J. Hydrol. Hydromech., 64, 2016, 1, 12–22
DOI: 10.1515/johh-2016-0011

Variability of snow line elevation, snow cover area and depletion in the main Slovak basins in winters 2001–2014

Pavel Krajčí[1*], Ladislav Holko[1], Juraj Parajka[2, 3]

[1] Institute of Hydrology, Slovak Academy of Sciences, Racianska 75, 831 02 Bratislava, Slovak Republic.
[2] Institute of Hydraulic Engineering and Water Resources Management, Vienna University of Technology, Karlsplatz 13/222, Vienna, Austria.
[3] Centre for Water Resource Systems, Vienna University of Technology, Karlsplatz 13/222, Vienna, Austria.
[*] Corresponding author. E-mail: krajci@uh.savba.sk

Abstract: Spatial and temporal variability of snow line (SL) elevation, snow cover area (SCA) and depletion (SCD) in winters 2001–2014 is investigated in ten main Slovak river basins (the Western Carpathians). Daily satellite snow cover maps from MODIS Terra (MOD10A1, V005) and Aqua (MYD10A1, V005) with resolution 500 m are used.

The results indicate three groups of basins with similar variability in the SL elevation. The first includes basins with maximum elevations above 1500 m a.s.l. (Poprad, Upper Váh, Hron, Hornád). Winter median SL is equal or close to minimum basin elevation in snow rich winters in these basins. Even in snow poor winters is SL close to the basin mean. Second group consists of mid-altitude basins with maximum elevation around 1000 m a.s.l. (Slaná, Ipeľ, Nitra, Bodrog). Median SL varies between 150 and 550 m a.s.l. in January and February, which represents approximately 40–80% snow coverage. Median SL is near the maximum basin elevation during the snow poor winters. This means that basins are in such winters snow free approximately 50% of days in January and February. The third group includes the Rudava/Myjava and Lower Váh/Danube. These basins have their maximum altitude less than 700 m a.s.l. and only a small part of these basins is covered with snow even during the snow rich winters.

The evaluation of SCA shows that snow cover typically starts in December and last to February. In the highest basins (Poprad, Upper Váh), the snow season sometimes tends to start earlier (November) and lasts to March/April. The median of SCA is, however, less than 10% in these months. The median SCA of entire winter season is above 70% in the highest basins (Poprad, Upper Váh, Hron), ranges between 30–60% in the mid-altitude basins (Hornád, Slaná, Ipeľ, Nitra, Bodrog) and is less than 1% in the Myjava/Rudava and Lower Váh/Danube basins. However, there is a considerable variability in seasonal coverage between the years. Our results indicate that there is no significant trend in mean SCA in the period 2001–2014, but periods with larger and smaller SCA exist. Winters in the period 2002–2006 have noticeably larger mean SCA than those in the period 2007–2012.

Snow depletion curves (SDC) do not have a simple evolution in most winters. The snowmelt tends to start between early February and the end of March. The snowmelt lasts between 8 and 15 days on average in lowland and high mountain basins, respectively. Interestingly, the variability in SDC between the winters is much larger than between the basins.

Keywords: MODIS; Snow line; Snow cover; Snow depletion curves; Slovakia.

INTRODUCTION

Seasonality of river discharge is in many parts of the world significantly affected by snowmelt. This is not an attribute of only high latitude northern or mountain basins. For example, snowmelt influences runoff and flood regime in the Danube River basin (central Europe) also at gauging stations which are far from the mountains (e.g. Holko et al., 2011; Parajka et al., 2010). Snow cover is also an important indicator of the climatic character of a winter. Thus, analysis of spatial and temporal variability of snow cover at catchment scale helps to evaluate changes in flood regimes (Hall et al., 2014), to forecast snowmelt runoff in the spring period (e.g. Nester et al., 2012) and is an important indicator for attributing increasing air temperature in climatic studies (Pepin et al., 2015). Traditionally, the snow cover climatology is based on snow depth observations at climate stations (Šamaj and Valovič, 1988; Šamaj et al., 1991; Lapin et al., 2007). Such estimation has the advantage of relatively long records, but the limitation is rather sparse observation network, particularly in the mountains.

Spatial patterns of snow cover can be more easily derived from remote sensing observations. One of the most commonly used is the MODerate-resolution Imaging Spectroradiometer (MODIS) operating on satellites Aqua and Terra. MODIS data has been successfully applied in snowmelt modeling (Day, 2013; Georgievsky, 2009; Li and Wiliams, 2008; Ma et al., 2013; Tekeli et al., 2005), calibration of distributed snow models (Franz and Karsten, 2013; He et al., 2014; Parajka and Blöschl, 2008a) or climatological research of snow cover variations (Foppa and Seiz, 2012; Gascoin et al., 2015; Mishra et al. 2013; Liang et al. 2008; Tang et al. 2013; Wang and Xie, 2009). The advantage of using MODIS data is its high spatial and temporal resolution, the limitation is larger cloud coverage, particularly in mountains, which limits snow cover detection (Parajka et al., 2012). There have been different methods proposed and tested for cloud reduction in the past (see e.g. summary in Parajka and Blöschl, 2012). One of the most efficient approaches for the mountains is the snow line approach (Parajka et al., 2010). Krajčí et al. (2014) proposed and evaluated a regional snow line elevation method (RSLE) in the upper Váh basin and reported an overall accuracy between 73% and 92%. The average accuracy in the forest exceeded 90% for the period January to March.

The main objective of this study is to evaluate spatial and temporal variability of snow cover characteristics determined by the RSLE method in the main Slovak river basins. MODIS snow products data are available since spring 2000. Despite their potential and numerous applications in snow research, the regional assessment of snow cover area in different basins is still rare. This article strives to fill the gap and analyze variability of snow line elevation (SL), snow cover area (SCA) and snow depletion curves (SDC) in the main Slovak basins in period 2000–2014. It is for the first time that the MODIS snow cover patterns are analyzed for the main Slovak basins in which snow cover has extremely high spatial and temporal variability.

METHODS

Regional snow line elevation (SL) is determined from the MODIS satellite data by the RSLE methodology (Krajčí et al., 2014). The cornerstone of the approach is to find an elevation for which the sum of snow covered pixels below (P_S) and land pixels above the snow line (P_L) is minimized (Fig. 1).

The entire area above and below the snow line (A_{SL}) is considered as snow covered and snow free, respectively. The relative snow covered area of a basin (SCA in %) is calculated as:

$$SCA = \frac{A_{SL}}{A_T} \cdot 100 \qquad (1)$$

where A_{SL} represents the area above the SL and A_T is total basin area.

The snow covered area is used to calculate the snow cover depletion curves (SDC). The SDC relates the areal extent of the snow cover (SCA) to elapsed time (Jain, 2011). The SDC represents period of snow cover depletion from maximum basin SCA to complete melt of snow cover in particular basin. The decrease of snow covered area during the snowmelt period represents a link between snow climatology and hydrology and can be used for parametrization of snowmelt in large scale models (Liston, 1999) or operational snowmelt runoff forecasting (Seidel and Martinec, 2004). Large cloud coverage does not allow us to estimate SL and SCA for each day. Therefore, we use linear interpolation to calculate snow line elevation for days when cloud coverage exceeds 70%. The selection of this threshold is based on previous investigations of Krajčí et al. (2014). Interpolated SL values so allow consistent calculation of snow cover characteristics for all basins. An example of MODIS snow cover maps and interpolated SL values for the Váh River basin to Liptovský Mikuláš basin is presented in Fig. 1. The left, middle and right map in the upper panel shows the estimated and interpolated snow line elevation in March 30, April 7 and April 25, respectively. Figure 1 indicates that when applying 70% threshold then SL need to be interpolated for 55% of days in winter 2006. This frequency is lower for larger basins and decrease with decreasing mean basin elevation. For selected Slovak basins it varies on average between 42% in Poprad to 35% in Lower Váh/Danube basin.

The seasonal and inter-annual variability of SL and SCA characteristics is described by selected percentiles (25%, 50%, 75%) indicating typical (median) conditions and the scatter (i.e. measure of variability) around the median (difference in 75- and 25- percentiles). The frequency of days with at least 50% snow coverage and the snow depletion curves for selected winters are used to show the variability in snow cover duration across Slovakia.

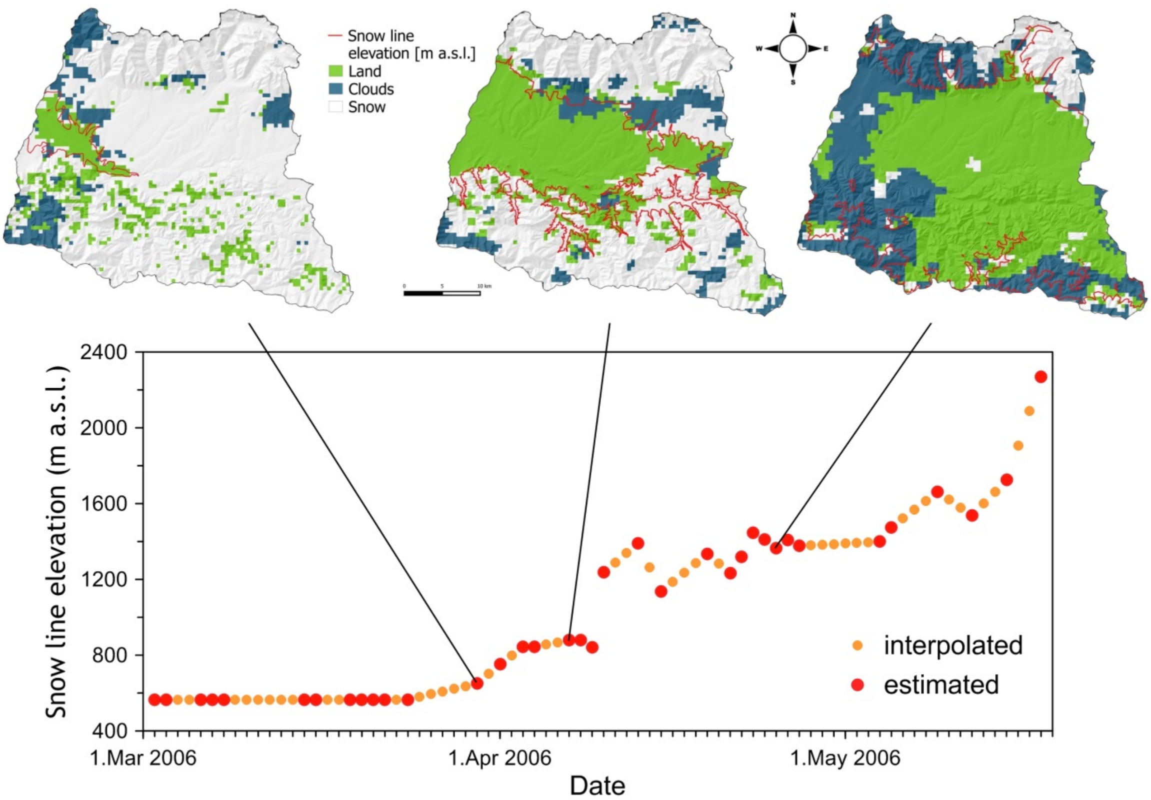

Fig. 1. Estimation of snow line (SL) elevation for Váh/Liptovský Mikuláš basin in spring 2006. Points represent estimated and interpolated SL elevation, respectively. SL is interpolated for days with cloud coverage larger than 70%.

STUDY AREA AND DATA

In this study, Slovakia is divided into ten main river basins: Lower Váh/Danube, Myjava/Rudava, Nitra, Bodrog /Uh, Ipeľ, Slaná, Hornád, Hron, Upper Váh and Poprad according to Majerčáková (2002). Part of the Váh and Uh River basins is situated outside of Slovakia, so the analyses presented here consider only Slovak parts of these rivers. The delineation of the main river basins is based the actual basin boundaries, with an exception of splitting the Váh River basin into the Upper and Lower parts. Splitting the Váh River and combining the Lower Váh with small Danube tributaries allows a more uniform representation of the runoff regime in the lowland part of Slovakia. Figure 2 shows location of the basins and indicate their runoff regime type. All river basins are affected by snowmelt and represent three runoff regimes defined by Šimo and Zaťko, 2002: (a) temporary snow regime in high mountains; (b) snow-rain regime in middle mountains and (c) rain-snow regime in lowlands.

Table 1 summarizes the main basin characteristics. Size of the basins ranges from 1966 km^2 (Poprad) to 9421 km^2 (Upper Váh), mean elevation varies from 154 m a.s.l. (Lower Váh/Danube) to 852 m a.s.l. (Poprad). There are no glaciers in Slovakia. The seasonal snow cover entirely melts by summer except a few firn fields in highest parts of the High Tatra Mountains in northern Slovakia.

The snow cover data are obtained from MODIS Terra and Aqua satellites. These datasets are available since 2000. For analyses, we use the daily snow cover products (MOD10A1 (V005), MYD10A1 (V005), Hall et al., 2006). The images were downloaded from the NSIDC data center and reprojected to the JTSK projection by using MRT tool. In order to reduce the effects of clouds, both products were merged by using methodology presented in Parajka and Blöschl (2008b). The final combined gridded maps show three classes (snow cover, land, clouds) in spatial resolution of 500 m. The variability in snow cover characteristics is evaluated for winters in the period 2000–2014. Seasonal snow cover is typically present in different parts of Slovakia between November and May. The winter period is thus defined between these months.

Snow line elevation and hypsometeric curves of the basins are derived from a digital elevation model (DEM) with spatial resolution of 500 m. This DEM is resampled from original 10m DEM of Slovakia. The 500 m resolution is selected to represent the spatial resolution of MODIS snow cover maps.

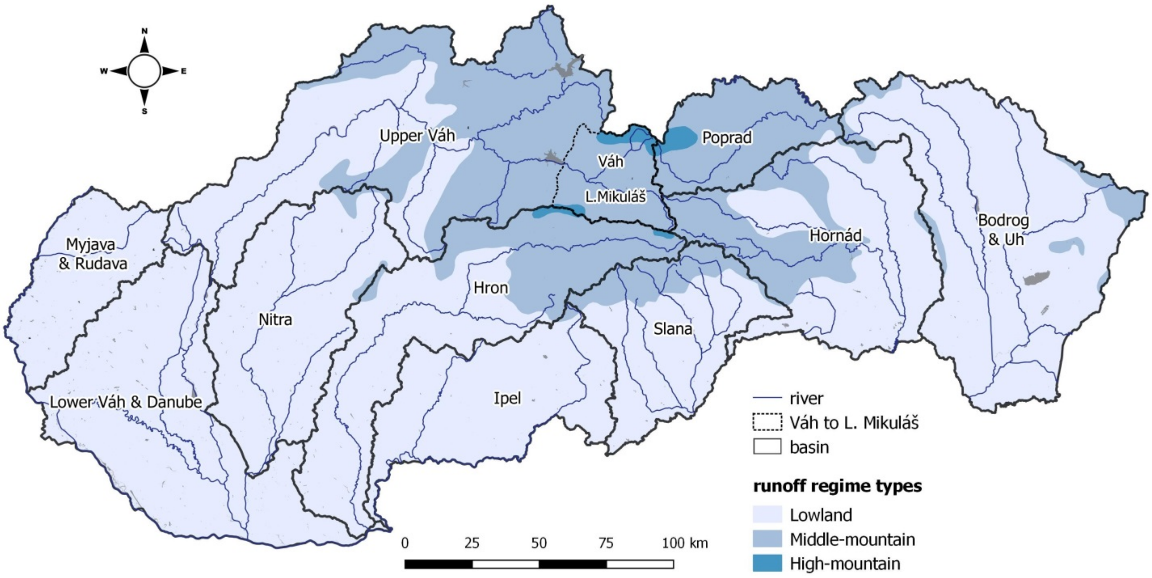

Fig. 2. Location of main Slovak basins and type of runoff regime. Dashed line indicates Váh to Liptovský Mikuláš basin, where the regional snow line method has been evaluated (for more details see Krajči et al., 2014).

Table 1. Elevation (m a.s.l.) and size (km^2) of the main Slovak basins. Elevation is estimated from a digital elevation model of 500 m spatial resolution.

Basin	Size	Min. elevation	Max. elevation	Mean elevation
Lower Váh/Danube	5985	102	699	154
Myjava/Rudava	2264	136	693	244
Bodrog/Uh	7269	74	1118	311
Nitra	4490	108	1288	312
Ipeľ	3650	105	1084	349
Slaná	3208	150	1448	458
Hornád	5325	159	1846	537
Hron	5463	105	1928	550
Upper Váh	9421	160	2270	704
Poprad	1966	398	2429	852

RESULTS
Snow line (SL) elevation

Seasonal variability of snow line elevation in the main Slovak basins is presented in Figure 3. While whiskers show the 10% and 90% percentiles, the box shows the 25%, 75% percentiles and median of SL elevation in different months. The blue area shows the hypsometric curve of each basin derived from DEM. The results indicate that the lowest SL elevation and hence the largest snow coverage occurs in all basins in January and February. There are, however, differences between the basins in terms of the number of days the SL elevation is below the mean basin elevation. In Poprad and Upper Váh basins, the SL occurs below the mean basin elevation in more than 50% of days in the period December to February. In these basins, the SL has the largest variability within the winter period, particularly in November and April, when most of the investigated basins are without snow cover for most of the time. Contrary, in the Lower Váh/Danube, Myjava/Rudava, Ipeľ, Nitra and Slaná and basins, the median SL is above the mean basin elevation in the entire winter season. Here, the seasonal variability in the SL is the smallest, but the median SL is situated at elevations which represents less than 20% (Myjava/Rudava) and 40% (Ipeľ, Slaná) of the basin area. In Lower Váh/Danube basin, the median SL is situated in elevations which represent less than 5% of basin area. Hron, Bodrog/Uh and Hornád basins have

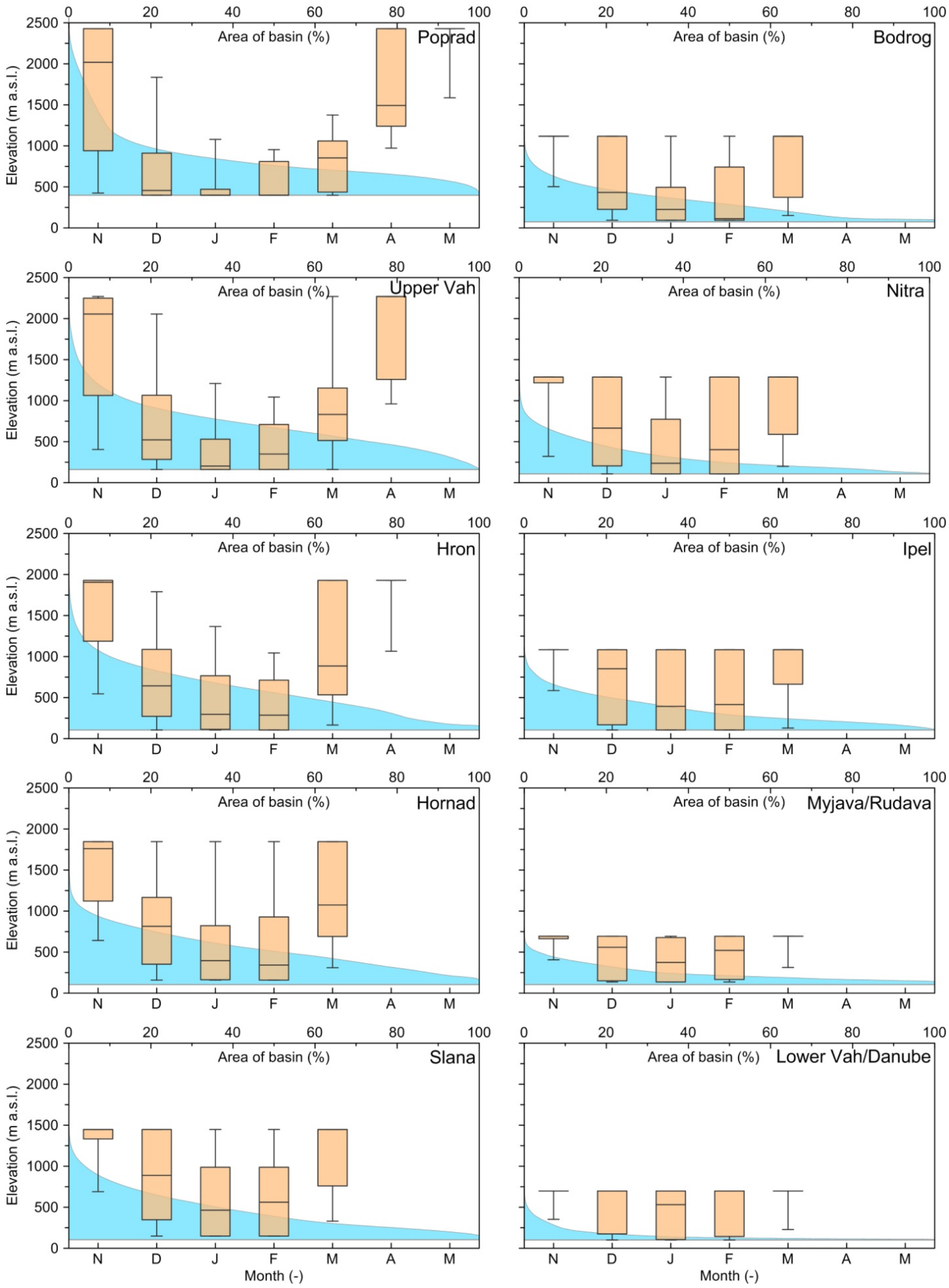

Fig. 3. Seasonal variability (November to May) of snow line elevation in main Slovak basins in the period 2001–2014. Box-whisker plots represent 10%, 25%, 50%, 75% and 90% percentiles of snow line elevation. Blue area represents hypsometric curve of the basin.

the median of SL below the mean basin elevation in January and February and 50% days in December is at least 20% of area covered by snow. Inter-annual variability of SL elevation is presented in Fig. 4. In order to more clearly exhibit differences between the basins and snow poor and rich winters, box-whiskers plots (Fig. 4) show the SL variability in January and February only. Results of Fig. 4 indicate that the snow richest winters are 2003, 2005, 2006 and 2013 and winters in 2001, 2002, 2007, 2008, 2010, 2011, 2014 are characterized by large median value of SL elevation, so are classified as snow poor. The lowest SL values in the period 2001–2014, i.e. the snow-richest winters, occur in 2003, 2006 and 2013. The highest SL values in individual basins, i.e. the snow-poorest winters occurred in different winters (in 2007 or 2014).

Figures 3 and 4 indicate that there is a considerable difference in the SL elevations between the basins. Three groups of basins are identified in Slovakia according to similar SL regime. The first group includes Poprad, Upper Váh, Hron and Hornád which have considerable parts of the basin above 1000 m a.s.l. and the highest elevations exceed 1500 m a.s.l. Winter median SL in these basins is equal or close to minimum elevation in snow rich winters. Even in snow poor winters have

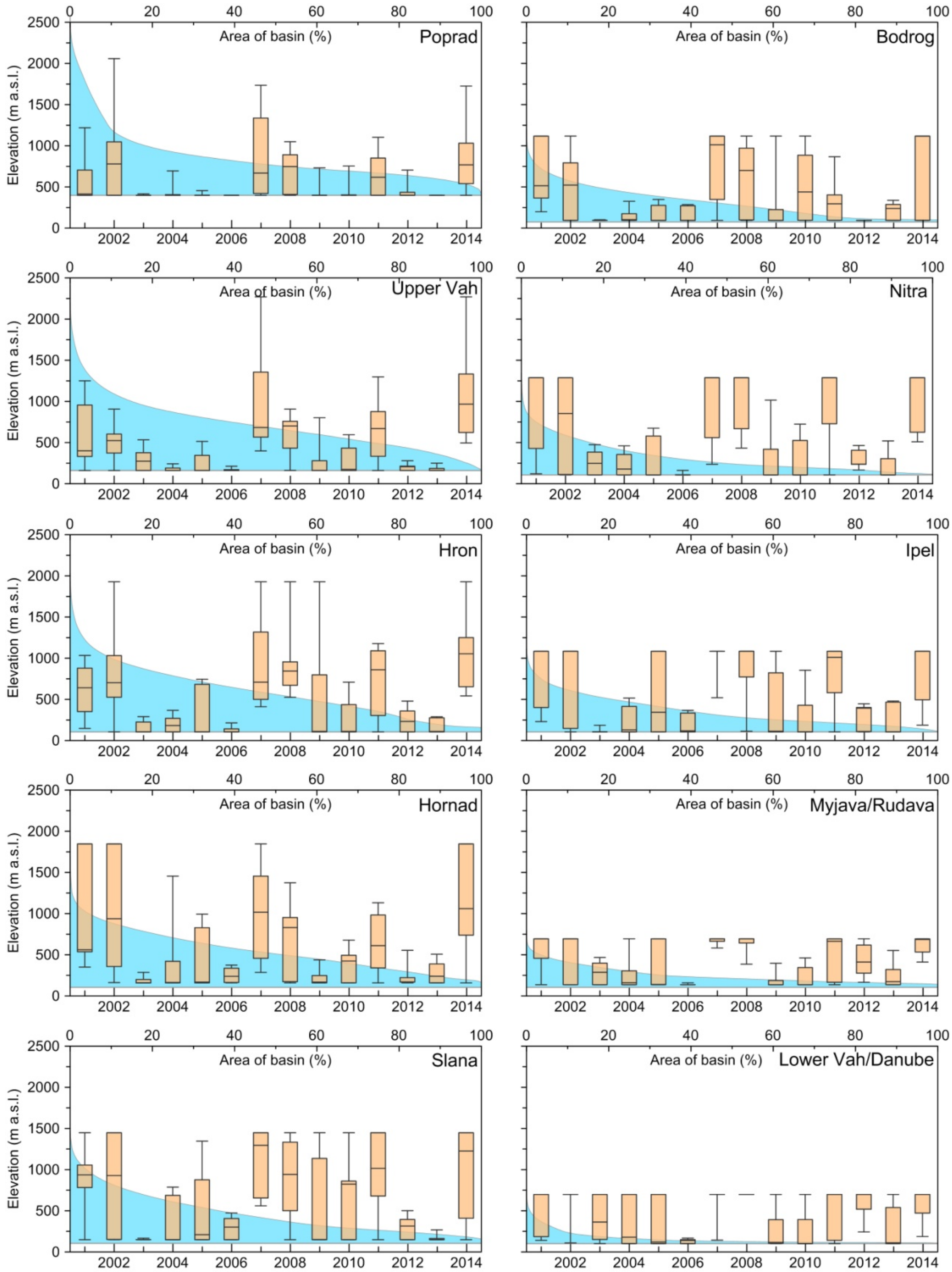

Fig. 4. Inter-annual variability in snow line elevation in main Slovak basins in January and February. Box-whisker plots represent 10%, 25%, 50%, 75% and 90% percentiles of snow line elevation. Blue area represents hypsometric curve of the basin.

Poprad, Upper Váh and Hron the SL close to the mean basin elevation. Larger snow cover strongly reflects in the dominant rain-snow runoff regime with highest flows in May and June (Šimo and Zaťko, 2002).

Second group of basins consists of mid-altitude basins with maximum elevation around 1000 m a.s.l. (Slaná, Ipeľ, Nitra, Bodrog). Median SL varies between 150 and 550 m a.s.l. in January and February, which represents approximately 40–80% snow coverage. Median SL value during the snow poor winters is at maximum basin elevation. This means that in such winters are basins snow free approximately 50% of days in January and February. Dominant runoff regime in these middle-mountain basins is rain-snow combined with distinct secondary increase of runoff at the end of the autumn (Šimo and Zaťko, 2002).

The third group of basins includes the Rudava/Myjava and Lower Váh/Danube. These basins have their maximum altitude only less than 700 m a.s.l. Only a small percentage of the Lower Váh/ Danube basin area is covered with snow for half of the season even during the snow rich winters. The Danube and Morava Rivers have their origin outside of Slovakia, mountain parts of these basins were not studied in this work. However, their runoff regime is influenced by the mountains located outside of Slovakia. Therefore, they exhibit the snow-rain combined, temporary snow and rain-snow combined regimes (Šimo and Zaťko, 2002).

Snow cover area (SCA)

Figure 5 shows the seasonal distribution of SCA in the main Slovak basins. The snow coverage typically starts in December and last to February. In the highest basins (Poprad, Upper Váh), the snow season sometimes tends to start earlier (November)

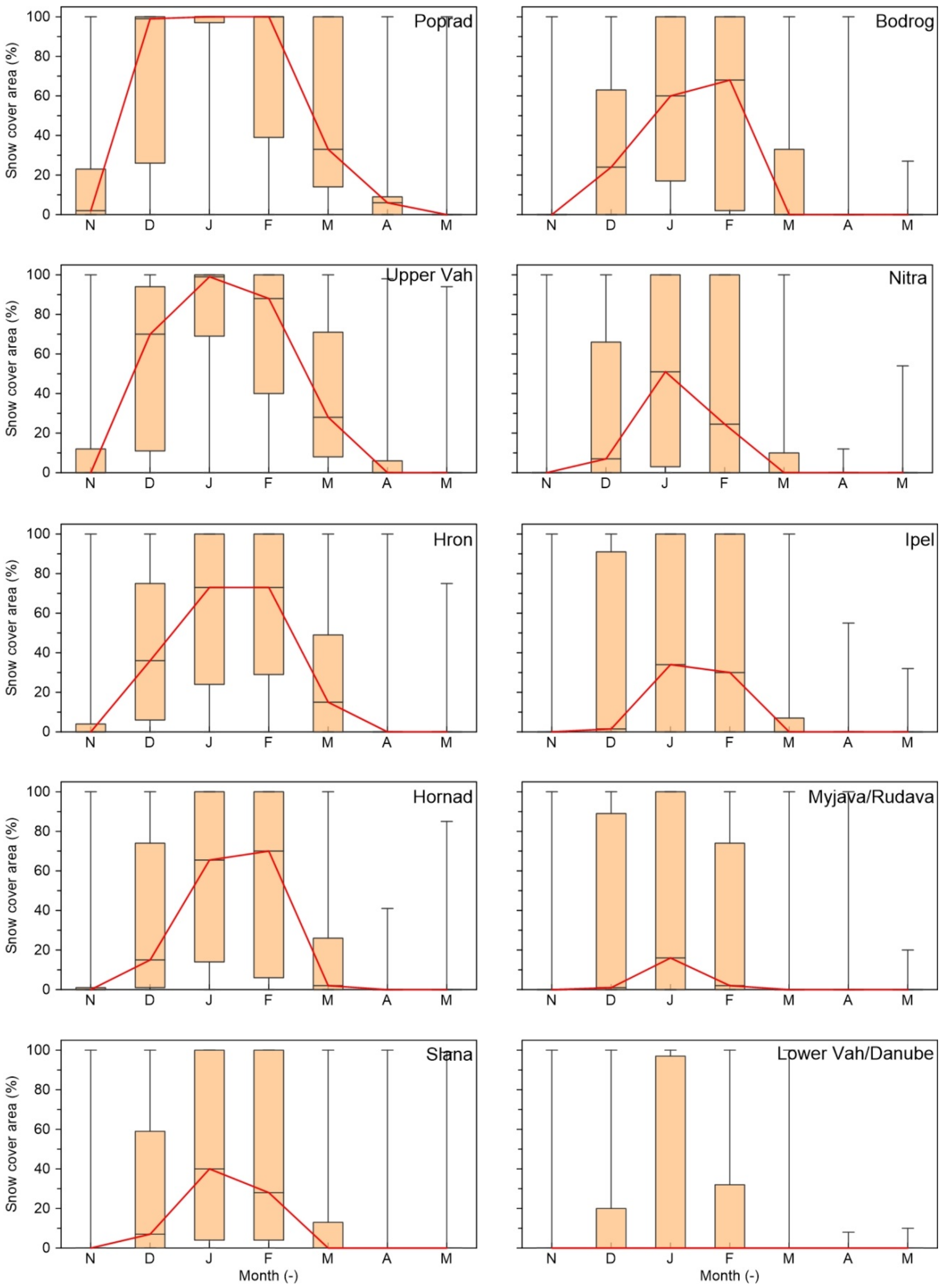

Fig. 5. Seasonal variability of snow cover area (SCA, %) in main Slovak basins. The whiskers show 10% and 90% percentiles, box plots show 25% and 75% percentiles, the line connects the median of SCA for particular months.

and lasts to March/April. The median of SCA in November and April is, however, less than 10% in these basins. The lowest basins (Lower Váh, Myjava/Rudava) are not significantly covered with snow in the winter period. The median of SCA exceeds 10% in Myjava/Rudava basin only in January. The lowest SL elevation in January and February translates into the largest SCA values in all basins. The median SCA is above 70% in the highest basins (Poprad, Upper Váh, Hron) and varies between 25–70% in the mid-altitude basins (Slaná, Ipeľ, Nitra, Bodrog) in January and February. However, there is a considerable variability in seasonal coverage between the years. The SCA variability between years increases with decreasing mean elevation of the basins. For example, while Poprad basin is fully snow covered almost every January, the mean daily SCA varies between 30%–100% in Hron and it is between snow free and snow covered in lower basins. In November, December, March, the basins can be without significant snow cover even in the highest basins.

Inter-annual variability of the mean winter SCA is presented in Figure 6. It is calculated as the mean of all daily SCA values in the winter period. The largest mean SCA is observed in almost all basins in 2006. The exception is the Hornád and Slaná, where is the largest SCA observed in 2013. It ranges between more than 50% in the highest to more than 28% in the lowest basins. In snow poor winters (i.e. 2007, 2014) it decreases to less than 30% in Poprad and Upper Váh and less than 10% in Ipeľ, Myjava/Rudava and Lower Váh/Danube basins. The mean SCA in 2006 is 2 (Poprad) to more than 10 times (Myjava/Rudava and Lower Váh/Danube) larger than in 2014. Interestingly, there is no significant trend in mean SCA in the period 2001–2014, however periods (several winter seasons) with larger and smaller SCA exist. The blue line in Figure 6

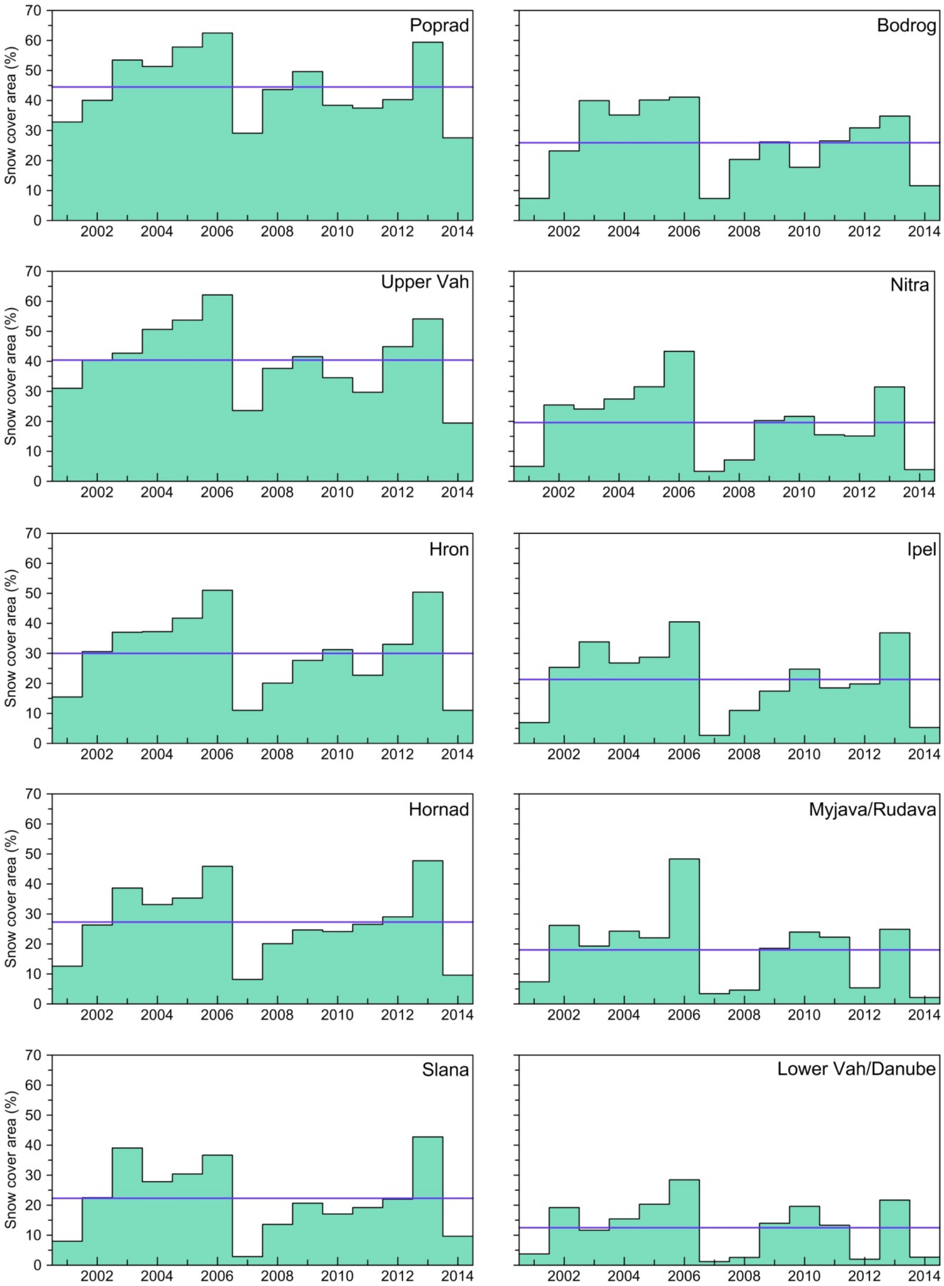

Fig. 6. Inter-annual variability of mean winter (November-May) snow cover area (SCA, %) in main Slovak basins; the line represents the mean calculated for period 2001–2014.

Table 2. Number of days with at least 50% snow cover area (SCA) in the winter period (November–May); the yellow cells indicate the snow-poorest and blue indicates snow-richest winters in individual basins.

Winter period	L. Váh/ Danube	Myjava/Rudava	Nitra	Bodrog/ Uh	Ipeľ	Slaná	Hornád	Hron	Upper Váh	Poprad
2001	6	14	8	13	9	10	22	31	62	64
2002	38	53	49	50	50	41	54	58	80	67
2003	22	35	44	81	69	81	82	80	89	107
2004	30	50	55	83	50	53	71	89	112	108
2005	43	47	61	88	59	61	73	82	121	123
2006	50	105	88	88	80	81	103	112	133	132
2007	1	6	4	15	2	1	15	13	35	48
2008	3	5	8	43	21	20	38	26	82	81
2009	26	39	41	61	34	39	54	46	91	103
2010	39	49	46	36	48	33	54	63	69	75
2011	24	49	31	52	36	37	57	43	61	79
2012	3	6	28	61	31	50	61	79	98	83
2013	43	49	58	72	70	88	111	112	122	126
2014	4	2	4	26	8	15	14	18	42	55

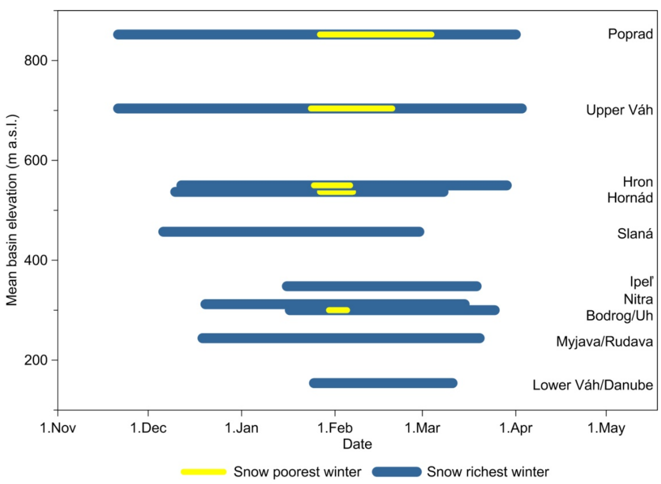

Fig. 7. Duration of period with SCA exceeding 50% and at least 3 days in a row (without interruption) of the basins in the snow richest and snow poorest winter in the period 2001–2014. In some of the basins, SCA over 50% didn't exceed 3 days, that is why there isn't snow poorest winter indicated. Table 2 indicates, which winter is snow poor and rich in the main Slovak basins.

shows the long-term mean winter SCA and it is clear that winters in the period 2002–2006 have noticeably larger mean SCA than in the period 2007–2012. This translates into significantly shorter periods with at least 50% snow coverage of the basins (Table 2). Particularly in lower and mid-altitude basins, the number of days with at least 50% SCA is two times larger in the period 2002–2006 than in 2007–2012. In the high elevation basins (Poprad, Upper Váh), these number of days increases in about 20–30%. The differences are even larger between the snow rich and poor winters (Figure 7). For example 50% of Upper Váh is covered with snow for 133 days 2006, which represents more than one third of the year. This period is long enough to have a significant impact on hydrological regime of the river and determines the time and magnitude of spring peak discharges. While at least three months of snow coverage larger than 50% (i.e. 90 days) is quite typical in the highest basins (Poprad, Upper Váh), there are several winters with less than 15 days in the lowest basins. Interestingly, the duration of the snow richest winter is not always determined by the mean elevation of the basins. The snow richest winter in Myjava/Rudava basin (in 2006) has longer duration than Bodrog, Nitra and Ipeľ, which are basins with higher mean elevation.

Snow cover depletion (SCD)

Snow depletion curves (SDC) in most winters do not have a simple evolution. Depletion of the snow cover is typically interrupted by temporary increases of the SCA. In fact, relatively uninterrupted SDCs have been found in all basins only in winter 2005. The SDC tends to start later and lasts longer in basins with higher mean elevation. Interestingly, the variability in SDC between the winters is much larger than between the basins. The SDC of analyzed winters starts between beginning of February to the end of March and on average lasts between eight days in lowlands to approximately 30 days in the highest mountains (Poprad). Figure 8 presents examples of SDC for the snow rich (2006) and poor (2014) winter. Snow depletion in Poprad basin starts the latest (March, 27) in 2006 and lasts more than three weeks. In the Upper Váh basin, the SDC starts six days earlier and also lasts six days shorter than in Poprad basin. Interestingly, there are two pairs of basins (Hron and Bodrog/Uh, Hornád and Nitra) with quite similar SDC that belong to different groups of basins. They start differently, but last approximately to the April, 1 in all four basins in 2006. The SDC in the lowest basins starts around March, 7, but in Myjava/Rudava basin snowmelt occur more than 10 days earlier than in Lower Váh/Danube basin. SDCs in 2014 are different. SDC is typically shorter than 10 days and less than 7 days in the highest and mid-altitude basins, respectively. The exceptions are Slaná and Hron basins where SDC lasts 12 and 23 days, respectively, however a significant decrease of SCA (more than 70%) is observed in less than 5 days. In the lowland basins, there are several episodes of short (i.e. less than 5 days) snow cover and snow cover appears and melts very quickly.

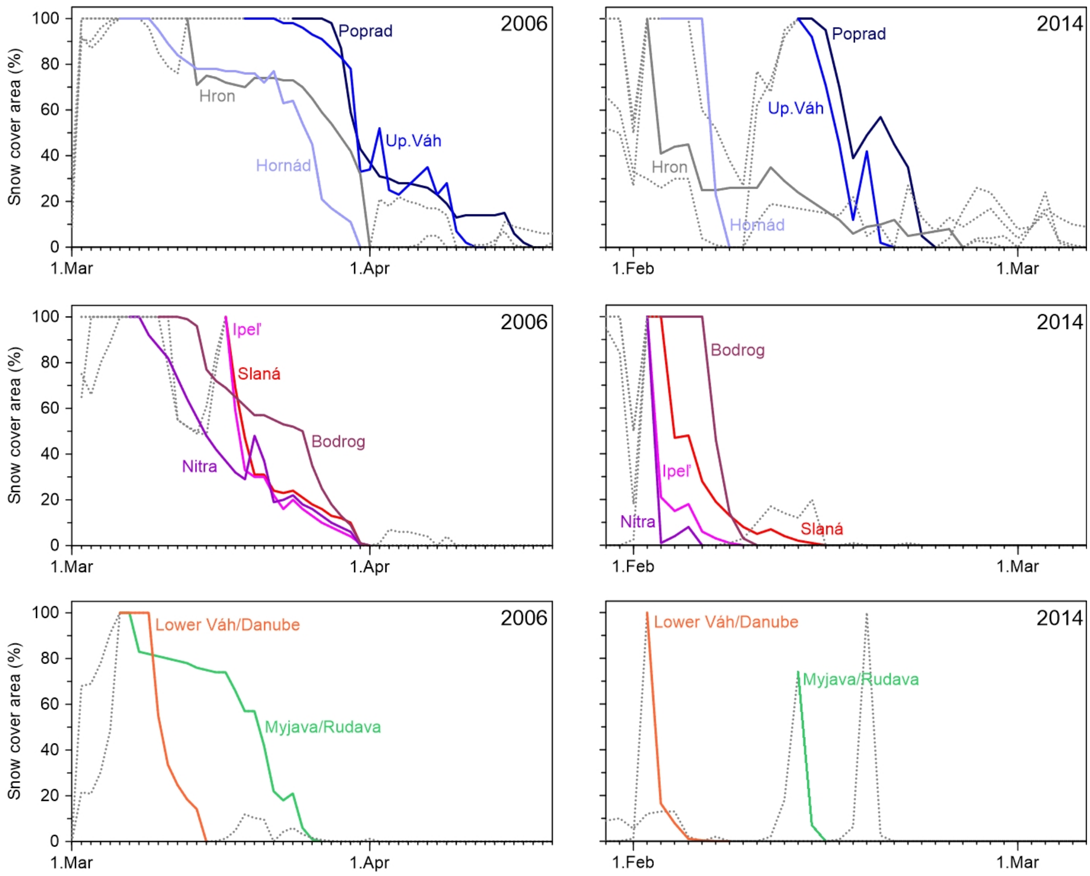

Fig. 8. Snow depletion curves in the main Slovak basins in snow rich (2006, left panels) and poor (2014, right panels) winter. Thick lines indicate main snow depletion curve of selected winter, dotted lines show the entire change in snow cover area in selected periods and basins.

DISCUSSION AND CONCLUSIONS

This study evaluates the variability in snow line elevation, snow cover area and snow depletion curves in the main Slovak basins. In comparison to previous assessments based on station data or interpolated point snow depth measurements, it examines, for the first time, daily snow cover patterns observed by MODIS satellite for the entire basins. The main advantage of satellite data is that they provide spatial snow cover patterns at high spatial resolution and accuracy (Parajka and Blöschl, 2006). Previous assessments have evaluated duration of snow cover at selected climate stations or elevation zones. When we compare our results with trend assessment of Lapin et al. (2007), we see similar temporal patterns. Lapin et al. (2007) evaluated changes in the number of days with snow at five stations in Tatra Mountains in the period 1921–2006, and showed an increase of days with snow in the period 2001–2006. Our results also indicate an increase of mean snow cover area in that period, however a significantly lower snow cover area is observed in the next period 2007–2012. These results indicate that there is no significant change in the mean basin snow cover area in the period 2001–2014, but periods of snow rich and snow poor winter do exist, particularly in the mountain basins.

Results of the mean index of scatter analysis (i.e. variability around the snow line, Krajčí et al., 2014) show values between 3.4% in lowland and 12.2% in mountain basins, which is comparable or even less than found in Krajčí et al. (2014).

The comparison of snow rich and poor winters has demonstrated significant differences in the snow cover area, start and duration of snow cover depletion in the main Slovak basins. Winter 2006 represents snow rich winter with long snow cover depletion. This winter was reported by Dietz et al. (2012) as an exceptionally cold winter with an extraordinary long snow cover duration, particularly in Central Europe. Snow melt between late February and early April led to floods in large river basins of Danube and Elbe. Our results show that this winter has the largest number of days with at least 50% basin coverage and also the largest mean annual snow cover area in almost all basins (except Slaná and Hornád). The length of snow cover depletion, however, differs between the basins and winters. On average, we found that the snow cover depletion increases 1.4 days per 100 m of mean basin elevation. The longest snow cover depletion is 2 to 4 times longer than the mean.

Obviously, snow cover area and duration increases with increasing mean basin elevation. The differences between the eastern and western part of Slovakia due to increased effect of continentality are seen only in some winters. For example, if we compare Nitra and Bodrog, which are basins with similar mean elevation, the significant differences in mean snow cover area or snow cover duration are observed in winters 2003, 2008, 2012 or 2014. On average, mean winter snow cover area and duration of snow cover in Bodrog is 6% and 17 days larger than in Nitra basin, respectively. The patterns and duration of snow cover depletion are, however, not related to the mean snow cover area. The mean snow cover depletion is two days longer in Nitra (12 days) than in Bodrog (10 days) basin.

Our analysis focuses on the main Slovak basin. These basins are quite large and do not allow to investigate the other effects (such as orographic effects, orientation of the basin, effect of vegetation) that might control the spatio-temporal evolution of snow cover at smaller spatial scale. In the future we plan to extend the analysis to smaller basins. Our plan for the future is not only to evaluate the snow cover changes but also to investigate the link between snow cover characteristics and snowmelt induced runoff.

Acknowledgements. This work was supported by grant VEGA 2/0055/15 and OeAD (Austrian Agency for International Cooperation in Education and Research) Action Slovakia-Austria Ernst Mach grant (ICM-2014-09039) financed by the Austrian Federal Ministry of Science, Research and Economy (BMWFW). We would also like to thank the Austria Science Funds (FWF) as part of the Vienna Doctoral Programme on Water Resource Systems (DK-plus W1219-N22) and FWF Project for financial support. Support from the European Research Council under the ERC Advanced Grant ''Flood Change'', project no. 291152, is also gratefully acknowledged.

REFERENCES

Day, A.C., 2013. Modeling snowmelt runoff response to climate change in the Animas River Basin, Colorado. J. Geol. Geosci., 2, 110.

Dietz, A.J., Wohner, Ch., Kuenzer, C., 2012. European snow cover characteristics between 2000 and 2011 derived from improved Modis daily snow cover products. Remote Sensing, 4, 2432–2454.

Foppa, N., Seiz, G., 2012. Inter-annual variations of snow days over Switzerland from 2000–2010 derived from MODIS satellite data. Cryosphere, 6, 331–342.

Franz, K.J., Karsten, L.R., 2013. Calibration of a distributed snow model using MODIS snow covered area data. Journal of Hydrology, 494, 160–175.

Georgievsky, M.V., 2009. Application of the Snowmelt Runoff model in the Kuban river basin using MODIS satellite images. Environmental Research Letters, 4, 1–5.

Gascoin, S., Hagolle, O., Huc, M., Jarlan, L., Dejoux, J.-F., Szczypta, C., Marti, R., Sánchez, R., 2015. A snow cover climatology for the Pyrenees from MODIS snow products. Hydrology and Earth System Sciences, 19, 2337–2351.

Hall, D.K., Riggs, G.A., Salomonson, V.V., 2006. MODIS snow and sea ice products. In: Qu, J.J., Gao, W., Kafatos, M., Murphy, R.E., Salomonson, V.V. (Eds.): Earth Science Satellite Remote Sensing - Volume I: Science and Instruments. Springer, New York, pp. 154–181.

Hall, J., Arheimer, B., Borga, M., Brázdil, R., Claps, P., Kiss, A., Kjeldsen, T.R., Kriauciuniene, J., Kundzewicz, Z.W., Lang, M., Llasat, M.C., Macdonald, N., McIntyre, N., Mediero, L., Merz, B., Merz, R., Molnar, P., Montanari, A., Neuhold, C., Parajka, J., Perdigão, R. A.P., Plavcová, L., Rogger, M., Salinas, J.L., Sauquet, E., Schär, C., Szolgay, J., Viglione, A., Blöschl, G., 2014. Understanding flood regime changes in Europe: A state of the art assessment. Hydrology and Earth System Sciences, 18, 2735–2772.

He, Z.H., Parajka, J., Tian, F.Q., Blöschl, G., 2014. Estimating degree-day factors from MODIS for snowmelt runoff modeling. Hydrology and Earth System Sciences, 18, 4773–4789.

Holko, L., Gorbachova, L., Kostka, Z., 2011. Snow hydrology in Central Europe. Geography Compass, 5, 4, 200–218.

Jain, S.K., 2011. Depletion of snow cover. In: Encyclopedia of Snow, Ice and Glaciers. Springer, Dordrecht, pp. 200–201.

Krajčí, P., Holko, L., Perdigão, R.A.P., Parajka, J., 2014. Estimation of regional snowline elevation (RSLE) from MODIS images for seasonally snow covered mountain basins. Journal of Hydrology, 519, Part B, 1769–1778.

Lapin, M. Faško, P., Pecho, J., 2007. Snow cover variability and trends in the Tatra Mountains in 1921–2006. In: Ducrocq, V. (Ed.): Proceedings of the 29th International Conference on Alpine Meteorology, Chambery, France. Météo France, Chambery, pp. 683–686.

Liang, T.G., Huang, X.D., Wu, C.X., Liu, X.Y., Li, W.L., Z.G., Guo, Z.G., Ren, J.Z., 2008. An application of MODIS data to snow cover monitoring in a pastoral area: A case study in Northern Xinjiang, China. Remote Sensing of Environment, 112, 1514–1526.

Liston, G.E., 1999. Interrelationships among snow distribution, snowmelt, and snow cover depletion: implications for atmospheric, hydrologic, and ecologic modeling. Journal of Applied Meteorology, 38, 1474–1487.

Li, X., Williams, M.W., 2008. Snowmelt runoff modelling in an arid mountain watershed, Tarim Basin, China. Hydrol. Process., 22, 3931–3940.

Ma, Y., Huang, Y., Chen, X., Li, Y., Bao, A., 2013. Modelling Snowmelt Runoff under Climate Change Scenarios in an Ungauged Mountainous Watershed, Northwest China. Mathematical Problems in Engineering, 9 p.

Majerčáková, O., 2002. Basins of the main rivers with water balance. 1:2 000 000. Atlas krajiny Slovenskej republiky. Bratislava : Ministerstvo životného prostredia SR, 103 p. (In Slovak.)

Mishra, B., Babel, M.S., Tripathi, N.K., 2013. Analysis of climatic variability and snow cover in the Kaligandaki River Basin, Himalaya, Nepal. Theoretical and Applied Climatology, 116, 681–694.

Nester, T., Kirnbauer, R., Parajka, J., Blöschl, G., 2012. Evaluating the snow component of a flood forecasting model. Hydrology Research, 43, 762–779.

Parajka, J., Blösch, G., 2006. Validation of MODIS snow cover images over Austria. Hydrology and Earth System Sciences, 10, 679–689, DOI: 10.5194/hess-10-679-2006

Parajka, J., Blöschl, G., 2008a. The value of MODIS snow cover data in validating and calibrating conceptual hydrologic models. Journal of Hydrology, 358, 3–4, 240–258.

Parajka, J., Blösch, G., 2008b. Spatio-temporal combination of MODIS images – potential for snow cover mapping. Water Resour. Res., 44, W03406, DOI: 10.1029/2007WR006204.

Parajka, J, Pepe, M., Rampini, A., Rossi, S., Blöschl, G., 2010. A regional snow line method for estimating snow cover from MODIS during cloud cover. Journal of Hydrology, 381, 203–212.

Parajka, J., Blöschl, G., 2012. MODIS-based snow cover products, validation, and hydrologic applications. In: Chang, N.-B. (Ed.): Multiscale Hydrologic Remote Sensing: Perspectives and Applications. Chapter 9. CRC Press, Boca Raton, FL, pp. 185–212.

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, 16, 2365–2377.

Pepin, N., Bradley, R.S., Diaz, H.F., Baraer, M., Caceres, E.B., Forsythe, N., Fowler, H., Greenwood, G., Hashmi, M.Z., Liu, X.D., Miller, J.R., Ning, L., Ohmura, A., Palazzi, E., Rangwala, I. , Schöner, W., Severskiy, I., Shahgedanova, M., Wang, M.B., Williamson, S.N., Yang., D.Q., 2015. Elevation-dependent warming in mountain regions of the world. Nature Climate Change, 5, 424–430.

Seidel, K., Martinec, J., 2004. Remote Sensing in Snow Hydrology: Runoff Modelling, Effect of Climate Change. Springer Science & Business Media, Chichester, 150 p.

Šamaj, F., Brázdil, R., Dobrovolný, P., Faško, P., Košťálová, J., Valovič, Š., 1991. Variabilita charakteristik sněhových poměrů v karpatské části ČSFR v období 1920/21–1984/85.

[Variability of snow cover characteristics in Carpathian part of CSFR, in period 1920/21–1984/85]. In: Zborník prác Slovenského hydrometeorologického ústavu, zväzok 34, SHMÚ Bratislava, 176 p. (In Slovak.)
Šamaj, F., Valovič, Š., 1988. Snehové pomery na Slovensku. [Snow conditions in Slovakia]. ALFA, Bratislava, 128 p. (In Slovak.)
Šimo, E., Zaťko, M., 2002. Types of runoff regime 1:2 000 000. In: Atlas krajiny Slovenskej republiky. Ministerstvo životného prostredia SR, Bratislava, 103 p.
Tang, Z., Wang, J., Li, H., Yan, L., 2013. Spatiotemporal changes of snow cover over the Tibetan plateau based on cloud-removed moderate resolution imaging spectroradiometer fractional snow cover product from 2001 to 2011. J. of Applied Remote Sensing, 7, DOI: 10.1117/1.JRS.7.073582
Tekeli, A.E., Akyürek, Z., Şorman, A.A., Şensoy, A., Şorman, A.Ü., 2005. Using MODIS snow cover maps in modeling snowmelt runoff process in the eastern part of Turkey. Remote Sensing of Environment, 97, 216–30.
Wang, X., Xie, H., 2009. New methods for studying the spatiotemporal variation of snow cover based on combination products of MODIS Terra and Aqua. Journal of Hydrology, 371, 1–4.

Received 23 July 2015
Accepted 28 November 2015

Note: Colour version of Figures and Table 2 can be found in the web version of this article.