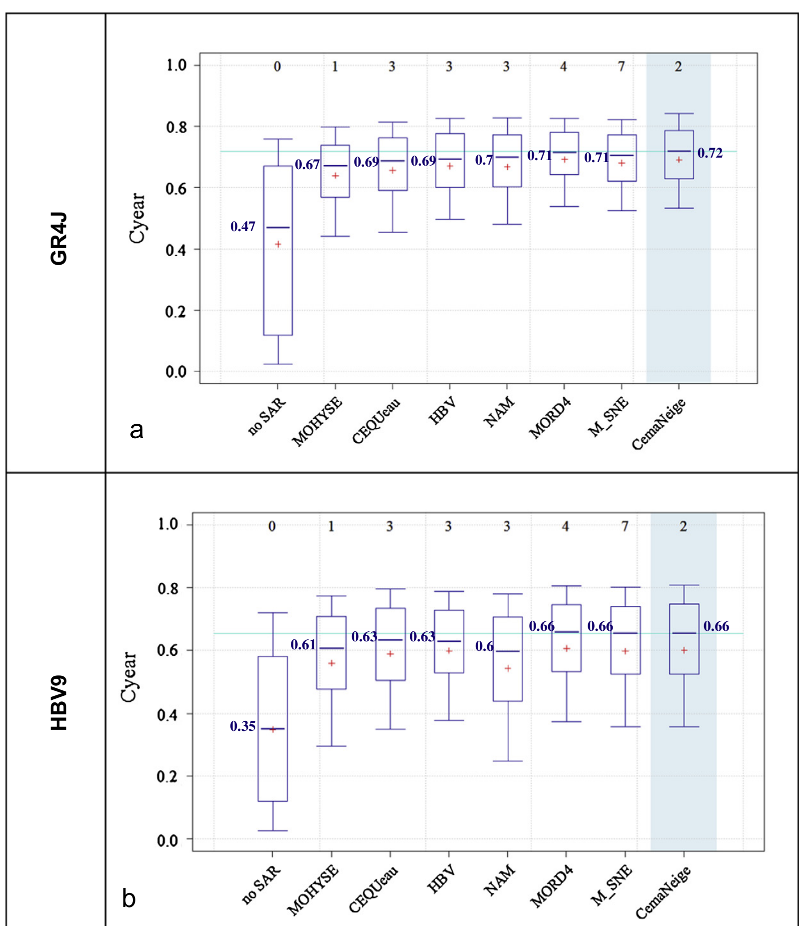


Fig. 12. Comparison of the efficiency distributions of the GR4J and HBV9 model combined with CemaNeige (C_{year}) and six other SARs, and without any SAR (median values are reported and number of free parameters in the SAR are shown in the top).

Table 4
Mean performances of two precipitation–runoff models (GR4J and HBV9) in validation without any snow accounting routine, with one of the six reference SARs and with CemaNeige over the 380 catchments.

Hydrological models	Assessment criteria	SAR option (number of optimized parameters)							
		Without snow routine (–)	MOHYSE (1)	CEQUeau (3)	HBV (3)	NAM (3)	MORD4 (4)	M_SNE (7)	CemaNeige (2)
GR4J	C_{year}	0.415	0.640	0.657	0.671	0.668	**0.692**	0.681	**0.692**
	C_{snow}	0.285	0.580	0.606	0.615	0.633	0.652	0.634	**0.653**
	C_{melt}	0.157	0.481	0.504	0.535	0.576	0.576	0.547	**0.582**
HBV9	C_{year}	0.348	0.560	0.590	0.600	0.543	**0.607**	0.598	0.601
	C_{snow}	0.221	0.504	0.545	0.561	0.516	**0.567**	0.549	0.562
	C_{melt}	0.122	0.425	0.470	0.493	0.462	0.500	0.485	**0.503**

The bold identifies the option which yielded the best performance.

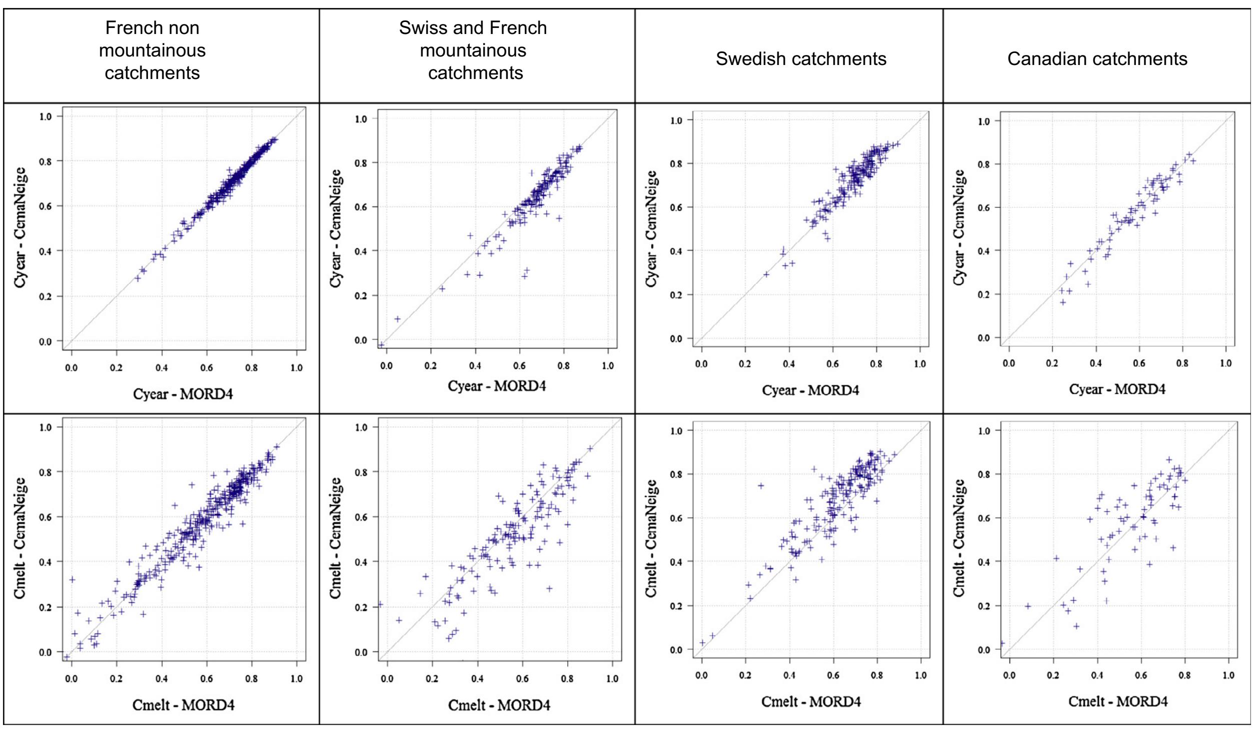


Fig. 13. Comparison of C_{year} (first line) and C_{melt} (second line) criteria using MORD4 and CemaNeige SARs associated with GR4J on four catchment subsets.

Table 5
Number of catchments for which C_{melt} has the highest value for each of the seven tested SARs.

	MOHYSE	CEQUeau	HBV	NAM	MORD4	M_SNE	CemaNeige	Total
GR4J	3	15	55	**107**	79	28	**93**	380
HBV9	6	46	**82**	52	67	49	**78**	380

The bold identifies the option which yielded the best performance.

- CemaNeige shows better performances than MOHYSE, CEQUeau and NAM, whatever the hydrological model and the criterion. For these three SARs, a fixed threshold temperature is used to determine the precipitation form, contrary to CemaNeige. Moreover, MOHYSE and NAM do not consider any snowpack internal state which proved to be useful in a SAR (see Section 4.4).
- In comparison with HBV SAR, CemaNeige performances are clearly better when associated with the GR4J model. When associated with the HBV9 model, both mean performances are rather similar although CemaNeige is slightly better for high percentiles and slightly worse for low percentiles than HBV-SAR. This result is due to the snow correction factor of HBV-SAR which allows a modification of the water balance (something not possible with CemaNeige).
- In comparison with M_SNE – the most parameterized SAR in our selection – CemaNeige always shows higher performances with both hydrological models. M_SNE includes many processes, which introduces free parameters requiring calibration. Nevertheless, the sensitivity tests presented in this paper have shown that introducing processes such as the liquid water retention and refreezing or the ground-snowpack melt brings no significant improvement on average at catchment scale (He et al., 2010; Valéry, 2010).

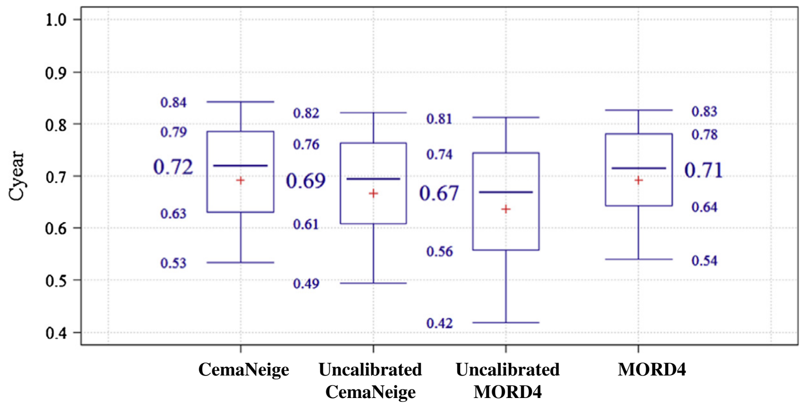


Fig. 14. Comparison of the efficiency distribution (C_{year}) of CemaNeige and MORD4 SARs, associated with the GR4J model in gauged and ungauged conditions.

- Last, CemaNeige and MORD4 present very similar performances: on the whole dataset of 380 catchments, CemaNeige is as efficient as MORD4 with only two degrees of freedom (instead of four in MORD4) but considering a distribution with five elevation zones while MORD4 is lumped.

Finally, Table 5 presents the number of catchments for which the criterion C_{melt} has the highest value for the seven tested SARs. CemaNeige appears to be one of the most efficient and robust in a majority of conditions with MORD4 and NAM.

5.2. Comparison by country group

To go further in the comparison of CemaNeige with MORD4, we made an analysis over catchments subsets. Fig. 13 compares performances of both C_{year} and C_{melt} of Cemaneige and MORD4 associated with the GR4J model:

- On French non-mountainous and Canadian catchments, both SARs present similar performance efficiency on average for both C_{year} and C_{melt} criteria.
- On mountainous basins (Switzerland and French Alps), MORD4 shows higher performances than CemaNeige. The parametric treatment of the snow depletion curve in MORD4 seems particularly efficient in complex terrain like in the Alps, with large elevation gradients. Note that MORD4 was specifically built to be applied on French Alpine catchments.
- Finally, on Swedish catchments, CemaNeige yields better performances than MORD4 for both C_{year} and C_{melt}. The more complex structure of MORD4 is not the most efficient in every situation, especially on high-latitude catchments.

5.3. Testing Cemaneige without calibration

To end up this assessment, we evaluated the efficiency of Cemaneige and MORD4 in a no-calibration context (with their free parameters fixed to median values): on Fig. 14, Cemaneige proves more robust, as it retains a satisfying level of performance with fixed parameters. This capacity can be extremely useful for catchments which do not have snowpacks every year: indeed, on some subperiods with little snow, calibration of SARs' free parameters would yield unrealistic values. Hence, using default values for parameters appears more robust than calibration. Finally, this result in a no-calibration context is promising in order to use CemaNeige on ungauged basins.

6. Conclusions

6.1. Synthesis

In this paper, we gave a detailed description of a generic snow accounting routine, Cemaneige, which we designed to be 'as simple as possible, but not simpler'. This SAR can be used on top of any lumped hydrological model. This paper also provides a detailed analysis of sensitivity of the chosen option, based on a set of 380 catchments from four countries.

CemaNeige, appears both robust and efficient over a large variety of climatic conditions and in combination with different hydrological models. We consider it to be a useful tool for hydrology, especially in data-scarce conditions (only daily P and T are required, it can function with calibrated parameters as well as with fixed parameters).

6.2. Limits of CemaNeige

To avoid any misunderstanding, we wish to stress the limits of the snow accounting routine proposed in this paper. Our aim was to build a generic and basic structure. The sensitivity analysis presented here has helped us identifying what appear to be the essential components of a hydrological SAR. But this structure can naturally be inferior to 'custom-tailored' solutions on some catchments. But even where complexification would appear required, we would personally favor restarting systematically from the CemaNeige structure and complexify it progressively as needed by the simulation requirements.

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