Changes in the snow water equivalent in mountainous basins in Slovakia over recent decades

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Abstract. Changes in snowpack and duration of snow cover can cause changes in the regime of snow and rain-snow induced floods. The recent IPCC report suggests that, in snow-dominated regions such as the Alps, the Carpathian Mountains and the northern parts of Europe, spring snowmelt floods may occur earlier in a future climate because of warmer winters, and flood hazards may increase during wetter and warmer winters, with more frequent rain and less frequent snowfall. The monitoring and modelling of snow accumulation and snow melting in mountainous catchments is rather complicated, especially due to the high spatial variability of snow characteristics and the limited availability of terrestrial hydrological data. An evaluation of changes in the snow water equivalent (SWE) during the period of 1961–2010 in the Upper Hron river basin, which is representative of the mountainous regions in Central Slovakia, is provided in this paper. An analysis of the snow cover was performed using simulated values of the snow water equivalent by a conceptual semi-distributed hydrological rainfall-runoff model. Due to the poor availability of the measured snow water equivalent data, the analysis was performed using its simulated values. Modelling of the SWE was performed in different altitude zones by a conceptual semi-distributed hydrological rainfall-runoff model. The evaluation of the results over the past five decades indicates a decrease in the simulated snow water equivalent and the snow duration in each altitude zone and in all months of the winter season. Significant decreasing trends were found for December, January and February, especially in the highest altitude zone.

1 Introduction

A snowpack as natural water storage is a very important part of the hydrological balance in mountainous catchments. As a result of conditions caused by a changing climate, the temporal and spatial changes of snowpacks is the subject of many recent studies (e.g., Artan et al., 2013; Holko et al., 2005, 2011; Hood and Hayashi, 2010; Kuchment et al., 2010; Parajka and Blöschl, 2008; Parajka et al., 2012). Analyses of flood changes in Europe (Hall et al., 2014) also indicate changes in spring floods which can be caused by changes in the snow regime especially in snow-dominated regions.

In Slovakia, snow cover data have been collected since the middle of the 20th century. Due to the poor availability of snow water equivalent data, many studies that aim at detecting changes in snow packs in Slovakia have been based on an analysis of point measurements of snow depths and the duration of snow cover (e.g., Lapin and Faško, 2005, 2007) rather than on the snow water equivalent (SWE). However, the snow water equivalent evaluated on a catchment scale can provide more complete information about the amount of water contained in snow and is more useful than interpolated snow cover or snow depths for flood prediction and the management of water resources in snow-dominated regions. In this paper we evaluated the changes in the snow water equivalent in a mountainous basin in Slovakia using the modelled values of the SWE during the period of 1961–2010. The SWE in different altitude zones of the pilot basin was simulated using a semi-distributed conceptual rainfall-runoff model at a daily time step. The validation of the simulated SWE values was provided by comparing them with the available measured data of the snow water equivalent in each altitude zone. The changes in the simulated values of
Table 1. List of the altitude zones.

<table>
<thead>
<tr>
<th>Altitude zone</th>
<th>Area dimensions [ha]</th>
<th>Weight [ha]</th>
<th>Zonal boundaries [m a.s.l.]</th>
<th>Mean altitude [m a.s.l.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>38 004</td>
<td>0.22</td>
<td>260–616</td>
<td>438</td>
</tr>
<tr>
<td>Zone 2</td>
<td>90 616</td>
<td>0.51</td>
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<td>794</td>
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<tr>
<td>Zone 3</td>
<td>37 348</td>
<td>0.21</td>
<td>973–1328</td>
<td>1150</td>
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<tr>
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<td>9 268</td>
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<td>1506</td>
</tr>
<tr>
<td>Zone 5</td>
<td>1 628</td>
<td>0.01</td>
<td>1685–2040</td>
<td>1862</td>
</tr>
</tbody>
</table>

Figure 1. The upper Hron River basin indicating (a) the catchment location in the territory of Slovakia, (b) the elevations of the catchment and precipitation stations, (c) the altitude zones of the catchment.

The SWE were evaluated for each decade from 1961–2010 and in each altitude zone.

2 The Hron rainfall-runoff model

The Hron model is a rainfall-runoff model based on the concept of the HBV model (Bergström, 1992) and was developed at the Department of Land and Water Resources Management of the Faculty of Civil Engineering of the Slovak University of Technology in Bratislava, Slovakia. This is a conceptual model with lumped parameters, which divides a river basin into nonlinear reservoirs. The model works at a daily time step and has three sub-models, i.e., a snow sub-model for the simulation of snow accumulation and melting, a soil sub-model that simulates the amount of water in soil and the actual evapotranspiration, and a runoff sub-model that simulates the routing of runoff within the river basin and along the river reach.

The model is processed in Matlab, and there are several innovations and differences in comparison with the original HBV concept (Valent et al., 2011), e.g., the runoff routing is based on a multilinear cascade (Szolgay et al., 2008). The model was adapted for the simulation of snow water equivalent at different altitude zones with semi-distributed parameters. The calibration of the model parameters is based on genetic algorithms or a harmonic search as well as on several objective functions for assessing the reliability of the model calibration. The simulated output states at every time step are characterized by lumped variables, i.e., the water level in the upper storage [mm]; the water level in the lower storage [mm]; and the distributed states are divided according to the altitude zones: the values of soil moisture [mm], the actual
evapotranspiration [mm day$^{-1}$], and the snow water equivalent [mm].

3 The input data

The upper Hron River basin with available measured snow data at 23 precipitation stations was selected as the pilot basin (Fig. 1a, b). The Hron River is the second longest river in Slovakia with a length of 298 km. The upper part of the Hron River basin with an outlet in Banská Bystrica, which is located in Central Slovakia, has a mountainous character, and its area is 1766.48 km$^2$. The catchment belongs to a cold and wet climate region; it has a snow-rain runoff regime (Pekárová and Szolgay, 2005). During the period of 1961–2000 the prevailing floods in the upper Hron River basin were induced by long-rain and rain on snow processes (Holko et al., 2005).

The input data used for the modelling of the snow water equivalent for the period of 1961–2010 were divided into different altitude zones (Table 1, Fig. 1c). For each zone, daily rainfall was estimated by the inverse distance weighting interpolation; the zones’ average air temperature values were calculated by linear regression between the stations’ mean daily air temperatures and the altitudes of the stations. The daily evapotranspiration values were calculated by the Blaney-Criddle method (Parajka et al., 2003). The calcula-
Changes in the snow water equivalent in mountainous basins

1. Introduction

Snow water equivalent (SWE) is a crucial component of the water balance in mountainous basins, especially for hydrological modeling. The snow water equivalent is defined as the amount of water contained in the snowpack per unit area. Accurate estimation of SWE is essential for predicting runoff, reservoir operation, and water supply planning.

2. Methods

The study used a rainfall-runoff model to simulate the SWE in the Upper Hron basin. The model was calibrated using genetic algorithms to achieve the best agreement between observed and modelled mean daily discharges at the basin outlet. Calibration was performed during the period of 1961–1990, and validation was done during 1991–2010.

3. Results

The simulated SWE was verified by comparing it with weekly measured data in each altitude zone for the period of 1981–2000. The comparison showed a satisfactory degree of agreement between daily simulated and weekly measured SWE values. Some differences could be attributed to estimating basin averages from measured SWE data related to missing data at some rain gauge stations and windward and leeward effects caused by the complexity of the terrain.

4. Discussion

The changes in the simulated SWE were evaluated by comparing the mean, minimum, and maximum daily values of SWE on each calendar day of the decades of 1961–1970, 1971–1980, 1981–1990, 1991–2000, and 2001–2010 in each altitude zone. The results showed a decreasing trend in the simulated SWE and a reduction in the snow cover duration in recent decades.

5. Conclusion

The study highlights the importance of accurate SWE estimation in mountainous basins. The developed model provides a valuable tool for hydrological assessments and water resource management in the Upper Hron basin.

References

[Provide a list of references related to the study.]
from early October to the second half of May in the period of 1961–1971, but in the last period of 2000–2010 the end of snow cover had moved to the end of April. The reduction of the snow cover duration is more clearly visible in the fourth altitude zone; in the first decade the snow cover started in the second half of September and ended at the end of June. In the last decade the snow cover started in early October and ended in early May. In the earliest decade, snow was present throughout the year in the highest altitude zone, but in the last decades snow occurred only from the end of August to mid-June, and more than a month now is without snow cover in altitude zone 5.

The decreasing trends of simulated SWE in all altitude zones were confirmed in the previous research of the authors by a non-parametric Mann-Kendall test (Kotriková and Hlavčová, 2014). The significance of the trends was tested at the 95 % level of significance and it is shown in Table 2.

5 Conclusions

The objective of this paper is an evaluation of changes in the simulated snow water equivalent in the last 50 years for different altitude zones of a selected mountainous catchment in Slovakia. Modelling of the snow water equivalent was performed using a semi-distributed hydrological rainfall-runoff model known as Hron, which was adapted for modelling the different altitude zones. The Hron model provides more detailed output data than its lumped version, which con-
tributes to increasing the level of accuracy of the modelling of snow accumulation and snow melting in mountainous basins (Kotríková and Hlavčová, 2014).

The upper Hron River basin was divided into five altitude zones. The parameters of the model were calibrated for the period of 1961–1990 and validated for the last 20 years. The robustness of the simulated values of snow water equivalent was verified by comparing them with the weekly measured data of SWE at each altitude zone for the period of 1981–2000. The comparison indicates a satisfactory degree of agreement between the simulated SWE in each altitude zone and the measured SWE. The results suggest a decreasing tendency in the simulated snow water equivalent in the upper Hron River basin during the period of 1961–2010 in all the months of the winter season (from November to April), which confirmed the results of the authors’ previous research. The modelled outcomes also revealed a significant decrease in the SWE in some months of the summer season (from May to July), especially in the higher altitude zones.

The results also show a reduction in the snow cover duration, especially in the higher altitude zones. This reduction could be caused by the increasing air temperatures and changes in precipitation in recent decades. The shift of date of the ending of the snow cover towards the winter months may indicate an earlier occurrence of spring snowmelt floods in this region. This may imply that flood risk may increase during warmer winter seasons with more frequent floods induced by rain-on-snow processes.

Figure 5. Simulated mean daily SWE for the decades of (a) 1961–1971 and (b) 2001–2010 in each altitude zone of the Upper Hron.
Table 2. The significance of decreasing trends of the simulated SWE in all altitude zones.

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References


