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Stream water temperature:
a short review with special reference to diurnal dynamics

Abstract
Dynamic changes in stream water temperature are caused by thermal energy exchange at the interface between the water and the atmosphere, and between the water and the streambed. This heat flux is the result of physical processes which are stimulated by external drivers that control water temperature both in temporal and spatial scales. For streams, the most characteristic are diurnal fluctuations of temperature. For the purposes of this paper, electronic data loggers were used which allowed a presentation of the diurnal cycles of water temperature in a small lowland river. The measurements confirmed that meteorological conditions have a significant impact on the diurnal dynamics of stream temperature.

Keywords
Stream water temperature • Heat exchange processes • Diurnal dynamics • Data loggers • Świder river.

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Introduction

Temperature is one of the most important characteristics of the quality of flowing waters. It affects other physical and chemical water features and also influences distribution, activity and metabolic rates of all organisms living in the lotic environments (Beschta et al. 1987; Vannote et al. 1980). Because of the importance and high susceptibility to external factors, including anthropogenic influences, extensive studies on stream thermal regimes in temperate climate zone are carried out, particularly in England, Canada and the US. These studies focus on river heat budgets (Benyahya et al. 2012; Hebert et al. 2011; Johnson 2004; Webb & Zhang 1997; 1999), modeling of water temperature (Caissie, El-Jabi & Satish 2001; Deas & Lowney 2000; Mitchell 1999; Mohseni & Stefan 1999; Pilgrim, Fang & Stefan 1998; Westhoff et al. 2007) and temperature relationships between streams and groundwater systems (O'Driscoll & DeWalle 2006). Much attention is also paid to the influence of land cover (Brown et al. 2010; Hrachowitz et al. 2010; Malcolm et al. 2004), riparian vegetation (Beschta 1997), hydraulic parameters of the channels (Gu & Li 2002) and reservoirs (Olden & Naiman 2010). Polish literature on similar issues is decisively less numerous. Gołek (1961) described river water temperature as one of the most neglected hydrological parameters. This gap is partially filled with publications focusing mainly on the temperature of selected streams. Water temperature of the Ropa river was described by Soja (1973) and Wiejaczka (2007a; 2007b; 2011), water temperature of the lower Vistula was presented by Marszelewski & Strzyżewska-Pietrucień (2009) and finally, selected parameters of thermal regimes of the rivers in the Vistula catchment were recognized by Oksiuta (2010).

This paper has two main objectives. The first three sections present a short literature review on the processes and drivers of stream water temperature with special attention given to the diurnal dynamics. The fourth section, based on continuous measurements collected by data loggers in the field experiment, shows examples of daily water temperature cycles in different meteorological conditions. These diurnal dynamics is still poorly recognized in Polish lowland rivers and such field investigations are desirable.

Stream temperature: concept and processes

The temperature of flowing waters is fundamentally dependent on the amount of thermal (heat) energy loaded to the channel (Gu & Li 2002; Poole & Berman 2001). Its value is directly proportional to the amount of thermal energy and inversely proportional to the volume of water in which energy is dispersed. As a result, water temperature can be understood as a measure of the concentration of thermal energy in a stream in a specific time and place and can be described conceptually by the equation given by Poole & Berman (2001):

$$T_w \approx Q_n/V \qquad (1)$$

where T_w – water temperature, Q_n – total net heat energy added to the stream, V – volume of water.

Thermal energy dispersed in water is the result of heat transfer at two interfaces: between the water surface and the atmosphere, and between the water and the streambed (Theurer, Voos & Miller 1984). The most important process is the exchange of thermal energy between the water surface and the atmosphere which was presented by Evans, McGregor & Petts (1998) who compared

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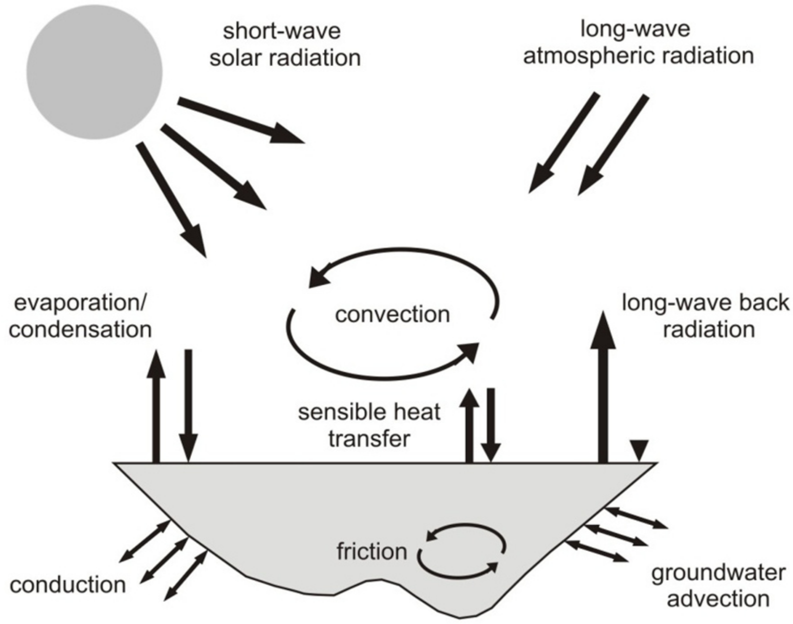

Fig. 1. Main heat exchange processes. Based on Theurer, Voos& Miller (1984)

fluxes forming the heat budget of the river Blithe. They found that 82% of energy is exchanged between the water surface and the atmosphere, 15% between the water and the streambed and the remaining 3% of energy is derived from other sources. Heat flux occurs as the result of physical processes, mainly through radiation, evaporation, convection, conduction, fluid friction and advection (Fig. 1) (Evans, McGregor & Petts 1998; Hannah et al. 2008; Hebert et al. 2011; Theurer, Voos & Miller 1984; Webb & Zhang 1997; 1999). Therefore, the heat budget of a short reach of stream, without tributaries and at a constant flow rate, can be described by the following equation:

$$Q_n \approx \pm Q_r \pm Q_e \pm Q_h \pm Q_{hb} + Q_{fc} \pm Q_a \qquad (2)$$

where Q_n – total net heat energy added to the stream, Q_r – heat flux due to radiation, Q_e – heat flux due to evaporation/condensation, Q_h – heat flux due to sensible heat transfer between air and water, Q_{hb} – heat flux due to streambed conduction, Q_{fc} – heat flux due to fluid friction, Q_a – heat flux due to advection (groundwater, precipitation).

Radiation is the most important non-advective form of heat flux (Webb & Zhang 1997). Thermal energy is transported by electromagnetic waves and does not require physical media (ed. Kożuchowski 2005). The main source of radiation affecting river heat budgets is the sun, but the atmosphere, riparian vegetation, terrain and water also contribute (Deas & Lowney 2000; Theurer, Voos & Miller 1984).

Evaporation is an isothermal transformation of water into vapor, which requires a known amount of heat called the heat of vaporization (ed. Kożuchowski 2005). The rate of evaporation is mainly a function of the temperature of evaporating water (which is a measure of the energy supply) and the water vapor pressure in the air above the liquid (Hebert et al. 2011). It also depends on the wind speed, which determines fast air circulation (Hannah et al. 2008). Condensation is the opposite process to evaporation and results in thermal energy being gained by a stream (Webb & Zhang 1997).

Conduction occurs when the kinetic energy (and thus temperature) of two bodies in contact is different (Theurer, Voos & Miller 1984). In the case of flowing waters, conduction is a process of energy transfer between the water surface and the overlying air (called sensible heat transfer) and between the water and the streambed sediment (Deas & Lowney 2000; Hondzo & Stefan 1994).

Convection is the process of heat transport through the movement and mixing of particles, which significantly affects the amount of evaporation, as well as sensible heat transfer between the water and the overlying air (Theurer, Voos & Miller 1984).

Fluid friction is the least important non-advective process taken into account in the river heat budgets (Webb & Zhang 1999). The portion of the potential energy of the flowing water that is not converted into other forms is converted by this process into thermal energy (Theurer, Voos & Miller 1984).

Advection is the horizontal transfer of bodies with their characteristic properties, such as the amount of thermal energy (ed. Kożuchowski 2005). This means an external supply of water from groundwater inflows, precipitation, tributary inflows and runoff over a hill slope surface (Webb & Zhang 1997; 2004). As a result of mixing, the amount of thermal energy dispersed in a stream may increase or decrease, which depends on the volume and temperature of water added to the stream (Poole & Berman 2001).

Drivers of stream temperature

The intensity of physical processes responsible for heat flux is stimulated by a number of external drivers. They include mainly meteorological parameters, morphological and geological parameters of the channel, shading, stream flow and groundwater inflows (Olden & Naiman 2010; Poole & Berman 2001).

The most important meteorological parameter controlling water temperature of rivers is direct solar radiation (Evans, McGregor & Petts 1998; Hannah et al. 2008; Johnson 2003). Over 99% of the radiant energy emitted by the sun is short-wave radiation i.e. has wavelengths of less than 0.4 microns (ed. Kożuchowski 2005). The intensity of solar radiation incident on the water surface of a stream is a function of latitude, the time of year and topography (Theurer, Voos & Miller 1984). It should also be taken into account that solar radiation is absorbed and diffused by the atmosphere and clouds and is even reflected by the water surface (Deas & Lowney 2000). Despite this, short-wave solar radiation is the main source of energy and is responsible for cyclic changes

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in temperature over time (Malcolm et al. 2004; Webb & Zhang 2004). Ambient air temperature is another driver of water temperature (Evans, McGregor & Petts 1998). It determines the amount of long-wave radiation emitted by the atmosphere (Hebert et al. 2011), and also affects the process of evaporation and condensation as the amount of vapor needed for saturation of the subsurface layer of the air is a function of its temperature (Theurer, Voos & Miller 1984). Air temperature is also a primary factor influencing sensible heat transfer between the water and air (Deas & Lowney 2000). Finally, wind speed affects the rate of evaporation and convection, while cloud cover reduces direct solar radiation and reflects long-wave water radiation (Theurer, Voos & Miller 1984).

Water temperature is also controlled by the morphological parameters of the channel, such as width and depth. Width determines the water surface available for energy exchange (Poole, Risley & Hicks 2001). In consequence, small narrow streams can be totally shaded by riparian vegetation and banks, whereas wide rivers may be fully available for direct solar radiation. The depth of the watercourse affects its heat capacity as a deeper channel reduces the amount of thermal energy that can be potentially absorbed (Poole & Berman 2001). Then, the channel slope determines the amount of thermal energy produced in the volume of water by the process of fluid friction; the greater the slope, the more heat is produced (Webb & Zhang 1997). Finally, the dominant geographical orientation of the river channel has an impact on the time and the size of the absorption of solar radiation during the day (Malcolm et al. 2004). The type of substrate material also plays a significant role in forming water temperature. Every material has a different roughness which influences the intensity of the fluid friction (Theurer, Voos & Miller 1984). Substrate material also affects the amount of heat exchanged in the process of streambed conduction; each type (such as granite, sandstone, limestone but also organic matter, wood or concrete) is characterized by a different coefficient of thermal conductivity (Hondzo & Stefan 1994). The type of the substrate material also influences the size of the hyporheic flow, which reduces the amplitudes of the temperature in streams (Evans & Petts 1997; Johnson 2004).

Shade is responsible for the area of the stream water surface sheltered from direct solar radiation (Beschta 1997) and it can be the result of topography as well as riparian vegetation (Theurer, Voos & Miller 1984). Shade, associated with natural topography, is a function of season, latitude of the area and the dominant channel orientation. Shade related to riparian vegetation depends on the season, height of trees, their crown sizes and density (Theurer, Voos & Miller 1984). Moreover, riparian vegetation causes a significant reduction in the amplitude of water temperature (Brown et al. 2010; Hannah et al. 2008).

Stream flow determines the heat capacity of water. For a higher flow rate, the same heat load causes lower temperature growth than for a lower flow rate (Poole & Berman 2001). In addition, Gu and Li (2002) reported that the maximum water temperature significantly decreases with an increase in flow rate, thus causing the reduction of daily variations in temperature.

Groundwater inflow also plays an essential role in forming stream temperature (Johnson 2004; Webb & Zhang 1997). Its temperature is generally stable, which results in the inflow having a high impact on reducing diurnal and annual amplitudes of the stream temperature (O'Driscoll & DeWalle 2006). The groundwater mixes with the surface water of streams in the hyporheic zone and this area is of great importance to most aquatic insects and fish (Allan 1998).

Each driver of stream temperature is highly variable, both in time and space. It results in dynamic changes in water temperature as well as in forming different thermal regimes (Poole, Risley & Hicks 2001).

Diurnal dynamics of stream temperature

Characteristic fluctuations in water temperature during the day are widely observed in streams in temperate climate (Caissie 2006). Undoubtedly, radiation plays a major part in forming the diurnal heat budget. For example, Evans, McGregor & Petts (1998) found that during the warm summer-autumn study period in the river Blithe the average net short-wave radiation and net long-wave radiation constituted as much as 97.6% and almost 54% of the total channel energy gains and losses respectively. A significant part of the radiation in the river heat budget was also noted by Herbert et al. (2011). In the case of the Catamaran Brook and the Little Southwest Miramichi River in Canada, on average short-wave radiation during the summer study period was responsible for 63% and 89% of the energy gains respectively, while in turn, energy losses from long-wave radiation accounted for 40% and 56% of losses respectively. Similar results were obtained by Webb & Zhang (1997; 1999) in winter conditions. In consequence, changes in the diurnal radiation balance have a dominant influence on the daily course of the stream temperature. However, it is also modified by the effects of other processes. Energy loss due to evaporation is highest in the afternoon hours, which can inhibit temperature growth during this period, especially in summer (Evans, McGregor & Petts 1998; Webb & Zhang 1999). The intensity of sensible heat transfer, which is the second source of energy in most river heat budgets, also changes during the day. The greatest heat flux occurs during the night and in the afternoon, when the highest temperature gradient between the water and the air appears (Hebert et al. 2011; Webb & Zhang 1997). Finally, thermal energy loss due to bed conduction is usually the largest in the afternoon, while at night the direction of conductive heat flux changes and the stream gains energy (Webb & Zhang 1999; Westhoff et al. 2007).

Diurnal fluctuations of water temperature are close to diurnal fluctuations of ambient air temperature, measured near the stream (Wiejaczka 2007a). The minimum values of water temperature are observed in the morning, usually between 06:00 and 09:00, while the maximum values occur most frequently in the afternoon and early evening, between 15:00 and 20:00 depending on the season (Beschta et al. 1987; Caissie 2006). An important parameter of the diurnal cycle is the daily amplitude of water temperature. Its size depends on the intensity of solar radiation as well as the length of the day, so amplitudes change with the annual cycle (Malcolm et al. 2004). The smallest amplitudes are observed in winter and they then increase in spring to reach a peak in summer before decreasing in autumn. Changes in diurnal dynamics of water temperature are also affected by weather conditions (Poole, Risley & Hicks 2001). Amplitudes are generally higher on sunny days and lower on days with cloud cover (Webb & Zhang 1997). The diurnal cycle of temperature is also dependent on other factors, such as stream flow. In fact, a greater volume of water shows greater resistance to weather conditions (Wiejaczka 2007a).

Methods and study area

The empirical part of this paper is based on data derived from measurement carried out in downstream part of the Świder river (Fig. 2), a 99.9 km long tributary of the Vistula River which drains an area of approximately 1,160.70 km^2. The Świder river has an average flow of 4.31 m^3/s (at hydrometric profile Otwock – Wólka Mlądzka). River catchment is characterized by temperate climate with average annual air temperature of 8°C, and average annual precipitation of approximately 600 mm. The study reach is meandering with an average depth of about 50 cm and width of 12 – 15 m. The banks are usually covered with riparian vegetation dominated by willows, poplars and pines. The Świder river can be considered as a good example of small lowland Polish river.

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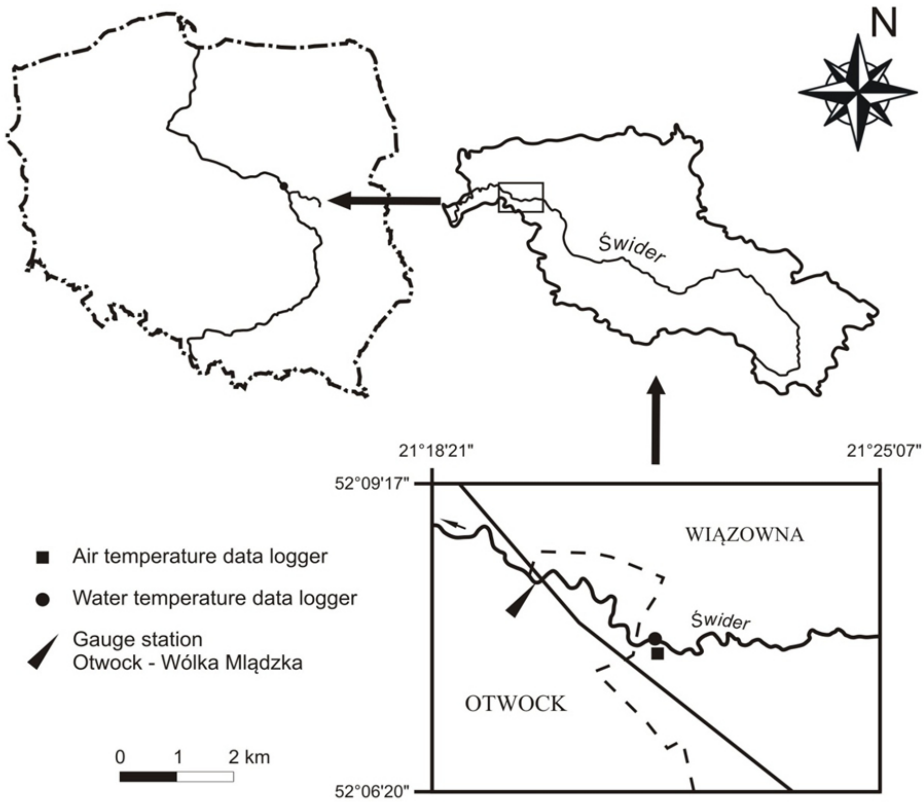

Fig. 2. Study area and data logger deployment places

For the study, the temperature was recorded using two electronic Onset HOBO data loggers (Fig. 3). The first data logger measured water temperature and was placed at a depth of about 50 cm in the middle of the riffle. Good mixing of water molecules at this place caused that cross-sectional temperature gradient was not observed. The accuracy of the device was 0.2 °C, while the resolution was 0.02 °C. The data logger was installed inside a perforated tube made of PVC, which was bolted to a small concrete block. This housing ensured constant contact of flowing water with the device and protection from direct solar radiation, while its appropriate weight stabilized the device during periods of highwater levels. The housing described above allowed for trouble-free operation even under full ice cover. The second data logger was responsible for measuring the air temperature. It was located approximately 120 m from the water temperature data logger and about 20 m from the river bank. The logger was placed on the north wall of an unheated store room in an anti-radiation shield at a height of 2 m above ground level. The accuracy of the device was 0.2°C while the resolution was 0.02°C.Both data loggers were synchronized. The interval between measurements was 30 minutes, which was sufficient to capture dynamic changes in water temperature. Before installation, the devices were calibrated and differences between their measurement results did not exceed 0.1°C.

Diurnal cycles of water temperature are shown for two typical summer and two typical winter days. Each case is presented on the graph and is based on 49 temperature measurements. The daily average flows were obtained from the hydrometric gauge station at Otwock – Wólka Mlądzka, which is located 3 km downstream from the study area. The theoretical context for the results is provided by the findings of heat budget studies (Benyahya et al. 2012; Evans, McGregor & Petts 1998; Hebert et al. 2011; Webb & Zhang 1997; 1999).

Results

The diurnal cycle of water temperature in summer during sunny days is shown in Fig. 4. On 5 July 2012, the daily average air temperature was 24.6°C, the daily average water temperature was 23.6°C and the amplitudes were successively 13.1°C and 3.5°C. The daily average flow was 1.42 m^3/s. The minimum water temperature occurred at 06:30 CEST, while the maximum at 15:30 CEST. The water temperature cycle was similar to a slightly flattened sinusoid. A short, intensive growth phase and then a long phase of decline of temperature were observed. Furthermore, water temperature began to fall early, before the air temperature reached its maximum. This was due to the high intensity of the evaporation process, which contributed greatly to energy losses and reached the maximum efficiency in the afternoon. Presented cycle was typical for days in which the temperature was controlled by radiation factors – short-wave solar radiation which is the main source of thermal energy since the morning till the afternoon, and long-wave water radiation which is responsible for energy losses - reaching the highest values at midnight and in the morning hours.

A different cycle of water temperature is typical for cloudy summer days. On 21 June 2012, the daily average air temperature was 20.0°C, the daily average water temperature was 19.6°C, while the amplitudes were 9.7°C and 1.1°C respectively. The daily average flow was 4.02 m^3/s. The minimum water temperature was recorded at 07:00 CEST and the maximum at 19:00 CEST. The water temperature cycle was definitely aligned and both the growth and decline phases were relatively small (Fig. 5). The slow increase in water temperature observed in the afternoon was the result of sensible heat transfer between the air and the water, which has significant impact during cloudy days. As a result, the temperature growth phase was long and ended shortly before sunset. Decline phases in the morning and

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Fig. 3. Air (left) and water (right) temperature data loggers, with their housings in the study area

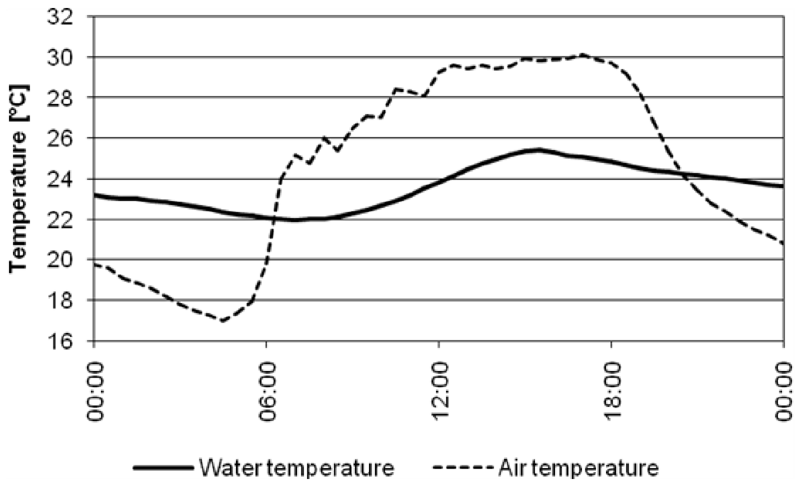

Fig. 4. The 24 hour cycle of the water temperature during a sunny summer day - 5 July 2012

evening were slow which was also affected by the cloud cover that substantially reduced energy loss through reflecting long-wave water radiation.

Another cycle can occur in winter thermal conditions. On 15 January 2012, the daily average air temperature was -2.3°C, the daily average water temperature 1.4°C, while the amplitudes were successively 2.2°C and 1.1°C. The daily average flow was 4.43 m³/s. The maximum temperature was recorded at 00:00 CET and the minimum at 23:30 CET. During that day, the water temperature showed very small dynamics and it was gradually decreasing (Fig.6) in spite of a short and slight growth phase in the afternoon. This increase probably occurred as the result of absorption of short-wave solar radiation which also contributed to the visible increase in the air temperature. However the downward trend was maintained, generally as an effect of emission of long-wave radiation by water, leading to its continuous cooling. This process was clearly accelerated by sensible heat transfer – all 24-hour air temperature was characterized by negative value.

A specific cycle ofwater temperature can occur in winter conditions, when a very low air temperature is observed. On 28 January 2012 the daily average air temperature was only -11°C, the daily average water temperature was 0.1°C, while the amplitudes were 6.2°C and 0°C respectively. The daily average flow was 5.60 m³/s. Additionally, ice cover was observed even in areas of fast water flow, in some places covered with snow. Under these conditions, water temperature was constant throughout the day and did not show any dynamics (Fig. 7). The complete absence of growth and decline phases was generally due to the lack of heat flux. The ice cover formed a layer of insulation for short-wave solar radiation. Further, the heat budget was not affected by evaporation and sensible heat transfer with air. A small, constant amount of thermal energy was probably generated in the process of fluid friction that prevented freezing. The temperature value may also indicate that the groundwater feeding in the observed river reach was generally small and insignificant.

Conclusions

Stream water temperature is a measure of the concentration of thermal energy dispersed in a defined volume of water. Heat flux between the water and the environment occurs due to physical processes such as radiation, evaporation, condensation, conduction, convection, fluid friction and advection. The amount of thermal energy transported in these processes is controlled by external drivers which include direct solar radiation, air

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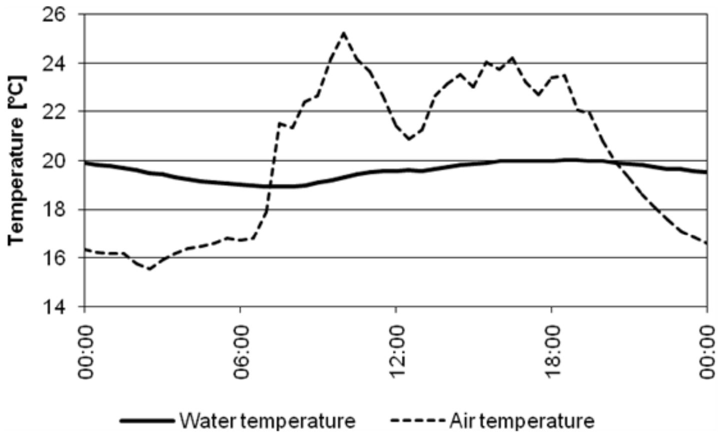

Fig. 5. The 24 hour cycle of the water temperature during a summer day with full cloud cover - 21 June 2012

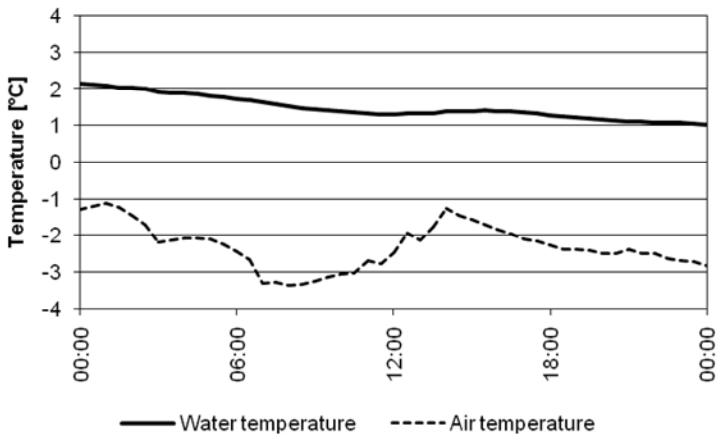

Fig. 6. The 24 hour cycle of water temperature during a winter day - 15 January 2012

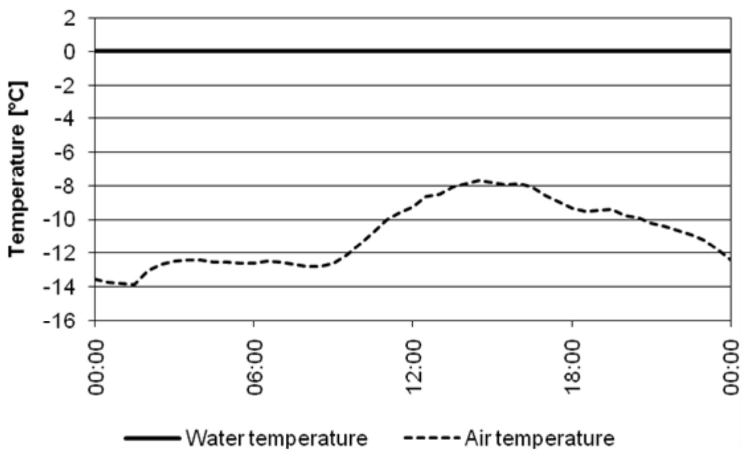

Fig. 7. The 24 hour cycle of water temperature during a winter day 28 January 2012, the river was covered with ice

temperature, shading, morphological and geological parameters of the channel, stream flow and groundwater inflows. The variable impact of drivers causes dynamic fluctuations in water temperature and forms distinct thermal regimes. For streams, diurnal temperature variations are the most characteristic. For short intervals they result from the changing intensity of physical processes, especially radiation, evaporation, bed conduction and sensible heat transfer. In consequence, as confirmed by the measurements conducted in the Świder river, the daily cycle of water temperature is modified by meteorological conditions depending on the season. The largest temperature dynamics is observed in summer, especially on sunny days, whereas smaller amplitudes and more aligned cycles of temperature appear in cloudy days. In winter, both the amplitudes and the dynamics of water temperature are generally small, due to the low intensity of processes, mainly short-wave radiation. For special winter conditions when ice cover is observed, water temperature can be constant throughout the day. Results are similar to those presented in previous studies (Brown et al. 2010; Malcolm et al. 2004). Finally, the successful application of data loggers in the field experiment shows a simple way to collect large amount of temperature data, which can be used in a wide range of research on thermal regimes of streams.

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