Determination of diurnal water level fluctuations in headwaters

Marek Marciniak and Anna Szczucińska

ABSTRACT

The aim of this paper is to study diurnal fluctuations of the water level in streams draining headwaters and to identify the controlling factors. The fieldwork was carried out in the Gryżynka River catchment, western Poland. The water levels of three streams draining into the headwaters via a group of springs were monitored in the years 2011–2014. Changes in the water pressure and water temperature were recorded by automatic sensors – Schlumberger MiniDiver type. Simultaneously, Barodiver type sensors were used to record air temperature and atmospheric pressure, as it was necessary to adjust the data collected by the MiniDivers calculate the water level. The results showed that diurnal fluctuations in water level of the streams ranged from 2 to 4 cm (approximately 10% of total water depth) and were well correlated with the changes in evapotranspiration as well as air temperature. The observed water level fluctuations likely have resulted from processes occurring in the headwaters. Good correlation with atmospheric conditions indicates control by daily variations of the local climate. However, the relationship with water temperature suggests that fluctuations are also caused by changes in the temperature-dependent water viscosity and, consequently, by diurnal changes in the hydraulic conductivity of the hyporheic zone.

Key words | daily fluctuations, evapotranspiration, groundwater, headwaters, hyporheic zone

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INTRODUCTION

In the temperate zone, annual changes in climatic conditions impose seasonal fluctuations of water levels observed for both surface and subsurface waterbodies. These fluctuations are induced primarily by natural water supply conditions, such as precipitation (e.g. Dobek 2007), melting of snow layers (e.g. Gribovszki *et al.* 2006), as well as by the yearly changes of evapotranspiration intensity (e.g. Goodrich *et al.* 2000; Czikowsky & Fitzjarrald 2004).

The above-mentioned factors responsible for the variations in surface water and groundwater levels have already been widely discussed in the literature. However, short-term, i.e. daily, changes have been examined less frequently.

One of the key papers on this topic was published by Gribovszki *et al.* (2010), who linked the daily fluctuations in water level and discharge of streams to infiltration losses, precipitation (in tropical climate), melting and freeze-thaw processes (in polar zones and alpine areas) and evapotranspiration (in temperate climates). Gribovszki *et al.* (2008) found evapotranspiration to be the main factor influencing diurnal water level fluctuations in large river valleys. The effect of evapotranspiration on daily changes in the position of the water level was previously reported by such researchers as Troxell (1936), Wicht (1941), Tschinkel (1963), Lundquist & Cayan (2002), Loheide (2008) and Szilágyi *et al.* (2008).

Diurnal water level fluctuations may also be driven by the daily changes in atmospheric pressure (Turk 1975). Short-term variations in the shallow groundwater table and, in particular, the stream water level have also been considered in the context of variable conditions of the hyporheic zone (Sophocleous 2002; Olsen & Townsend 2003; Packman & Selehin 2003; Runkel *et al.* 2003; Dong *et al.* 2014). In this contact zone between surface water

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and groundwater, the seepage of groundwater into the streambed may vary within a day following changes in temperature conditions (Ronan *et al.* 1998; Hatch *et al.* 2006). The resulting changes in the volume of water drained by the stream should be observed as diurnal variations in surface water level.

The aim of this paper is to analyse daily water level fluctuations in the watercourses draining into outflow zones as well as to identify the factors controlling these changes.

STUDY AREA

The research was conducted in the Gryżynka River catchment situated in the western part of the Polish Lowlands (Figure 1). The river, with a surface catchment area covering ca. 80 km^2, was also shown in previous studies (Szczucińska 2009) to drain water from endorheic areas surrounding it from the north-east and north-west. From numerical model calculations, it was estimated that the groundwater basin of the river is ca. 30% larger than its surface catchment area. Groundwater outflows were found to supply ca. 30% of the Gryżynka River; however, the total contribution of groundwater is greater and may cover as much as 80% of the supply (Choiński 2005). Following the classification by Dynowska (1971), the river displays a rainfall-, snow- and groundwater-dominated hydrological regime, resulting in high hydrological inertia and stable annual discharge.

The study area is located within the extent of Pleistocene glaciations. The Pleistocene ice sheet formed

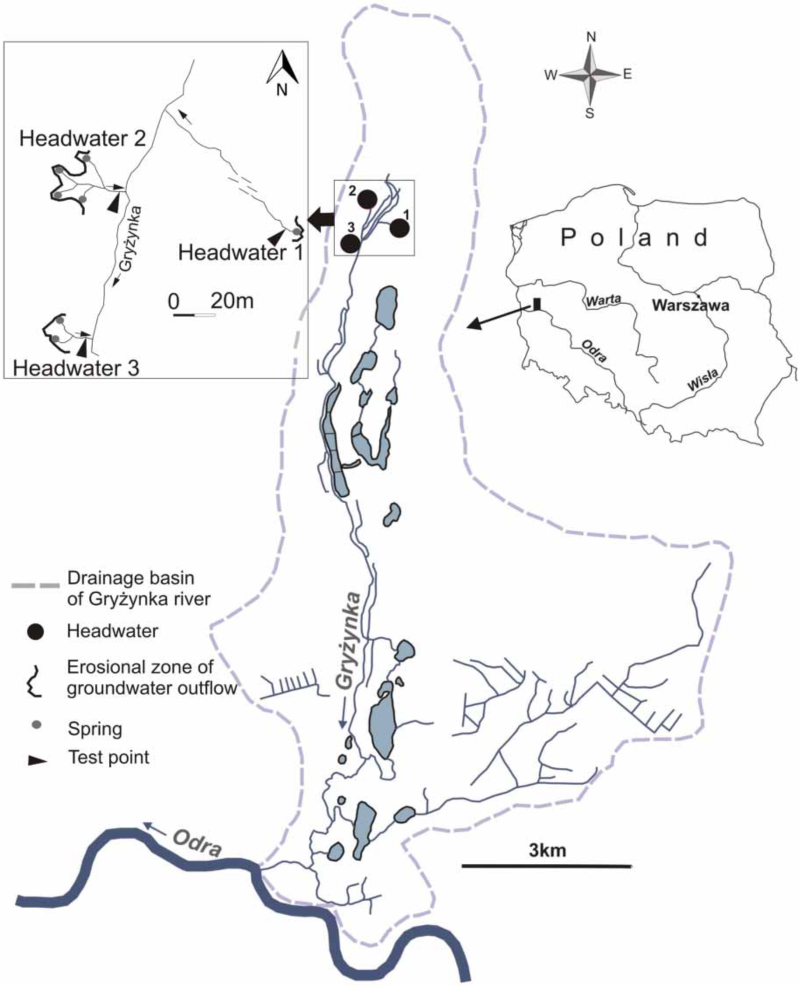

Figure 1 | Location of the study area and measuring posts in the headwaters examined.

interstratified levels of interglacial deposits (mainly mixed-grained sands and gravels) and tills (Żynda 1967). The thickness of Quaternary sediments in the catchment ranges between several and 150 m. The Gryżynka River, draining this area, flows in a postglacial channel cut into a sandur surface in its northern and central part. Altitude differences between the channel bottom and sandur surface reach up to 30 m. The bottom of the channel is covered by lakes and peat bogs, and the slope base includes a total number of 354 documented outflows, springs and seeps within the catchment (Szczucińska 2009).

Groundwater outflows are usually found in so-called outflow zones. Particular zones may include only a single spring or seep; however, most of them comprise several forms of groundwater outflows, both springs and seeps. In the Gryżynka River catchment, groundwater outflows are supplied with water from loose, mostly underslope, sediments, in which water flows towards the surface due to gravity.

The southern part of the channel overlaps an ice-marginal valley with a terrace level composed of sands, gravels and fluvial silts. As the study site is dominated by fluvioglacial sediments, enabling development only of soils too poor for plant production, forests, extending across ca. 76% of the area, became the main form of land management. Other forms include crop fields, water bodies and farm buildings, covering 16%, 4% and 4% of land, respectively.

Groundwater within the Gryżynka River catchment is supplied by precipitation. The hydraulic conductivity of sediments in this area, estimated in a model (Szczucińska 2009), varies from 2×10^{-6} m/s in fine-grained sands to 2×10^{-5} m/s in medium- and coarse-grained sands. The main water-bearing levels, often discontinuous, penetrate the Quaternary deposits. In contrast with the water tables of surface horizons, located at depths of up to several meters, the deeper inter-till water-bearing levels, found below 5 m, are often confined.

The study area, situated within the temperate climate zone, shows mean annual air temperatures (MAAT) higher than in adjacent regions and is marked by the MAAT isotherm of 8.2 °C. The mean annual amount of rainfall in the area amounts to ca. 590 mm, with the highest precipitation recorded in the summer months of July and August.

METHODS

Measurements of water level and water temperature in watercourses draining three outflow zones were carried out between 13th October 2011 and 4th November 2014 with MiniDiver microprocessor loggers. MiniDiver records the fluctuations in water level derived from changes in pressure exerted by the water column and measured by a pressure sensor with 0.05% FS (full scale) precision. Measurement frequency, initially set at 2 h, was later increased to 15 min. As MiniDiver measures the absolute pressure (hydraulic + atmospheric) above the sensor, the collected data required adjustment for changes in atmospheric pressure. Therefore, this parameter (along with air temperature) was recorded by the BaroDiver logger in the same time intervals as set for MiniDiver. The Diver-Office software was used to correct results obtained with MiniDiver for the BaroDiver pressure records. Water level and water temperature were measured with ±0.5 cm and ±0.1 °C precision, respectively.

The daily amounts of rainfall recorded at a measuring post in Gryżyna were obtained from the Institute of Meteorology and Water Management.

The authors interpreted four time intervals during which the amplitudes of daily water level fluctuations were well visible and could be presented against diversified meteorological conditions:

- winter 2012 (from 1st to 13th February no rain and from 14th to 29th February with rain);
- spring 2012 (from 16th to 30th April after winter with snow cover);
- summer 2013 (from 16th to 27th July no rain and from 28th July to 5th August with rain);
- spring 2014 (from 16th to 30th April after winter with no snow cover).

For the selected time intervals, water and temperature level charts in a time function were prepared for each of the studied headwaters considering the following observed meteorological parameters: barometric pressure, air temperature and precipitation.

Statistical analysis of the data registered in the region was performed by calculating the coefficients of correlation among: (1) water and air temperature; (2) water level and air temperature; and (3) water level and water temperature. Such analysis was carried out for both momentary and mean daily values. Daily water level amplitudes were analysed as a function of air temperature, and a correlation coefficient was calculated for the relationships. We calculated how water thermal expansion and thermal changes influence hydraulic conductivity, therefore they also impact water level fluctuations (Fetter 2001). Furthermore, for each of the analysed headwaters, we generated a curve depicting mean daily fluctuations of the water level. In order to do so it was necessary to: (1) calculate the mean daily water level; (2) calculate the standard deviation of the water level at every hour from the daily mean; and (3) determine the average of the calculated deviations, subsequently obtaining values of average deviations of the water level from the daily mean for every hour.

RESULTS

Seasonal changes in meteorological and hydrological parameters

Winter 2012

In the first 12 days of February 2012, an anticyclone with pressure attaining 1,026 hPa was observed. The mean daily air temperatures amounted to −10 °C with a daily amplitude of 19.6 °C (Figure 2). This was also the recording time of the minimum temperature, −19.5 °C, of this period and entire hydrological year 2011/2012. No precipitation occurred after 21st January 2012. After a warm front passage on the 13th and 14th of February 2012, the second part of the month was affected by different meteorological conditions. Atmospheric pressure decreased by 18 hPa, whereas the mean daily air temperature increased to 3.4 °C. In this period, air temperature was positive throughout all days (only in the night of 27th February 2012 fell to –5.5 °C), causing the melting of the snow layer.

Moreover, rainfall, with a mean intensity of 3.9 mm/d, was recorded nearly every day between 13th February and 29th February. Incidentally (on 24th February), rainfall intensity reached 9.5 mm/d. Such meteorological conditions triggered intensive surface flow on slopes surrounding the examined outflow zones. In all of them, rainfall resulted in lower amplitudes of daily water level fluctuations (Figure 2), which decreased by 62% (from 2.9 to 1.1 cm) in headwaters No. 1 and No. 3 and by 58% (from 3.6 to 1.5 cm) in headwater No. 2.

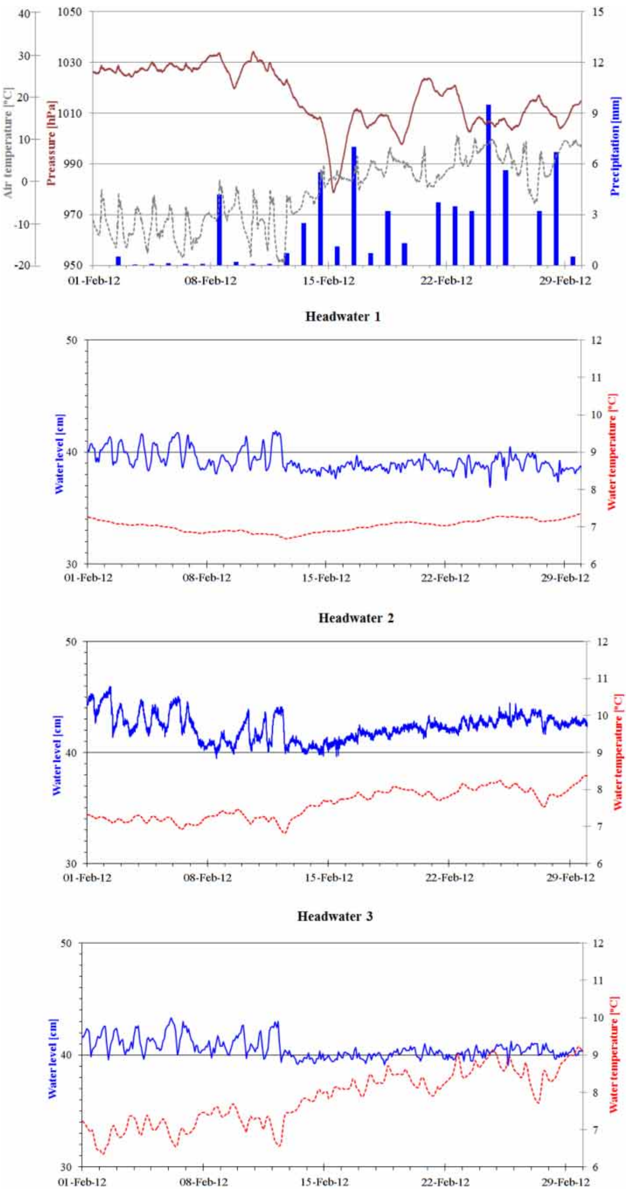

Figure 2 | Fluctuations in water level and temperature in headwaters and the accompanying meteorological conditions in winter 2012.

The correlation between water temperature in outflow zones and air temperature increased with the distance between the site of temperature measurement and water outflow from the ground to surface. This factor also affected the daily temperature pulse, barely detectable in the outflow zone of headwater No. 1 but strong in headwaters Nos 2 and 3. In headwater No. 1, water temperature was stable and slightly oscillated around 7.0 °C, whereas in headwaters Nos 2 and 3 it increased from 6.9 °C to 8.5 °C and from 6.4 °C to 9.0 °C, respectively.

Spring 2012

In the second half of April 2012, atmospheric pressure was slightly lower than normally observed, varying between 984 and 1,009 hPa (Figure 3). Mean daily air temperature systematically increased from 6 to 20 °C, with daily amplitude attaining 26 °C. Rainfall occurred only twice, on 20th July (7 mm/d) and 23rd July (8 mm/d).

In all outflow zones observed, the amplitude of water level fluctuations gradually rose (Figure 3) from 1.4 cm on 16th April 2012 to 2.4 cm on 30th April 2012 in headwater No. 1 and analogously from 2.3 to 3.4 cm in headwater No. 2 and from 1.8 to 2.6 cm in headwater No. 3.

All outflow zones also showed increasing mean daily water temperatures; they were from 8.2 to 8.9 °C in headwater No. 1, from 8.5 to 10.3 °C in headwater No. 2, and from 8.8 to 10.5 °C in headwater No. 3. Gathered from larger surfaces, the water flowing through the measuring points of headwaters Nos 2 and 3 may have been affected by the longer exposure to air temperature.

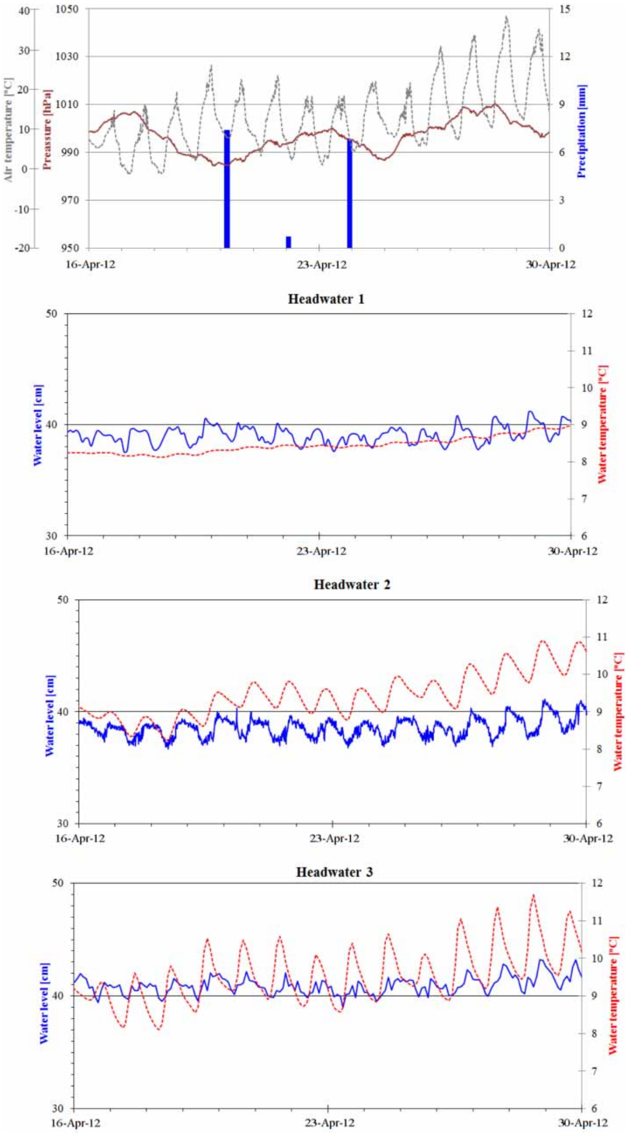

Figure 3 | Fluctuations in water level in headwaters and temperature and the accompanying meteorological conditions in spring 2012.

Summer 2013

The end of July and beginning of August 2013 were marked by stable pressure conditions. The pressure oscillated slightly around the isobar of 1,010 hPa (Figure 4). Mean daily air temperatures attained ca. 21.9 °C with a daily amplitude of up to 24 °C. This was a practically rainless period with incidental rainfall recorded only on 27th July, 28th July (highest intensity of 20 mm/d) and 4th August.

Precipitation caused a decrease in the amplitude of daily water level observed in all outflow zones (Figure 4). The summer amplitudes of daily water level fluctuations were high and reached 3.9 cm in headwater No. 1, 3.5 cm in headwater No. 2, and 3.6 cm in headwater No. 3.

In the summer, the waters of outflow zones showed temperatures ca. 3 °C higher than during winter. In headwater No. 1, the mean daily water temperature amounted to 10.5 °C with a daily amplitude of 0.6 °C. Analogously, the parameters attained values of 10.7 °C and 1.5 °C in headwater No. 2 and 10.1 °C and 1.2 °C in headwater No. 3, respectively.

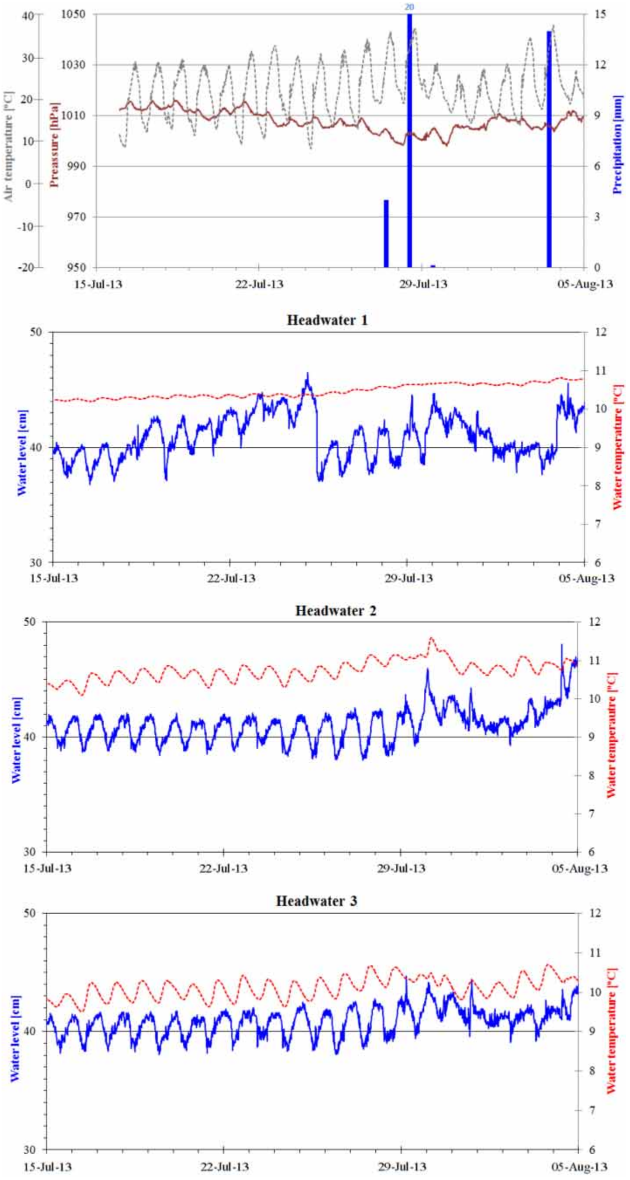

Figure 4 | Fluctuations in water level in headwaters and temperature and the accompanying meteorological conditions in summer 2013.

Fluctuations in the water level of outflow zones can be disturbed by various factors, as exemplified in Figure 4. The rapid changes in water level recorded on 30th July and 4th August may be explained by the initial damming of the flow at the measuring weir by obstacles, such as branches and leaves, which were eventually removed due to greater discharge after rainfall. On 25th July, the water level changed intensively as the measuring weir was cleaned by the observer.

Spring 2014

In the second half of April 2014, the study area showed an initial barometric pressure of 1,021 hPa which strongly decreased by ca. 20 hPa after 2 days. Afterwards, pressure oscillated between 1,000 and 1,010 hPa (Figure 5). Mean daily air temperature attained ca. 7.5 °C at the beginning but finally rose to ca. 9.5 °C. The amplitudes of daily air temperature amounted to ca. 15 °C. Rainfall of low intensity was recorded only twice in this period, on the 18th and 23rd April. While the first event did not affect the fluctuations in water level strongly, the second rainfall decreased their amplitude in all outflow zones (Figure 5).

The mean daily water temperatures of the zones attained the following values: 9.1 °C in headwater No. 1, 9.9 °C in headwater No. 2 and 9.7 °C in headwater No. 3. The amplitudes of daily water temperature in the outflow zones amounted to 1.1 °C in headwater No. 1, 2.4 °C in headwater No. 2 and 3.0 °C in headwater No. 3.

In the summer, maximum water levels were between 4 and 6 am, and minimum water levels were between 11.30 am and 12.30 pm, whereas air temperatures attained maximum and minimum values at ca. 3 pm and ca. 6 am, respectively. The occurrence of maximum and minimum water temperatures in outflow zones may be delayed with respect to extreme air temperatures. Pulsations in water temperature were observed to strongly depend on the distance between the measuring point and water outflow from the ground to the surface. In the winter period, maximum water levels were recorded slightly earlier, between 2 and 5 am, whereas minimum water levels slightly later, between 1.30 and 2.30 pm. Winter air temperature attained maximum and minimum values at ca. 1 pm and 7 am, respectively. The mean daily water temperatures of winter and summer differed by ca. 3.5 °C.

DISCUSSION

The research results show the daily water level fluctuations in headwaters and springs (Gribovszki *et al.* 2010), an issue discussed relatively rarely in the literature. The widely discussed changes in water levels, especially in groundwaters,

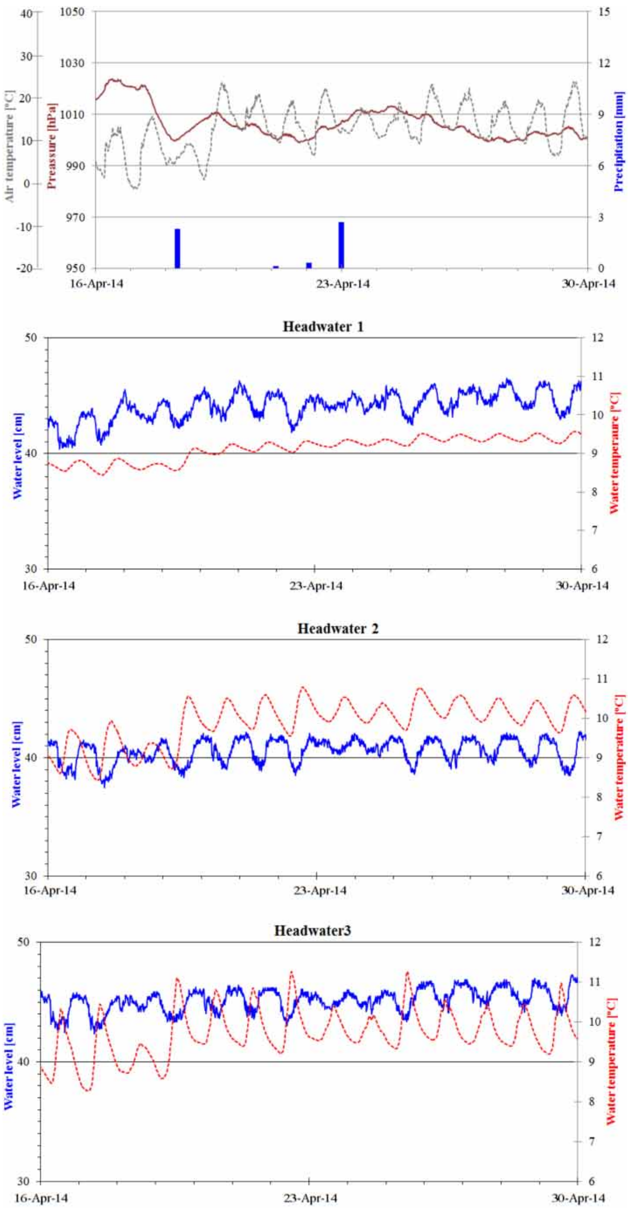

Figure 5 | Fluctuations in water level in headwaters and temperature and the accompanying meteorological conditions in spring 2014.

indicate evapotranspiration (Gribovszki *et al.* 2006; Shah *et al.* 2007) as the most crucial element in determining the fluctuations, both daily (Ridolfi *et al.* 2007; Lautz 2008; Fong *et al.* 2012) and seasonally (Healy & Cook 2002; Andrzejewska 2007; Herrnegger *et al.* 2012).

An analysis of water balance in the headwaters and literature data (Gribovszki *et al.* 2010) shows that the amplitude of daily water level fluctuations is significantly impacted by both precipitation and evapotranspiration. Moreover, based on Darcy's law, it can be inferred that the size of a stream in the case of groundwater that feeds into a headwater is influenced by the hydraulic conductivity of a hyporheic zone (dependent on water temperature and the degree of bottom sediments being loosened). Darcy's law also says that the hydraulic gradient between surface water in a headwater and groundwater in the area that feeds into the headwater determines the stream of groundwater feeding the headwater and, at the same time, influences the size of daily water level fluctuations. The impact that particular factors have on daily water level fluctuations in the headwaters is discussed below. A flowchart containing observational data against the processes that impact water level fluctuations is depicted in Figure 6.

The influence of precipitation is most visible in the second half of February 2012. At that time continuous rainfall and higher temperatures resulted in the melting of snow cover. This, in turn, led to a marked decrease in the amplitude of daily water level fluctuations in all the headwaters by approximately 60%. In the case of the other time intervals the amplitudes decreased after each rainfall.

The recorded water level fluctuations in the three headwaters were conditional upon daily changes in evapotranspiration. This is confirmed by the daily fluctuation in amplitude amounting to 3.60 cm. It is higher in the summer

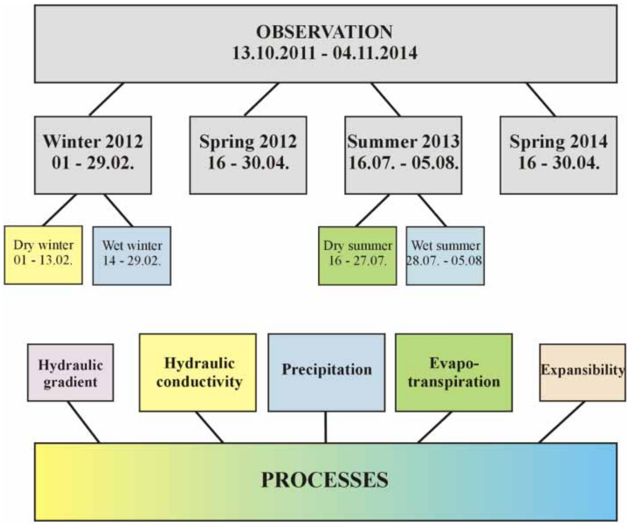

Figure 6 | Flowchart of observational data on the background of the processes determining fluctuations in water level.

than in the winter and can be observed during a longer rainless period. In stable meteorological conditions the amplitude amounts to 3.31 cm (Figure 7). A similar relationship was also noted by other authors (Meyer 1960; Gribovszki *et al.* 2010). In a similarly wooded area, Andrzejewska (2007) and Krogulec (2007) observed daily fluctuations in underground water which disappeared in winter and reappeared during plant vegetation. The amplitude of underground water fluctuation stood at approximately 3.5 cm and was similar to fluctuations observed in the headwaters. The fact that daily fluctuations in water level in the headwaters did not cease in winter confirms that in addition to evapotranspiration there are other factors that determine daily water level fluctuations in the examined headwaters.

For the subperiod when only evapotranspiration influenced water level fluctuations, we calculated mean amplitudes and the deviation of the amplitude at selected hours from the mean values (Figure 8). Fluctuations with a daily amplitude of ca. 2.5 cm were observed, similar to the cases described by Gribovszki *et al.* (2010). High levels were observed during the night, with a maximum around 4 am. Minimum water levels were observed around 12 pm.

Another key factor that impacts water level fluctuations is the hydraulic conductivity of the hyporheic zone. A rise in air temperature is strictly related to insolation conditions, or the solar energy supply through radiation. This leads to the warming of water which improves filtration conditions. The hydraulic conductivity is higher in higher temperatures, which is conducive to increasing filtration intensity (Dietze & Dietrich 2011; Dong *et al.* 2014). A higher rate of underground water outflow helps rock granules in the hyporheic zone float. This causes bottom sediments to loosen in the headwaters and in stream and river bottoms, which is characteristic of underground water drainage. Increased underground water outflow contributes to a rise in the amplitude of daily water level fluctuations (Figure 9). As air temperature decreases, the reverse sequence of processes takes place, which effects a decrease in the amplitude of daily water level fluctuations.

Calculations were performed to quantitatively assess the impact that changes in the hydraulic conductivity have on daily water level fluctuations. Based on Darcy's filtration law and the dependence of the infiltration coefficient on water temperature (Fetter 2001), a formula was derived of the dependence of the amplitude of daily water level fluctuations on water temperature changes:

$$\Delta h = \frac{0.0337(T_2 - T_1) + 0.00022(T_2^2 - T_1^2)}{1 + 0.0337\,T_1 + 0.00022T_1^2}b \qquad (1)$$

where Δh is the amplitude of daily water level fluctuations (cm); T_1, $T_2 =$ initial and final water temperature (°C), b is water depth in the headwater (cm).

The conducted calculations (Equation (1)) showed that the daily water change from 7 to 10 °C alters the water level amplitude of 2 cm with the water depth of approximately 20 cm, which is typical of most headwaters. However, the above formula does not consider the hydraulic conductivity caused by the loosening of bottom sediments in the headwaters. For this reason it can be expected that change in the amplitude of daily water level fluctuations stemming from change in the hydraulic conductivity will be much higher.

To some extent, the loosening of bottom sediments can be enhanced by thermal expansion and decreases in water viscosity (Ma & Zheng 2010). Water volume change caused by temperature rise can be calculated using the formula:

$$\Delta V = \beta \cdot V_0 \cdot \Delta t \qquad (2)$$

where ΔV is the change in volume of water (m^3); β is coefficient of thermal expansion (from water $\beta = 1.81 \times 10^{-4}$ 1/°C); V_0 is initial volume of water (m^3), Δt is change in temperature (°C).

The change in spring water temperature amounts to 3 °C during an entire hydrological year. Such a change in water temperature will alter water volume by no more than 0.4% of the original value (Equation (2)). The amplitude of daily water temperature is smaller than 1 °C. This is why water thermal expansion influences amplitude changes to a minimum extent but can support the process of loosening bottom sediments.

Furthermore, the amplitude of water level fluctuations can also be affected by the hydraulic gradient. According to Darcy's law, the size of an underground water stream feeding into a headwater is greatly influenced by the

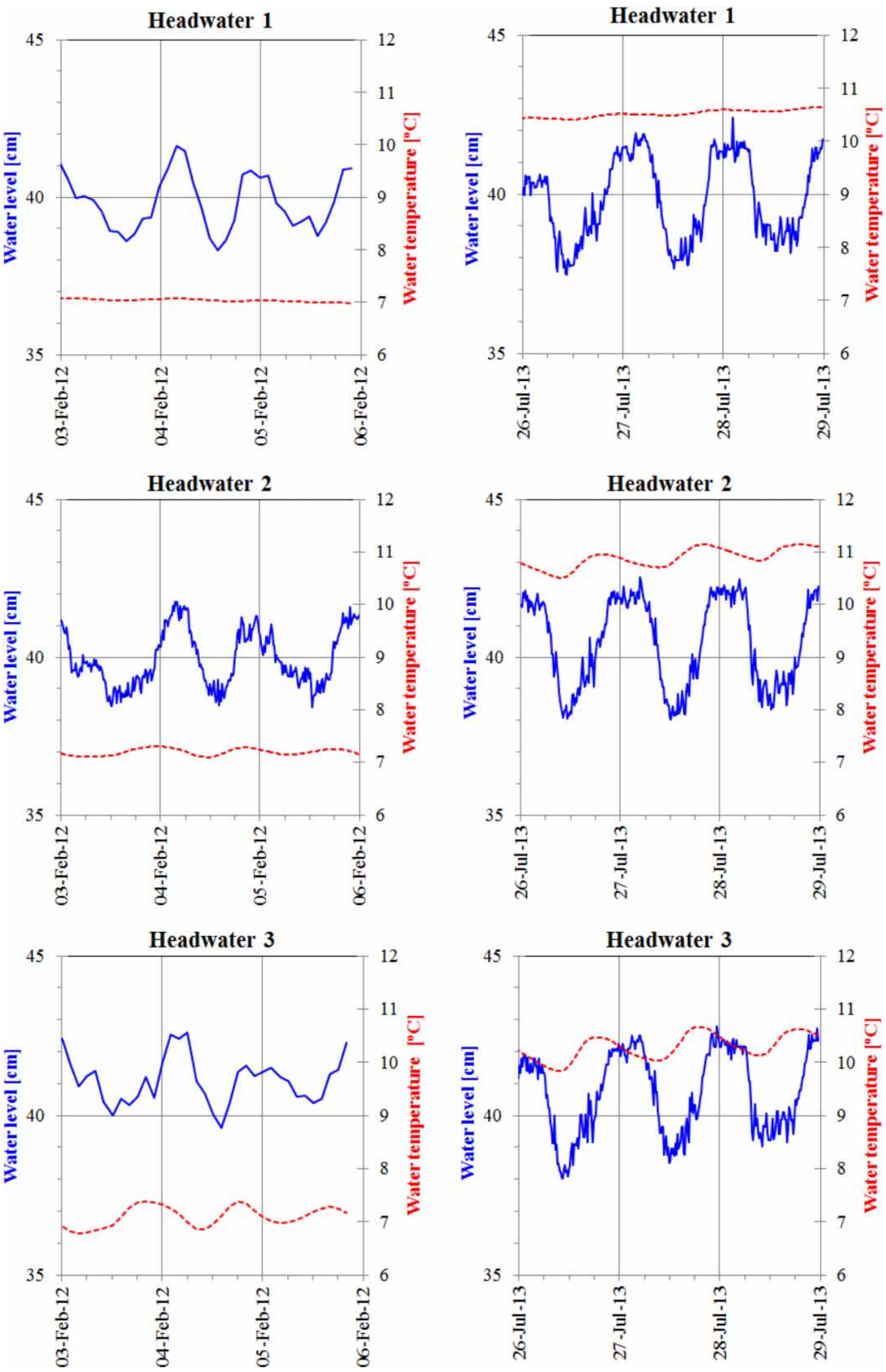

Figure 7 | Comparison of winter (2012) and summer (2013) water level fluctuations in outflow zones.

hydraulic gradient between surface water in the headwater and underground waters in the area feeding into the headwater. The level of underground water is subject to seasonal fluctuations and is higher in summer months, which results from precipitation and snowmelt infiltration feeding into underground water. It can therefore be

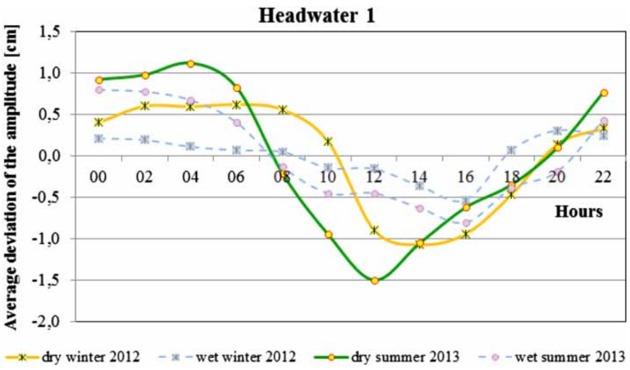

Figure 8 | Average daily deviation of the amplitude for subperiods: 1-dry winter 2012, 2-wet winter 2012, 3-dry summer 2013, 4-wet summer 2013 for example headwater No.1.

expected that the amplitudes of daily water level fluctuations in headwaters will be higher in summer months.

Statistical data analysis

The following mean daily values were recorded based on on-site observations: air temperature, water level and temperature and amplitudes of daily water level fluctuations. The calculation results are presented in Appendix 1 (available with the online version of this paper).

Statistical analysis of the dependence between daily fluctuation amplitudes and air temperature (Figure 10) showed that a significant correlation level can be obtained only under conditions in which daily fluctuations in water level are primarily determined by one of the factors dependent on air temperature: evapotranspiration and the hydraulic conductivity of the hyporheic zone and precipitation. The above correlation may still be disturbed by precipitation and by changes in hydraulic gradient which does not depend on air temperature. In natural conditions all of these factors overlap and, by doing so, conceal their influence on the daily fluctuations in water level. Thus, the correlations between daily water level fluctuations and air temperature are low because they are disturbed by factors independent of air temperature.

During the dry and frosty winter of 2012 (from 1st to 13th February) precipitation and evapotranspiration had a small effect on daily water level fluctuations. The hydraulic gradient at this time of year is small, but because of the high daily air temperature amplitude (from −15 to −3 °C) daily changes in the hydraulic conductivity occurred, which resulted in high water level fluctuation amplitudes (Appendix 1) (from 2.5 to 3.2 cm). The lowest fluctuation amplitudes always occurred after precipitation and snowmelt (from 1.2 to 1.6 cm).

In the winter of 2012, after a snowy winter the inflowing underground waters were colder (Figure 7), which led to a decrease in the hydraulic conductivity of the hyporheic zone resulting in decreased underwater feeding. At that time high air temperature amplitudes were recorded (from 5 to 25 °C) (Figure 3), which increased evaporation. As a result, the recorded water level fluctuation amplitudes were lower (from 2.1 to 2.8 cm) than in spring 2014 after a snowless winter (from 2.9 to 3.2 cm, with the exclusion of 23rd and 24th April, when an influence of precipitation marked its presence).

In spring 2014, a lack of inflowing, cool meltwater led to hyporheic zone waters being slightly warmer (in spring 2012 Headwater 1 8.5 °C; Headwater 2 9.5 °C; Headwater 3 9.6 °C, and in spring 2014, 9.1 °C, 9.9 °C, 9.7 °C, respectively). Hydraulic conductivity in the zone was higher, which contributed to greater underground water inflow. At the same time lower air temperatures (in spring 2012 from 5 to 25 °C and in spring 2014 from 7 to 19 °C) were accompanied by smaller evapotranspiration. As a result, greater amplitudes of daily water level fluctuations were recorded.

In spring 2012, summer 2013 and spring 2014 the obtained correlations were low due to the fact that the processes impacting water level fluctuations suppressed each other. A different situation occurred in winter 2012, when evapotranspiration was marginal. Changes in hydraulic conductivity at a time of low air temperatures and no precipitation resulted in high amplitudes, which were observed in the first half of February. In the second half, the air temperature rose significantly. At the same time, some precipitation events occurred and the process of thawing took place, resulting in a low amplitude of fluctuations. Such a sequence of events led to a high correlation coefficient.

Winter 2012 and summer 2013 were divided into two subperiods: dry (without precipitation) and wet (with precipitation), as only one process that impacts water level fluctuations is observed in such subdivisions. The two analyzed spring seasons could not be divided in a similar manner, since all three processes take place during this part of the year. The correlation between the amplitude of water level fluctuations and air temperature for each

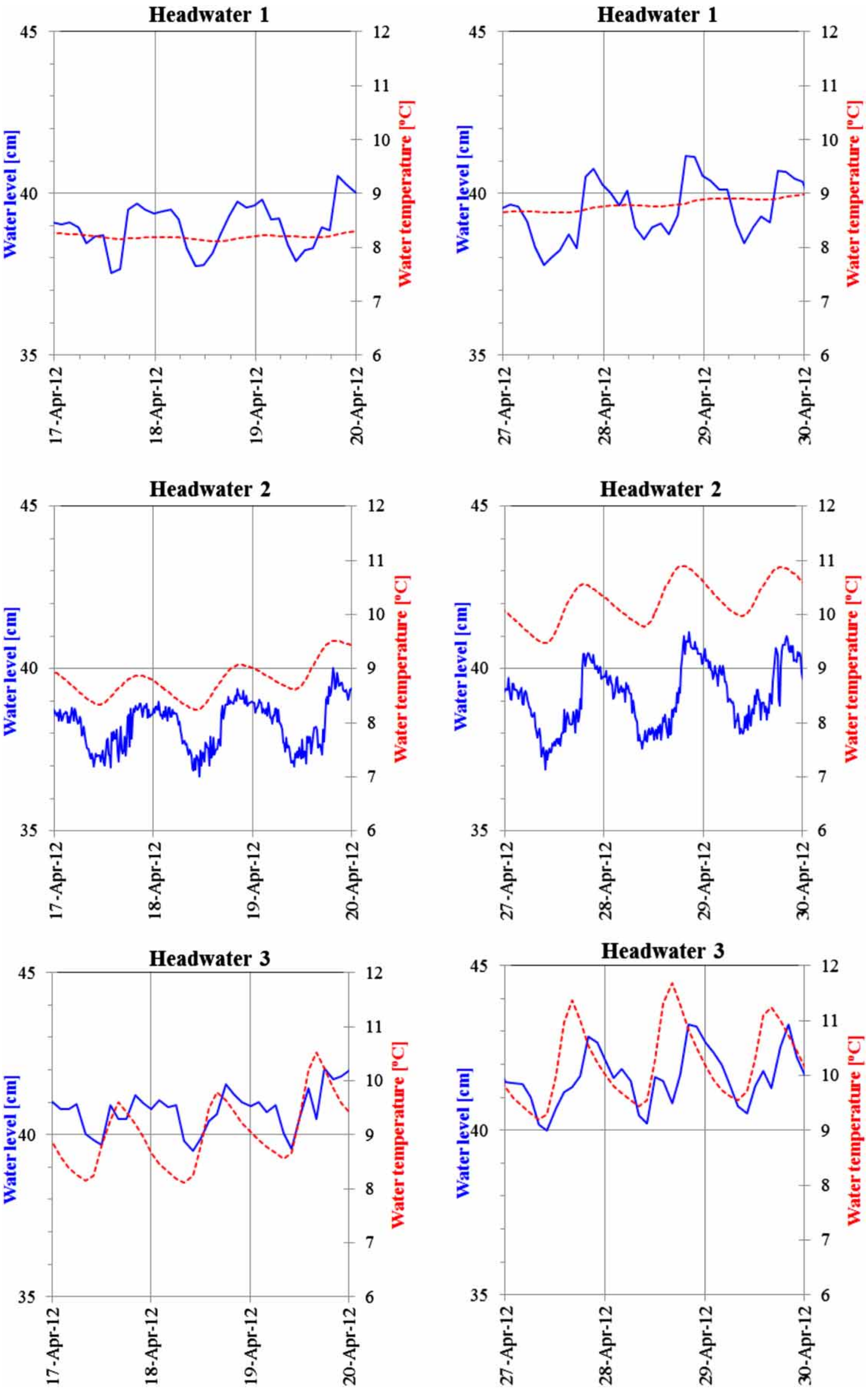

Figure 9 | Changes in daily water level fluctuations in headwaters resulting from evapotranspiration and warming of the ground surface (spring 2012).

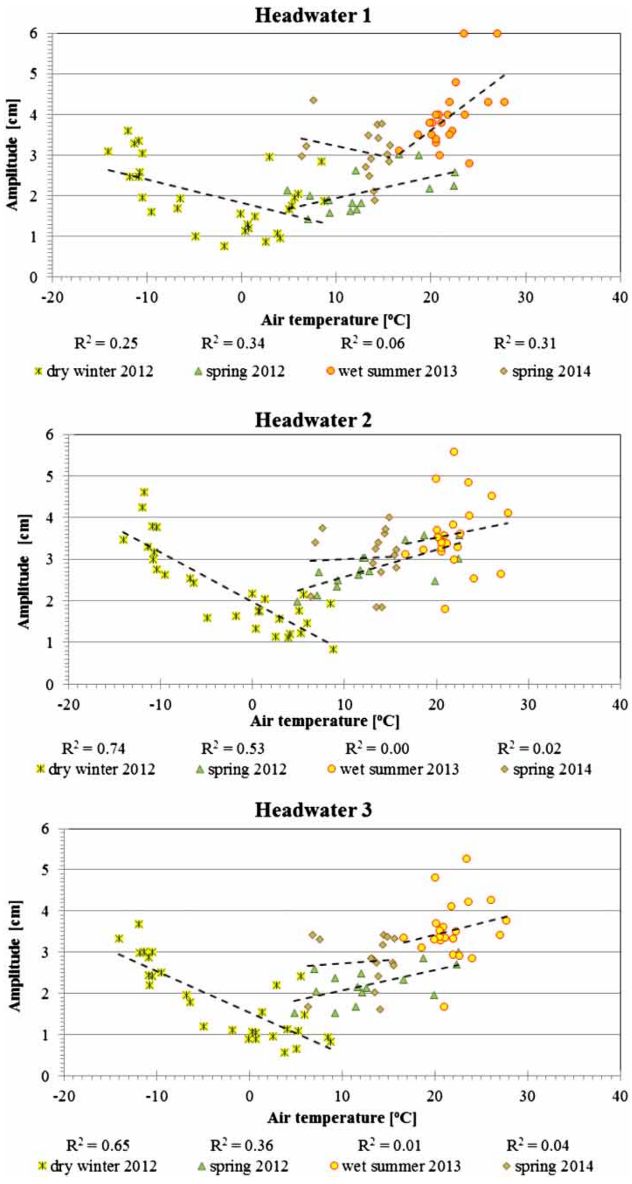

Figure 10 | Correlation coefficients of daily water level amplitudes in the headwaters and air temperature during the research periods: 1-winter 2012, 2-spring 2012, 3-summer 2013, 4-spring 2014.

subperiod is shown in Figure 11. A dominant role of one process is only visible during dry subperiods. The variable hydraulic conductivity of bed sediments and evapotranspiration were dominant factors during the dry winter 2012 and dry summer 2013 subperiods, respectively. High correlations coefficients were obtained only for these dry subperiods. No significant correlation was obtained for wet subperiods, when precipitation occurred and, therefore, two factors governing water level movements interacted.

CONCLUSIONS

Diurnal water level fluctuations in headwaters depend primarily on the amount of solar energy reaching the hyporheic zone. The intensity of insolation may be affected by numerous factors such as latitude, season, meteorological and geomorphological conditions, vegetation, and shading.

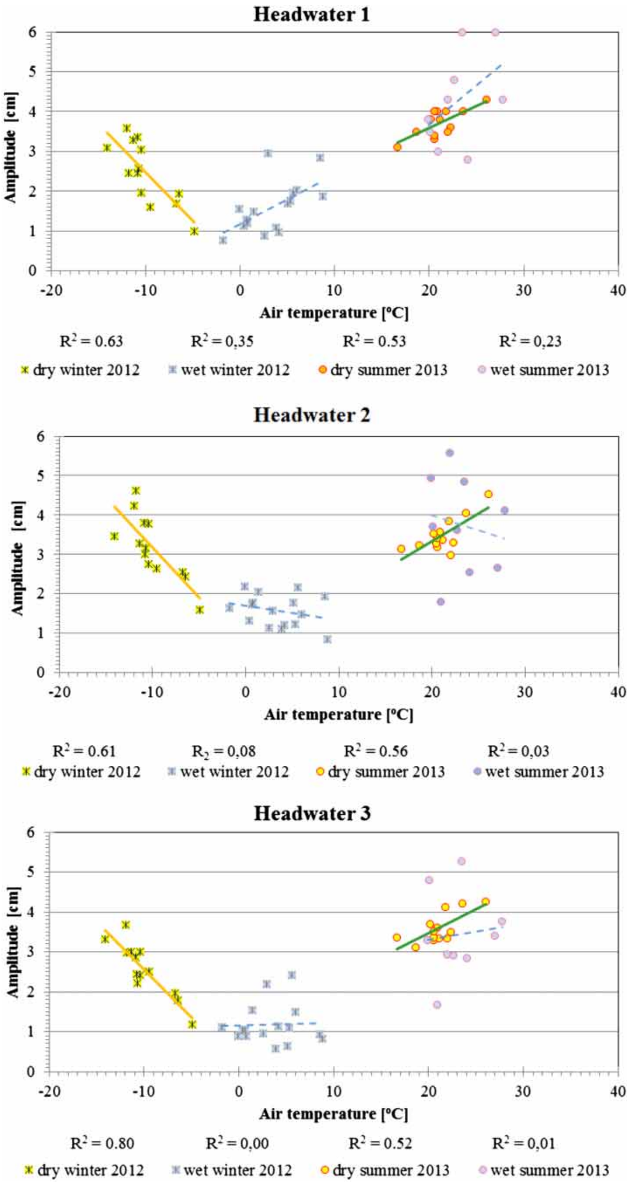

Figure 11 | Correlation coefficients of daily water level amplitudes in the headwaters and air temperature during the research subperiods: 1-dry winter 2012, 2-wet winter 2012, 3-dry summer 2013, 4-wet summer 2013.

The above-mentioned factors affect precipitation, evapotranspiration, changes in filtration parameters of the hyporheic zone and changes in hydraulic gradient determine the daily fluctuations in water level in headwaters. As a result, the processes overlap and conceal one another. As insolation (along with air and water temperature) increases, evaporation increases as well, causing lower amplitudes of daily water level fluctuations. Simultaneously, the same factor (increasing insolation, air and water temperature) improves the filtration parameters of the hyporheic zone and therefore facilitates groundwater outflow, resulting in higher amplitudes of daily water level fluctuations.

Diurnal water level fluctuations may be clearly observed only in rainless periods. Rainfall, snow melt and slope flow suppress the amplitudes of the daily water level. An increase in the hydraulic gradient causes higher water inflow to a headwater, which is particularly visible during periods of high levels of underground waters following a thawing process.

Among the described underlying mechanisms of daily water level fluctuations in headwaters it is difficult to determine dominant and subordinate processes. Such conclusions could be drawn on the basis of studies performed in controlled laboratory conditions considering only one factor and its effects per experiment. Such research should result in the formulation of a mathematical model of the functioning of the hyporheic zone.

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