## Chapter 5

# Spatial and temporal variability of water resources in the Polish Tatra Mountains

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**Abstract**: Increasing human impact on the Tatra Mountains water resources exerted by local residents, tourists, and ski lobby prompted the Tatra National Park to install a modern monitoring network launched in 2008 (42 digital water gauges). The Tatra Mountains streams are characterized by a simple hydrologic regime with one flood season lasting from April to July. Up to 75% of the annual river runoff outflows from the Tatra Mountains catchments in the summer half-year season (May–October). The contribution of base flow is between 30% and 55% and it tends to be the highest in catchments with a relatively high carbonate rock content as well as in catchments with substantial thickness of fluvioglacial cover and moraine cover. The highest spring discharge is attributed to vaucluse springs (Chochołowskie, Goryczkowe, Lodowe Źródło, Olczyskie, Bystrej) which have recharge area beyond the topographic catchments. Two hydrographic regions have been identified in the Tatra National Park dependent on geology complex, which determines water circulation patterns as well as groundwater and surface water: the Tatra Mountains region (I) and flysch region (II). The Tatra Mountains region consists of three subregions: crystalline subregion (Ia), high mountain, karst, limestone, dolomite subregion (Ib), and dolomite, shale, middle mountain subregion (Ic).

**Keywords**: vaucluse springs, runoff, streams, hydrological regions

## Hydrological network

The first water level gauges in streams in the Polish Tatra Mountains were operating in the 1960s (Białka, Cicha Woda) and 1970s (Poroniec, Potok Kościeliski, Czarny Dunajec). These gauges were installed by the national service i.e. the Institute of Meteorology and Water Resources. Subsequently, the scientific group led by Prof. Danuta Małecka from the University of Warsaw (Małecka 1984) has operated a network of gauges supervised by the Tatra National Park (TNP) to 1999. TNP staff have been monitoring water levels at 29 gauges ever since. The number of water level measurements varies seasonally from 4 to 15 per month. Human impact exerted by local residents and tourists on the Tatra Mountains water resources prompted TNP to install a modern monitoring network for both groundwater and surface water as part of its standard water monitoring work. This new network launched in 2008 includes 42 digital water gauges that measure water levels and temperatures at least once per hour (Fig. 5.1). An additional 11 monitoring sites were activated in 2013 that gauge physical and chemical characteristics of water in two river catchments: Bystra and Sucha Woda (Żelazny et al. 2013–2016). The results are viewable online. Furthermore, hydrologic monitoring is performed in the Kościeliski Potok catchment, which is affected by deforestation caused by very strong, gusty winds and the bark beetle. This program has been in effect since 2014 and focused on the effect of deforestation on catchment water resources. In addition to providing research material, these types of monitoring efforts help assess development projects in and around TNP, as well as assist in determining limits of water resources exploitation (Pęksa 2010, 2013; Pociask-Karteczka, Ed. 2013).

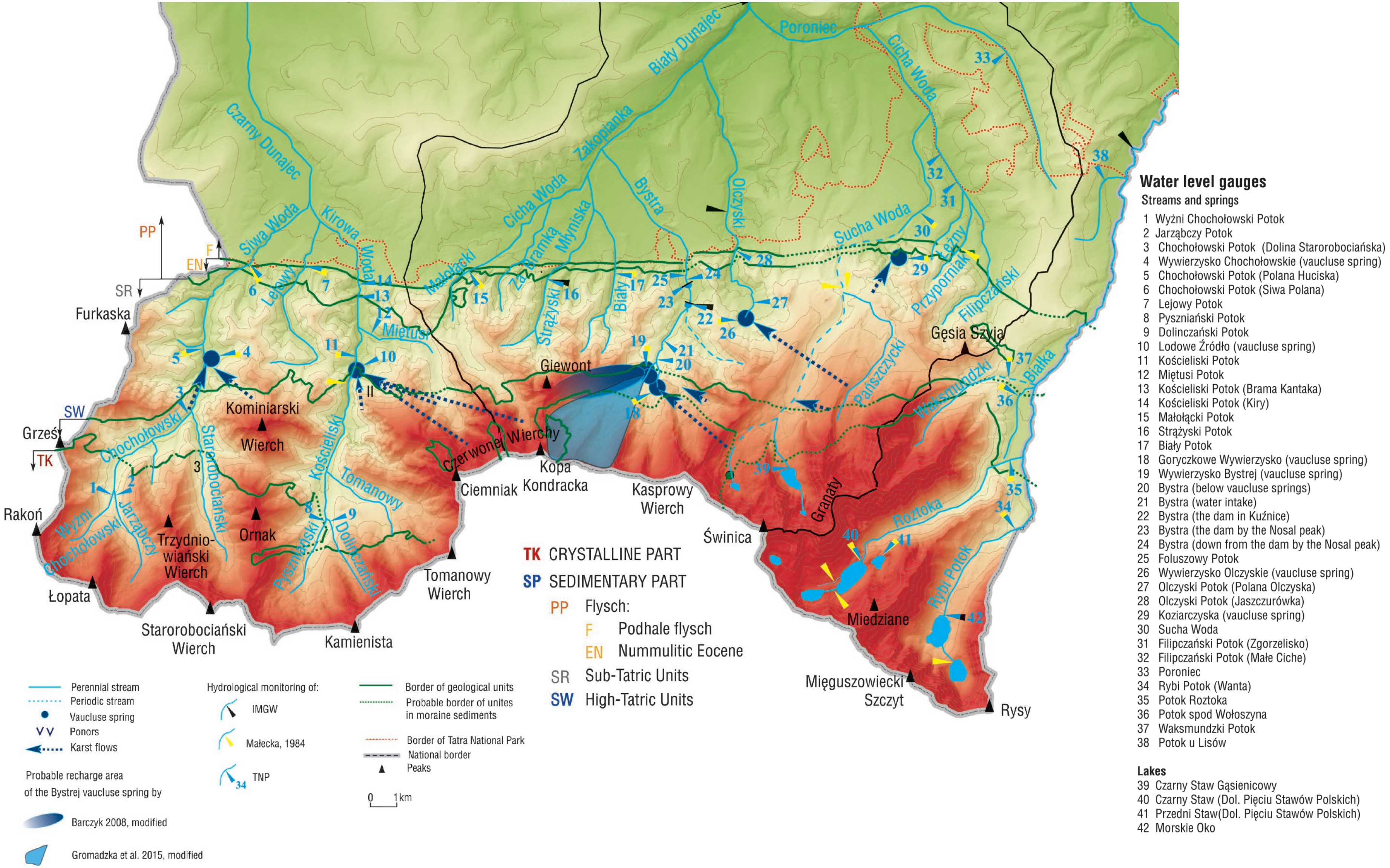

**Fig. 5.1.** Location of water gauging sites and karst flows (Barczyk 2008; Dąbrowski, Głazek 1968; Gromadzka et al. 2015; Łajczak 1996; Małecka 1984; Pęksa 2010; Żelazny 2012; modified).

## River runoff regime

The Tatra Mountains streams are characterized by a simple hydrologic regime with one flood season, with the exception of Poroniec stream. Flood season occurs from April to July. Summer half-year runoff volume (May–October) is between 60% and 75% of the total annual river runoff. The highest discharge is recorded in May and June, especially when snowmelt is accompanied by rainfall that helps accelerate the melting of snow. High discharge in the snowmelt season lasts long enough in many catchments that it becomes superimposed upon the higher summer discharge period, especially in July when it is caused by rainfall (Łajczak 1996; Pociask-Karteczka et al. 2010, 2018; Żelazny et al. 2015d, 2016).

The low discharge period (passive period) usually lasts from August to March and sometimes is interrupted by somewhat higher discharge in autumn (Żelazny et al. 2016). The passive period is characterized by a partial stoppage in water circulation due to the accumulation of water in the snow cover (Łajczak 1996).

The most variable discharge over the annual cycle is found in small streams in the crystalline part of the Tatra Mountains: Waksmundzki Potok, Rybi Potok, Roztoka, and Dolinczański Potok, as well as in larger streams such as Kościeliski Potok and Chochołowski Potok (Fig. 5.2). The streams above are characterized by extremely low runoff in autumn and winter – caused by lack of precipitation and a very low groundwater supply due to poor groundwater aquifers in the crystalline

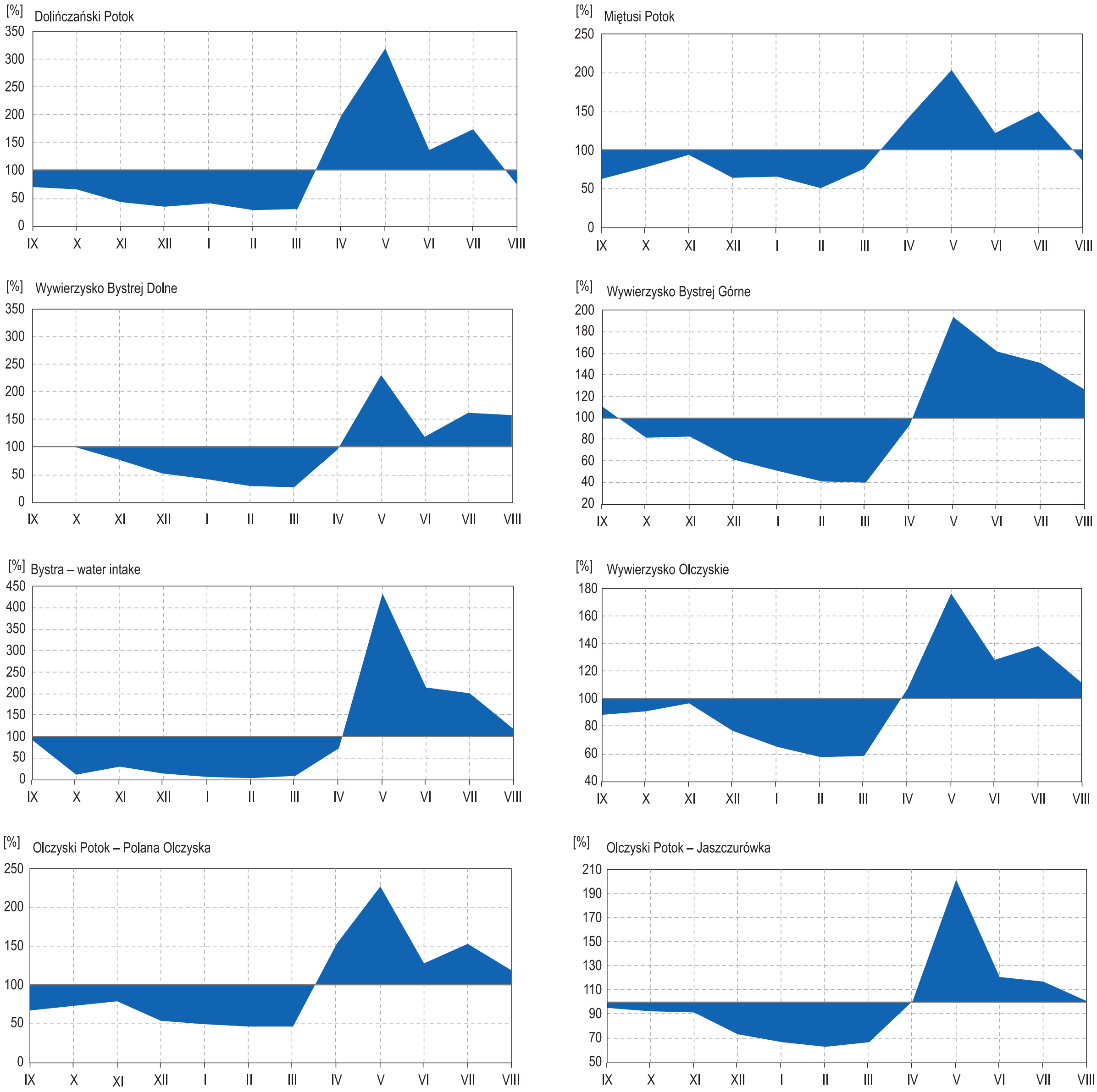

**Fig. 5.2.** Contribution of mean monthly discharge to the mean annual discharge of streams and springs in 2012–2014 (Żelazny et al. 2013, 2014, 2016, modified).

rocks. The least variable discharge over the annual cycle is noted in streams within the sedimentary part of the Tatra Mountains within Low-Tatric and High-Tatric Units (Lejowy Potok, Małołącki Potok, Miętusi Potok, and Filipczański Potok streams), as well as in streams recharged by vaucluse springs (Bystra, Olczyski Potok, Sucha Woda). The discharge in these streams remains quite high even in autumn and winter. The higher the discharge of the spring, the greater the impact on the stream. This pattern may be observed in the Olczyski Potok stream where the stream regime and spring regime are virtually identical. However, water intakes for household use in Zakopane in the downstream section leads to large variability in discharge downstream of water intakes (Fig. 5.2; Żelazny et al. 2015d, 2016).

## Springs[1]

The mean density of springs in the Polish Tatra Mountains is 4.8 springs·km$^{-2}$ and this value has been stable since the 1950s (Ziemońska 1966, Żelazny 2012). The density of spring reaches locally even 16 springs·km$^{-2}$, as in the Morskie Oko lake catchment (Pociask-Karteczka, Bochenek 2014). Most springs (85.2%) has a very low discharge – less than 1.0 dm$^3$·s$^{-1}$ (Photo. 5.1). The share of high discharge springs over 10 dm$^3$·s$^{-1}$ is very small at 1.5%, with five being vaucluse springs with discharge at more than 100 dm$^3$·s$^{-1}$. Vaucluse springs play the most significant role in the formation of water resources in the the Tatra Mountains. The discharge of five vaucluse springs is 1760 dm$^3$·s$^{-1}$, i.e. 65% of discharge of all springs in the Polish Tatra Mountains, which equals 2726 dm$^3$·s$^{-1}$ (Fig. 5.3). This is the equivalent of a specific runoff of 12.9 dm$^3$·s$^{-1}$·km$^{-2}$ (i.e. 406 mm). The highest spring discharge is noted in the Bystra catchment – this equals 767 dm$^3$·s$^{-1}$. This is 28.1% of the total runoff of all springs in the Tatra Mountains (Figs. 5.4, 5.5). A higher spring discharge and

**Photo. 5.1.** The moraine spring in the upper part of the Bystra stream catchment (Photo. M. Żelazny).

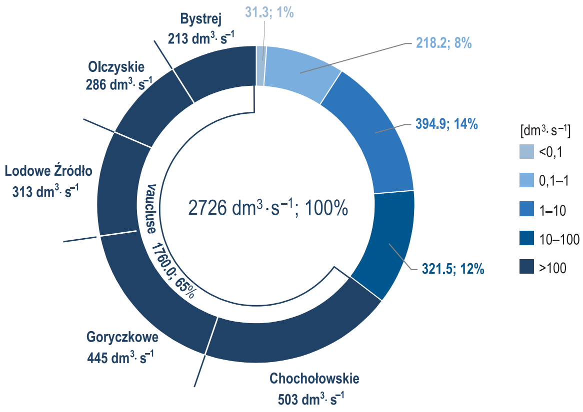

**Fig. 5.3.** Percent share of discharge from springs of particular discharge ranges (Żelazny 2012, modified).

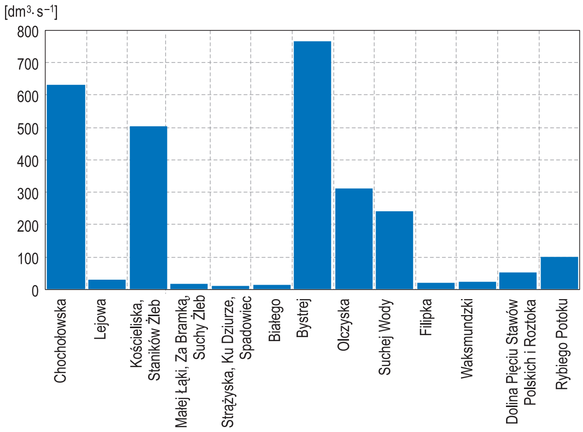

**Fig. 5.4.** Total spring discharge in the Tatra Mountains catchments (Żelazny 2012, modified).

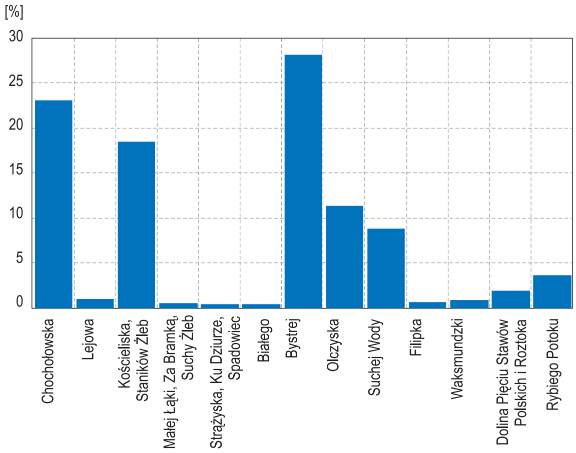

**Fig. 5.5.** Share of spring discharge in water resources in particular catchments of the Tatra Mountains (Żelazny 2012, modified).

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a little lower share of spring water resources are noted in the following stream catchments: Chochołowski Potok (respectively 631.6 dm$^3$·s$^{-1}$ and 23.17%), Kościeliski Potok (respectively 503.4 dm$^3$·s$^{-1}$ and 18.47%), and Olczyski Potok (respectively 311.7 dm$^3$·s$^{-1}$ and 11.43%). The lowest discharge and lowest share of total spring water resources are noted in the following stream catchments: Strążyski Potok, Potok ku Dziurze, and Spadowiec (respectively 12.8 dm$^3$·s$^{-1}$ and 0.47%), Małołącki Potok, Potok za Bramką, Suchy Żleb (respectively 16.4 dm$^3$·s$^{-1}$ and 0.60%), Filipka (respectively 19.9 dm$^3$·s$^{-1}$ and 0.73%, Żelazny 2012).

The largest spring water resources expressed as total specific runoff of all springs occur in the following catchments: Olczyski Potok (67.9 dm$^3$·s$^{-1}$·km$^{-2}$), somewhat smaller in Bystra (42.2 dm$^3$·s$^{-1}$·km$^{-2}$), and many times smaller in the following catchments: Chochołowski Potok (18.3 dm$^3$·s$^{-1}$·km$^{-2}$) and Kościeliski Potok (13.6 dm$^3$·s$^{-1}$·km$^{-2}$; Fig. 5.6). Specific runoff noted in the catchments built of sedimentary rocks (16.9 dm$^3$·s$^{-1}$·km$^{-2}$) is almost four times higher than that in areas formed of crystalline rocks (4.9 dm$^3$·s$^{-1}$·km$^{-2}$; Fig. 5.7, Żelazny 2012).

The largest spring water resources are in the area below 1200 m a.s.l., where the total spring runoff reaches at 2227 dm$^3$·s$^{-1}$, which equals 81.7% of all water resources in the Polish Tatra Mountains (Fig. 5.8). There are three altitudinal belts with very high spring discharge rates: 950–1000 m a.s.l., 1050–1100 m a.s.l. and 1150–1200 m a.s.l. The first belt features 61 springs delivering 972 dm$^3$·s$^{-1}$ (35.7% of the water resources of the Polish Tatra Mountains, Fig. 5.9). This belt includes two large vaucluse springs in the Tatra Mountains, Wywierzysko Chochołowskie, which yields 503 dm$^3$·s$^{-1}$ as well as Lodowe Źródło, which yields 313 dm$^3$·s$^{-1}$. The belt from 1050 and 1100 m a.s.l. features 86 springs with a total discharge of 336.8 dm$^3$·s$^{-1}$ (12.4% of the water resources of the Polish Tatra Mountains). This belt also includes the large vaucluse spring i.e. Wywierzysko Olczyskie (286 dm$^3$·s$^{-1}$). Discharge of

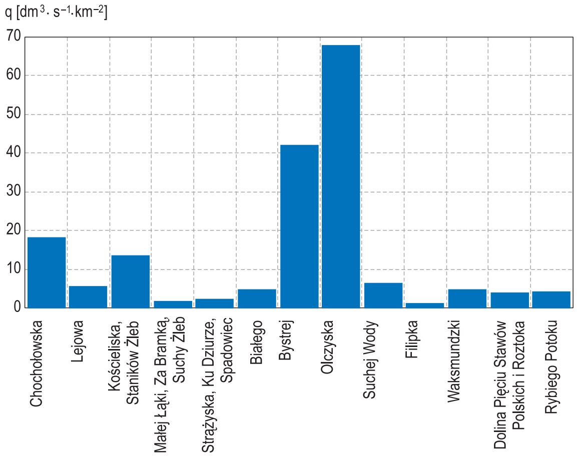

**Fig. 5.6.** Specific discharge of springs in the Tatra Mountains stream catchments (Żelazny 2012, modified).

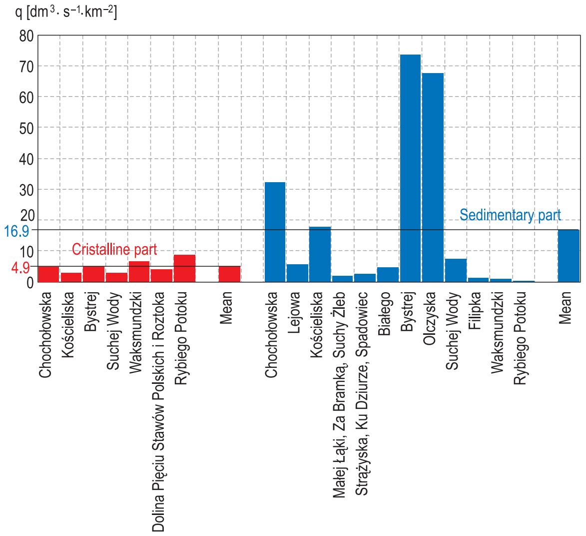

**Fig. 5.7.** Specific discharge of springs in the Tatra Mountains valleys versus local geology (Żelazny 2012, modified).

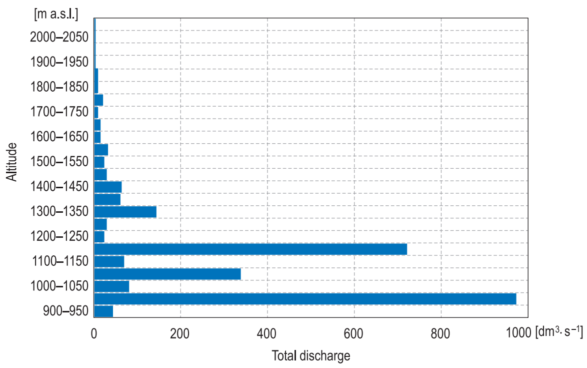

**Fig. 5.8.** Total spring discharge in selected altitudinal belts in the Tatra Mountains (Żelazny 2012, modified).

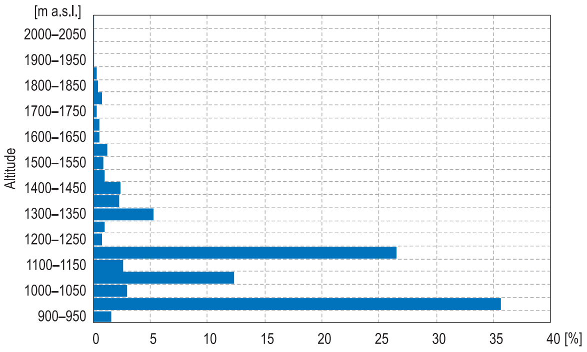

**Fig. 5.9.** Share of total spring discharge in total water resources in selected altitudinal belts in the Tatra Mountains (Żelazny 2012, modified).

86 springs in the third belt equals 721.5 dm$^3$·s$^{-1}$ i.e. 26.5% of the total discharge of all springs in the Polish Tatra Mountains. This zone includes two vaucluse springs: Wywierzysko Goryczkowe (445 dm$^3$·s$^{-1}$) and Wywierzysko Bystrej Dolne (213 dm$^3$·s$^{-1}$), both in the Bystra catchment (Żelazny 2012).

## Water temperature regime

Surface water and groundwater of the Tatra Mountains exhibit a great variability of thermal regimes, which results from the presence of streams, vaucluse springs influence as well as lakes (Żelazny et al. 2015b). Maximum water temperature in lakes and streams occur frequently in August due to low water levels combined with increased atmospheric heating. In the case of vaucluse springs, maximum water temperatures are recorded in September. The highest stream water temperature (> 15°C) is observed in the Filipczański, Roztoka and Rybi. The average water temperature of streams is similar (4.9 ± 1.1°C). Minimum water temperature in streams occur frequently during the winter season, from December to March. In lakes, minima of water temperature usually occur between November and May. The highest minimum temperature are observed in karst springs and streams discharged by karst springs such as Bystra and Olczyski Potok (Żelazny et al. 2018).

Water temperature time series are characterized by the presence of several cycles such as daily, weekly, 8–30 days, half-yearly, and annual, which appear in seven different patterns. The Tatra Mountains lakes display a pattern with 8–30 days, half-yearly and annual cycles (Fig. 5.10). Vaucluse springs are characterized by two patterns with a) exclusively low-frequency components in the form of annual cycle, and b) less frequently both, annual and half-year cycles (Fig. 5.10). Vaucluse springs are characterized by relatively low and stable water temperature over the year. Small temperature amplitudes or even their lack indicate deep water circulation. One such example is the Lodowe Źródło vaucluse spring with an average water temperature of 4°C and annual water temperature amplitude never exceeding 1°C.

Streams represent four patterns with different complexity. Most often they are characterized by the lack of half-year cycle and the presence of daily and annual cycles (Fig. 5.10). The thermal regime of streams depends

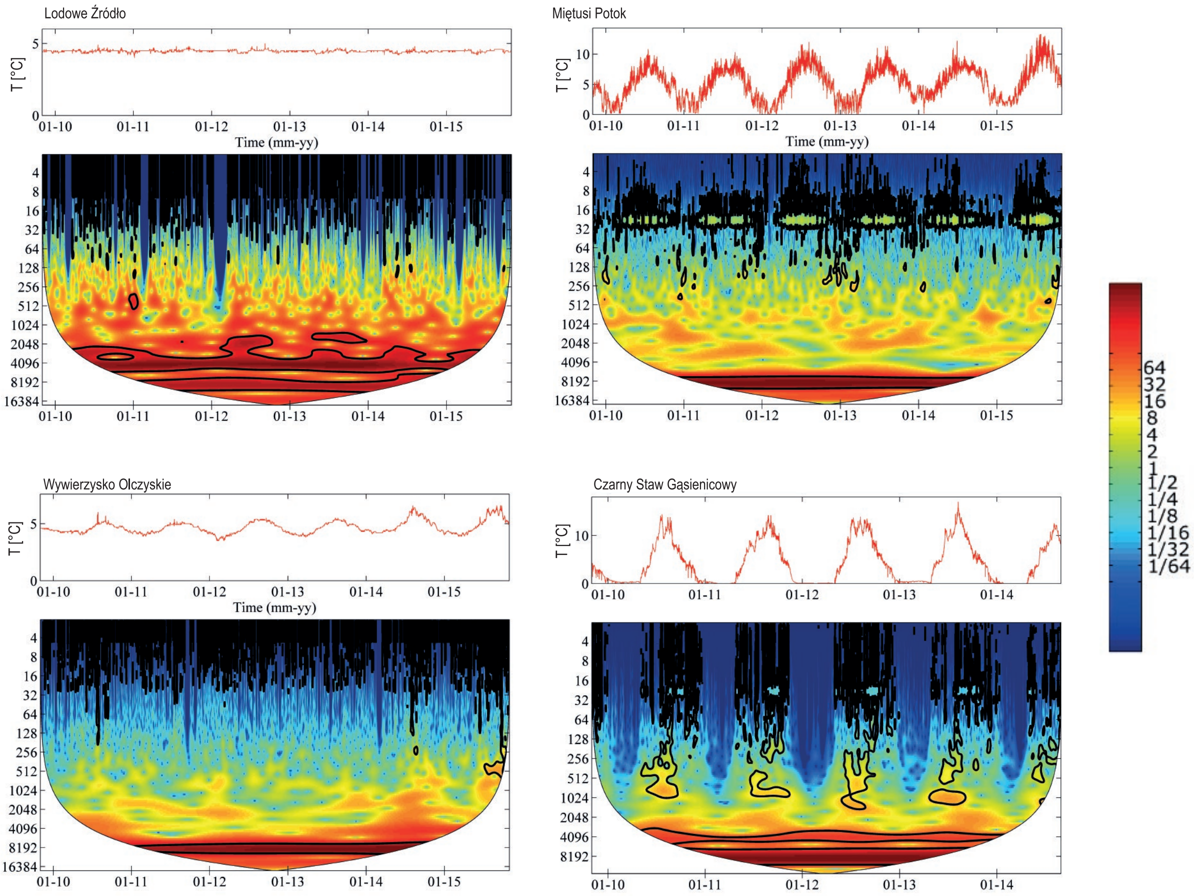

**Fig. 5.10.** Sample wavelet power spectra of water temperature time series (Żelazny et al., 2018). The upper plot shows the original time series of water temerature.

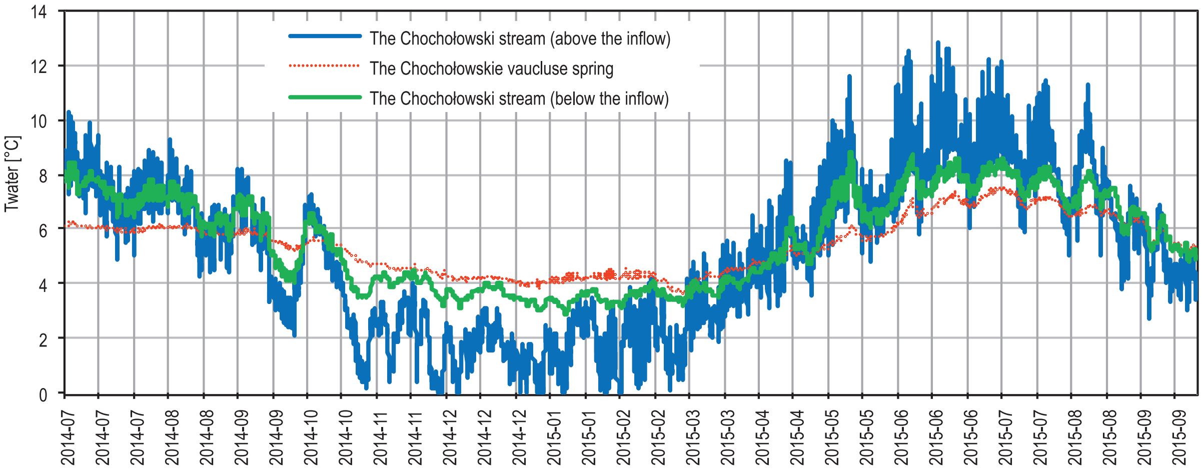

**Fig. 5.11.** Time series of water temperature in Chochołowski Potok stream (both upstream and downstream of water influx from the Wywierzysko Chochołowskie vaucluse springs) and Wywierzysko Chochołowskie vaucluse spring from January 2014 to September 2015 (Żelazny et al. 2018).

on cold water supply from snowmelt and groundwater. The latter diminish amplitudes of water temperature fluctuations and dampen daily cycles of water temperature. The dampening of daily cycle occurs especially in stream courses located directly below the inflow of karstic groundwater and gradually disappears with the distance from the karst water inflow. Moreover, vaucluse springs influence the energy budget of gaining streams (e.g. Chochołowski Potok, Kościeliski Potok, Bystra, Olczyski Potok and Sucha Woda) by cooling the stream water in summer and warming it in winter. The impact of groundwater on stream water temperature is clearly visible when comparing time series obtained from the Chochołowski Potok and the Chochołowskie vaucluse spring (Fig. 5.11).

The daily cycle occurring in water temperature time series is associated with air temperature, which in mountain conditions depends on the elevation above sea level. The annual cycle of water temperature is the most common and results from the seasonal changes in the temperate climate zone. The semi-annual cycle is associated with the presence of ice cover in lakes, which in fact, has significantly shortened over the last century. The 8–32 day cycle may be related to short periods of summer stratification that are preceded by equally short periods of spring turnover (Żelazny et al. 2018).

## Surface water resources in The Tatra Mountains National Park in 2012–2014

Mean annual river runoff for 16 streams in the Tatra Mountains in the period 2012–2014 is 7.75 m$^{3}$·s$^{-1}$, which is the equivalent of 244.1 mln m$^{3}$ of water, while mean low discharge equals 2.026 m$^{3}$·s$^{-1}$, which is the equivalent of 63.8 mln m$^{3}$ of water (Tab. 5.1, Żelazny et al. 2013, 2014).

High specific runoff (> 50 dm$^{3}$·s$^{-1}$·km$^{-2}$) occurs in catchments built of the High-Tatric units (crystalline part) including the catchments of the following streams: Pyszniański Potok (64.1 dm$^{3}$·s$^{-1}$·km$^{-2}$), Rybi Potok (60.4 dm$^{3}$·s$^{-1}$·km$^{-2}$), Wyżni Chochołowski Potok (55.7 dm$^{3}$·s$^{-1}$·km$^{-2}$), Dolinczański Potok (54.7 dm$^{3}$·s$^{-1}$·km$^{-2}$), and Goryczkowy Potok (51.8 dm$^{3}$·s$^{-1}$·km$^{-2}$, Fig. 5.12). Specific runoff is lower in some of these catchments due to local geomorphologic and hydrogeologic conditions, as in the case of the following streams: Roztoka (42.5 dm$^{3}$·s$^{-1}$·km$^{-2}$), Jarząbczy Potok (39.6 dm$^{3}$·s$^{-1}$·km$^{-2}$), Waksmundzki Potok (39.0 dm$^{3}$·s$^{-1}$·km$^{-2}$). Discharge in Jarząbczy Potok stream is reduced by water intake generated by a hydroelectric plant located near the tourist lodge in the Chochołowski Potok catchment. A river beds of the Roztoka and Waksmundzki Potok "lose" water, which is why it is reasonable to presume that the total water resources of these catchments are much larger. The analysis of water conditions appears that runoff in the crystalline part of the Tatra Moun-

**Table 5.1.** Water resources characteristisc in the Polish Tatra Mountains in 2012–2014 (Żelazny et al. 2013, 2014, 2016).

| Characteristic | The Tatra Mountains (179.5 km$^{2}$) | |
|---|---|---|
| | mean | low |
| Runoff [m$^{3}$·s$^{-1}$] | 7.75 | 2.03 |
| Specific runoff [dm$^{3}$·s$^{-1}$·km$^{-2}$] | 43.2 | 11.3 |
| Runoff index [mm] | 1360 | 356 |
| Volume [milion m$^{3}$] | 244.1 | 63.8 |

tains is strongly divided into two parts: (1) Western Tatra Mountains, (2) High (eastern) Tatra Mountains. The western part is characterized by higher specific runoff (53.4 dm$^{3}$·s$^{-1}$·km$^{-2}$) than the eastern part (48.4dm$^{3}$·s$^{-1}$·km$^{-2}$). However, the High Tatra Mountains are characterized by a larger total amount of water resources than the Western Tatra Mountains due to their larger surface area (29.2 km$^{2}$ and 16 km$^{2}$, respectively, Tab. 5.2; Żelazny 2015e).

**Table 5.2.** Stream water resources characteristisc in the High-Tatras units of the Tatra Mountains in 2012–2014 (Żelazny et al. 2013, 2014, 2016).

| Characteristic | High Tatra Mountains (29.2 km$^{2}$) | | West Tatra Mountains (16 km$^{2}$) | |
|---|---|---|---|---|
| | mean | low | mean | low |
| Specific runoff [dm$^{3}$·s$^{-1}$·km$^{-2}$] | 48.4 | 9.4 | 53.4 | 11.0 |
| Runoff index [mm] | 1524 | 297 | 1681 | 245 |
| Volume [milion m$^{3}$] | 44.5 | 8.6 | 26.9 | 5.5 |

The Tatra Mountains built of Sub-Tatric Units are characterized by lower water resources and this includes catchments such as those of the following streams: Małołącki Potok (18.6 dm$^{3}$·s$^{-1}$·km$^{-2}$), Filipczański Potok (23.9 dm$^{3}$·s$^{-1}$·km$^{-2}$), Biały (26.1 dm$^{3}$·s$^{-1}$·km$^{-2}$), Lejowy Potok (27.7 dm$^{3}$·s$^{-1}$·km$^{-2}$), Strążyski Potok (29.1 dm$^{3}$·s$^{-1}$·km$^{-2}$), Sucha Woda (20.4 dm$^{3}$·s$^{-1}$·km$^{-2}$), Poroniec (43.7 dm$^{3}$·s$^{-1}$·km$^{-2}$, Fig. 5.12). On the other hand, very high resources are found in catchments with large vaucluse springs having recharge area beyond the topographic catchments, as shown by Małecka (1993). Examples of catchments of high specific runoff include the following:

- Olczyski Potok (92.9 dm$^{3}$·s$^{-1}$·km$^{-2}$ ) – recharge area in the Pańszczyca catchment (crystalline part),
- Bystra (75.1 dm$^{3}$·s$^{-1}$·km$^{-2}$) – recharge area in the Sucha Woda catchment (crystalline part),
- Kościeliski Potok (57.1 dm$^{3}$·s$^{-1}$·km$^{-2}$) – recharge area in the Czerwone Wierchy massif (sedimentary part),
- Potok u Lisów (86.1 dm$^{3}$·s$^{-1}$·km$^{-2}$),
- Potok spod Wołoszyna (73.7 dm$^{3}$·s$^{-1}$·km$^{-2}$).

## Hydrology of the Bystra stream catchment

The Bystra stream is a tributary of Zakopianka – a right-hand tributary of Białka flowing towards the Dunajec river – the right-hand tributary of the Vistula river. The Bystra stream catchment is located on the border between the Western and the High Tatra Mountains (Photo. 5.2). The highest point of the area is the Kondracka Kopa (2004 m a.s.l.). The water level gauge is located at the elevation of 955 m a.s.l. The average slope is 26.8°. The Bystra stream catchment is characterized by a particularly complex geological and tectonic structure. The northern part of the catchment is built of sedimentary rocks of the Sub-Tatric Units, which include dolomite, limestone, and shale (Bac-Moszaszwili et al. 1979, Piotrowska et al. 2015). The southern part is built of crystalline rocks and is divided into western and eastern parts. The western part (with Kondratowa Hala clearing) has no permanent watercourses, small number of springs of low discharge reaching 0.5 dm$^{3}$·s$^{-1}$. The eastern part (with the Goryczkowy Potok stream) features relatively high discharge springs reaching 10.0 dm$^{3}$·s$^{-1}$ and a permanent watercourse that disappears in a ponor in the area of the Hala Goryczkowa clearing (Fig. 5.13). The southern and middle parts of the catchment were strongly transformed by glaciers, which led to the formation of glacier cirques and thick moraine formations (Klimaszewski 1988). Moreover, there are numerous karst phenomena such as ponors, caves, and vaucluse springs in the middle part of the catchment (Barczyk 2008; Dąbrowski, Głazek 1968; Małecka 1997; Wit-Jóźwik, Ziemońska 1960a; Wrzosek 1933). Research on the water balance in the Tatra Mountains has shown that the runoff-rainfall ratio for the Bystra catchment is 1.04,

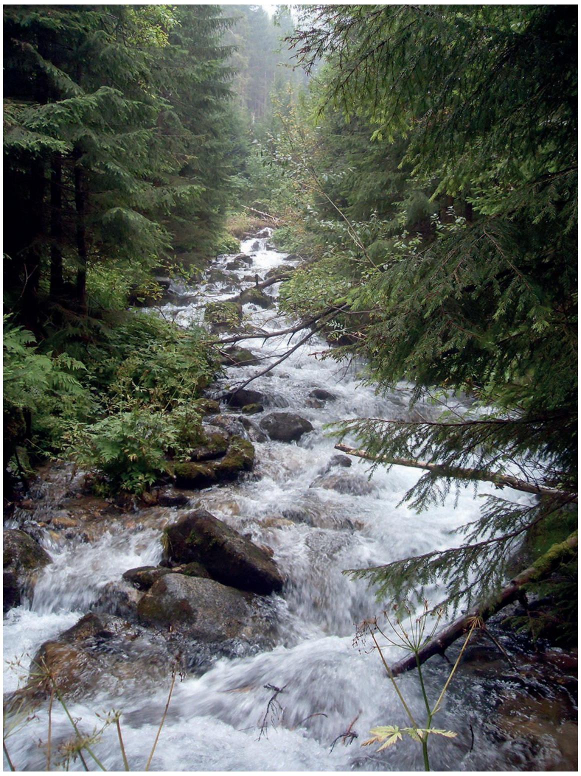

**Photo. 5.2.** The Bystra stream in the middle course (Photo. J. Pociask-Karteczka).

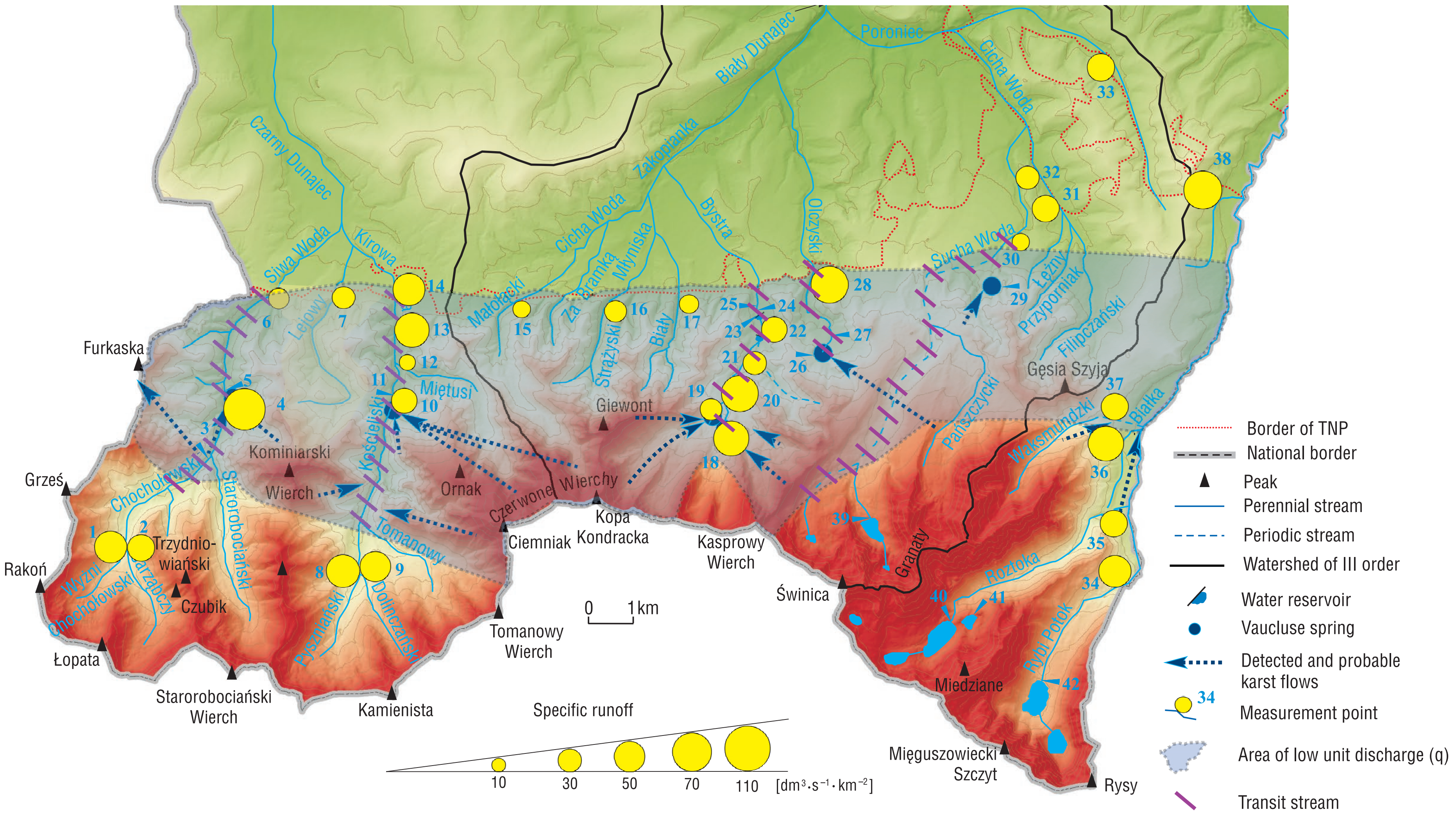

**Fig. 5.12.** Water resources expressed in specific runoff in the Polish Tatra Mountains in 2013 (Barczyk 2008; Dąbrowski, Głazek 1968; Gromadzka et al. 2015; Łajczak 1996; Małecka 1984; Pęksa 2010; Żelazny 2012; Żelazny et al. 2013, 2014, 2016; modified).

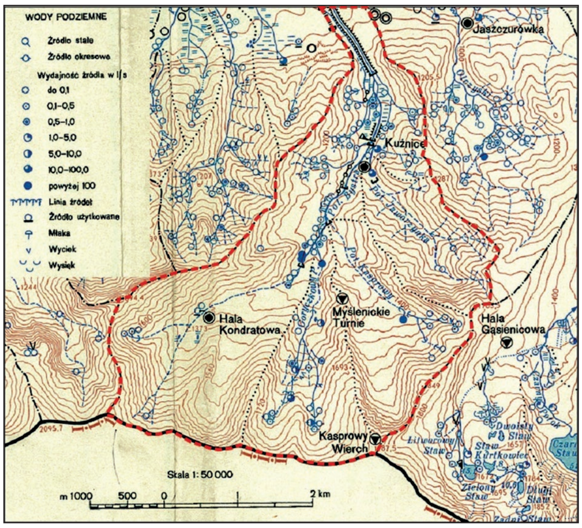

**Fig. 5.13.** Hydrologic map (red line – watershed of the Bystra stream catchment; Wit, Ziemońska 1960a, b, 1985).

which means that river runoff exceeds atmospheric precipitation (Małecka 1993, 1996). As it was mentioned before, the Bystra catchment is the second catchment, following the Olczyski Potok catchment, in terms of water resources in the Tatra Mountains. Its middle part includes one of the largest springs in Poland – Wywierzysko Goryczkowe vaucluse spring – with a discharge of about 700 dm$^3$·s$^{-1}$ (Małecka 1997). The recharge area of Wywierzysko Goryczkowe vaucluse spring is located beyond its topographic catchment – in the Sucha Woda catchment as shown in the 1960s by Dąbrowski and Głazek (1968) who used the dye-tracing technique.

The east slopes of the Giewont massif feature two vaucluse springs: Wywierzysko Bystrej Dolne and Wywierzysko Bystrej Górne (Photo. 5.3). The Wywierzysko Bystrej Górne vaucluse spring is an intermittent and virtually disappears in the winter, while the Wywierzysko Bystrej Dolne vaucluse spring is permanent (Barczyk 2008, Małecka 1997; Wit, Ziemońska 1960a, b). The total discharge of both springs is 321 dm$^3$·s$^{-1}$. According to Małecka (1997) and Barczyk (2008), the most likely recharge area of both springs is the Giewont massif and perhaps the eastern parts of the Czerwone Wierchy massif. However contemporary hydrochemical research has shown that the most likely recharge area is located in the Sucha Kondracka and Sucha Kondratowa subcatchments, because the total dissolved solids were not enough higher if the recharge area were located on the Giewont massif (Gromadzka et al. 2015). A third vaucluse spring appears south of the Wywierzysko Bystrej Górne vaucluse spring following heavy precipitation every dozen years or so.

**Photo. 5.3.** The Wywierzysko Bystrej Górne vaucluse spring (Photo. J. Pociask-Karteczka).

Anthropogenic pressure to use water in Bystra catchment for artificial snowing is significant, which makes it important to identify the amount of water resources available during wintertime low flow periods. Detailed studies of this problem have been conducted since 2013 and especial hydrographic network was established there. The highest, crystalline part of the Bystra catchment is drained by two streams: Potok Zakosy (5.5 dm$^3$·s$^{-1}$) and the stream at the Goryczkowa Rówień (1.9 dm$^3$·s$^{-1}$). The two streams then merge to form Goryczkowy Potok stream (Fig. 5.14), although its discharge is much smaller than that expected from the sum of the discharge values for the two contributing streams: 2.3 dm$^3$·s$^{-1}$. This is explained by the disappearance of water from Goryczkowy Potok stream into thick moraine formations and ponors. A complete disappearance of water in Goryczkowy Potok stream in fact was observed already in the 1950s in the downstream section of the catchment. More recent research has shown that water loss in the channel occurs in an upper section of the catchment – higher than what had been described by Wit and Ziemońska (1960a, b). Discharge of the Bystra stream increases abruptly in the middle part of the catchment due inflow of water from the Wywierzysko Bystrej Górne, Wywierzysko Bystrej Dolne, and Goryczkowe Wywierzysko vaucluse springs and reaches 996 dm$^3$·s$^{-1}$ (2010-2014). This is the equivalent of a specific runoff of 126.4 dm$^3$·s$^{-1}$·km$^{-2}$, which gives it most likely the largest specific runoff in Poland (Tables 5.3, 5.4).

There have been observed a regular increase of the Bystra stream discharge in May in the period 2010––2015. The most regular pattern of minimum discharge has been observed in the winter time – January or February (Fig. 5.15). The longest low discharge period in 2010–2014 lasted from September 2011 to March 2012 (Fig. 5.16). However, the lowest discharge (244 dm$^3$·s$^{-1}$) was noted during the year 2014 winter

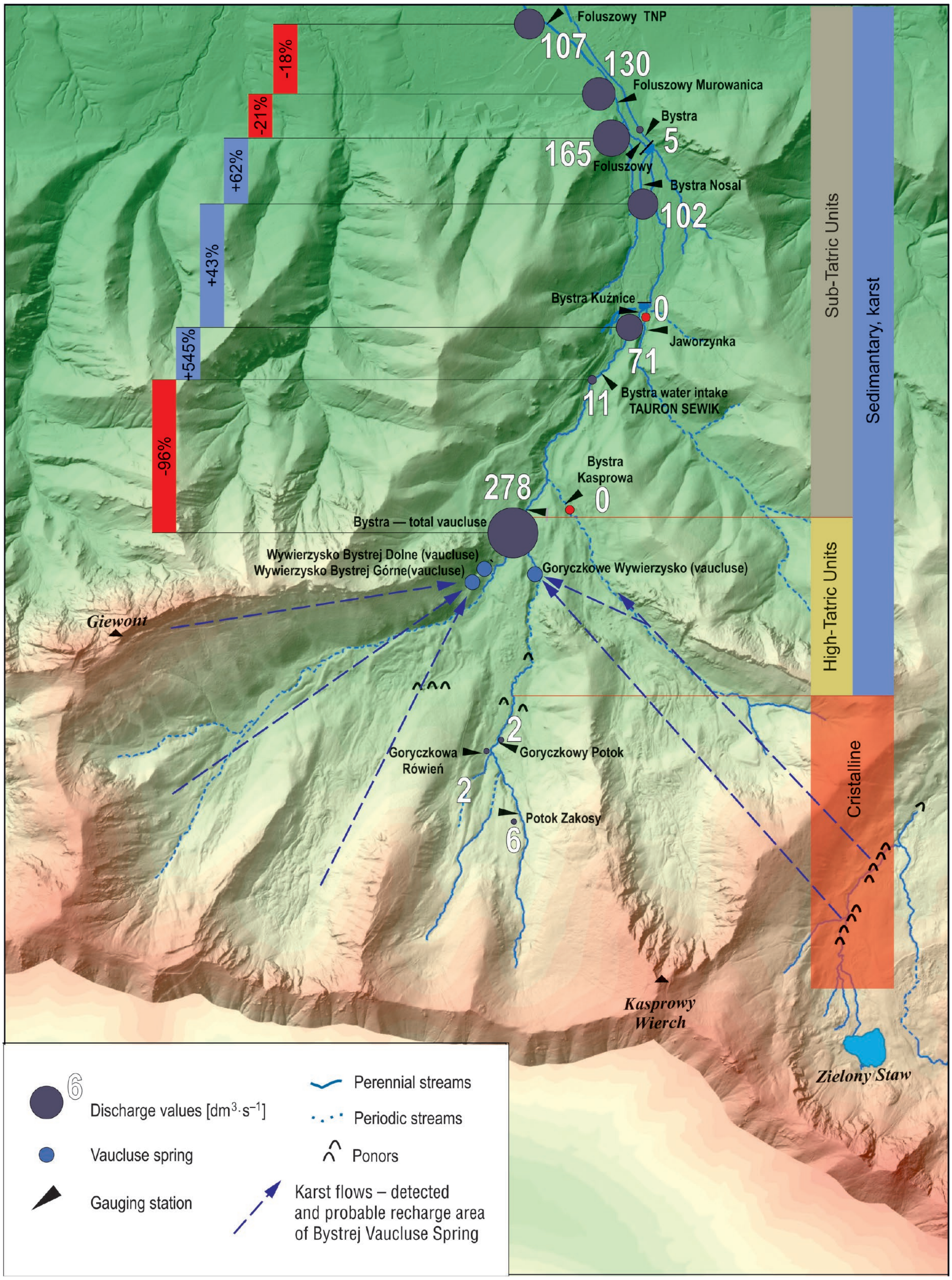

**Fig. 5.14.** Water resources along the longitudinal profile of Bystra stream on 16 January 2015 (Barczyk 2008; Dąbrowski, Głazek 1968; Gromadzka et al. 2015; Łajczak 1996; Małecka 1984; Pęksa 2010; Żelazny 2012; Żelazny et al. 2013, 2014, 2015a, 2016; Żelazny et al. 2013–2016; modified).

**Table 5.3.** Characteristics of the discharge of the Bystra stream below the vaucluse springs (Goryczkowe, Bystrej Górne, Bystrej Dolne) in the period 2010–2014 (Żelazny et al. 2015a).

| Year | Discharge Q [dm$^3$·s$^{-1}$] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $Q_{mean}$ | $Q_{min}$ | $Q_{max}$ | $Q_{25\%}$ | $Q_{50\%}$ | $Q_{75\%}$ | $Q_{10\%}$ | $Q_{90\%}$ |
| 2010 | 1119 | 291 | 3781 | 650 | 858 | 1448 | 469 | 2170 |
| 2011 | 803 | 291 | 2433 | 469 | 653 | 1088 | 379 | 1511 |
| 2012 | 875 | 335 | 2472 | 423 | 778 | 990 | 423 | 1774 |
| 2013 | 1049 | 423 | 2956 | 614 | 842 | 1314 | 514 | 1954 |
| 2014 | 1136 | 244 | 5982 | 469 | 911 | 1663 | 379 | 2105 |
| Mean | 996 | 317 | 3525 | 525 | 808 | 1301 | 433 | 1903 |

**Table 5.4.** Characteristics of specific runoff of the Bystra stream catchment below the vaucluse springs (Goryczkowe, Bystrej Górne, Bystrej Dolne) in the period 2010–2014 (Żelazny et al. 2015a).

| Year | Specific runoff q [dm$^3$·s$^{-1}$·km$^{-2}$] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $q_{mean}$ | $q_{min}$ | $q_{max}$ | $q_{25\%}$ | $q_{50\%}$ | $q_{75\%}$ | $q_{10\%}$ | $q_{90\%}$ |
| 2010 | 142.0 | 36.9 | 479.8 | 82.5 | 108.9 | 183.8 | 59.5 | 275.4 |
| 2011 | 101.9 | 36.9 | 308.8 | 59.5 | 82.9 | 138.1 | 48.1 | 191.8 |
| 2012 | 111.0 | 42.5 | 313.7 | 53.7 | 98.7 | 125.6 | 53.7 | 225.1 |
| 2013 | 133.1 | 53.7 | 375.1 | 77.9 | 106.9 | 166.8 | 65.2 | 248.0 |
| 2014 | 144.2 | 31.0 | 759.1 | 59.5 | 115.6 | 211.0 | 48.1 | 267.1 |
| Mean | 126.4 | 40.2 | 447.3 | 66.6 | 102.6 | 165.1 | 54.9 | 241.5 |

low flow period (specific discharge equivalent is 31 dm$^3$·s$^{-1}$·km$^{-2}$; Tables 5.3, 5.4).

The human impact in the Bystra stream catchment increases downstream. As a result, discharge of the Bystra stream declines significantly (by even 96%, Fig. 5.14). A regular daily cycle of water use may be observed – less water is used at night leading to higher discharge at night time, and more water is used in daytime, especially around noon and in the afternoon hours (Fig. 5.17). The discharge of the Bystra stream increases to 71 dm$^3$·s$^{-1}$ in Kuźnice where it runs in a stone-laden channel (while the discharge of the Bystra stream rechaes 278 dm$^3$·s$^{-1}$ in the upper course). There are also three spring water intakes at Kuźnice in the lower part of the Bystra catchment (Gonciska, Jedle, and Kórnickie). The Bystra stream divides in Kuźnice down of the dam build of granitic rocks: Bystra flows down in a stony channel and another creek – known in Zakopane as Foluszowy Potok – flows partly in a moraine material and stony channel.

## Hydrologic regions

Two hydrographic regions have been identified in Tatra National Park based on local geology, which determines water circulation patterns as well as groundwater and surface water supply levels in the Park (Fig. 5.18):

- the Tatra Mountains region (I),
- flysch region (II).

The Tatra Mountains region consists of three subregions (Ziemońska 1966, Siwek et al. 2015, Żelazny et al. 2015b):

- crystalline subregion (Ia),
- high mountain, karst, limestone, dolomite region (Ib),
- dolomite, shale, middle mountain region (Ic).

Crystalline subregion (Ia) is characterized by shallow water circulation and high water retention across the valley bottom in moraine formations and glacial lakes. Due to its high elevation above sea level, the region receives the highest amounts of precipitation, mostly in the form of snow. High mountain, karst, limestone, dolomite region (Ib), with developed karst system allows for substantial water retention and migration of groundwater as well as the occurrence of large groundwater aquifers. The significant discrepancy in size of the hydrogeological and topographical catchment is very common characteristic for vaucluse karst springs located in this region. Ponors, dry river channels, periodic and intermittent streams are typical here. The region at the lowest altitude, is the dolomite and shale region (Ic), which is characterized by shallow water circulation, a well-developed

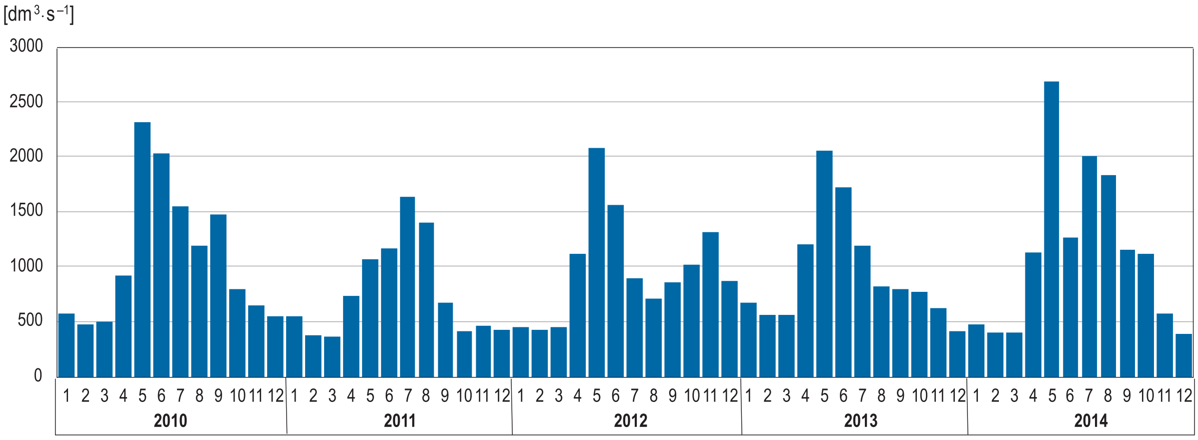

**Fig. 5.15.** Mean monthly discharge of Bystra downstream of the vaucluse springs in the period 2010–2014 (Żelazny et al. 2015a, modified).

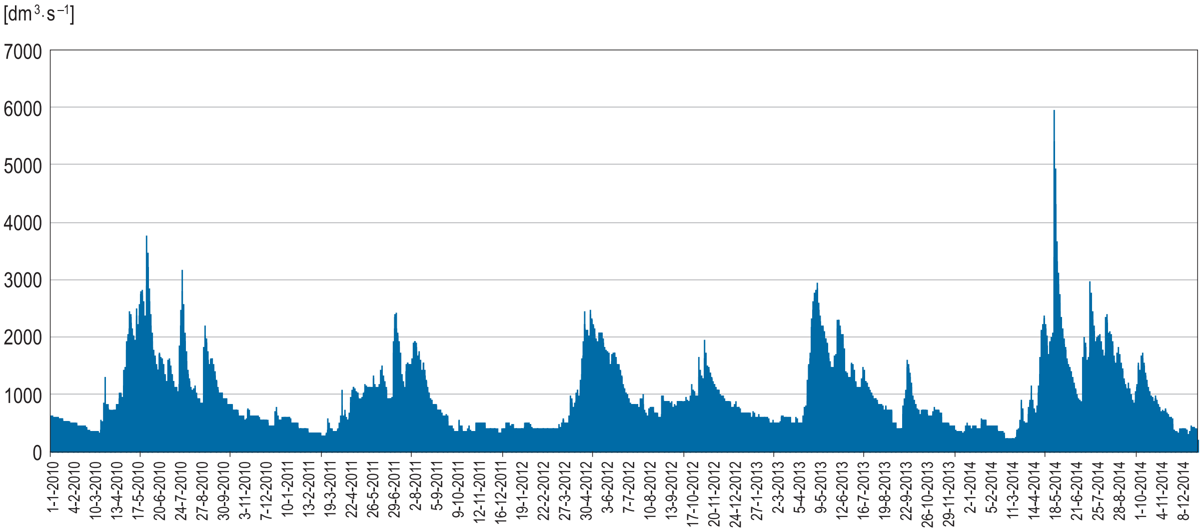

**Fig. 5.16.** Daily discharge of Bystra downstream of the vaucluse springs in the period 2010–2014 (Żelazny et al. 2015a).

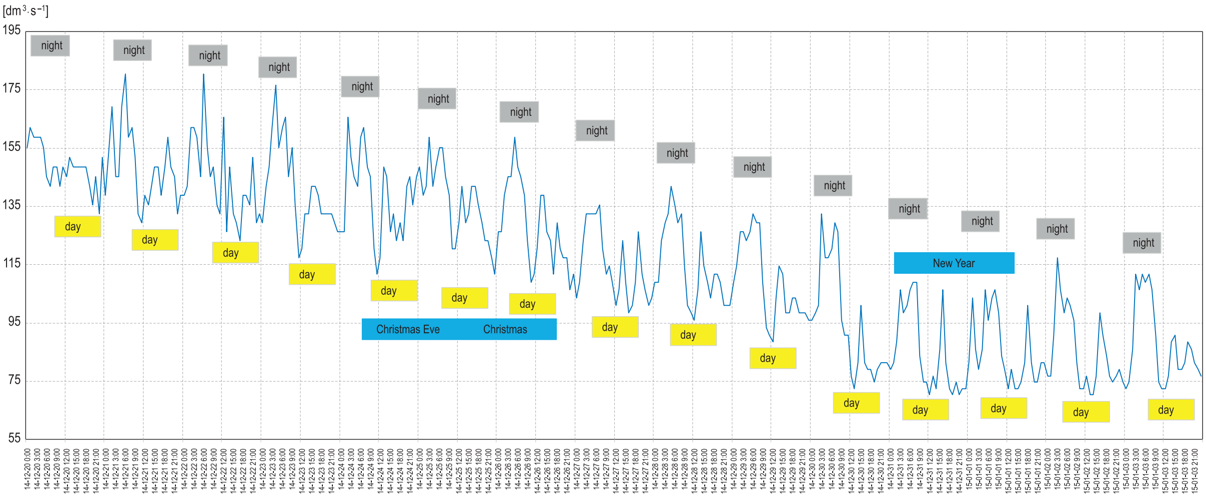

**Fig. 5.17.** Diurnal changes in discharge of Bystra stream at Kuźnice gauging station from December 2014 to January 2015 (Żelazny et al. 2015a).

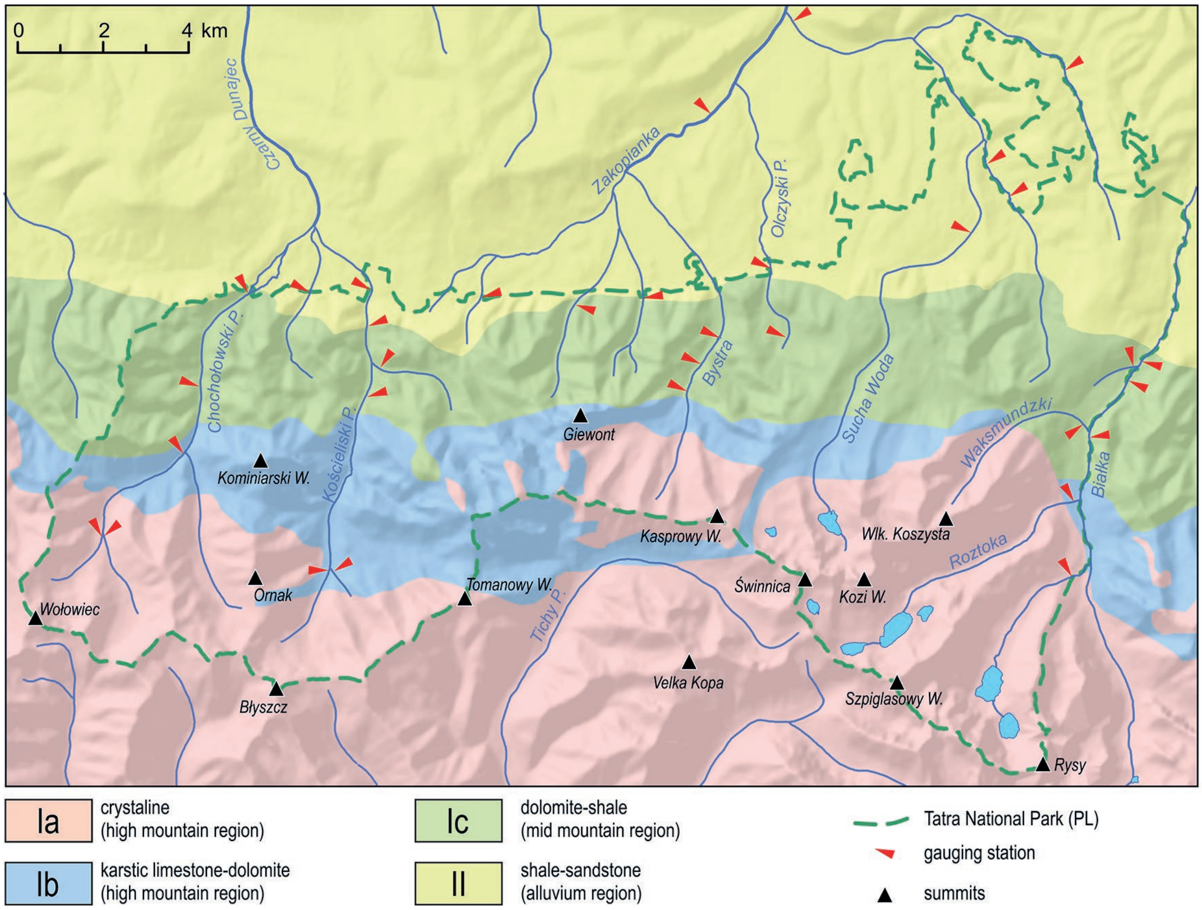

**Fig. 5.18.** Hydrographic regions in the Tatra Mountains (Ziemońska 1966, Żelazny et al. 2015c, modified).

river network, and a presence of numerous springs of low discharge.

The flysch region (II) is located across the Tatra Mountains foreland, and is primarily formed of sandstone and shale. It is a hydro-geologically distinct environment, but recharge areas of flysch formations also include parts of the Tatra Mountains region.

One of the key parameters indicating water resources level is the contribution of base flow in river runoff. Catchments characterized by a high base flow tend to be particularly valuable for water use purposes, as they are less sensitive to seasonal changes in hydro-meteorological conditions. The contribution of base flow in the Tatra Mountains river runoff is between 30% and 55% and it tends to be the highest in catchments with a relatively high carbonate rock content (subregion Ib) as well as in catchments with substantial thickness of fluvioglacial cover and moraine cover including gravel and sand (Żelazny et al. 2015c).