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Water temperature fluctuation patterns in surface waters of the Tatra Mts., Poland

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A R T I C L E I N F O

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A B S T R A C T

In this study, we aim to characterise natural variability of water temperature in surface waters of the Tatra Mts. and determine the dominant factors controlling its spatial diversity and seasonal patterns. For this purpose, a total of 33 time series of water temperature representing lakes, vaucluse springs and streams were analysed using the continuous wavelet transform (CWT). The periodicity analysis were conducted with the Morlet wavelet on hourly sampled data covering a period of 5 years. The principal components analysis (PCA) has been applied to describe the relationships among variables and extract potential sources of water temperature variability. The results showed an extremely high heterogeneity in temporal patterns of water temperature fluctuations among streams when compared to lakes and vaucluse springs. Wavelet analysis of water temperature time series revealed the presence of seven different configurations of periodical patterns. The lowest variability was observed among vaucluse springs that are supplied by groundwaters. Temporal fluctuations of water temperature in lakes contained four different types of oscillations. Streams were among the most diversified in terms of water temperature patterns exhibiting low, medium and high frequency behaviour. The PCA analysis confirmed the dependence of water temperature on weather conditions, catchment characteristics and flow rate explaining 88.97% of the total variability in the data. The results obtained from this study emphasize the importance of continuous data collection for capturing the long-term dynamics and consistent temporal patterns in time series. The study also demonstrates that wavelet analysis is helpful to identify cyclical patterns in time series of water temperature, and therefore may be useful in the classification of thermal regimes in surface waters.

1. Introduction

Water temperature is one of the most essential physical properties of water influencing the functioning of aquatic ecosystems. It affects stream metabolism, the distribution of species and rate of biochemical reactions (Demars et al., 2011). The temperature regime of surface waters, defined as the regular pattern of water temperature fluctuations, is shaped by a variety of interrelated factors such as climatological conditions, recharge sources (meltwater, groundwater, precipitation), basin characteristics and human activity (Brown et al., 2006; Brown and Hannah, 2007, 2008; Caissie, 2006; Vanzo et al., 2015). Therefore, studies on the thermal regime require not only sufficiently long time series (Webb et al., 2008), but also relevant methods for capturing its main components (Turschwell et al., 2016).

Temporal fluctuations of water temperature have usually been analysed in time domain, taking into account different statistical measures of the thermal regime such as mean, minimal and maximal temperatures. These measures have been further extended by some additional descriptors such as magnitude, variability, duration, frequency, timing and the rate of change (Arismendi et al., 2013; Maheu et al., 2016). However, apart from general informative content, none of these metrics consider water temperature variability at multiple temporal scales simultaneously (Steel and Lange, 2007). The transformation of time series into frequency domain may provide far more detailed characteristics of the thermal regime like dominant frequencies, periodicities in time series, their duration and occurrence in time (Drewnik et al., 2018; Kirchner et al., 2004; Rajwa-Kuligiewicz et al., 2015, 2016; Zolezzi et al., 2009, 2011). Those characteristics of water temperature regime are equally important because they strongly influence aquatic ecosystems. From this point of view, spectral methods, such as the wavelet transform, constitute an adequate alternative for standard statistical analysis.

Nowadays, studies on the thermal regime of rivers and streams became of particular importance in terms of climate changes, especially

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in mountainous regions that remain unaffected by human activity. In here, water temperature can be considered as a good indicator of climate changes as well as a tracer of physical processes in catchments (Ficklin et al., 2013). The use of temperature as a tracer has a long history (Constantz, 2008; Stonestrom and Constantz, 2003). Measurements of water temperature help to elucidate the mechanisms that control different hydrologic processes, identify possible groundwater sources, and recharge zones as well as depths and lengths of groundwater circulation.

So far, the natural variability of water temperature in surface waters in the Tatra Mts. has not yet received a comprehensive study. Apart from the basic interest in the average values of groundwaters and surface water temperature, seasonal variability and potential spatial diversity, the detailed long-term variability has never been reported. Most early studies were either unsystematic, often limited to manual single spot measurements, or covered relatively short periods of time. Therefore, data obtained from those studies tend to be heterogeneous and poses relatively high percentage of missing values.

In the present work, we investigated natural inter- and intra-annual variability of water temperature in streams, karst springs, and lakes located in the Tatra Mts. using high resolution data. We attempted to find an answer on how does the natural variability of water temperature at those different locations accounts for the type and number of periodicities occurring in time series. The main goals of this study were to: (1) detect dominant modes of water temperature variability; (2) describe patterns of temporal variability of water temperature and their different configurations; and (3) identify the key drivers that influence thermal variability of streams, springs and lakes.

2. Site description

The Tatra Mts. are the highest mountain range in the Carpathian Mountains forming a natural border between Poland and Slovakia. They occupy a total area of about 750 km^2, 1/5 of which is located on Polish territory (Fig. 1). Both Polish and Slovak parts of the Tatra Mts. are protected within the Tatra National Park approved as an International Biosphere Reserve UNESCO and area of Nature 2000. The Tatras have preserved their natural character with high mountain relief, pristine landscape and a variety of natural features such as canyons, waterfalls, a dwarf pine belt, alpine meadows, lakes and rocky peaks.

The geological structure of the Tatra Mts. is complex. The Tatra Mts. consist of crystalline basement core and sedimentary cover. The crystalline core comprises igneous (mainly granitic) and metamorphic rocks whose main outcrops are located in western and eastern parts of the Polish Tatras, respectively. Crystalline rocks of the Tatra Mts., which formed during the Variscan orogeny have undergone multiple phases of tectonic activity. The sedimentary cover is composed of Mesozoic rocks such as sandstones, limestones, marls, dolomites and slates, which were thrusted over the core in northern direction during Eo-Alpine orogenic phase (Anczkiewicz et al., 2015 and references therein). The main geological units are locally covered by quaternary sediments associated with the Pleistocene glaciation and Holocene processes of erosion and accumulation (Uchman, 2004). The outcrops of crystalline rocks are situated in the southern part of the Polish Tatra Mts., along the main ridges. Sedimentary rock outcrops preserved mainly to the north and build lower parts of the mountains (Bac-Moszaszwili et al., 1979, Piotrowska et al., 2015).

One of the characteristic features of the Tatra Mts. is a vertical zonation of climatic conditions, vegetation cover and morphogenetic processes (Hess, 1996; Kotarba and Starkel, 1972; Piękoś-Mirkowa and Mirek, 1996; Skiba et al., 2015). The average sums of precipitation in the Tatras vary from 1120 mm at the foothills up to 1800 mm at the mountain peaks (Żmudzka, 2010), whereas the average air temperature ranges between +6.0 °C and −2.0 °C respectively (Niedźwiedź, 1992).

In terms of hydrology, the area stands out from the rest part of the Carpathian Mts. exhibiting a great diversity of ice phenomena because

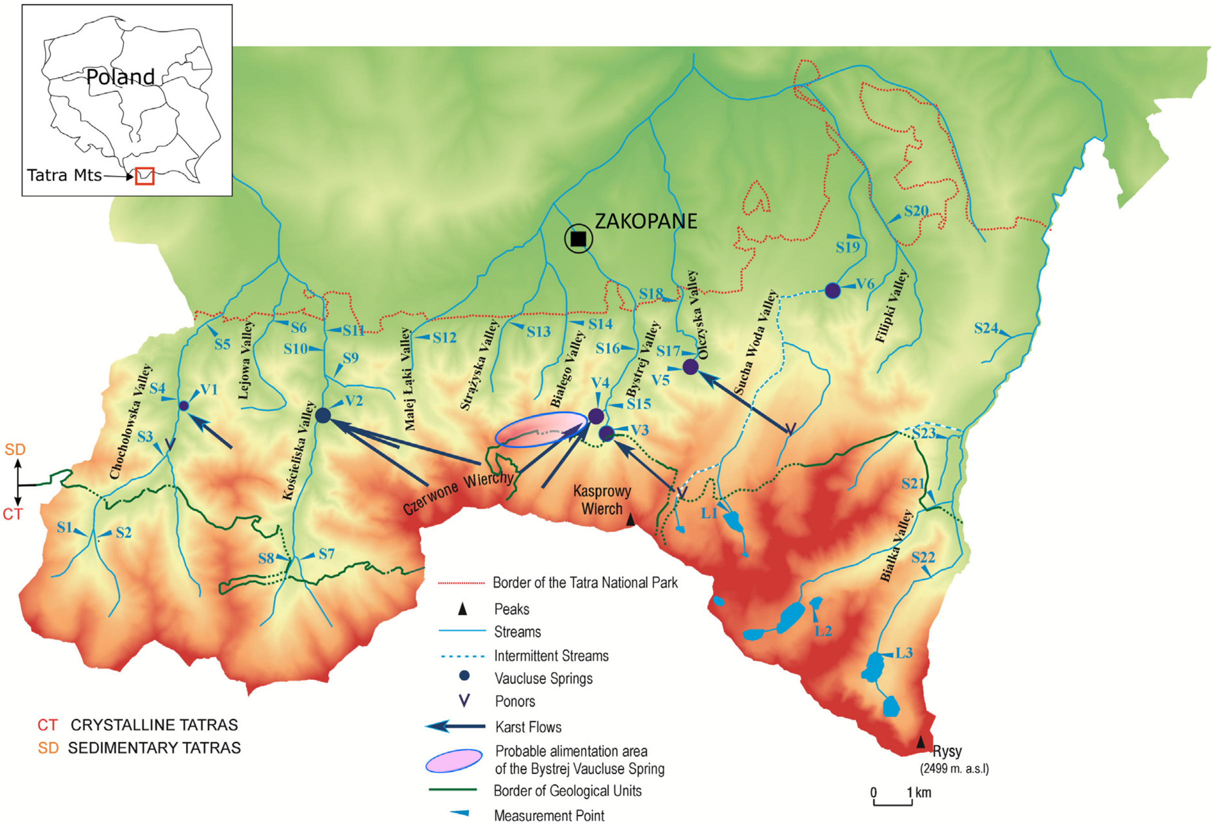

Fig. 1. Study site with the location of monitoring sites. A detailed description of the measuring sites is summarised in Table 1.

it tends to be affected by local hydrogeological conditions (Żelazny et al., 2015). The Tatra Mts. constitute a source area for many streams, most of them fed by groundwaters. Flowing waters of the Tatra Mts. are represented by small streams with a steep gradient, turbulent current and rocky bottom. Both, high-velocity streams and those fed by karst springs may lack of ice cover even when temperatures drop below freezing. The distribution of springs varies significantly depending on geological structure. The highest number of springs is associated with areas built of quaternary deposits (e.g., moraine formations), whereas the highest flowrates are characteristic for vaucluse springs occurring in karstified carbonate rocks. This type of springs has an extensive alimentation area (i.e., recharge zone) that is located beyond the topographic boundary of the catchment and are recharged by karst flows from other parts of the massif (arrows in Fig. 1 show documented karst flows). Crystalline part of the Tatra Mts. is relatively poor in terms of abundance and flowrate of springs (Małecka, 1997). Lakes occurring in the Tatra Mts. are of glacial origin such as tarns and bedrock-moraine dammed lakes. Among them, the most spectacular type known as the paternoster lake is represented by lakes in the Five Polish Lakes Valley (Pociask-Karteczka et al., 2014).

3. Materials and methods

3.1. Data sets

Data used in the present study were obtained from 33 monitoring sites located in the Tatra National Park, including streams (24 pts), karst springs (6 pts) and lakes (3 pts) (Fig. 1). Please note the term ‘karst spring’ is used interchangeably with ‘vaucluse spring’. The latter has been adopted from earlier studies carried out in the Tatra Mts. (Barczyk, 2002, 2008; Małecka, 1997). Measurement points were chosen to represent various types of catchments and recharge zones in terms of morphology and geological units. Characteristics of selected sites including mean flowrate, elevation, afforestation degree, channel slope and geology are summarised in Table 1. Channel slopes were calculated based on a 10x10 m Digital Elevation Model (DEM), with respect to all pixels located along the streamline. Afforestation degree was calculated with reference to the elementary basins cut by the streamline. Measurement points were arranged by valleys (from west to east) and by elevation above sea level (from the highest point to the lowest point in the given valley). For the sake of simplicity, streams flowing through different geological units are referred to as transit (Table 1).

Water temperature data comprised of 33 sets of time series collected at 1-hour time interval using Orpheus Mini water level loggers (manufactured by *OTT Hydromet*), with 0.1°C accuracy. The OTT Orpheus Mini logger is an integrated pressure sensor and data logger supplied with Lithium batteries of min. 5 years longevity operating within the temperature range from −25 °C to 70 °C. The instrument features a ceramic pressure cell that provides the stability in long-term measurements as well as mechanical resistance to pressure overload and corrosive waters. Some of the loggers are paired with OTT ITC for remote data transfer.

Loggers were installed either in springheads or on the bed of streams and lakes. Automatic measurements were verified several times a year by manual measurements at site using WTW Handheld Conductivity Meters. The retrieved data from data loggers cover a period of approximately 5 to 6 years between 01.11.2009 and 31.10.2015 (Fig. 1, Table 1). Prior to analysis, time series were inspected for exceptionally high values. Negative values of water temperature were considered erroneous and were replaced by 0°C.

3.2. Time series analysis

Water temperature fluctuations in 33 time series were analysed in frequency domain using the Continuous Wavelet Transform (CWT) to adequately capture variability in one framework. During the transformation original time series are decomposed into components called wavelets that represent shifted and scaled versions of a mother wavelet. The wavelet transform of a particular time series is given by the following equation:

$$CWT_x^{(\psi)}(a,b) = W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-b}{a}\right)dt \tag{1}$$

a∈ R^+, b∈ R,

where $W(a,b)$ represents a matrix of wavelet coefficients that are a function of scale (a) and translation (b), $a^{-0.5}$ is a normalisation factor ensuring the same energy of the wavelet for different a values of the scale, ψ denotes the mother wavelet, $x(t)$ is the time series, whereas the asterisks (*) indicates a complex conjugate. The mother wavelet is characterised by limited duration and average that is equal to 0. In this study, the Morlet wavelet has been applied as the mother wavelet, which is defined as:

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{\left(-\frac{\eta^2}{2}\right)} \tag{2}$$

where η denotes dimensionless time and ω_0 ($\omega_0 = 6$) is a dimensionless frequency. The Morlet wavelet relatively well resembles the shape of environmental time series and has a fairly good localisation in time and frequency (Cazelles et al., 2008; Grinsted et al., 2004; Kumar and Foufoula-Georgiou, 1997; Labat, 2008). The mother wavelet is subjected to scaling (a) and translation (b), resulting in a matrix of continuous wavelet coefficients that measure the similarity between analysed fragment of time series and the mother wavelet. The wavelet power was normalised by variance to have unit energy at all timescales $\int_{-\infty}^{\infty} \psi^2(t)dt = 1$ (Grinsted et al., 2004). In this way, narrow wavelets (small scales) can detect fast-changing features, while stretched wavelets (large scales) allow for the separation of low-frequency characteristics (Kumar and Foufoula-Georgiou, 1997). The main result of the continuous wavelet transform is a three-dimensional colour map of the wavelet power spectrum ($|W(a,b)|^2$), which shows the distribution of power at certain scale a (period) and time position b.

The finite length of the time series results in edge effect, which is visible at both sides of the wavelet power spectrum (Torrence and Compo, 1998). This is due to the fact that the wavelet is moved along the signal and the convolution is calculated for each time step, and for each scale. Consequently, calculations at edges of the signal require non existing values. This region is termed as the cone of influence (COI). The statistical significance of results obtained from wavelet analysis was assessed against the null hypotheses that the signal is generated by a stationary process with a theoretical red noise power spectrum (Grinsted et al., 2004). All calculations were performed in MATLAB software basing on a script developed by Grinsted et al. (2004).

The principal components analysis (PCA) was applied to identify independent variables shaping water temperature variability in relation to abiotic components of the physical environment. Component loadings in the PCA analysis were calculated based on 17 variables including hydrological (8), meterological (5) and physical (4) parameters such as: minimum, maximum, median, average, amplitude and coefficients of variability of water temperature (T_w *Min*, T_w *Max*, T_w *Me*, T_w *Av*, T_w *Amp*, and T_w C_v, respectively), minimum, maximum, average, and amplitude of air temperature (T_a *Min*, T_a *Max*, T_a *Av*, and T_a *Amp*, respectively), precipitation totals (P), average stream discharge and coefficient of variability of the stream discharge (Q *Av* and Q C_v, respectively), elevation (E), catchment area (A), channel slope (S) and afforestation degree (F). Air temperature data and precipitation totals were aggregated as the annual values, while T_w *Min*, T_w *Max*, T_w *Me*, T_w *Av* were calculated for the whole analysed period of time. T_w *Amp* was calculated as the difference between maximum and minimum values of water temperature recorded in the whole analysed period of time. T_a

Table 1
Characteristics of monitoring sites.

	Valley	Stream/ spring/ lake	ID	Q (m^3s^{-1})	E (m a.s.l.)	A (km^2)	S (%)	F (%)	Moraine	Geology
1.	Chochołowska	Wyżni Chochołowski Stream	*S1*	0.164	1183	2.94	25.20	39.2	Y	CR
		Jarząbczy Stream	*S2*	0.175	1178	4.42	17.70	40.6	Y	CR
		Chochołowski Stream (near Starorobociański)	*S3*	0.725	1028	10.00	4.70	79.5	Y	CR
		Chochołowskie Vaucluse Spring	*V1*	0.655	986	–	–	–	N	CB
		Chochołowski Stream (Polana Huciska)	*S4*	1.100	972	18.00	7.51	96.3	Y	TR
		Chochołowski Stream (Siwa Polana)	*S5*	1.176	912	34.33	2.18	90.5	Y	TR
2.	Lejowa	Lejowy Stream	*S6*	0.132	941	4.75	7.83	80.5	N	CB
3.	Kościeliska	Dolinczański Stream	*S7*	0.097	1160	1.78	22.35	20.0	Y	CR
		Pyszniański Stream	*S8*	0.321	1143	5.00	12.58	13.3	Y	CR
		Lodowe Vaucluse Spring	*V2*	0.444	999	–	–	–	N	CB
		Miętusi Stream	*S9*	0.095	980	6.02	8.86	84.5	MX	CB
		Kościeliski Stream (Brama Kantaka)	*S10*	1.655	950	33.80	2.22	88.6	Y	TR
		Kościeliski Stream (Kiry)	*S11*	1.984	945	34.71	1.44	92.8	Y	TR
4.	Małej Łąki	Małołącki Stream	*S12*	0.104	948	5.57	12.96	97.2	MX	CB
5.	Strążyska	Strążyski Stream	*S13*	0.112	946	3.75	12.64	86.1	N	CB
6.	Białego	Biały Stream	*S14*	0.074	941	3.83	19.21	86.8	N	CB
7.	Bystrej	Goryczkowe Vaucluse Spring	*V3*	0.533	1183	–	–	–	N	CR
		Bystre Vaucluse Spring	*V4*	0.264	1167	–	–	–	N	CB/CR
		Bystra Stream (downhill)	*S15*	0.565	1152	7.78	8.10	68.5	Y	TR
		Bystra Stream (Kuźnice)	*S16*	0.426	1021	12.23	7.87	77.7	Y	TR
8.	Olczyska	Olczyskie Vaucluse Spring	*V5*	0.444	1056	–	–	–	N	CB/CR
		Olczyski Stream (Polana Olczyska)	*S17*	0.479	1029	4.59	9.22	93.7	N	CB/CR
		Olczyski Stream (Jaszczurówka)	*S18*	0.427	913	8.20	5.73	93.8	N	CB/CR
9.	Suchej Wody	Czarny Staw (Gąsienicowa Valley)	*L1*	51 m*	1624	–	–	–	Y	CR
		Koziarczyska Vaucluse Spring	*V6*	0.144	913	–	–	–	N	CB
		Sucha Woda Stream	*S19*	0.605	924	25.84	3.42	86.4	N	TR
10.	Filipki	Filipczański Stream (Małe Ciche)	*S20*	0.430	869	10.00	5.70	86.4	MX	CB
11.	Białka	Przedni Staw (the Valley of the Five Polish Lakes)	*L2*	34 m*	1668	–	–	–	Y	CR
		Roztoka Stream	*S21*	0.570	1031	13.42	13.51	39.0	Y	CR
		Morskie Oko	*L3*	50 m*	1395	–	–	–	Y	CR
		Rybi Stream (Wanta)	*S22*	0.639	1170	10.59	8.69	52.4	Y	CR
		Spod Wołoszyna Stream	*S23*	0.192	996	3.50	5.09	93.9	Y	CB/CR
		U Lisów Stream	*S24*	0.193	961	4.00	13.29	88.7	Y	CB/CR

S1-S24 – streams, *L1-L3* – lakes, *V1-V6* – vaucluse springs, * – an approximate depth of lakes, Q – discharge, E – elevation, A – catchment area, S – stream slope, F – afforestation degree, MX – mixed, CR – crystalline, CB – carbonate, TR – transit.

Amp was calculated for the annual values. The number of the most important factors was determined based on the Kaiser criterion. Factor loadings ≥ 0.45 were used to indicate significant correlations.

The choice of particular parameters and restricting the PCA analysis to streams was intentional. The minimum and maximum water temperatures actually differentiate investigated streams to those, which are recharged by vaucluse springs and those, which are not. This is because streams recharged by vaucluse springs exhibit higher minimum water temperature (water temperature never drops to 0 °C) and lower maximum water temperature. In turn, the parameters such as average, maximum, and minimum annual air temperatures and precipitation totals describe climatic conditions in the studied area. Therefore, the greater the differences between meteorological characteristics and parameters defining the thermal conditions of streams (water temperature in streams), the more likely is the impact of other factors, e.g. topographic or hydrogeological on stream water temperature.

4. Results

4.1. Water temperature fluctuations in surface waters

The analysis of time series showed that data obtained from lakes are characterised by wider interquartile range and contain more extreme maximum values when compared to data from streams and springs (Fig. 2). Wide temperature fluctuations have also been observed in some of the streams such as *S20–S22* and *S6*. It is also visible that the distribution of points shows a right skewness because the majority of points are located above the median value. In contrast to lakes, vaucluse springs displayed a relatively constant water temperature over the year and a smaller spread of values, with water temperatures rarely exceeding 7˚C. The Lodowe spring (*V2*) is of particular interest because the amplitude of water temperature fluctuations during the year never exceeded 1˚C. It can also be noted that water temperature data from vaucluse springs are pretty symmetrically distributed. Roughly the same applies to streams because the median value is located in the middle of the box (Fig. 2).

Water temperature maxima varied among sites more than minima that are limited by the freezing point of water. During the investigated period of time, maxima of water temperature in lakes and in a vast majority of streams predominantly occurred in August owning to reduced water levels and increased atmospheric heating. In the case of vaucluse springs, the maxima of water temperature were frequently recorded in September. Among streams, the highest water temperatures (greater than 15 °C) occurred at sites *S20*, *S21* and *S22* (Fig. 2). The average water temperature among streams was very similar (4.9 ± 1.1 °C). The minima of water temperature in streams were frequently observed during winter, from December to March. In lakes, the minima of water temperature usually occurred in an extended period of time, from November till May. Karst springs (*V1-V6*) and streams fed by karst springs (e.g., *S15, S17*) exhibited the warmest minimum water temperature (Fig. 2).

4.2. Factors controlling water temperature variability in streams

According to the PCA analysis, water temperature variability in streams is shaped by four independent factors that together explained 88.97% of the total variability (Table 2; Fig. 3). The first factor (*F1*) explained the maximum variance and subsequent factors explained progressively smaller portions of the total variance.

First factor (*F1*) explained 48.54% of the variability in the data set. It is tightly bound with the altitudinal zonation (Table 2). It describes the negative relation between air and water temperature and physical

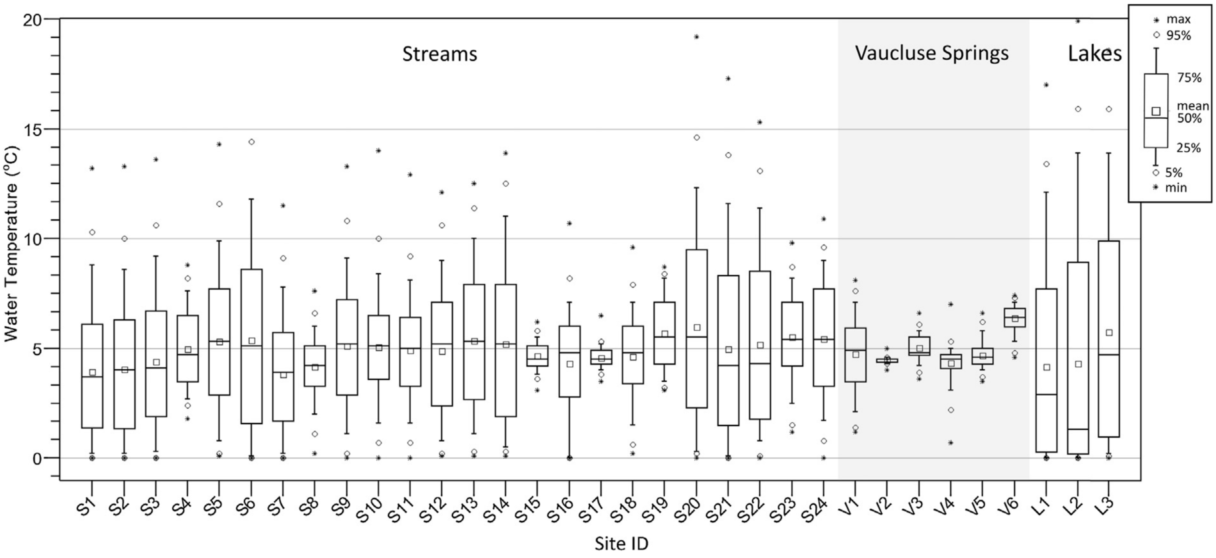

Fig. 2. Water temperature boxplots for each monitoring site for the period from November 2009 to October 2015.

characteristics of the stream. This dependence can be expressed by the relation: the higher air (F_L: T_a *Av*, T_a *Max* = 0.96, T_a *Amp* = 0.90, T_a *Min* = 0.89) and water temperature (F_L: T_w *Me* = 0.90, T_w *Av* = 0.83), the lower elevation of the measuring point (F_L: $E = -0.94$), the lower precipitation amounts (F_L: $P = -0.90$), and slightly lower slope of the stream (F_L: $S = -0.63$). This relation reflects the vertical zonation of climatic conditions and vegetation cover in high mountain regions.

Second factor (*F2*) explained 22.54% of the variability and is associated with the thermal and hydrological regime of the stream (Table 2). It expresses a negative relation: the lower water temperature variability (F_L: T_w $C_v = -0.95$), amplitudes (F_L: T_w *Amp* = −0.93) and maxima (F_L: T_w *Max* = −0.91), the higher the minima of water temperature (F_L: T_w *Min* = 0.85), and slightly higher average discharge of the stream (F_L: *Q Av* = 0.45).

Third factor (*F3*) explained 12% of the variability (Table 2). It describes the negative relation: the higher average discharge of the stream (F_L: *Q Av* = 0.82), the greater the area of the catchment (F_L: $A = 0.75$), and lower the slope of the stream (F_L: $S = -0.61$). This factor was identified as 'hydrologic'.

Fourth factor (*F4*) explained barely 5.89% of the total variability (Table 2) and it does not describe any relation because it only controls

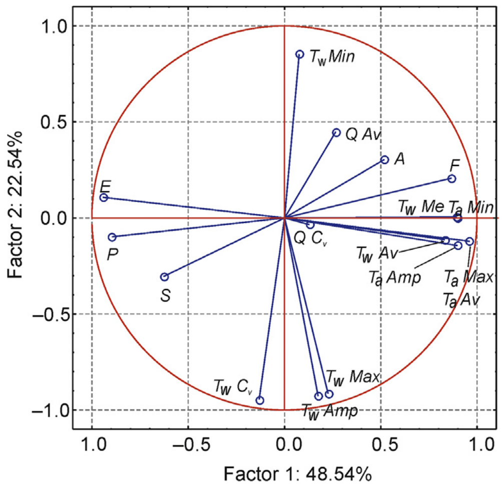

Fig. 3. Principal Component Analysis (PCA) – the projection of the variables on the factor plane (see details in Table 2).

Table 2
Results of the PCA analysis showing variables and corresponding factor loadings (F_L). Factor loadings ≥0.45 marked in bold.

Parameter			Index	*F1*	*F2*	*F3*	*F4*
Hydrological	Water Temperature (T_w)	Min	T_w *Min*	0.08	**0.85**	−0.18	0.10
		Max	T_w *Max*	0.23	**−0.91**	0.28	−0.03
		Amplitude	T_w *Amp*	0.17	**−0.93**	0.26	−0.09
		Median	T_w *Me*	**0.90**	0.00	−0.26	0.07
		Average	T_w *Av*	**0.83**	−0.11	−0.08	0.08
		C_v	T_w C_v	−0.13	**−0.95**	0.16	0.04
	Discharge (*Q*)	Average	*Q Av*	0.27	**0.45**	**0.82**	−0.13
		C_v	*Q* C_v	0.13	−0.03	0.23	**0.96**
Meteorological	Air Temperature (T_a)	Average	T_a *Av*	**0.96**	−0.12	−0.13	−0.02
		Max	T_a *Max*	**0.96**	−0.12	−0.14	0.00
		Min	T_a *Min*	**0.89**	0.00	−0.07	−0.14
		Amplitude	T_a *Amp*	**0.90**	−0.14	−0.17	0.07
	Precipitation Amounts		*P*	**−0.90**	−0.10	0.13	0.08
Physical	Elevation (*E*)		*E*	**−0.94**	0.11	0.08	−0.04
	Catchment Area (*A*)		*A*	**0.52**	0.30	**0.75**	−0.05
	Channel Slope (*S*)		*S*	**−0.63**	−0.30	**−0.61**	0.03
	Afforestation Degree (*F*)		*F*	**0.87**	0.21	−0.14	−0.04
Accounted variance (%)			*Var*	48.54	22.54	12.00	5.89

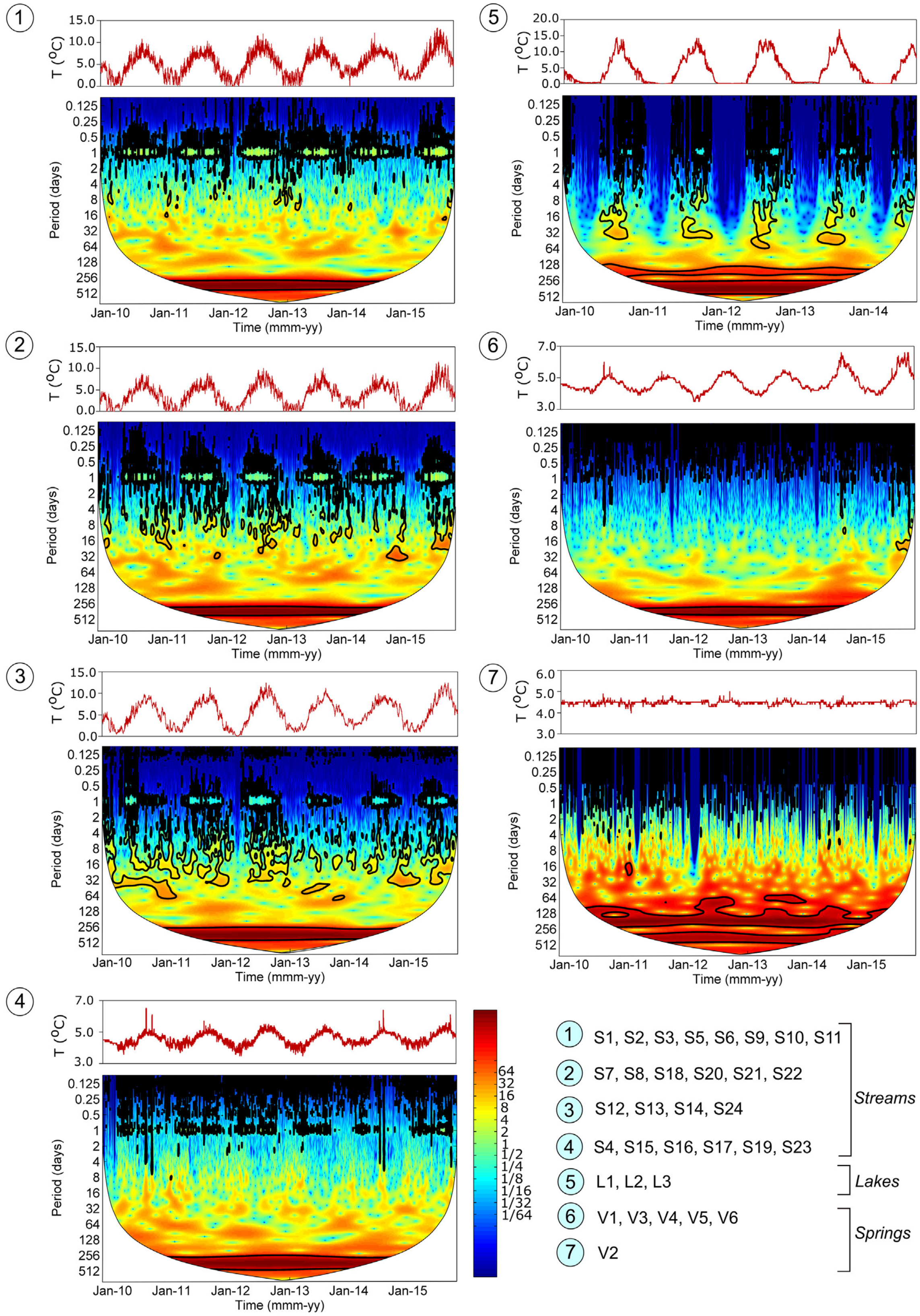

Fig. 4. Wavelet power spectra of water temperature time series: 1st configuration (example: the Miętusi Stream), 2nd configuration (example: the Dolinczański Stream), 3rd configuration (example: the Strążyski Stream), 4th configuration (example: the Olczyski Stream), 5th configuration (example: Czarny Staw Gąsienicowy Lake), 6th configuration (example: the Olczyskie Vaucluse Spring), 7th configuration (example: the Lodowe Spring). The upper window shows corresponding time series. Black contour lines designate the 5% significance level against the red noise. Colour bar shows the wavelet power normalised by variance. Blue colours indicate weak wavelet coefficients while red colours large wavelet coefficients. The white area located outside of the power spectrum represents the cone of influence. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Significant periodicities in the wavelet power spectra.

ID	Periodicities					Type of configuration
	Daily	Weekly	8–30 Days	Half year	Annual	
S1	X				X	1
S2	X				X	1
S3	X				X	1
S5	X				X	1
S6	X				X	1
S9	X				X	1
S10	X				X	1
S19	X				X	1
S20	X				X	1
S7	X	X			X	2
S8	X	X			X	2
S18	X	X			X	2
S21	X	X			X	2
S12	X		X		X	3
S13	X		X		X	3
S14	X		X		X	3
S22	X		X		X	3
S24	X		X		X	3
S4	X *dampen*				X	4
S11	X *dampen*				X	4
S15	X *dampen*				X	4
S16	X *dampen*				X	4
S17	X *dampen*				X	4
S23	X *dampen*				X	4
L1	X *dampen*		X	X	X	5
L2	X *dampen*		X	X	X	5
L3	X *dampen*		X	X	X	5
V1					X	6
V2				X	X	7
V3					X	6
V4					X	6
V5					X	6
V6					X	6

the variability of stream discharge (F_L: $Q\ C_v = 0.96$).

4.3. Periodical patterns of water temperature

In majority of cases, water temperatures in streams followed an expected temporal pattern reflecting seasonal changes in air temperature. Wavelet analysis of all 33 wavelet power spectra enabled to detect several periodical patterns in time series including: daily, weekly, 8–30 days, half-year and annual, which occur in 7 different types of configurations (Fig. 4; Table 3). The results showed that one characteristic configuration of patterns can be assigned to lakes and two configurations of patterns to vaucluse springs. Among streams, four distinct configurations of temporal patterns were found.

All temporal patterns in the wavelet power spectrum were distinguished based on the statistical significance of periods (greater than 95% confidence level) occurring in the wavelet power spectrum, their length and occurrence in time (Fig. 4, Table 3). Some of periodicities were marked as 'dampen' indicating either a less strong or narrower periodic band. For the sake of simplicity, similar wavelet power spectra of time series were arranged into the same type of configuration. Due to the limited space, only one exemplary wavelet power spectrum for each type of configuration was presented.

As identified from the wavelet power spectra, the first type of configuration contains a strong diurnal cycle occurring in a warm period of the year and annual cycle (Fig. 4; Table 3). The wavelet power spectra of the second configuration contains additional intermittent fine-scale oscillations concentrated at the weekly period band occurring in late summer that indicates localised features of temporal variations. The third type of configuration displays an additional periodicity located in elongated period band between 8 and 32 days that appear intermittently (Fig. 4; Table 3). It is characteristic for lower reaches of independent streams (*S12*, *S13*, *S14* and *S24*) (Fig. 1). Notably, medium frequency oscillations that are displaying in the wavelet power spectrum take the form of single isolated patches of varying amplitudes rather than a persistent band. This phenomena is probably related to fast water circulation, which causes rapid changes in water temperature.

As opposed to the first configuration, the fourth configuration shows a weak diurnal cycle and strong annual cycle (Fig. 4; Table 3). It seems that streams arranged into this type (*S4*, *S15*, *S16*, *S17*, *S19* and *S23*) are less sensitive to daily fluctuations of air temperature. In fact, some of them are located below the inflow of karstic groundwaters (Fig. 1) that generally display low frequency oscillations, therefore the diurnal cycle in those time series is far less pronounced. It especially pertains to the Olczyski stream (*S17*), which is fed by groundwaters from the Olczyskie vaucluse spring (*V5*); and the Bystra stream (*S15*), which is recharged partially by groundwaters coming from the Bystre vaucluse spring (*V4*) and the Goryczkowe vaucluse spring (*V3*).

The wavelet power spectrum of the fifth configuration is representative for lakes located at high altitudes in the eastern part of the Tatra Mts. (*L1*, *L2* and *L3*), and contains four distinct periodicities: weak and short diurnal periodicity, intermittent periodicity between 8 and 32 days band, semiannual (half year), and annual (Fig. 4; Table 3). The occurrence of semi-annual cycle in lakes is associated with temporal freezing of the upper layer of the water column, which usually lasts up to 6 months, from December do the end of April.

Water temperature power spectrum of the sixth configuration contains solely a single periodicity at the annual timescale and is devoid of the diurnal cycle. It is characteristic for vaucluse springs (*V1*, *V3*, *V4*, *V5* and *V6*), which exhibit relatively low and stable water temperature (Fig. 4; Table 3). Over the wintertime, water temperature in vaucluse springs remains constant as opposed to lakes that exhibit deeper minima due to the temporal presence of ice cover. In contrast to the other vaucluse springs, the Lodowe spring (*V2*) alone represents the seventh type of configuration containing an additional periodicity corresponding to the semiannual cycle (half year) (Fig. 4; Table 3). This example demonstrates that water temperature fluctuations in the Lodowe spring (*V2*) reflect a secondary contribution, which might be caused either by combined local forcing or site-specific characteristics (*e.g.*, greater alimentation area).

It is also visible that vaucluse springs can significantly modify thermal patterns even in different stretches of the same stream. Depending on the distance from the vaucluse spring different configurations of temporal patterns can be observed such as between *S4* and *S5* supplied by *V1*; between *S17* and *S18* recharged by *V5*; and between *S15* and *S16* supplied by *V3* and *V4* (Figs. 1 and 4; Table 3).

5. Discussion

The present study has revealed that surface waters in the Tatra Mts. display relatively high temporal and spatial heterogeneity of thermal conditions. It has been demonstrated that temporal fluctuations of water temperature depend not only on the type of analysed system (i.e., lake, stream, or spring), but also on site-specific characteristics. Streams that were expected to behave in a similar manner showed the greatest diversity in configurations of periodical patterns (i.e., 4 different types). Aside from the daily and annual cycles, the intermittent 8–32 days and weekly periodicities were also noted (Fig. 4; Table 3). As opposed to vaucluse springs, lakes reflected the configuration with the highest number of periodical patterns. Relatively more cycles were detected in the warm period of year (April-October) than in the cold period (November-March). The observed increase in periodicity and variability of water temperature in the warm period of year are in close agreement with earlier findings of Arismendi et al. (2013) and Rajwa-Kuligiewicz et al. (2016).

In the PCA analysis, the projection of cases (streams) on the factor plane defined by the first two factors (Fig. 6) showed a clear contrast in water temperature between small streams located close to the mountain ridges (e.g., *S1*, *S7* and *S8*) and those located at lower elevations in mountain valleys (e.g., *S5* and *S20*). This relation is associated with the altitudinal zonation in the Tatra Mts., which is localy strengthened by hydrogeological conditions associated with the presence of high discharge karst springs in the middle sections of valleys. The analysis of the chemical composition of waters in the Chochołowska Valley indicated that waters from the Chochołowskie vaucluse spring (*V1*) strictly determine the water chemical composition of the Chochołowski stream (Żelazny et al., 2011). Our results showed, however, that water temperature of the Chochołowski stream is controlled by the vaucluse sping in a quite different way. The results of wavelet analysis showed that vaucluse springs tend to suppress the daily cycle of water temperature in streams located below the groundwater inflow (Fig. 4, configurations 1 and 4). Then, after reaching a certain distance downstream, the daily cycle of water temperature begins again but in a different temperature range.

Second identified relation in the PCA analysis (Fig. 6) showed a clear distinction between independent streams (e.g., *S6* and *S14*) and those, which entirely originate from vaucluse springs (e.g., *S15* and *S17*). The results showed that the important role of vaucluse springs is manifested in the increase of discharge and minimum water temperature in the lower sections of gaining streams and dampening of the daily cycle in the section of the stream located directly below the inflow of karstic groundwaters (Table 2).

The relation between different configurations of temporal patterns (Fig. 4) and statistical measures describing water temperature variability (Fig. 2) could not be fully expalained. Our results suggest that relatively weak correlations between water temperature and environmental variables may result from the presence of other factors that were not taken into account in the PCA analysis.

5.1. The dependence of water temperature patterns on weather conditions, discharge and stream characteristics

One of the most common features of all analysed time series is the presence of annual cycle (Fig. 4; Table 3) that has the strongest intensity and reflects seasonal changes in the temperate climate zone. Stream water temperature is regulated by the air temperature through the heat exchange at the air-water interface (e.g., Webb et al., 2003; Mohseni et al., 1998). This is especially visible for greater timescales and is valid for the entire temperature range above 0 °C. According to Bogan et al. (2003) the full effect of weather on stream water temperature is clearly visible at the weekly timescale providing that heat inputs are solely from the atmosphere and streams are located far from groundwater or meltwater sources. Our results have shown a strong linkage between water temperature and air temperature, which is conditioned by the elevation above sea level (Table 2). The mean annual water temperature of streams tends to coincide with the average annual air temperature for a given climatic belt indicating an important role of climatic vertical zonation in mountain areas (Niedźwiedź, 1992). It however, may vary significantly depending on catchment size and groundwater inputs (Erickson and Stefan, 2000).

A major role in heat exchange is played by insolation, which increases daily amplitudes of water temperature in a warmer period of the year. During winter (December-February) diurnal fluctuations of water temperature either vanish or almost disappear (Brown et al., 2010; Łaszewski, 2013; Rajwa-Kuligiewicz et al., 2016). The impact of solar radiation on water temperature is strongly pronounced in unforested catchments and upper parts of the Tatra Mts. located above the tree line. The shading caused by riparian vegetation prevents from large changes in water temperature, whereas the removal of riparian tree cover may dramatically increase the incoming shortwave radiation. An immediate effect of shading on water temperature has been documented elsewhere (Brown et al., 2010; Johnson, 2004; Johnson and Jones, 2000; Kalny et al., 2017).

Most often water temperature fluctuations in streams are related to the amount and depth of water in the stream. Shallow streams tend to be influenced by conductive heat flux between streambed and water column, which becomes insignificant for timescales longer than one day (Stefan and Sinokrot, 1993). By contrast, streams that carry larger volumes of water have a greater capacity for heat storage, thus are less responsive to alternations in the energy budget (Brown, 1969). This particularly refers to the lower reaches of streams (i.e., gaining streams) that are either recharged by vaucluse springs or collect water from larger areas (Fig. 1). The results showed that stream discharge increases with increasing area of the catchment and decreasing channel slope (Table 2). The PCA analysis showed that stream discharge affects mainly the extremes of water temperature such as minima and maxima, amplitudes as well as the coefficients of variability (C_v). Worth noting is also the relation between those metrics: the lower the coefficients of variability (T_w C_v), amplitudes (T_w *Amp*) and maxima (T_w *Max*) of water temperature the higher the minima of water temperature (T_w *Min*) (Table 2). This relation reflects lower reaches of streams (i.e., gaining streams), which exhibit higher mean water temperature due to the lower elevation, and higher minima of water temperature owning to the recharge from vaucluse springs (Table 2; Fig. 6). By contrast, the mean and median values of water temperature are primarily shaped by the altitudinal zonation (Table 2). Surprisingly, the variability of discharge in streams (Q C_v) appears to be unrelated to water temperature variability (T_w C_v) or to other variables, as evidenced by small factor loadings (Table 2). Although somewhat inconclusive, the results suggest that potential errors in the estimation of stream discharge might be more significant at high and low flows. This can additionally be enhanced by higher variability of flow in intermittent streams in which the flow can disappear in bed material (e.g., *S19*).

5.2. Groundwater impact on stream water temperature

The results showed that the wavelet power spectrum of the third configuration displayed a greater number of periodicities in time series. Notably, streams arranged into this type (*S12-S14* and *S24*) are located in carbonate catchments and are recharged by waters of both deep and shallow circulation such as shallow groundwaters percolating in rock debris and those circulating within the underground system of vacuums and karstic corridors, respectively. Conversely, smaller streams flowing in the crystalline part of the Tatra Mts. have relatively fast and shallow circulation with a dominance of surface runoff. Their flowrate depends on the amount of precipitation, whereas their temperature is conditioned by the mean air temperature owning to the shallowness of circulation and small water depths (Łajczak, 1996). Apparently, the presence of moraine covers on the crystalline basement may act as a transient storage significantly elongating the circulation of water.

Undoubtedly, water temperature in mountain streams is largely controlled by the inputs of cool water from snowmelt as well as hyporheic flows and groundwaters. Groundwaters tend to moderate water temperature fluctuations in temperate climate zone (Ward, 1985). Gaining streams recharged by groundwaters have relatively stable water temperature regimes (Constantz, 1998; Crisp et al., 1982) compared to running waters located far downstream of the recharge zones, which tend to reflect higher temporal variability (Tague et al., 2007; Webb and Zhang, 1999). Therefore, close to springs, the thermal behaviour of streams is not necessarily in equilibrium with energy fluxes affecting lower parts of the water course (Stefan and Sinokrot, 1993; Sinokrot et al., 1995). Our results have shown that streams assigned to the fourth configuration (*S4, S15-S17, S19* and *S23*) reflected little variability because their temperature is conditioned by the recharge from karst springs. For instance, the hydrological regime of the Olczyski stream (*S17*) for the most part of the year is shaped by the outflow from the Olczyskie vaucluse spring (*V5*), especially in winter, streamflow is derived entirely from the spring (Małecka, 1997; Małecka and Humnicki, 1989). Those types of streams are less sensitive to weather

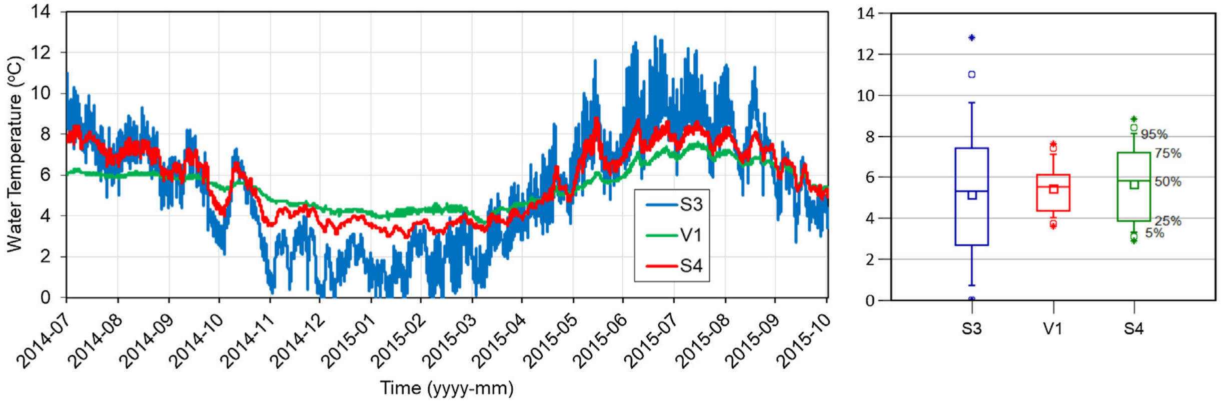

Fig. 5. Time series of water temperature and corresponding boxplots: *S3* – the Chochołowski stream above the inflow from the vaucluse spring, *V1* – the Chochołowskie vaucluse spring, *S4* – the Chochołowski stream below the inflow form the vaucluse spring.

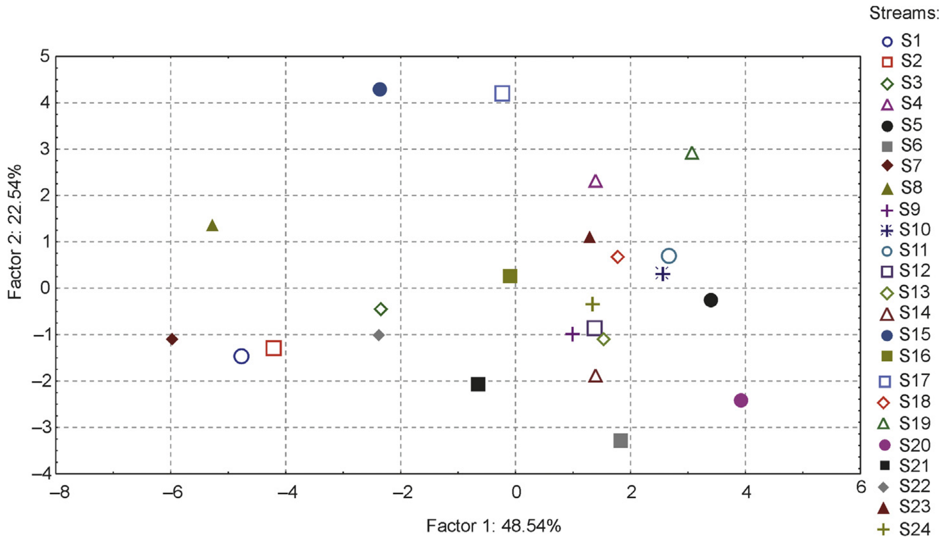

Fig. 6. Sample ordination plot showing the projection of cases (streams) on the factor plane.

conditions (Brown and Hannah, 2008) due to the strong influence of advective inputs of cold water (Tague et al., 2007). Cold water inflows that originate from large groundwater aquifers can strongly modify reach to segment-scale stream water temperature and may alter stream temperature patterns over large downstream distances (Tague et al., 2007). According to Webb and Zhang (1999) groundwaters can alter the heat budget of streams in two different ways, having a cooling effect in summer and warming in winter. It is because karst springs exhibit the warmest minimum water temperature (Brown and Hannah, 2008). This situation is clearly visible when comparing time series of water temperature and corresponding boxplots of temporal variability obtained from upstream and downstream sections of the Chochołowski stream and the Chochołowskie vaucluse spring itself (Fig. 5). Given the above, the contribution of groundwaters, on the one hand tends to lower and stabilise water temperature in streams by reducing the amplitudes of daily fluctuations, on the other, prevents from ice sheet forming during the wintertime (Żelazny et al., 2015).

5.3. Thermal inertia of spring waters

In general, groundwater temperature is roughly equal to the temperature of geological formation from which the groundwater originates (Sinokrot et al., 1995; Genthon et al., 2005). Spring waters from fractured aquifers tend to exhibit relatively small amplitudes of water temperature (Manga, 1999). Low temporal variability of water temperature indicates that the majority of spring water is confined to the deeper part of the aquifer, which is located beneath the zone of seasonal temperature changes (Szczucińska and Wasilewski, 2013). It is presumably associated with a transit time of recharge waters flowing through a well-developed karst network. In such cases, the elongation of flow paths does not give a noticeable increase in heat exchange (Linan Baena et al., 2009). This feature is evident for all karst springs.

According to Pitty et al. (1979) the variability of water temperature in karst springs may have different origins. In shallow and fast flowing groundwaters, the seasonal rhythm can be associated with air and soil temperature prevailing during rainfall events. Spring waters can also be influenced by air temperature as they move through a fissure network or a soil cover overlying the opening of the spring. Finally, water temperature in springs may be altered by the air circulation in caves, caverns and voids, especially in places of the direct contact with air temperature.

Vaucluse springs that were arranged to the sixth configuration (*V1, V3, V4, V5* and *V6*) did not show any consistent cyclical pattern besides the annual cycle. In this context, a distinct behaviour of the Lodowe spring (*V2*) (Fig. 4; Table 3) may potentially be associated with an additional water supply from different parts of the recharge area, which was suggested in earlier studies of Wolanin and Żelazny (2010), who documented semiannual changes in the chemical composition of the Lodowe spring. The Lodowe spring is a typical ascending spring where the water flows out of limestone at the area of few tens of m^2. According to Małecka (1997), water hardness of the Lodowe vaucluse spring increases after rainfalls, which can be explained by the activation of water stagnating in hollows that do not take part in the circulation at low water stages. Eventually, both rainfalls and snowmelt episodes may also initiate an additional outflow from gullies situated above the spring, which drains the excess of water from the karst aquifer.

5.4. Water temperature fluctuation patterns in the Tatra' lakes

As opposed to streams and springs, lakes undergo seasonal thermal stratification resulting in the vertical differences in water density. This stratification however, tends to be deformed during the year by meltwater inflows and strong winds. The latter generate waving that enhances vertical circulation of water masses leading ultimately to mixing phenomenon. This is commonly known as the winter stagnation, and spring and autumn turnover (homothermy). Summer stratification (anothermy) in the Tatra lakes most frequently establishes during the warm period of the year. During the cold period, surface cooling promotes a reverse thermal stratification (catothermy) and lowering of the water level. Most recent studies revealed that short periods of homothermy in Morskie Oko lake (up to 1 week) most frequently occur in May and November (Choiński et al., 2015).

The diurnal cycle occurring in time series is originating from changes in air temperature as evidenced by a strong positive correlation between air and water temperatures in the Tatra lakes (Ptak et al., 2017). According to the earlier studies in Morskie Oko lake, clearly defined diurnal cycles from May to November reach approximately 10 m depth (Choiński, 2010; Choiński and Łyczkowska, 2008). Our results showed, however, that daily cycles observed during summer months are limited to a relatively short period of time indicating equally short period of summer stratification (Fig. 4). The periodicities of about 8–32 days that occur in the warm period of the year may be related to these short periods of summer stratification that are preceded by equally short periods of homothermy (Fig. 4). Other small scale variability in water temperature can be attributed to varied sources such as tributary inflows or groundwaters that infiltrate into lakes from thick covers of Quaternary sediments (moraines). Notably, the annual cycle observed in time series is related to climatic conditions, semi-annual cycle is, in turn, associated with the presence of ice cover.

The timing of seasonal processes of thawing, warming, and cooling may however vary depending on the altitude. Łajczak (1982) showed that the duration of ice cover in the Tatra lakes differs markedly depending on whether it is northern and southern exposure. Šporka et al. (2006) clarifies that although, the timing of ice-off among the lakes is linearly dependent on elevation above sea level, cooling seems to be independent of elevation, as well as lake area and water depth (Novikmec et al., 2013). The largest temperature differences in surface water temperature between individual lakes most frequently occur in mid-July as a result of altitudinally dependent differences in the timing of ice-off among the lakes (Šporka et al., 2006). At the beginning of 20th century the Tatra lakes were permanently covered with ice of about 10.5 months (Szaflarski, 1932). More recent studies in Morskie Oko lake suggests that freeze-up of lake is delayed in time of about 4.1 days per decade, while the ablation tends to take place earlier at a rate of 4.5 days per decade (Pociask-Karteczka and Choiński, 2012). These findings confirm a general trend of decreasing ice duration on lakes throughout the Northern Hemisphere and serve as an evidence of climate warming in this part of Europe.

6. Conclusions

The results obtained from this study have shown that water temperature fluctuations in waters of the Tatra Mts. depend not only on the type of analysed system (stream, spring or lake), but also on the altitudinal zonation and hydrogeological conditions. The results demonstrated that groundwaters exert a strong influence on the stability of water temperature and thereby indicate the dominant role of hydrogeology in shaping the thermal and hydrological regime of surface waters.

The combination of two methods, namely the wavelet analysis and PCA analysis, allowed for a better explanation of the observed variability in water temperature time series. Wavelet analysis enabled the identification of natural periodicities in time series that could not be captured using standard statistical measures such as mean or interquartile range, whereas the PCA analys helped to determine factors such as atitudinal zonation and hydrological conditions responsible for the observed variability.

The results showed that most vaucluse springs, except the Lodowe spring, reflected the simple type of configuration with a single annual periodicity. Streams and lakes exhibited the complex types of configurations, containing a growing number of periodical patterns. In fact, the complex type of configuration seems to be the most expected due to the location of the studied area in the temperate climate zone with distinct altitudinal zonation in mountainous areas.

It has been demonstrated that the wavelet power spectra of water temperature fluctuations in lakes are markedly different from those obtained from streams and springs. In lakes located at high altitudes the additional half-year periodicity and weak diurnal periodicity are apparent. Streams in the Tatra Mts. represent the most diversified types of configurations. Most of them contain two main frequency components reflecting diurnal and annual cycle. The hydrogeology of the area appeared as the main factor that strongly determines the number of periodicities in time series.

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