Hydrology of the High Tatra Mountains and the influence of the windfall in November 2004 on hydrological regime of the upper Poprad river catchment

1L. Holko, 1Z. Kostka, 2J. Novák

1Institute of Hydrology, Slovak Academy of Sciences, Liptovský Mikuláš, Slovakia, holko@uh.savba.sk;
2Slovak Hydrometeorological Institute, Košice, Slovakia

Abstract
Slovakia as a mountainous country is sometimes called the roof of central Europe, because most of precipitation runs off from the country. The highest part of the Carpathians (the largest mountain range in Europe) is situated in the Tatra Mountains (The Western, High and Belianske Tatra mountains) which form part of the European water divide. Most of Slovakia is drained to the Black Sea basin. Just two bigger Slovak rivers flow to the Baltic Sea. The bigger of them, the Poprad river originates in the High Tatra Mountains. The High Tatra Mountains were hit by an extraordinary windfall on 19 November 2004. This paper provides a brief information on the history of hydrological and meteorological measurements on the territory of the High Tatra Mountains and reports on the analyses of hydrological impacts of the windfall. Despite the extraordinary extent of deforestation, hydrological data did not indicate severe changes of runoff regime in the upper Poprad river catchment and its subcatchments. However, compared to other Slovak rivers, the streams of the upper Poprad river subcatchments have higher flashiness index, probably owing to higher percentage of agricultural lands.

Introduction
The High Tatra Mountains are the highest part of the Carpathian Mountains which are according to some sources (e.g. Wikipedia) the largest European mountain range. Hydrological importance of the Tatra Mountains (i.e. the Western, High and the Belianske Tatra Mountains) was highlighted, e.g. by Molnár and Pacl (1988). Although they cover just 3% of the territory of Slovakia, their contribution to runoff is 3 times higher, i.e. 9%. Since the area is part of the Tatra National Park, the oldest national park on the territory of Slovakia, forest management was very restricted in the last decades. As a result, the areal extent of forests on the territory of the national park significantly increased since the 1950’. Topographic conditions enhance the occurrence of strong falling winds in the Tatra Mountains. They cause regular windfalls. However, an extraordinary falling wind which occurred on 19 November 2004 caused the largest historically documented deforestation on the territory of the High Tatra Mountains. Among other questions, it raised also the question on the impacts of deforestation on hydrological regime of the upper Poprad river basin.

The objective of this paper is to provide a brief information on the history of hydrological and meteorological measurements in the area of the Tatra Mountains and report on the analyses of hydrological impacts of the extraordinary windfall which occurred in the area on 19 November 2004.
Hydrological and meteorological observations on the territory of the Tatra Mountains

According to Pacl (1973) the first descriptive hydrographic works from the territory of the Tatra Mountains are known from the 17th century. They were focused more on the lakes, than on rivers. Just the big flood in 1813 described by Swedish botanist G. Wahlenberg who was at that time in the Tatra Mountains resulted in deeper interest in rivers. Hydrographic service on the territory of present Slovakia was established in the second half of the 19th century. The first gage in the area of the Tatra Mountains (the Studený creek/the Oravský Biely creek) was installed in 1920. The gage on the Poprad river at Matejovce was installed in 1921. Since 1922 and 1924 there are gages on the Biely Váh river at Východná and the Belá river at Podbanské, respectively. Other 10 gages were built until 1938. The network was extended in 1940-44 by 8 gages and in 1946-1960 by other 7 gages (all above information by Pacl, 1973). Pekárová et al. (2007, 2009) recently extended the annual runoff data series from the Belá river by regression analysis back to the year of 1895 (Fig. 1).

Most of the above gages became part of the national observation network maintained by the Slovak Hydrometeorological Institute. Except that, a lot of other monitoring was performed by different institutes. For example, the Belá river catchment was included among the representative basins of UNESCO in framework of International Hydrological Decade (1965-1974); Pekárová et al., 2009. Systematic research of hydrological cycle in the mountains is performed since the end of the 1980' in the Jalovecký creek catchment in the Western Tatra Mountains (e.g. Holko and Kostka, 2009). A lot of monitoring connected with hydrological cycle, e.g. precipitation, snow or interception measurements has been performed also by the Research Station of the Tatra National Park.

The overview of the history of meteorological measurements in the Tatra Mountains was published by Šamaj (1973). He stated that the first meteorological measurements (air temperature) were made in the 1720'. The oldest preserved observations are from the years 1789-1800. Systematic measurements are archived since 1873. Meteorological measurements in Starý Smokovec started in 1875. Similar meteorological station was established in 1881 in Liptovský Hrádok. Other stations in Tatranská Lomnica, Poprad and Štrbské Pleso were established at the turn of the 19th and 20th centuries. The network was substantially developed in the 1920' when about 15 new stations started to operate. Important high mountain stations were established between 1936 and 1940 at the Kasprový Wierch (Poland), the Skalnaté Pleso lake and at the Lomnický štít mountain. Other 15 stations were built until 1950. Majority of the stations were situated in the Poprad river catchment which drains the High Tatra Mountains whereas the Western Tatra Mountains had very few observations.

Otruba (1973) provided interesting information regarding the occurrence of windfalls. Except other wind characteristics, he has described also the occurrence of falling winds on the southern part of the Tatra Mountains. He stated that falling winds which destroy higher vegetation were quite common above 1500-1600 m a.s.l. (where higher vegetation is dominantly represented by the dwarf pine). At lower elevations, i.e. the elevations where forests occur, they were much less frequent. Yet, they caused smaller damages (several hundreds cubic meters of blowdowns) every second/third year. Larger damages (several thousands cubic meters of blowdowns) occurred approximately every fifth/sixth year. Strong falling winds which cause very large damages also below 1000 m a.s.l. (ten to hundred thousands cubic meters of blowdowns) were very rare. Such damages were reported, in November 1915 (the wind affected the area between Tatranská Polianka, Starý Smokovec and Tatranská
Lomnica) or in September 1941 (damages between Štrbské Pleso and Vyšné Hágy). The more detailed information about windfalls on the territory of the High Tatra Mountains including the impacts on the forests (volumes of blowdowns and affected areas) was recently published by Koreň (2005). Fig. 1 taken from Holko et al. (2009) shows the estimated volumes of documented blowdowns against annual discharge of the Belá river (which is the longest discharge series in Slovakia except the Danube river in Bratislava) since the end of the 19th century.

Fig. 1. Annual discharges of the Belá river (courtesy Pekárová et al., 2009) and volumes of the blowdowns adopted from Koreň (2005);

**Hydrological cycle in the area of the Tatra Mountains**

There are numerous studies which evaluate hydrological regime in the region (e.g. Pacl, 1973; Molnár and Pacl, 1988; Drako et al., 1990; Majerčáková and Škoda, 1993; Holko et al., 2001; Majerčáková et al., 2007). Mean annual precipitation in the Tatra Mountains is 1150 mm (Molnár and Pacl; 1988). About 70% of annual precipitation runs off. However, runoff coefficients highly vary from about 0.92 in the streams located high in the mountains to about 0.50 in the main valley (the Poprad river at Matejovce) – Pacl, 1973. Minimum precipitation occurs in winter (15% of the annual total in the valley, 25% in the mountains), maximum in summer (50% of annual total in the valley, 30% in the mountains) – Drako et al., 1990. The existence of mountain barrier results in pronounced altitude gradients in precipitation including the spillway effect on the windward side (Fig. 2).

Fig. 2. The influence of the High Tatra massif on the altitudinal distribution of annual precipitation (Molnár and Pacl, 1988); the profile has the NW-SE orientation, prevailing winds come from the north-west.
Topography and water divides of the catchments in the High Tatra Mountains area are shown in Fig. 3 and their selected characteristics are given in Table 1. The main river draining the area is the Poprad river.

The density of the rivers in the Tatra Mountains is 1 km of river length per 1 km$^2$ of area (Pacl, 1973). Runoff regime is strongly affected by the accumulation of precipitation in winter and its release in spring. Seasonal distribution of runoff is given in Table 2. Fig. 4 shows that maximum runoff in different catchments occurs from May/April to June. Šimo and Žaťko (2002) characterized the runoff regimes of the streams in the area of the High Tatra Mountains as the temporary snow or combined snow-rain regimes. The characteristics of the two types are given in Table 3.

Table 1. Selected characteristics of the small catchments in the High Tatra Mountains; A-catchment area, H-mean elevation; S-mean slope; P-mean annual precipitation 1931-1980 (from the isoline map); R-mean annual runoff 1931-1980 (from the isoline map); F – forested area before the windfall in November 2004; the characteristics are based on the data of the Slovak Hydrometeorological Institute (SHMI).

<table>
<thead>
<tr>
<th>Stream</th>
<th>Gage</th>
<th>A [km$^2$]</th>
<th>H [m a.s.l.]</th>
<th>S [°]</th>
<th>P [mm]</th>
<th>R [mm]</th>
<th>F [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poprad</td>
<td>Štrbské Pleso</td>
<td>17</td>
<td>1841</td>
<td>25</td>
<td>1765</td>
<td>1158</td>
<td>31</td>
</tr>
<tr>
<td>Mlynica</td>
<td>Svit</td>
<td>83</td>
<td>991</td>
<td>9</td>
<td>862</td>
<td>311</td>
<td>43</td>
</tr>
<tr>
<td>Poprad</td>
<td>Svit</td>
<td>46</td>
<td>1399</td>
<td>16</td>
<td>1224</td>
<td>828</td>
<td>53</td>
</tr>
<tr>
<td>Velický creek</td>
<td>Poprad-Veľká</td>
<td>58</td>
<td>1094</td>
<td>9</td>
<td>921</td>
<td>528</td>
<td>42</td>
</tr>
<tr>
<td>Slavkovský creek</td>
<td>Poprad-Matejovce</td>
<td>43</td>
<td>1017</td>
<td>9</td>
<td>813</td>
<td>376</td>
<td>49</td>
</tr>
<tr>
<td>Studený creek</td>
<td>Veľká Lomnica</td>
<td>30</td>
<td>1404</td>
<td>18</td>
<td>1244</td>
<td>950</td>
<td>27</td>
</tr>
<tr>
<td>Skalnatý creek</td>
<td>Veľká Lomnica</td>
<td>34</td>
<td>1100</td>
<td>12</td>
<td>961</td>
<td>678</td>
<td>65</td>
</tr>
<tr>
<td>Poprad</td>
<td>Matejovce</td>
<td>315</td>
<td>1018</td>
<td>9</td>
<td>864</td>
<td>427</td>
<td>40</td>
</tr>
</tbody>
</table>
Table 2: Seasonal distribution of runoff; the High Tatras, south [%], Pacl 1973.

<table>
<thead>
<tr>
<th></th>
<th>XI</th>
<th>XII</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.0</td>
<td>4.0</td>
<td>3.5</td>
<td>3.0</td>
<td>6.5</td>
<td>10.0</td>
<td>14.5</td>
<td>16.5</td>
<td>13.5</td>
<td>9.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Fig. 4. Seasonal distribution of runoff in selected subcatchments of the upper Poprad river catchment; Parde’s coefficients.

Table 3. Hydrological characteristics of the runoff regimes types in the catchments of the High Tatras (Šimo and Zat'ko, 2002); Roman numerals represent months, e.g. I is January, XII is December, etc.

<table>
<thead>
<tr>
<th>Regime</th>
<th>Accumulation period</th>
<th>High discharge period</th>
<th>Maximum mean monthly discharge</th>
<th>Minimum mean monthly discharge</th>
<th>Secondary increase of water yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporary snow</td>
<td>X-III (IV)</td>
<td>IV-VII (VIII)</td>
<td>V-VI</td>
<td>I-II</td>
<td>weak</td>
</tr>
<tr>
<td>Combined snow-rain</td>
<td>XI-III</td>
<td>IV-VI</td>
<td>V (VI&lt;IV)</td>
<td>I-II</td>
<td>weak</td>
</tr>
</tbody>
</table>

The most extreme flood in the region occurred in June 1958. Daily precipitation on 29 June 1958 varied from 63.3 mm in the valley to 170 mm in the mountains and the peakflows in the streams were 50-100 times higher than the mean annual flow (Pacl, 1959).
Analyses of the impact of windfall on hydrological regime of the upper Poprad river and its subcatchments

One of the first studies devoted to the assessment of the influence on windfall on hydrological regime in the region was published by Kostka et al. (2005) who used spatially distributed hydrological model to simulate the snow accumulation and melt. Simulations with different vegetation scenarios showed higher snow water equivalents and runoff after the windfall, but the impacts were not very high. Simulated snow water equivalents on the territory affected by the windfall were on average only by 10-30 mm higher in the snow-poor and snow-rich winters, respectively.

Holko et al. (2009, 2009a) used rainfall and runoff data since the 1960’s to analyse the changes in hydrological regime after the windfall and compared the hydrological balance in the small catchment and their headwater areas. A number of characteristics was used including water balance, minimum and maximum runoff, runoff thresholds, number of runoff events, selected characteristics of runoff events, runoff coefficients, flashiness indices and baseflow. Despite increased spring runoff minima which in one catchment (the Velický creek) after the deforestation exceeded previously observed values, it can be generally concluded that the deforestation was not clearly manifested in the analysed data. Fig. 5 indicates that the increase of runoff after the windfall was not observed.

Table 4. Summary results of the analysis of hourly runoff data from hydrological years 2002-2007 in the Velický creek and the Slavkovský creek catchments; TC-time to peak (from the beginning of the event to peakflow), Q₀ – discharge at the beginning of runoff event, Q_max – peak discharge.

<table>
<thead>
<tr>
<th></th>
<th>Velický creek</th>
<th>Slavkovský creek</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>TC [hours]</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Q₀ [m³.s⁻¹]</td>
<td>1.215</td>
<td>1.590</td>
</tr>
<tr>
<td>Q_max [m³.s⁻¹]</td>
<td>6.049</td>
<td>3.921</td>
</tr>
<tr>
<td>Q_max/Q₀</td>
<td>4.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Q_max/Q₀/TC</td>
<td>0.6</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Results of the analysis of runoff events in the catchments with the largest deforestation is given in Table 4. It is obvious that in both catchments the number of events and discharges at the beginning of the events slightly increased after the deforestation. At the same time, the times to peak were longer and the peak discharges were smaller, i.e. the events were less extreme. We have also analysed the relationships among the events characteristics before and after the deforestation. The results showed that peak discharges were higher when the catchments were wetter, but the correlations were rather weak (coefficients of determination below 0.3). Flashiness indices (Baker et al., 2004) did not indicate the change in the flashiness (frequency and rapidity of short term changes in streamflow) after the windfall either. (Fig. 6). From the point of view of integrated catchment management it may be interesting that comparison data from the upper Poprad river catchment with other mountain rivers in Slovakia showed that the streams in the upper Poprad river catchment had higher flashiness indices (Fig. 7). Cross-correlations revealed the
influence of agricultural land which covers larger areas in the upper Poprad river catchment (Holko and Kostka, 2008).

Fig. 5. Daily runoff before and after the windfall indicated by the grey vertical line; hydrological years 2001-2008; numbers in [%] show the deforestation caused by the windfall.
Fig. 6. Flashiness indices and deforestation of the catchments (the numbers in percents).
The above analyses showed that hydrological data from the standard network, i.e. at catchment scales $10^1$-$10^2$ km$^2$ did not indicate significant changes in runoff regime after the windfall. Apart from one exception the data from smaller catchments were not available. We have found only one headwater catchment where a short time series of discharges was available before the windfall. In December 2007 we restored the measurements in the catchment (the Jazierkový creek catchment, area 0.67 km$^2$, mean elevation 1041 m a.s.l.) which was completely deforested due to windfall. Fig 8 shows that the runoff regime in the catchment was rather flashy before the windfall, although the catchment was fully forested. Flashiness after the windfall was not higher than before it. Unfortunately, the data from the period before and after the windfall look completely different. Due to short and interrupted data series and recent extension of skiing facilities in the catchment which was always hydrologically complicated (the
catchment is situated in a moraine and the water divide is rather uncertain, there are uncontrolled human manipulations at the measuring weir) the analysis of the impact of the windfall on hydrological regime in this catchment is impossible.

Conclusions
Influence of landcover change (mainly deforestation, but also afforestation) on hydrological cycle has been studying since the beginning of the 20th century. Despite the existence of conflicting perceptions of land cover impacts on the hydrological cycle (e.g. relationships of forest and flooding) stated for example by Calder, 2004; Forsyth, 2005 or Jewitt, 2005, it can be generally concluded that the large-scale deforestation results in temporary increase of some runoff characteristics. However, many studies concluded that with regard to the flood prevention and erosion the control functions of the forests are evident, but limited (e.g. Bíba et al., 2006).
Analyses of measured data in the upper Poprad river catchment and its subcatchments did not indicate significant impacts of deforestation on runoff regime. We assume that there are several important reasons for that. Despite very large extent of deforestation, it has occurred around middle sections of the catchments. Headwaters where the dominant part of runoff is formed and where little forests exist anyway were not influenced. Deforestation occurred in areas formed by moraines that are have high infiltration capacity. Deforestation affected relatively “small” percentages of catchments’ areas and it went across the catchments (in the east-west direction, while the catchments are generally north-south oriented). Thus, not all the forests were destroyed. These may be the reasons why the deforestation which has changed the environment so seriously, was not manifested in studied hydrological data and did not result in severe flooding or erosion.

Acknowledgements
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