DOI: 10.2478/aslh-2014-0011 Acta Silv. Lign. Hung., Vol. 10, Nr. 2 (2014) 145–159

Changes in Snow Storage in the Upper Hron River Basin (Slovakia)

Katarína KOTRÍKOVÁ[a*] – Kamila HLAVČOVÁ[a] – Róbert FENCÍK[b]

[a] Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology, Bratislava, Slovakia
[b] Department of Mapping and Land Consolidation, Faculty of Civil Engineering, Slovak University of Technology, Bratislava, Slovakia

Abstract - An evaluation of changes in the snow cover in mountainous basins in Slovakia and a validation of MODIS satellite images are provided in this paper. An analysis of the changes in snow cover was given by evaluating changes in the snow depth, the duration of the snow cover, and the simulated snow water equivalent in a daily time step using a conceptual hydrological rainfall-runoff model with lumped parameters. These values were compared with the available measured data at climate stations. The changes in the snow cover and the simulated snow water equivalent were estimated by trend analysis; its significance was tested using the Mann-Kendall test. Also, the satellite images were compared with the available measured data. The results sow a decrease in snow depth and in snow water equivalent from 1961–2010 in all months of the winter season, and significant decreasing trends were indicated in the months of December, January and February.

snow depth / snow water equivalent / trend analysis / MODIS satellite images

Kivonat – A tározott hókészlet változásai a Garam (Hron) felső vízgyűjtőjében, Szlovákiában. A tanulmány Szlovákia hegyvidéki vízgyűjtőiben a hóborítottság változását értékeli, és bemutatja a MODIS műhold képek értékelését is ehhez kapcsolódóan. A hóborítottság változásának analízise magában foglalta a hótakaró vastagságának, a hóborítottság időtartamának és a szimulált hó-víz egyenértéknek a napi időlépcsőben történő értékelését, amelyhez a szerzők egy koncentrált paraméterű csapadék-lefolyás modellt használtak fel. Az modellezés során kapott értékeket a meteorológiai állomásokon rendelkezésre álló terepi mérési adatokkal hasonlították össze. A hóborítottság és a szimulált hó-víz egyenérték változását trend analízis segítségével becsülték, a megbízhatóság értékelésére Mann-Kendall tesztet használtak. A távérzékelési alapú adatokat a terepi mérési adatokkal is összehasonlították. Az eredmények alapján valószínűsíthető a hótakaró vastagságának és a hó-víz egyenértéknek általában a csökkenése a vizsgált 1961–2010-es időszakban minden egyes téli (téli félév) hónapra vonatkozóan, avval a kiegészítéssel, hogy a csökkenési tendencia szignifikáns a december, január és február hónapok esetében.

hótakaró vastagság / hó-víz egyenérték / trand elemzés / MODIS képek

[*] Corresponding author: katarina.kotrikova@stuba.sk; Radlinského 11, 813 68 BRATISLAVA, Slovakia

1 INTRODUCTION

Snow cover is a very important part of a hydrological balance. The most important value of snow is the snow water equivalent (SWE). The snow water equivalent is the value of the amount of water in snow. Knowledge of the temporal and spatial variability of SWE is significant for the correct assessment and prediction of runoff from snow melting processes.

Snow data is rarely available in Slovakia from the second half of the 19th century, but it is regularly available from the second half of the 20th century from standard rain gauge stations. The measured data include the height of the snow cover, the date of the first and last days with snow cover, the duration of the snow cover, the snow water equivalent, etc.

Several authors investigated the spatial and temporal changes in the snow depths, and the density of the snow cover, the spatial and temporal changes in snow water equivalent, the impact of vegetation during the snow melt, and the impact of vegetation and catchment characteristic on hydrological balance (Hood – Hayashi 2010, Kuchment et al. 2010, Artan et al. 2013), and also several authors in Slovakia (Holko 2000, Holko et al. 2011, Pekárová et al. 2009, Gaál et al. 2012). Another authors in Slovakia have used rainfall-runoff models for modelling extreme runoff from snow melt in river basins (Holko 2000). They used models such as the UEB EHZ model (Holko et al. 2005), the WaSiM-ETH model, or the HBV model with semi-distributed parameters (Parajka 2001, Pekárová – Miklánek 2006, Halmová et al. 2006, Lapin et al. 2007, Danko et al. 2010).

Snow is a main element of stream flow in alpine basins, and quantifying snow depth and its distribution is important for hydrological modelling. In this paper we analysed the changes in snow storage during recent decades in alpine basin, the upper Hron River basin. The analysis was performing by assessing changes in snow duration and changes in the simulated snow water equivalent by hydrological modelling using the rainfall-runoff model Hron. The significance of the changes was evaluated by a trend analysis.

In the individual chapters of this paper we describe the input data, the concept and parameters of the rainfall-runoff model Hron, the methodology for assessing the duration of the snow cover measured in selected climate stations, a simulation of the snow water, the results of the assessment of any changes in the snow duration and simulated SWE for the period 1961–2010, and the identification of any trends in snow duration and the SWE for the months from November to April.

In 3.3. chapter we describe another source of snow data, i.e., the satellite images of the Moderate Resolution Imaging Spectroradiometer (MODIS) snow product. These data were evaluated and validated by measured data from 2000–2010 in five climate stations. The overall degree of agreement and the misclassifications were evaluated and filtered for increasing the accuracy of the satellite images.

2 INPUT DATA

The river basin analysed in this paper is the upper Hron River basin with its outlet at Banská Bystrica. The Hron River is the second longest river in Slovakia; its length is 298 km. It has a snow-rain runoff regime; the highest mean monthly flows occur in April and the lowest mean monthly flows in January and February. The catchment belongs to a cold and wet climate region; the highest measured mean daily air temperature is 29°C; the mean annual air temperature is between 4 and 5°C; the highest average monthly air temperature is between 14 and 16°C; and the lowest average monthly air temperature is between –4 and –6°C (Pekárová – Szolgay 2005).

The data representing the snow cover included measurement of the daily data of the snow depths and the weekly data of the snow water equivalent at 5 climate stations on the Hron river basin from the period 1961–2010. The input data for modelling the basin's snow water equivalent by the rainfall-runoff model were daily rainfall data from 23 rain gauge stations, the mean daily values of the air temperature from 6 climate stations, and the mean daily discharges in the profile of Banská Bystrica for the period 1961–2010. The basin's daily rainfall was processed by the interpolation method of inverse distance weighting; the basin's average air temperature values were calculated by linear regression between the stations' mean daily air temperatures and the altitudes of the climate stations. The daily evapotranspiration values were calculated by the Blaney-Criddle method (Parajka et al. 2003). The calculations were based on the basin's average daily air temperature and the sunshine index of the river basin.

Satellite images of the Moderate Resolution Imaging Spectroradiometer (MODIS) snow product were available from the official website of the National Snow and Ice Data Centre (http://nsidc.org/) in a daily time step from 2000–2010. These data were obtained from the MODIS sensor on the Aqua and Terra satellites of NASA's Earth Observing System (EOS). The spatial resolution of the data was 500 m.

The list of climate stations with the available measured data of the snow depths and snow water equivalent is in *Table 1*, and their location is in *Figure 1*.

Table 1. List of climate stations with the available measured data of the snow depth and snow water equivalent

Station	Chopok	Lom nad Rimavicou	Telgárt	Brezno	Banská Bystrica
Altitude [m asl]	2008	1018	901	487	427

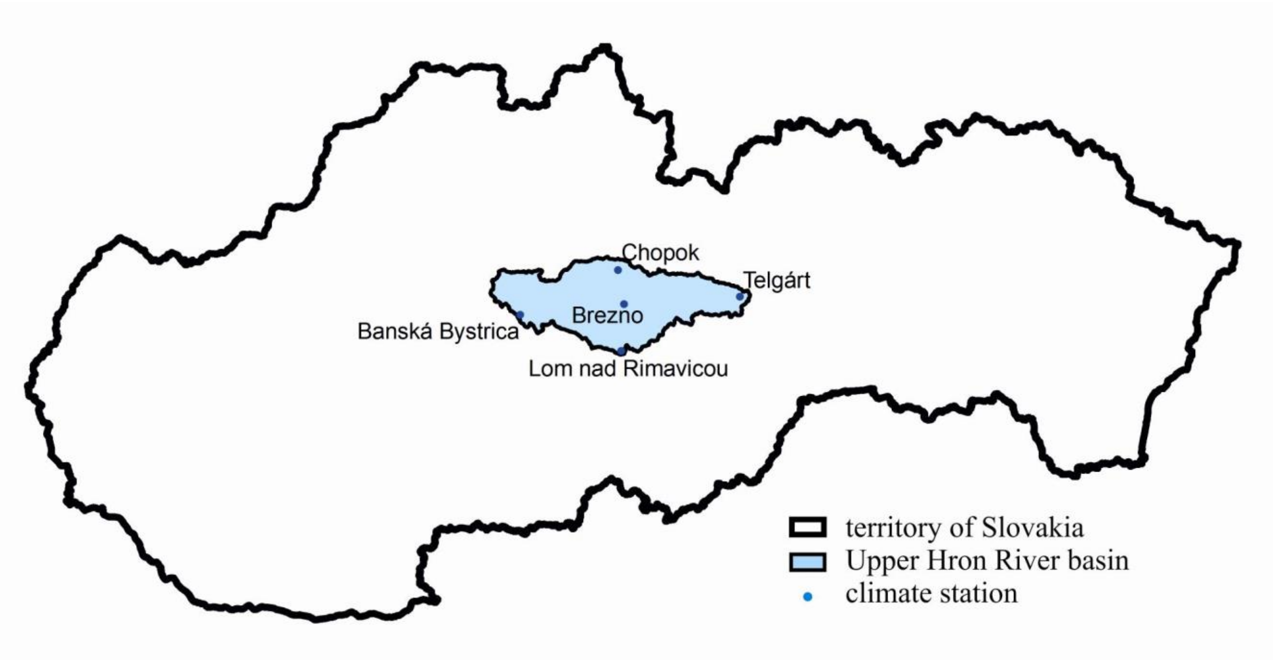

Figure 1. Location of climate stations with the available measured data of the snow depth and snow water equivalent

3 METHODOLOGY

3.1 Changes in duration of snow

The changes in snow cover from 1961–2010 were estimated by an analysis of the measured snow depth and its duration in the individual years and climate stations. In every year we totaled the number of days with a measurable snow depth. The data with values lower than 0.5 cm of snow depth we considered to be statistically irrelevant; therefore, only days with values higher than 0.5 cm of snow depth were taken into account.

The significance of the trend at the 95% level of significance was tested using the Mann-Kendall test. The Mann-Kendall test, which is one of the many methods used to detect trends, is the most widely used test. It is a non-parametric test which has the ability to deal with non-normalities, e.g., missing values. Its disadvantages include results that are not as strong as parametric tests.

3.2 Changes in snow water equivalent

The snow water equivalent was simulated by a rainfall-runoff model with lumped parameters. Its changes were assessed by a trend analysis, and the significance of the trends was tested using the Mann-Kendall test.

3.2.1 The rainfall-runoff model Hron

The model Hron is a rainfall-runoff model developed at the Department of Land and Water Resources Management of the Faculty of Civil Engineering of Slovak University of Technology in Bratislava (Kubeš 2007, Kubeš – Hlavčová 2002). The structure of this model is derived from the concept of the HBV model (Bergström 1976, 1992). This is a conceptual model with lumped parameters, which divides a river basin into 2 linear or nonlinear reservoirs according to the scheme in *Figure 2.*

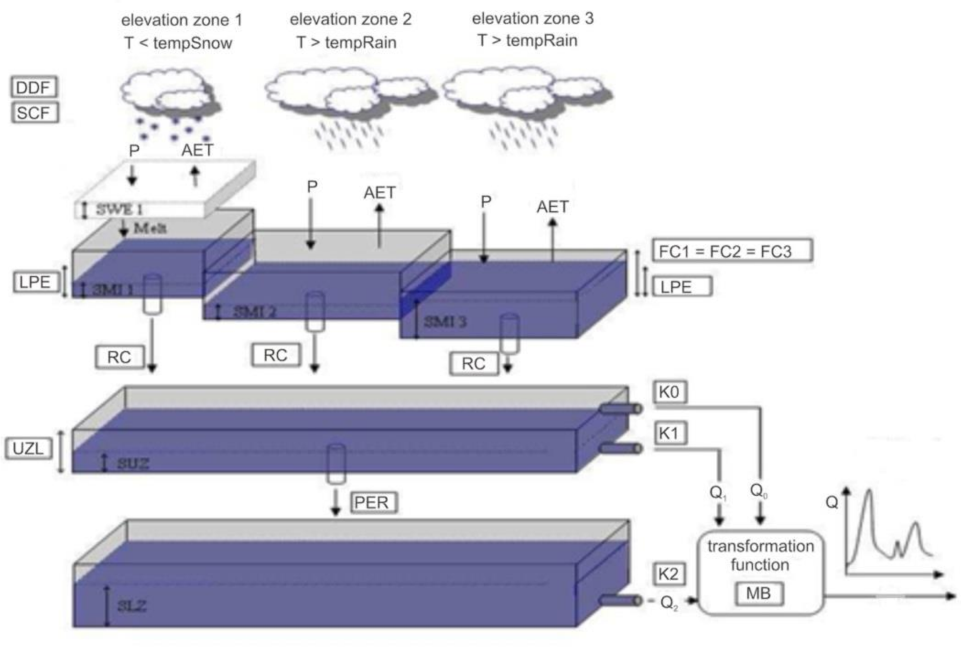

Figure 2. Scheme of the rainfall-runoff model Hron (Valent et al. 2011)

The model works in an hourly or daily time step and has three sub-models. The first sub-model is a snow sub-model for the simulation of snow accumulation and melting. The second, a soil sub-model, simulates the amount of water in soil and the actual evapotranspiration. The third, a runoff sub-model, simulates the transformation of the runoff in a river basin, respectively, the transformation of the flow in a river bed.

The manual or automatic calibration of model parameters is based on genetic algorithms or harmonic searching as well as on several objective functions for assessments of the reliability of the model's calibration. The actual version of the model Hron is programmatically processed in Matlab (Valent et al. 2011).

The calibrated model parameters are:

FC – field capacity [mm],
RC – recharge coefficient [–],
UZL – upper zone limit [mm],
tempRain – threshold temperature, above which all precipitation is liquid [°C],
tempMelt – threshold temperature, determining the snow melting process [°C],
tempSnow – threshold temperature, under which all the precipitation is solid [°C].
DDF – degree-day factor [mm/°C/day],
PER – percolation [mm],
LPE – limit of potential evapotranspiration [–],
K0 – parameter influencing the surface (Q_0) flow [–],
K1 – parameter influencing the subsurface (Q_1) flow [–],
K2 – parameter influencing the base (Q_2) flow [–],
SCF – snow correction factor,
MB – parameter determining the amount of days into which the total runoff is divided using a triangular weighted function.

The simulated basin states in every time unit are characterized by the state variables of the model: the values of the soil moisture *SM* [mm], the water level in the upper basin *SUZ* [mm], the water level in the lower basin *SLZ* [mm], and the snow water equivalent *SWE* [mm].

3.2.2 Calibration of model parameters

The aim of modelling the hydrological processes by the rainfall-runoff model Hron was to obtain the simulated daily values of the snow water equivalent. The reliability of the calibration of the model parameters using genetic algorithms was assessed by 1) compliance of the simulated and measured mean daily discharges in the basin outlet by the Nash-Sutcliffe coefficient; 2) validation with other samples of data by the differential split-sample test; and 3) comparison of the simulated and measured values of SWE.

In the process of calibrating the model parameters, the whole period of 1961–2010 was divided into five shorter periods, i.e., decades (starting in June 1961), for increasing the reliability of the simulated SWE in each decade. The parameters of the model were calibrated individually for each decade, and other decades were used for the validation of the model's parameters.

It was assumed that the SWE values obtained by the simulation with the parameters calibrated for the decades are more reliable than the values obtained by the simulation with the parameters calibrated for the whole 50 years. Therefore, the representative series of the snow water equivalent (the most reliable) was created by a combination of the simulated SWE from the decades with the calibrated parameters of each decade. The other series were created by a simulation of the period 1961–2010 with the parameters calibrated step by step from the first, second, third, fourth, and fifth decades.

The next step was the validation of the simulated SWE with the measured data. We compared the simulated daily values from the representative SWE series, which represents the basin's average data, with the measured basin's SWE averages. The basin's SWE averages were calculated from the measured SWE values at the climate stations by linear regression with the altitudes of the climate stations.

Finally, the changes in the simulated snow water equivalents in the basin were assessed by the trend analysis, and the significance of the trends was tested using the Mann-Kendall test.

3.3 Validation of the MODIS satellite data

The accuracy of the MODIS data was compared with the data measured from the area studied (Hall – Rigss 2007, Mauer et al. 2003). Two types of errors were evaluated in this validation. The sum of the misclassification of snow as land was divided by the total number of cloud-free days in percentages – the underestimation error; and the sum of the misclassification of land as snow was divided by the total number of cloud-free days in percentages – the overestimation error. The sum of correctly classified days (snow, snow and no snow, no snow) divided by the total number of cloud-free days in percentages represents the overall degree of agreement (Parajka – Blöschl 2006, 2008a, b, Parajka et al. 2012).

Subsequently, the temporal filtering of the MODIS images was used to increase the accuracy of the images. The pixels classified as clouds were replaced by the values of the same cells of the previous day to decrease these pixels. So, a pixel classified as a cloud was replaced by a pixel value if the pixel of the previous day was snow or land. Various time steps were used for the temporal filtering. Next, the MODIS data were compared with the measured data. The overall degree of agreement, underestimation and overestimation were calculated for all the decades at each station in all the months of the winter season.

4 RESULTS

4.1 Duration of snow cover

A graphic illustration of the changes in snow duration for the period 1961–2010 at 5 climate stations on the Hron River basin is shown in *Figures 3–7*. The graphs demonstrate the decreasing trend in the duration of the snow cover at 4 stations and the increasing trend at the Banská Bystrica climate station. The significance of the increasing and decreasing trends at the 95% level of significance was tested using the Mann-Kendall test.

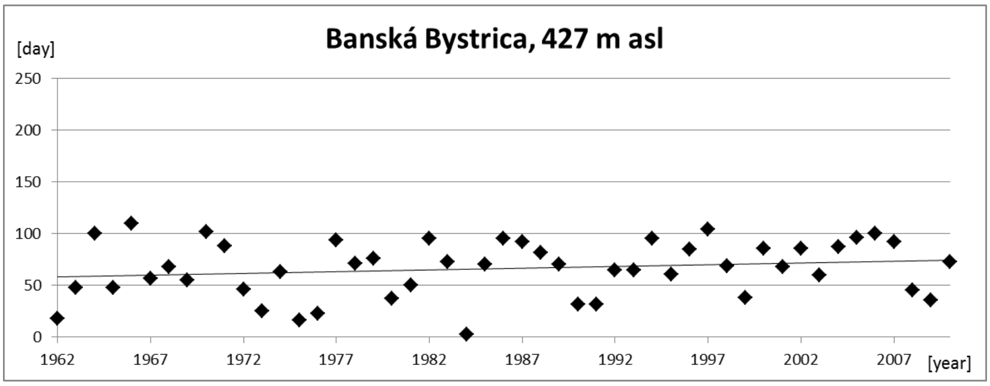

Figure 3. The duration of the snow cover at the Banská Bystrica climate station

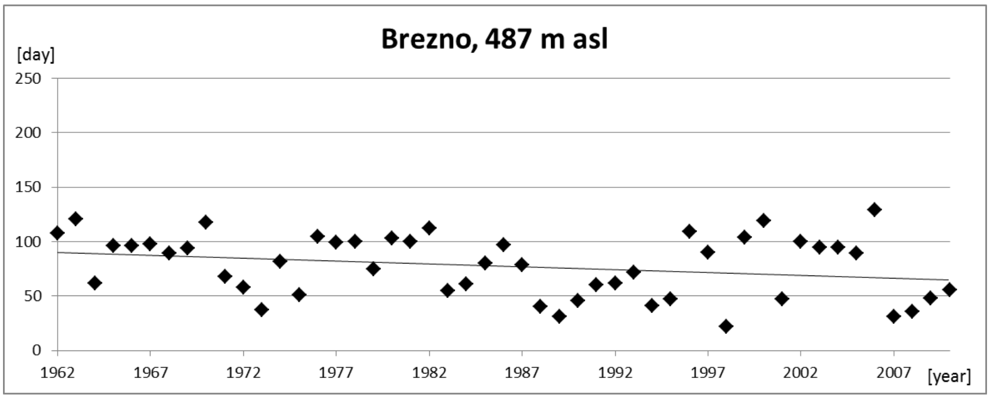

Figure 4. The duration of the snow cover at the Brezno climate station

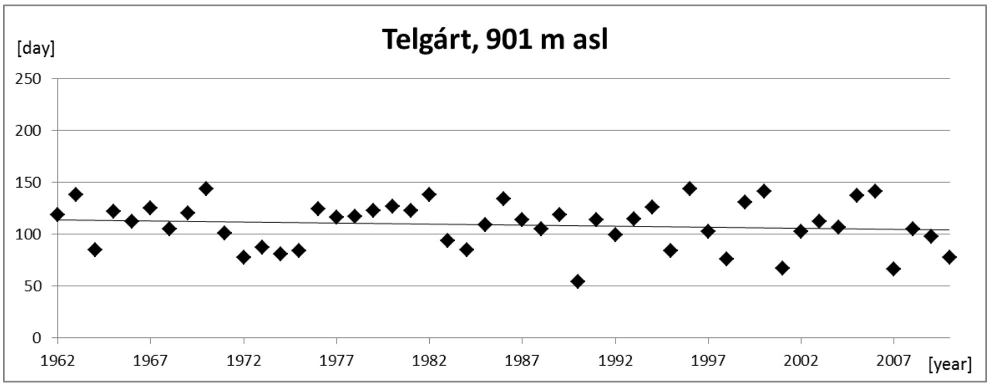

Figure 5. The duration of the snow cover at the Telgárt climate station

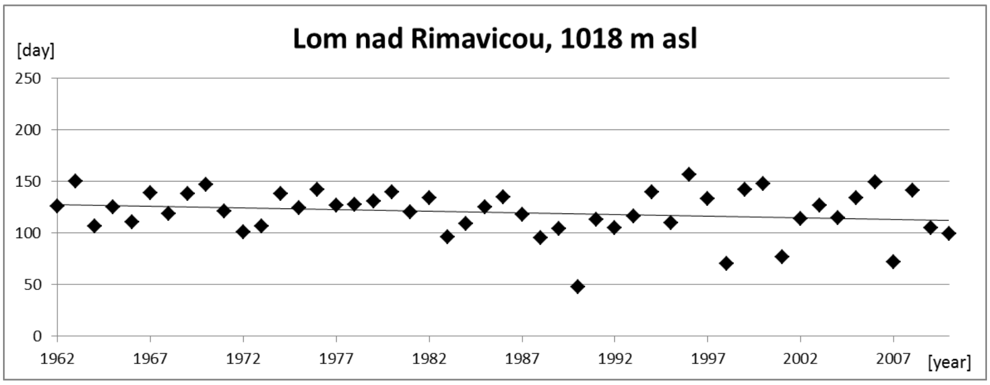

Figure 6. The duration of the snow cover at the Lom nad Rimavicou climate station

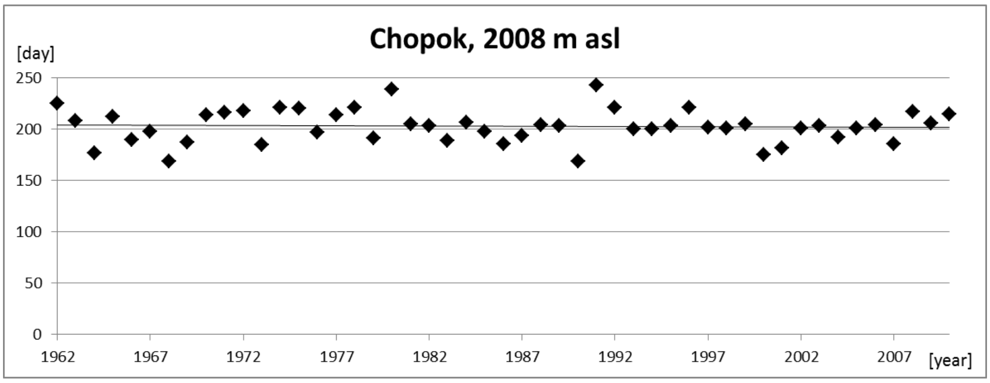

Figure 7. The duration of the snow cover at the Chopok climate station

We can see a decreasing trend in the duration of the days with snow cover, but no significantly trend were detected using the Mann-Kendall test.

4.2 Simulation of snow water equivalent

4.2.1 Calibration and validation of model parameters

It was mentioned that the parameters of the model were calibrated individually for each decade, and other decades were used for the validation of the model's parameters. The values achieved of the Nash-Sutcliffe coefficient are listed in *Table 2*.

Table 2. Values of the Nash-Sutcliffe coefficient for the calibration and validation periods (grey – calibration, white – validation)

↑ Validation ↓	1961–1971	1971–1981	1981–1991	1991–2000	2000–2010
1961–1971	0.7987	0.689	0.7301	0.7187	0.7162
1971–1981	0.7124	0.8041	0.7466	0.7379	0.7608
1981–1991	0.7175	0.7499	0.7341	0.7423	0.6546
1991–2000	0.7386	0.784	0.804	0.7911	0.6505
2000–2010	0.6701	0.7031	0.6889	0.6506	0.7595

A comparison of the simulated mean monthly SWE for the months of the winter season and the period 1961–2010 is shown in *Table 3* (Juričeková et al. 2013).

Table 3. Mean monthly basin averages of SWE for the period 1961 –2010

	Nov [mm]	Dec [mm]	Jan [mm]	Feb [mm]	March [mm]	April [mm]
Representative series of SWE	3.79	25.46	56.53	79.67	71.41	16.18
SWE simulated with parameters from period 1961–1971	3.67	24.58	54.46	75.82	67.14	14.34
SWE simulated with parameters from period 1971–1981	4.02	23.57	49.51	70.00	61.18	11.81
SWE simulated with parameters from period 1981–1991	3.94	26.36	58.52	82.97	75.82	18.63
SWE simulated with parameters from period 1991–2000	3.58	23.36	51.58	72.63	65.63	15.50
SWE simulated with parameters from period 2000–2010	4.06	24.09	52.04	69.98	59.58	10.14

The next step was the validation of the simulated SWE with the measured data. From the comparison of the simulated daily values from the representative SWE series with the measured basin's SWE averages, we can see a satisfactory compliance between the simulated and measured daily SWE values. Some differences could be caused by a problematic determination of the basin's average value of the measured SWE, which was caused by the missing data in some climate stations. As illustration, a comparison of the measured and simulated basin's SWE for the period's 1981–1990 *(Figure 8)* and 1991–2000 *(Figure 9)* are presented here.

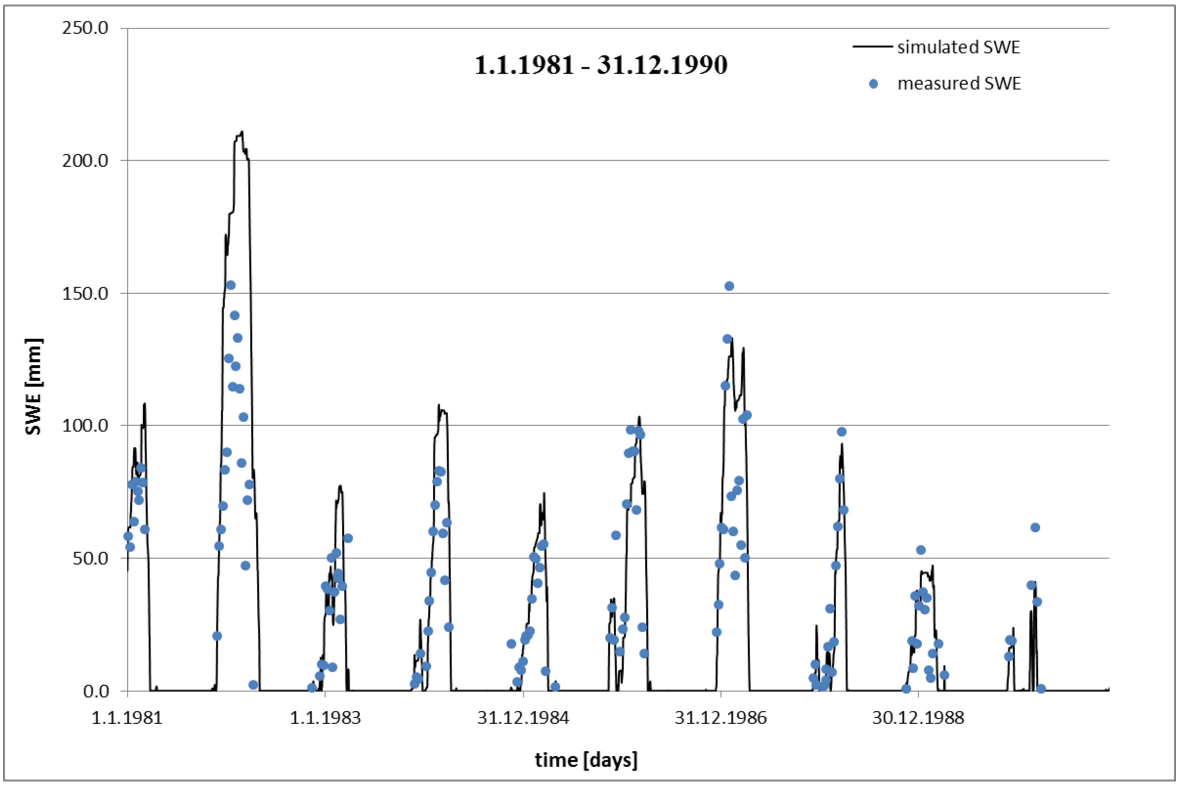

Figure 8. Comparison of the measured and simulated basin's SWE for the period 1981–1990

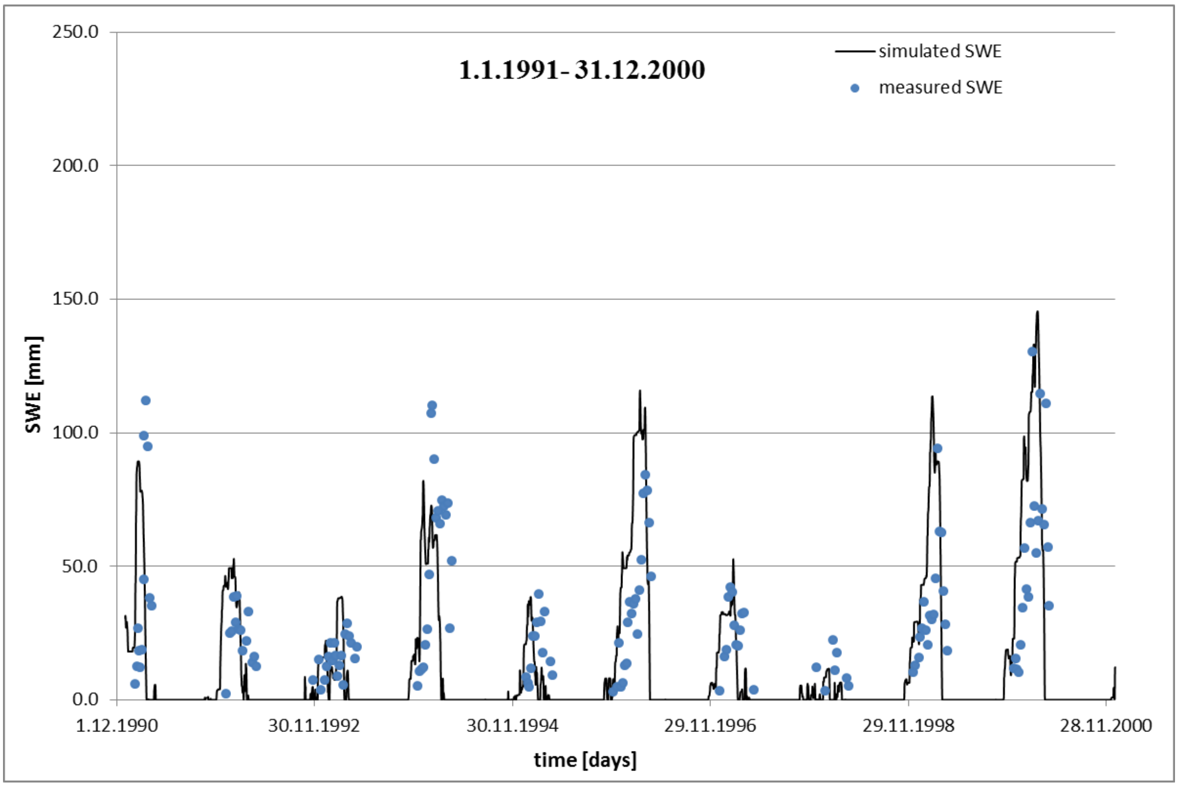

Figure 9. Comparison of the measured and simulated basin's SWE for the period 1991–2000

The changes in the simulated snow water equivalents in the basin were assessed by the trend analysis, and the significance of the trends was tested using the Mann-Kendall test *(Table 4)*. From the table we can see a statistically confirmed significant trend at the 95% level of significance in some months. From the results it is possible to indicate a decrease in the snow water equivalent on the upper Hron River basin in the period of 1961–2010 in all the months of the winter season, and significantly decreasing trends were indicated in the months of December, January and February.

Table 4. Significance of decreasing trends of the simulated basin's SWE in the individual months

Month	Significant trend (level of 95% significance)
November	No
December	Yes
January	Yes
February	Yes
March	No
April	No

4.3 MODIS satellite images

In this part of the study the validation of the MODIS data by comparing it with the measured data from the study area was provided. Next, the temporal filtering of the MODIS images was applied to increase the accuracy of the images. Finally, the MODIS data were compared with the measured data.

4.3.1 Validation of the MODIS satellite images

The monthly values of the overall degree of agreement of the MODIS satellite images are shown in *Table 5*, and the yearly values of the accuracy index of the overall agreement and misclassification of the original MODIS data are shown in *Table 6*.

Table 5. The monthly values of the overall degree of agreement of the original MODIS satellite images

	Banská Bystrica (%)	Brezno (%)	Telgárt (%)	Lom nad Rimavicou (%)	Chopok (%)
November	95.455	90.909	86.49	92.929	41.250
December	94.681	87.273	93.00	81.746	65.546
January	92.593	89.655	97.98	92.000	93.976
February	90.000	86.598	80.52	89.109	95.946
March	85.185	79.661	63.73	86.842	94.318
April	99.432	99.375	77.12	90.977	23.009

Table 6. Yearly values of the accuracy index of the overall degree of agreement and misclassification of the original MODIS data

	Banská Bystrica (%)	Brezno (%)	Telgárt (%)	Lom nad Rimavicou (%)	Chopok (%)
Overall degree of agreement	91.802	88.822	79.836	89.732	76.812
Underestimation	0.119	0.577	1.00	2.589	1.072
Overestimation	2.380	3.926	7.31	3.070	28.637

Subsequently, the temporal filtering of the MODIS images was used to increase the accuracy of the images. Next, the MODIS data were compared with the measured data. The overall degree of agreement, underestimation and overestimation were estimated for all the decades in each station in all the months of the winter season *(Tables 7–12)*.

Table 7. The monthly values of the overall degree of agreement of the satellite images after temporal filtering (time step: 1 day)

	Banská Bystrica (%)	Brezno (%)	Telgárt (%)	Lom nad Rimavicou (%)	Chopok (%)
November	94.44	92.64	85.47	93.17	40.91
December	93.06	86.14	92.36	80.66	66.07
January	93.85	90.14	96.03	90.57	93.23
February	89.68	88.11	81.67	87.42	96.30
March	86.54	78.61	68.39	88.02	95.35
April	98.74	99.10	75.71	89.58	21.56

Table 8. Yearly values of the accuracy index of the overall degree of agreement and misclassification of the sensor after temporal filtering (time step: 1 day)

	Banská Bystrica (%)	Brezno (%)	Telgárt (%)	Lom nad Rimavicou (%)	Chopok (%)
Overall degree of agreement	92.20	88.99	80.45	88.90	76.61
Underestimation	0.13	0.57	1.27	2.65	1.24
Overestimation	2.71	4.21	7.44	3.49	28.96

Table 9. The monthly values of the overall degree of the agreement of satellite images after temporal filtering (time step: 2 days)

	Banská Bystrica (%)	Brezno (%)	Telgárt (%)	Lom nad Rimavicou (%)	Chopok (%)
November	93.12	93.20	83.18	90.73	40.00
December	90.06	83.90	90.55	81.48	66.67
January	88.62	87.29	95.74	88.78	92.73
February	89.24	88.07	83.44	88.20	96.38
March	86.91	79.05	69.39	87.08	95.65
April	98.53	98.43	76.96	88.39	21.89

Table 10. Yearly values of the accuracy index of the overall degree of agreement and misclassification of the sensor after temporal filtering (time step: 2 days)

	Banská Bystrica (%)	Brezno (%)	Telgárt (%)	Lom nad Rimavicou (%)	Chopok (%)
Overall degree of agreement	90.83	88.21	81.38	88.11	76.66
Underestimation	0.14	0.52	1.42	2.77	1.31
Overestimation	3.53	4.79	7.68	3.91	29.12

Table 11. The monthly values of the overall degree of the agreement of satellite images after temporal filtering (time step: 3 days)

	Banská Bystrica (%)	Brezno (%)	Telgárt (%)	Lom nad Rimavicou (%)	Chopok (%)
November	91.56	93.70	81.40	89.83	39.20
December	88.57	82.55	88.28	81.97	67.53
January	86.15	86.12	96.31	89.19	91.62
February	88.59	87.06	85.55	89.05	96.27
March	86.88	78.75	69.60	87.29	95.72
April	98.63	98.19	76.23	88.26	21.93

Table 12. Yearly values of the accuracy index of the overall degree of agreement and misclassification of the sensor after temporal filtering (time step: 3 days)

	Banská Bystrica (%)	Brezno (%)	Telgárt (%)	Lom nad Rimavicou (%)	Chopok (%)
Overall degree of agreement	90.06	87.53	81.92	88.45	76.39
Underestimation	0.16	0.51	1.54	2.90	1.49
Overestimation	4.10	5.24	7.99	3.90	29.22

The mean value of the overall degree of the agreement of the original satellite images is 85.4%; the overestimation is 9.1%; and the underestimation of the images is 1.1%. After the temporal filtering, these values were changed. Overall, the values of the overall degree of the agreement has not changed significantly, but the mean value of the underestimation was changed by 0.25%, and the mean value of the overestimation after the temporal filtering in the 1–3 day time step was changed by more than 1% – the misclassification of snow as land is increasing, but the misclassification of land as snow is approximately the same (Parajka – Blöschl 2008a, Marchane et al. 2014). In our future work, we expect higher values of the overall degree of the filtered satellite images by a combination of temporal and spatial filtering.

5 DISCUSSION AND CONCLUSIONS

Snow cover is a significant natural phenomenon; precipitation is accumulated during some months in the winter season and then is released in a very short time. This has quantitative and qualitative impacts on the water cycle.

The changes in the duration of the snow cover were evaluated in the period of the hydrological years of 1962–2010. This assessment was conducted using measured data from the five climate stations in the upper Hron River basin from different elevations. From the comparison, we can see a decreasing trend in the duration of the days with snow cover and, according to the Mann-Kendall statistical test.

We focused on an assessment of the changes in the snow water equivalent values in the upper Hron River basin in the period of 1961–2010. In the catchment we simulated the daily values of the SWE by the rainfall-runoff model Hron with lumped parameters. The period of 1961–2010 was divided into five decades; they were particularly calibrated, and the other years were used for the validation of the parameters of the model Hron. In this way we wanted to review the impact of the changed parameters of the simulated values of the SWE.

From the Nash-Sutcliffe (NS) values we can see higher values of NS in every calibrated decade than in the validated periods, except for the period of 1981–1990. No significant change of the model's parameters was detected over time. We assume that the state variables of the model obtained by simulating a shorter period are more reliable than the simulated values obtained with the simulated parameters calibrated for the entire period of 50 years.

From the comparison of the basic SWE statistics simulated from the whole period of 1961–2010 with the different sets of model parameters calibrated, we can state that the different sets of model parameters had an effect on the simulated SWE values in the individual months. Therefore, for the final analysis we selected the simulated SWE achieved from the simulations of the individual decades with each of their own calibrated parameters. These values of the "representative" simulated SWE were also consistent with the measured basin's values, which were estimated from the available measured SWE data from the climate stations in the basin.

The changes in the representative simulated SWE were evaluated by the trend analysis in the individual months, and the statistical significance of the trends was assessed by the Mann-Kendall statistical test. From the results it is possible to demonstrate a decrease in the SWE on the upper Hron River basin in the period of 1961–2010 in all the months of the winter season, and significant decreasing trends were indicated in months of December, January and February.

Finally, we evaluated and validated the MODIS satellite images and evaluated the accuracy of the MODIS snow data. These data were compared with the measured data in the area of interest, and the index of the accuracy, the overall degree of the agreement, and the misclassifications of the sensor were determined. The mean value of the overall degree of agreement of the original satellite images for the winter seasons was 85.4%; the overestimation was 9.1%; and the underestimation of the images was 1.1%. After the temporal filtering, the misclassification of snow as land was increased, but the misclassification of land as snow was approximately the same.

Acknowledgement: This work was supported by the Slovak Research and Development Agency under Contract No. APVV-0303-11 and by the VEGA No. 1/0908/11 research project.

REFERENCES

ARTAN, G. A. – VERDIN, J. P. – LIETZOW, R. (2013): Large scale snow water equivalent status monitoring: comparison of different snow water products in the upper Colorado Basin, Hydrology and Earth System Sciences, Vol. 17, 5127–5139, doi:10.5194/hess-17-5127-2013

BERGSTRÖM, S. (1976): Development and application of a conceptual runoff model for Scandinavian catchments, SMHI Report RHO 7, Norrköping.

BERGSTRÖM, S. (1992): The HBV model – its structure and applications. SMHI Reports RH, No. 4, Norrköping.

DANKO, M. – HLAVČOVÁ, K. – KOHNOVÁ, S. – SZOLGAY, J. (2010): Posúdenie extrémneho odtoku z topenia snehu v povodí Račianskeho potoka (Estimation of extreme runoff from snow melt in the Račiansky potok basin). Acta Hydrologica Slovaca, Vol. 11, No. 1, IH SAS, Bratislava, Slovakia (in Slovak)

GAÁL, L. – SZOLGAY, J. – KOHNOVÁ, S. – PARAJKA, J. – MERZ, R. – VIGLIONE, A. – BLÖSCHL, G. (2012): Flood timescales: Understanding the interplay of climate and catchment processes through comparative hydrology. Water Resources Research, Vol. 48, W04511, doi:10.1029/2011WR011509.

HALL, D. K., RIGGS, G., A. (2007): Accuracy assessment of the MODIS snow products. Hydrological Processes, 21, pp. 1534–1547.

HALMOVÁ, D. – MÉSZÁROŠ, I. – MIKLÁNEK, P. – MITKOVÁ, V. – PEKÁROVÁ, P. (2006): Simulácia vodnej hodnoty snehu v experimentálnom mikropovodí Rybárik semi-distribuovaným zrážkovo-odtokovým modelom (Snow water equivalent simulation in experimental microbasin Rybárik with semi-distributed rainfall-runoff model). Acta Hydrologica Slovaca, Vol. 7, No.1, IH SAS, Bratislava, Slovakia (in Slovak)

HOLKO, L. (2000): Vyhodnotenie dlhodobých meraní parametrov snehovej pokrývky v horskom povodí (Evaluation of long-term snow cover data in a mountain catchment). Acta Hydrologica Slovaca, Vol. 1, No.1, IH SAS, Bratislava, Slovakia (in Slovak)

HOLKO, L. – GORBACHOVÁ, L. – KOSTKA, Z. (2011): Snow Hydrology in Central Europe. Geography Compass, Vol. 5, No. 4, 200-218, doi: 10.1111/j.1749-8198.2011.00412.x

HOLKO L. – KOSTKA, Z. – PECUŠOVÁ, Z. (2005): Sneh (Snow). In Scenáre zmien vybraných zložiek hydrosféry a biosféry v povodí Hrona a Váhu v dôsledku klimatickej zmeny (Scenarios of changes in selected components of the hydrosphere and biosphere in the Hron River Basin and the balance due to climate change), Eds. P. Pekárová and J. Szolgay, Veda Bratislava, Slovakia, 105–167 [in Slovak]

HOOD, J. L. – HAYASHI, M. (2010): Assessing the application of a laser rangefinder for determining snow depth in inaccessible alpine terrain, Hydrology and Earth System Sciences, Vol. 14, 901–910, doi:10.5194/hess-14-901-2010

JURIČEKOVÁ, K. – HLAVČOVÁ, K. – SZOLGAY, J. – BARTÓKOVÁ, L. – SZÁSZ, V. (2013): Posúdenie zmeny simulovanej vodnej hodnoty snehu na povodí horného Hrona (Evaluating changes in simulated snow water equivalent in the upper Hron River basin). Acta Hydrologica Slovaca, Vol. 14, No.1, IH SAS, Bratislava, Slovakia (in Slovak)

KUBEŠ, R. (2007): Návrh koncepčného zrážkovo-odtokového modelu pre hydrologické predpovede (Proposal for a conceptual rainfall-runoff model for hydrological forecasting). Bratislava, Slovakia (in Slovak)

KUBEŠ, R. – HLAVČOVÁ, K. (2002): Simulácia extrémnej zrážkovo-odtokovej situácie na povodí Hrona. (Simulation of extreme rainfall-runoff situation in the Hron River basin) In: X. international poster day "Transport of Water, Chemicals and Energy in the System Soil – Crop Canopy – Atmosphere". Bratislava, Slovakia: Institute of Hydrology SAS, Geophysical Institute SAS. ISBN 80-968480-9-7.

KUCHMENT, L. S. – ROMANOV, P. – GELFAN, A. N. – DEMIDOV, V. N. (2010): Use of satellite-derived data for characterization of snow cover and simulation of snowmelt runoff through a distributed physically based model of runoff generation, Hydrology and Earth System Sciences, Vol. 14, doi:10.5194/hess-14-339-2010

LAPIN, M. – MELO, M. – FAŠKO, P. – PECHO, J. (2007): Snow cover changes scenarios for the Tatra Mountains in Slovakia. Proceedings of the 29th International Conference on Alpine Meteorology, 4. – 8. 6. 2007, Chambéry, France

MARCHANE, A. – JARLAN, L. – HANICH, L. – BOUDHAR, A. – GASCOIN, S. – LE PAGE, M. – TAVERNIER, A. – FILALI, N. – BERJAMY, B. – KHABBA, S. – CHEHBOUNI, G. (2014): Snow cover dynamic in the Atlas Chain (Morocco) using daily MODIS products over the last decade. Geophysical Research Abstracts, Vol. 16/2014: EGU General Assembly 2013.

MAURER, E.P. – RHOADS, J.D. – DUBAYAH, R.O. – LETTENMAIER, D.P. (2003): Evaluation of the snow covered area data product from MODIS. Hydrological Processes, 17, 59–71.

NATIONAL SNOW AND ICE DATA CENTER, http://nsidc.org/

PARAJKA, J. (2001): UEB EHZ – Distribuovaný energeticky založený model akumulácie a topenia snehovej pokrývky (UEB EHZ – distributed energy based snow accumulation and melt model). Acta Hydrologica Slovaca, Vol. 2, No.2, IH SAS, Bratislava, Slovakia (in Slovak)

PARAJKA, J. – BLÖSCHL, G. (2006): Validation of MODIS snow cover images over Austria. Hydrology and Earth System Sciences, Vol. 10, doi: 10.5194/hess-10-679-2006

PARAJKA, J. – BLÖSCHL, G. (2008a): Spatio-temporal combination of MODIS images – potential for snow cover mapping. Water resources research, Vol. 40, doi: 10.1029/2007WR006204

PARAJKA, J. – BLÖSCHL, G. (2008b): The value of MODIS snow cover data in validating and calibrating conceptual hydrologic models. Journal of Hydrology, 358, 240–258.

PARAJKA, J. – HOLKO, L. – KOSTKA, Z. – BLÖSCHL, G. (2012): MODIS snow cover mapping accuracy in a small mountain catchment – comparison between open and forest sites. Hydrology and Earth System Sciences, Vol. 16, 2365–2377, doi: 10.5194/hess-16-2365-2012

PARAJKA, J. – MERZ, R. – BLÖSCHL, G. (2003) Estimation of daily potential evapotranspiration for regional water balance modeling in Austria. In: Proceedings of the 11th International Poster Day and Institute of Hydrology. Transport of Water, Chemicals and Energy in the Soil – Crop - Canopy - Atmosphere System, Bratislava, Slovak Academy of Sciences, Bratislava, Slovakia

PEKÁROVÁ, P. – MIKLÁNEK, P. (2006): Predpoveď odtoku z topenia snehu z malého povodia (Snowmelt runoff forecast in small basin). Acta Hydrologica Slovaca, Vol. 7, No.1, IH SAS, Bratislava, Slovakia (in Slovak)

PEKÁROVÁ, P. – MIKLÁNEK, P. – ONDERKA, M. – KOHNOVÁ, S. (2009): Water balance comparison of two small experimental basins with different vegetation cover. Biologia, Vol. 64, No. 3, ISSN 0006-3088, 487-491.

PEKÁROVÁ, P. – SZOLGAY, J. (2005): Scenáre zmien vybraných zložiek hydrosféry a biosféry v povodí Hrona a Váhu v dôsledku klimatickej zmeny (Scenarios of changes in selected components of the hydrosphere and biosphere in the Hron River Basin and the balance due to climate change), Veda Bratislava, Slovakia (in Slovak)

VALENT, P. – DANEKOVÁ, J. – RIVERSO, C. (2011): Neistoty pri kalibrácii zrážkovo-odtokového modelu HBV (Uncertainties in the HBV model calibration). Acta Hydrologica Slovaca, Vol. 12, No. 2, IH SAS, Bratislava, Slovakia (in Slovak)