Comparison of measured and simulated snow cover occurrence using two versions of the TUW hydrological model

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Abstract. Recent rapid developments in the hydrological sciences are markedly related to the development of mathematical modeling and its application in engineering practice, e.g., for the purposes of hydrological forecasting, the extrapolation of hydrological data over time and in space, as well as the estimation of hydrological extremes. Simulation of the water balance is also important for the effective management of water resources. Snow accumulation and melting fundamentally affect the water balance and belong among the most important components of the hydrological cycle. Snowmelt is a significant source of runoff, especially in mountainous regions. The basic snow cover characteristics are the bulk density of the snow, the snow water equivalent, and the height of the snow. This paper is focused on a comparison of snow cover occurrences as simulated by the TUW lumped and semi-distributed conceptual models, with measured values of the snow depths for two selected Austrian river basins. For the comparison, two types of catchments with flat and hilly characters were selected. The results show that the semi-distributed version of the TUW model simulates the occurrence of snow cover more accurately on both flat and hilly catchments. The spatially differentiated model inputs allow for a more representative representation of snow accumulation and melting than using lumped model inputs.

1. Introduction
Snow is an important component in the hydrological cycle; it is significant as a supply of water. The accurate estimation of snow cover properties is important for effective water resources management, especially in mountainous areas. In recent decades, a general decrease in snow cover in the mountainous regions of Europe has been recorded, mainly due to the effects of climate change. Increases in the average air temperature in mountainous regions have caused the displacement of the snow line at elevations of 150 m a.s.l. and higher [1]. Snow fundamentally affects the water balance and runoff in river basins; therefore, the modelling of snow accumulation and melting is also an important component in rainfall-runoff models. Rainfall-runoff models are often applied in solving various water resource problems, e.g., forecasting flood events, the effects of climate change, simulating extreme discharges, etc. We may encounter climatic conditions in simulation periods that are different from the calibration conditions of the models. Several authors have therefore pointed out that the use of these models in different climatic conditions leads to uncertainties that could affect the quality of the outputs [2-6].
Some of the current model-based approaches are limited both by the models biases and uncertainties about the input data [7]. One challenge in estimating snow processes in many regions is the sparse observational network of climate and hydrological variables. The preparation of model inputs and the resulting model simulations are affected by uncertainties of the measurements and their spatial interpolation. The impact of the spatial representation of model inputs on model simulations has still not been fully clarified.

The main objective of this paper is to compare the efficiencies of runoff and snow cover simulations by lumped and semi-distributed model input representations, through the use of two versions (lumped and semidistributed) of a conceptual hydrological rainfall runoff model. The aim is to calibrate the models to the daily discharges observed and to compare the duration of the snow cover simulations by both models with the daily snow depths observed in two catchments representing typical flat and hilly regions in Austria.

2. Methods and data

Runoff and snow were simulated by the TUW conceptual hydrological rainfall runoff model [8,9]. In this study, we used two versions of the TUW model, i.e., lumped and semi-distributed. While the lumped model only uses averaged model inputs over a whole catchment, the semi-distributed version uses model inputs distributed to elevation zones of 200 m. The model consists of three modules that represent snow accumulation and melting, root zone soil moisture changes, and runoff generation and routing. The snow accumulation and melting were simulated by using the degree-day approach. The model inputs were the mean daily air temperature, the daily precipitation, and the daily estimate of the potential evaporation. The model has 15 parameters: 5 are related to describing snow processes, 3 to changes in the soil moisture storage, and 7 parameters to runoff generation and routing processes. More details about the model can be found in [9].

The time series of the input data for the lumped TUW model were extracted from precipitation, air temperature, and potential evaporation grid maps. The grid maps of the precipitation and snow depths were interpolated by external drift kriging; the maps of the air temperatures were interpolated by the least-squares trend prediction method, and the potential evapotranspiration was calculated by the Blaney-Criddle estimation method [10]. The time series of the input data for the semi-distributed TUW model were interpolated from climate and precipitation stations to elevation zones.

Both versions of the model were automatically calibrated using the DEoptim differential evolution algorithm [11]. The objective function used in the model’s calibration consists of a combination of the Nash-Sutcliffe coefficient (NSE) and the logarithmic Nash-Sutcliffe (log NSE) coefficient:

\[
NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{sim} - Q_{obs})^2}{\sum_{i=1}^{n}(Q_{sim} - \bar{Q}_{obs,avg})^2} \quad (-)
\]

\[
logNSE = 1 - \frac{\sum_{i=1}^{n}(log(Q_{sim}) - log(Q_{obs}))^2}{\sum_{i=1}^{n}(log(Q_{sim}) - log(Q_{obs,avg}))^2} \quad (-)
\]

Qsim - simulated discharge, Qobs – observed discharge, Qobs,avg – average observed discharge

The lumped and semi-distributed versions of the TUW model were calibrated in the period 1981 – 1990 and validated in the 1991 – 2000 period. The models were applied in two Austrian catchments (Figure 1). The first was the Schwarzenau station on the Thaya River with a catchment area of 175.5 km², an average elevation of 570 m a.s.l., and lowland hypsometric characteristics. The second was a highland catchment, the Selzthal station on the Paltenbach River, with a catchment area of 368.7 km², an average elevation of 1280 m a.s.l, and highland hypsometric characteristics.
Simulations of the snow water equivalent (SWE) represented the duration of the snow cover and were compared with the interpolated snow depths from observations at climate stations in Austria [12].

Figure 1. Location of selected catchments (1.) lowland catchment, (2.) highland catchment

3. Results
The calibration and validation efficiencies of the lumped and semi-distributed TUW model are presented in Table 1. The results show that the NSE and logarithmic log NSE efficiencies are higher in the semi-distributed model than in the lumped version of the model. Also, the NSE and log NSE efficiencies are higher in the highland catchment.

Table 1. Results of the TUW model calibration efficiencies for the selected catchments

| ID    | Station   | Catchment | Type   | Calib/valid | Semi-dist NSE | Semi-dist Log NSE | Lumped NSE | Lumped Log NSE |
|-------|-----------|-----------|--------|-------------|----------------|-------------------|-------------|----------------|
| 208611| Schwarzenau| Thaya     | Low-land   | Calibration | 0.77           | 0.75              | 0.67        | 0.73           |
|       |           |           |         | Validation  | 0.65           | 0.63              | 0.66        | 0.65           |
| 210815| Selzthal  | Paltenbach| High-land | Calibration | 0.85           | 0.89              | 0.75        | 0.75           |
|       |           |           |         | Validation  | 0.77           | 0.73              | 0.70        | 0.74           |

Figure 2 shows the development of the snow cover and SWE during the 1996-2000 winter seasons in the validation period. Both model variants, i.e., the lumped and semi-distributed models, satisfactorily simulate the increase and decrease of snow cover in all the winter seasons during the period.
Figure 2. Comparison of simulated snow water equivalent (red line: lumped model, green line: semi-distributed model) and measured height of the snow cover (blue line), in five years of the validation period (1996-2000).

In Figure 3 the results for the selected winter season, i.e., 1.11.1999-1.7.2000, are presented; the observed snow cover is also shown more in detail. The green lines represent the lowest and highest hypsometric zones in the semi-distributed TUW model. The semi-distributed TUW model simulates the beginning of the winter season well, and its average elevation zone (purple line) also responds well to the end of the winter season. The red line represents the simulation of the SWE using the lumped TUW model. The lumped TUW model responds better to the occurrence of snow cover at the end of the winter season. Both the lumped and semi-distributed models did not correspond well with the short-term increases and decreases in the snow cover observed. The models underestimate peaks in the individual solid precipitation events.

Figure 3. Comparison of simulated snow water equivalent and measured height of the snow cover during the winter 1999/2000.
The mountainous river basin of the Paltenbach River includes 8 elevation zones (800-2400 m a.s.l.) in the semi-distributed TUW model. Because the average elevation of the basin is 1280 m a.s.l. we decided to select the 1200-1400 m a.s.l. elevation zone for a comparison of the simulated SWE with the lumped TUW model and the observed height of the snow cover. Figure 4 shows the behavior of the snow cover during the 1996-2000 season. Both model variants captured the increases and decreases of the snow cover in all the winter seasons in the period observed.

Figure 4. Comparison of simulated snow water equivalent (red line - lumped model, green line - semi-distributed model) and measured height of the snow cover (blue line) during five years of the validation period

In Figure 5, the simulations of the occurrence of snow cover in the selected winter season are illustrated from 1.11.1999 to 1.5.2000 in more detail. The green lines represent the lowest and highest hypsometric zones (there are only two elevation zones) in the semi-distributed TUW model. The semi-distributed TUW model again responds well at the beginning of the winter season and also at the end of the winter season. In the lowland catchment, the values of the SWE simulated by the lumped model (red line) are overestimated against the semi-distributed model. Neither the lumped nor the semi-distributed model responded well to the short-term increases and decreases in the snow cover. The models underestimated peaks in the individual solid precipitation events in the lowland areas as well as in the mountainous regions.
Figure 5. Comparison of the simulated snow water equivalent using lumped and the semi-distributed TUW model and measured height of the snow cover, winter 1999-2000

In Table 2, the results of the correlations between the simulated SWE of the lumped TUW model and the semi-distributed TUW model are shown. The simulated SWE from the lumped TUW model and the weighted average of the simulated SWE in the semi-distributed TUW model were used for the correlation. The results prove a very good relationship between the model outputs.

Table 2. Correlation between the lumped TUW model and semi-distributed TUW model

| ID    | Station   | Catchment | Type      | Correlation |
|-------|-----------|-----------|-----------|-------------|
| 208611| Schwarzenau| Thaya     | Low-land  | 0.95        |
| 210815| Selzthal  | Paltenbach| High-land | 0.96        |

4. Conclusions

Snow cover is significant as a supply of water and is an important part of runoff processes, especially in mountainous regions. It is necessary to observe how a model simulates each output component for better accuracy of simulations that can improve solving water resources management tasks. In this study, we compared the daily time series of the snow depth with the snow water equivalent simulated by the lumped and semi-distributed versions of the TUW rainfall-runoff model. Two Austrian catchments, one in the lowlands and one in the highlands, were selected to illustrate the results. The quality of the simulations of the snow water equivalent was assessed by a visual comparison, correlations between both, the lumped and semi-distributed TUW model simulations of SWE, and by the Nash-Sutcliffe efficiencies in the calibration and validation periods.

We can observe in the results that the model efficiencies and correlations between the simulations by the lumped and semi-distributed versions of the TUW model give us relatively good results and indicate that the model calibrations and validations are relatively reliable. The graphic comparison of the results showed a good agreement in the duration of the snow cover between the simulated SWE and snow depths in both catchments.
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