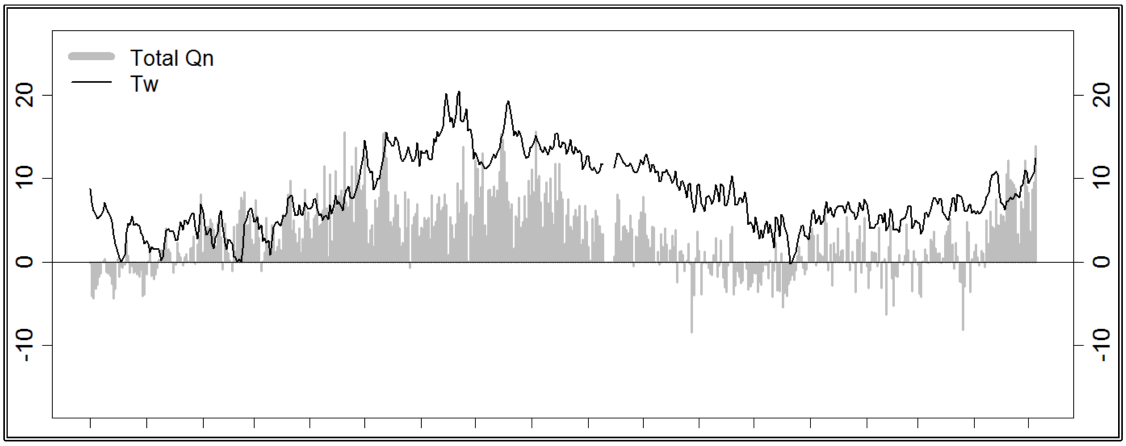
Laura Gangi

Water temperature and heat exchange dynamics of a Welsh upland stream



Master thesis

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IV Extended summary

Improving understanding of the processes determining stream temperature has been a research focus for decades and stream temperature research has been promoted recently by the debate on climate change. However, there are still few detailed medium- to long-term studies on the complex relationship between water temperature, heat exchange dynamics and hydrometeorological conditions. Furthermore, research on spatial stream temperature variability at the microscale is scarce, even though microthermal gradients have been shown to be ecologically important. This thesis conducts a hydrometeorological study of stream temperature and heat flux dynamics of a Welsh upland stream over one and a half years at annual, seasonal and sub-seasonal time scales. Additionally, stream temperatures were analysed at a microspatial scale over a summer period by *in situ* monitoring of temperatures and hydrological conditions as well as by detection of radiant water temperature via ground-based infrared (IR) thermometry.

The results demonstrate clear intra-annual variations in water column and streambed temperatures and energy fluxes at the air-water and water-streambed interfaces. Overall, the annual cycle of water column and streambed temperatures largely tracked seasonal fluctuations in the total energy available. Net radiation was the dominant heat source while evaporation was the major heat sink across the year. The contribution of sensible heat flux and bed heat flux to energy gains or losses varied seasonally and depended on prevailing air-water temperature gradients and thermal gradients within the streambed, respectively. In total, all heat gains and 94.85 % of heat losses occurred at the air-water interface, indicating that energy fluxes and groundwater influence at the streambed were of minor importance for this stream´s energy balance. The study also revealed that hydrological conditions can have a considerable impact on stream temperature. Accordingly, storm flows caused a consistent decline in water column temperature across all examined events which was mainly attributable to changes in water source contributions. Spatial temperature variability within the study reach was very low, irrespective of flow conditions as high flow velocities and turbulence within the water column appeared to prevent lateral or longitudinal temperature patterns.

Overall, the dominance of atmospheric conditions in the total energy budget of the stream may have some considerable implications with respect to global warming and changes in local land use as both directly affect the microclimate of the stream. This research highlights the need for further long-term empirical hydrometeorological studies that integrate both temporal and spatial analysis of thermal behaviour to help understand the complex relationship between stream temperature, energy exchange processes and reach-hydrology.

KEY WORDS stream temperature; thermal regime; energy balance; streambed; hydrometeorology; microthermal gradients

V Erweiterte Zusammenfassung

Die Erforschung der natürlichen Prozesse und Faktoren, die auf die Temperatur von Fließgewässern einwirken und diese bestimmen, ist schon seit mehreren Jahrzehnten ein wichtiger Forschungsschwerpunkt, der vor allem durch die Debatte zum Klimawandel wieder verstärktes Interesse erfährt. Sowohl Mittel- als auch Langzeitstudien, die sich mit dem komplexen Zusammenhang zwischen Wassertemperatur, Wärmeaustauschprozessen und hydrometeorologischen Bedingungen beschäftigen, sind bisher selten. Darüber hinaus ist die räumliche Variabilität von Fließgewässertemperaturen auf kleinskaliger Ebene noch wenig erforscht.

Das Ziel dieser Masterarbeit war es daher, basierend auf hydrometeorologischen Datenreihen über einen Zeitraum von anderthalb Jahren, die Wassertemperatur und Wärmeaustauschprozesse eines Walisischen Gebirgsbaches unter der Berücksichtigung verschiedener zeitlicher Ebenen zu analysieren. Die Untersuchung räumlicher Muster von Fließgewässertemperaturen auf Mikroebene stellte einen weiteren Schwerpunkt der Arbeit dar. Dazu wurde die Wassertemperatur an verschiedenen Stellen im Gewässer kontinuierlich über einen Zeitraum von 10 Wochen gemessen. Außerdem wurde die Oberflächentemperatur des Gewässers mittels Infrarotbildaufnahmen flächig erfasst.

Die Ergebnisse zeigen, dass Wasser- und Flussbetttemperatur, aber auch Energieflüsse an der Wasseroberfläche und am Flussbett während des Beobachtungszeitraums jahreszeitlichen Schwankungen unterlagen. Die Temperaturen in der Wassersäule und im Flussbett folgten mit einer leichten Verzögerung dem Jahresgang der absolut verfügbaren Energie innerhalb der Wassersäule. Im gesamten Jahresverlauf war die Nettostrahlung die Hauptwärmequelle des Fließgewässers während die Verdunstung an der Wasseroberfläche den Hauptwärmeverlust repräsentierte. Der fühlbare Wärmestrom und der Wärmefluss innerhalb des Flussbetts stellten je nach Jahreszeit einen Energieverlust oder –gewinn für das Gewässer dar und spiegelten die entsprechenden Temperaturgradienten zwischen Wasser und Atmosphäre bzw. Wasser und Flussbett wider. Die Bedeutung des Grundwassers und der Engergieflüsse am Flussbett für den gesamten Energiehaushalt des untersuchten Gewässers war relativ gering, da alle Energiegewinne und 94.85 % der Energieverluste an der Wasseroberfläche auftraten. Diese Arbeit zeigte auch, dass hydrologische Prozesse einen erkennbaren Einfluss auf die Temperatur von Fließgewässern haben können. Dies wurde besonders an der konsistenten Abnahme der Wassertemperatur als Reaktion auf Spitzenabflüsse deutlich.

Die räumliche Variabilität der Fließgewässertemperatur war sehr gering, unabhängig von den vorherrschenden Abflussbedingungen, da hohe Fließgeschwindigkeiten und die relativ hohe Turbulenz innerhalb der Wassersäule die Ausbildung von lateralen und longitudinalen Temperaturunterschieden verhinderten.

Die Dominanz der atmosphärischen Bedingungen im Hinblick auf den Energiehaushalt des untersuchten Baches bedeutet eine potentiell erhöhte Sensitivität des Gewässers gegenüber der globalen Erderwärmung und Landnutzungsänderungen im Einzugsgebiet, da diese Veränderungen direkt das gewässernahe Mikroklima beeinflussen. Insgesamt verdeutlicht diese Forschungsarbeit, dass weitere hydrometeorologische Langzeitstudien nötig sind, um den komplexen Zusammenhang zwischen Wassertemperatur, Energieflüssen und hydrologischen Prozessen weiter zu erforschen. Diese sollten dabei Untersuchungen zu räumlichen und zeitlichen Dynamiken von Fließgewässertemperaturen integrieren.

SCHLÜSSELWÖRTER Fließgewässertemperatur, Temperaturregime, Energiebilanz, Flussbett, Hydrometeorologie, Mikrothermische Gradienten

1 Introduction

1.1 Motivation

Water temperature is an important factor that affects the ecology, water quality and socio-economic importance of flowing waters by determining its physical, chemical and biochemical properties. For example, aquatic organisms including fish, invertebrates and microorganisms, depend on appropriate habitat conditions including a defined water temperature range (Hynes, 1970; Coutant, 1977). A relationship between water temperature and growth rate of Brown Trout (*Salmo trutta* L.) was first defined by Elliott (1975) and other studies demonstrating the temperature dependency of fish growth (Edwards et al., 1979; Jensen, 1990), fish diversity and distribution followed (Ward, 1994; Lyons, 1996; Wehrly et al., 2003). Apart from freshwater fish, the fecundity, adult size and composition of aquatic invertebrates varies markedly in association with the thermal regime of rivers (Markarian, 1980; Vannote and Sweeney, 1980; Milner et al., 2001) and also physiological processes of aquatic plants were found to be highly temperature sensitive (Anderson 1969; Vis et al. 2007). Furthermore, stream temperature influences the microbial nutrient decomposition in running waters (Cummins, 1974; Bott et al., 1984). Over the last decades, new interest in the temperature sensitivity of freshwater organisms has come up against the background of climate change and various studies showed that climate change is likely to affect distribution and abundance of aquatic biota via an increase in water temperatures (Kishi et al., 2005; Daufresne and Boet, 2007; Durance and Ormerod, 2007). In terms of the water quality of surface water, the interdependence of water temperature and dissolved oxygen concentration is an important feature. Accordingly, warmer water holds less dissolved oxygen than colder water which has critical implications for the respiration of aquatic organisms (Davis, 1975). Again, climate change has offered a new incentive to examine this issue of stream temperature (Cox and Whitehead, 2009). Another temperature related water quality aspect is the impact of temperature on rates of chemical processes which, for example, affects the suspended sediment content of rivers and streams (Lane et al., 1949; LeBosquet and Tsivoglou, 1950). Socio-economic issues of river temperature are related to water requirements in agriculture, industry, fishery and recreation (Raney, 1963; North, 1980; Hassan, 1985) and were also examined in respect of climate change. Accordingly, the increase in river temperatures is supposed to affect the efficiency of cooling water extracted from major rivers in the UK (Arnell, 1998) and is further expected to result in economic losses in fishery (Ficke et al., 2007). Over the years, many studies have shown that the thermal behaviour of rivers is very complex and is highly sensitive to both natural conditions and anthropogenic influence (Poole and Berman, 2001). Given this complexity of thermal processes there is still a certain lack of process understanding and a need for basic research on heat exchange processes including different temporal as well as spatial scales. An improved holistic understanding is required to predict potential implications of human activities and future climate change for in-stream temperatures and provides the possibility to manage river systems adequately in order to maintain or even improve the health of aquatic ecosystems and ensure socio-economic water demands in the future.

1.2 Literature review and state of the art

Given the high significance of stream water temperature the thermal behaviour of running waters has been the focus of numerous studies for the last decades. The following literature review shall provide some background on the past and present issues in water temperature research. Therefore, it includes a small retrospect on early studies of river water temperature and outlines some general trends in river thermal studies in the last 20 years. Finally, current research gaps are highlighted by summarising focuses and outcomes of recent research projects relevant to the study presented herein.

Early studies of river water temperature

Early studies related to the thermal behaviour of rivers were of a rather descriptive nature and focused on the identification of factors that influence thermal conditions in rivers. These studies provided some basic knowledge of the thermal behaviour of rivers and streams. Investigations often included the long-term monitoring of stream temperatures combined with measurements of air temperature and discharge. Macan (1958) registered water temperatures along a small stream over a time-span of 5 years using a mechanical thermograph. He identified some of the factors affecting water temperatures of a small stream such as shading and wind-exposure of the channel. A further outcome of this study was an equilibrium hypothesis for small streams which states that stream water temperature reaches an equilibrium with air temperature at a distance of a few kilometres from the source. In 1970 a similar study, which was also based on long-term thermographic temperature recordings, reported that the passage of stream water below the streambed may alter temperatures markedly (Crisp and Cren, 1970). Taking into account the change of the heat storage capacity related to altering stream discharge Smith (1975) focused on the thermal regime of a major river system and revealed that advective sources such as storm rainfall, snow melt or groundwater seepage may contribute to river temperature variability. In accordance with this finding, Smith and Lavis (1975) showed that groundwater influence can cause a reduction in water temperature of up to 5 °C. Apart from the basic interest in the factors that are responsible for river thermal processes many studies during the 20th century have investigated the thermal impact of human activities. In this respect, the effects of forest harvest on stream temperatures have been a major issue. Studies by Brown and Krygier (1970) and Harris (1977) were among the first to reveal the strong impact of timber harvesting on river thermal conditions. Many research projects on the anthropogenic disturbance of river thermal regimes were also related to the discharge of heated effluents to rivers (Davidson and Bradshaw 1967; Smith 1972). Another aspect in early river temperature studies was the ecological importance of stream temperatures for the habitat quality of running waters with regard to the growth and distribution of freshwater fish species (Benson, 1953; Gibson, 1966).

Besides these mostly descriptive studies, early attempts were made to predict water temperatures via different types of models (Raphael 1962b; Brown 1969). Early predictive approaches were mainly based on relationships between water temperature and meteorological variables such as air temperature. Associated with the characterisation of the annual stream temperature regime as a sine function (Ward, 1963), various stochastic models were developed in the subsequent years (Kothandaraman, 1971; Cluis, 1972; Tasker and Burns, 1974). Apart from models relying on statistical relationships between the water temperature and a single meteorological parameter such as air temperature, early deterministic models were developed which are based on physical processes and consider the total heat budget at the air-water interface (Raphael 1962b; Brown 1969).

Trends and gaps in recent water temperature research

In recent years, the thermal behaviour of flowing waters has gained a renewed interest for different reasons (reviewed by Webb et al., 2008). Firstly, a recent stimulus for new interest in river thermal behaviour has come from the identification of climate change (reviewed by Caissie, 2006). A lot of emphasis is thereby put on the river thermal dynamics of glacierised basins (Milner and Petts 1994; Uehlinger et al. 2003; Brown et al. 2006; Cadbury et al. 2008). In this context, mean water temperatures and fluctuations within an alpine stream have been found to increase with distance to the glacier and were shown to be highly dependent on the relative water source contributions and various basin characteristics, e.g. the valley geomorphology (Smith et al. 2001; Brown and Hannah 2008). In terms of the annual temperature regime of rivers in glacierised basins, Uehlinger et al. (2003) showed that water temperatures within an alpine river, fed by the meltwaters of two valley glaciers, first increase during spring but then decline again when the period of glacial melt begins. Against the background of global warming and the conceivable impact on the discharge and temperature regimes of alpine river systems, the thermal dynamics within alpine streams and rivers are likely to remain the focus of research in the next years. However, not only climate change but also the impacts of human activities have remained a major objective of river temperature studies. Despite decades of research on this topic, many studies on the thermal impacts of forest harvesting have also been published in the last few years with a focus on the harvest-related changes in microclimatic parameters (Johnson 2004; Moore et al. 2005a, 2005b). Furthermore, other anthropogenic impacts on stream temperatures have been investigated, such as changes in upland land use, channel engineering and the regulation of river flows (reviewed by Poole and Berman, 2001; Hester et al., 2009).

Another recent impetus to water temperature related research has come from the further development of modelling tools that allow the simulation of river thermal dynamics. Regression type models have been improved over the last years by a more detailed examination of the air to water temperature relationship (Stefan and Preud´homme, 1993; Webb and Nobilis, 1997; Mohseni et al., 1998). Especially with regard to climate warming, predictive approaches using air temperature to stream temperature relationships may gain in importance again (Pilgrim et al., 1998; Morrill et al., 2005). Stochastic models which are based on long-term data of water and air temperature and take advantage of the sinusoidal nature of the annual temperature cycle have also undergone progress in recent years and have meanwhile been applied to larger rivers (Caissie et al., 1998, 2001; Ahmadi-Nedushan et al., 2007; Benyahya et al., 2007). Furthermore, deterministic models, which in general employ an energy budget approach to predict water temperature, have been refined in the last years, for example by adapting model input parameters (reviewed by Webb et al., 2008).

Another technical progress which promoted research on water temperature in recent years was the improvement of temperature measuring techniques. Especially research projects with a focus on the spatiotemporal heterogeneity of stream temperatures have profited by this technical development which has allowed the extension of examination scales. The advent of distributed fibre-optic temperature sensors (DTS) has facilitated the accurate and reliable monitoring of water temperatures at large spatial scales. Selker et al. (2006) illustrated the potential of distributed fibre-optic measurements to record temperature distribution along a first-order stream while Lowry et al. (2007) used this technique to detect groundwater discharge in a peat-dominated wetland stream. Vogt et al. (2010) applied DTS on a further scale by measuring vertical temperature gradients in the streambed via this method. In addition to DTS, satellite- or aircraft-based thermal infrared imagery has been proven an effective method to measure surface water temperature of running waters with broad and detailed coverage over large spatial scales (Faux et al., 2001; Madej et al., 2006; Cristea and Burges, 2009) and has also been applied to detect ground-water discharge into streams (Loheide and Gorelick, 2006). Torgersen et al. (2001) were among the first to develop an airborne thermal infrared (TIR) remote sensing method to measure spatially continuous water temperature patterns in rivers and they reported that this technique was highly effective for this purpose. In the years after, the accuracy and uncertainty limits of TIR images have been the subject of various studies. Beside the well-known pitfalls of thermal imagery occurring during the measurements such as reflectance of long-wave radiation and vertical thermal stratification (Torgersen et al., 2001), the coarse spatial resolution associated with the restricted number of pixels, was identified as a major constraint especially of satellite-based remotely sensed thermal images (Cherkauer et al., 2005; Handcock et al., 2006). Given these impediments to using airborne thermal imagery for the examination of spatial water temperature patterns, Cardenas et al. (2008) relied on ground-based thermography with a handheld infrared camera to investigate temperature variability in fluvial systems on a smaller spatial scale. Their study demonstrated that water temperatures obtained via infrared thermometry compared well with those measured by a digital thermometer and thermal heterogeneity was found to be high during low stages associated with the occurrence of biological and morphological in-stream structures. Recently, ground-based infrared thermography was applied to detect and quantify localised groundwater inflow into a small stream via the temperature difference between stream water and groundwater (Schuetz and Weiler, 2010). However, no further studies involving ground-based IR imagery have been published until now and the potential of this method to detect spatial patterns of water temperature within smaller streams at a local scale has still to be explored.

Despite the advent of techniques such as DTS or TIR which allow a spatially continuous measurement of river temperatures, the *in situ* monitoring of river and stream temperatures has remained a widespread method in recent years promoted by the arrival of inexpensive miniature temperature loggers. Low-cost temperature sensors have facilitated the accurate and reliable monitoring of water temperatures at multiple sites over long time periods including different spatial scales such as longitudinal and vertical examination of temperature patterns, especially with regard to riffles and hyporheic exchange (Evans and Petts, 1997; Hannah et al., 2009) as well as investigations at the reach scale (Schmidt et al. 2006; Brown and Hannah 2008). Given its ecological relevance, current research has paid greater growing attention to microthermal variability in stream temperatures. Clark et al. (1999) examined the thermal heterogeneity over distances of a few centimetres to a few metres in small groundwater-dominated streams in Dorset, UK and detected lateral temperature differences of up to 7 °C between the channel margin and the main body of flow which were mainly related to differences in thermal capacity and shading. However, studies on microthermal gradients focusing on small spatial scales are still scarce compared to those concentrating on spatial thermal heterogeneity at the reach scale (Hawkins et al., 1997; Ebersole et al., 2003). In addition, studies of stream temperatures at various temporal rather than spatial scales have been just a minor issue in recent research on river thermal behaviour most of whom focusing on the investigation of annual stream temperature cycles (Caissie et al., 2005) and responses of water temperatures to storm events (Kobayashi et al. 1999; Brown and Hannah 2007). For example, Brown and Hannah (2007) examined the thermal response of alpine streams to storm events. They found a significant negative relationship between stream temperature and the storm magnitude appearing as a decrease in water and streambed temperatures in response to precipitation events. Spatial and temporal differences in responses to the storm event were referred to distinct event characteristics and the specific antecedent basin conditions. However, this study was limited to the thermal behaviour of alpine streams and there remains a paucity of related research on other stream types at different climatic conditions.

The improvement and arrival of affordable measuring techniques has also promoted a renewed interest in the empirical investigation of river heat budgets which involves generally detailed measurements of micrometeorological parameters at the water- atmosphere and water- streambed interfaces. A pioneer study on the nature of heat flux processes that control river temperatures with intent to predict temperatures of small streams based on the energy balance was conducted by (Brown 1969). This study was among the first to show that in unshaded streams the main energy-input during the day is gained from net all-wave radiation while evaporation and convection contribute less energy to the stream and conduction of heat into the underlying bed can account for a significant amount of energy loss. Very recently, some heat budget studies have focused on methodical aspects and commented on the representativeness of single microclimate measurements within reaches. Benyahya et al. (2010) compared the applicability of microclimate and remote meteorological data to predict water temperatures using a deterministic model. They found that especially the evaporative and sensible heat fluxes were highly variable in space, mainly due to the local heterogeneity of wind speed and net radiation. Therefore, they concluded that particularly for smaller and medium streams deterministic models perform better when using microclimate data. Another very recent heat budget study including a deterministic model to predict net radiation confirmed a considerable spatial variation of net radiation and wind speed within reaches (Leach and Moore, 2010a). Hence, the authors query the use of single measurements of net radiation and instead suggest the application of a deterministic model to predict net radiation accurately throughout reaches. This approach further allowed for the simulation of wildfire-effects on stream temperature and showed that standing dead trees mitigate natural disturbance after wildfires by reducing net radiation by about half compared to a clear-cut harvesting.

In general, over the last years, research on river heat budgets has focused on the investigation of distinct stream types at various spatiotemporal scales. Table 1 gives a summary of these studies and their respective research focuses. Webb and Zhang (1997) were among the first to examine the spatial and temporal variability in the river heat budget of moorland streams in south-west England based on on-site measurements of the energy balance components. In their comprehensive study they evaluated hydrometeorological data for 495 days from 11 study reaches in south-west England and measured the proportion of net radiation, sensible heat transfer, condensation, bed friction, conduction and evaporation as well as precipitation and groundwater fluxes accounting for heat gains or heat losses. Averaged over all investigated basins, net-radiation and evaporation were the most dominant non-advective heat sources but heat storage through groundwater was considerably present as well. Furthermore, the influence of individual heat budget components was demonstrated to be highly variable in time and space. Temporal variability was related to naturally occurring seasonal variations in the meteorological conditions while the high spatial variability between different reaches was related to specific reach characteristics such as channel morphology, valley topography, shading effects, riverbed and hydrological conditions. Another empirical study of river heat budgets with focus on a subarctic Scottish upland stream was provided by Hannah et al. (2004). In their study the temporal variability in river heat exchange processes was confirmed. Moreover, the streambed was identified as a major energy source over the monitoring period. The study was restricted to the salmon-spawning hatch season occurring from October to April, though, and the authors emphasised the need for further medium- to long-term empirical river energy budget studies. However, until today long-term empirical studies including data of more than one year are still scarce with the exception of the study provided by Hannah et al. (2008) where thermal and microclimatic differences between forest and moorland reaches in the Scottish Cairngorms were examined. Their study included measurements of water temperatures, bed temperatures and micrometeorological variables over two calendar years and allowed for a reach-specific analysis of seasonal and inter-annual patterns in the stream energy budget. Micrometeorological conditions varied significantly between the two reaches and resulted in a specific energy budget partitioning. Furthermore, the study showed that the streambed heat flux was relatively small compared to the heat exchange processes at the air-water interface and differed between the forest and moorland due to site-specific groundwater-surface water interactions.

Given the high local specificity of river heat budgets to catchment features, various rather short-term studies have been conducted on different stream types in distinct climatic regions over the last two decades. Evans et al. (1998) particularly took into consideration the thermal exchange processes at the riverbed of lowland rivers in the United Kingdom. It was found that the total energy exchange at the water-riverbed interface (15 %) was considerable but small compared to energy fluxes at the air-water interface (82 %) and showed micro-scale variations. Heat fluxes in groundwater-dominated streams in the United Kingdom have been analysed by Webb and Zhang (1999). Since the channels

Table 1. Summary of recent river heat budget studies (1997-2010), where Q^* = net radiation, Q_f = friction, Q_h = sensible heat flux, Q_e = evaporation/condensation, Q_b = bed conduction, K_s^*= short-wave radiation, L_s^* = long-wave radiation, Q_{bhf} = bed heat flux.

Author(s)	Study focus	Main findings	River / Catchment type	Temporal scale of heat budget analysis	Study period
Webb and Zhang 1997	Spatial/ seasonal variability in the components of the river heat budget	- Energy gains: Q^* (56 %), Q_f (22.2 %), Q_h (13.2 %), Q_e (5.8 %), Q_b (2.8 %) - Energy losses: Q^* (48.6 %), Q_e (30.4 %), Q_h (10.6 %), Q_b (10.4 %)	Moorland streams in south-west England	Daily averages/totals, Diel resolution	May ´92- Dec ´93
Evans et al. 1998	River bed processes	- Energy gains: K_s^* (97.6 %), Q_h (1.2 %), Q_f (1.1%) - Energy losses: L_s^* (53.98 %), Q_e (23.56 %), Q_b (16.27 %), Q_h (5.25 %), Q_e advected (0.94 %)	UK lowland river	Daily averages/totals, Diel resolution	July/Aug, Sep/Nov
Webb and Zhang 1999	Water temperatures and heat budgets	- considerable daily and diel variability in non-advective heat fluxes - heat storage via groundwater inflows - Energy inputs dominated by radiative fluxes	Chalk water courses in south-west England	Absolute average/totals over winter/summer, Daily averages/totals, Diel resolution	Feb/Mar, July
Hannah et al. 2004	(Sub-)seasonal dynamics of heat exchanges	- Energy gains: Q_h (38.7 %), Q_{bhf} (37 %), Q_f (24.3) - Energy losses: Q_e (73.1 %), Q^* (26.9 %)	Subarctic Scottish upland river	Daily averages/totals	Oct - April
Cozzetto et al. 2006	Processes controlling stream/hyporheic temperatures	- Energy gains: Q^* (99 %) - Energy losses: Q_e (30 %), Q_h (25–31%), Q_{bhf} (19–37 %), hyporheic exchange (6–21 %)	Polar desert glacial meltwater stream (gaining reach / losing reach)	Daily averages/totals	January
Hannah et al. 2008	Comparison of forest and moorland heat budgets and thermal patterns	- site-specific heat budget partitioning for moorland and forest - Q_{bhf} much smaller than fluxes at air-water interface with between-reach differences due to different groundwater influence	Subarctic Scottish upland (moorland and forest reach)	Daily averages/totals	2 full years
Benyahya et al. 2010	Microclimate and remote meteorological data as input for heat budget calculations	- primary heat gain by short-wave radiation - main heat losses by L_s^* and Q_e - microclimate data better than regional met. data for prediction of water temp.	Canadian river system (different river sizes)	Daily averages/totals	Apr/June, July/Aug, Sep/Oct
Leach and Moore 2010	Microclimate and stream budget in a wildfire-disturbed riparian zone	- high reach-scale spatial variability of energy exchange processes, especially net radiation	Snowmelt-dominated Canadian upland stream	Daily averages/totals, Diel resolution	May - March

under study were exposed, net radiation was an extremely dominant heat source in summer as well as in winter accounting on average for 90 % of the warming taking place. Owing to the relatively warm (cold) water of the spring-fed streams, a considerable proportion of heat losses in winter were attributable to evaporation whereas sensible heat transfer represented a heat source in summer. Furthermore, significant heating (cooling) of the groundwater-fed streams in winter (summer) occurred through advective groundwater fluxes. Cozzetto et al. (2006) studied thermal patterns of a glacial meltwater stream on a basin-wide, longitudinal and reach scale. They reported that net radiation accounted for 99 % of heat inputs whereas evaporation (30 %), convection (25-31 %), conduction (19-37 %), and hyporheic exchange (6-21 %) were significant heat sinks. However, no studies exist on energy exchange processes of upland rivers in mid- Wales. Given the fact that previous studies revealed a high heterogeneity of heat exchange processes at different reaches depending on the site-specific hydrological and climatologic features, there is a need for further studies including various stream types in diverse climatic regions. Until now, river energy balance studies have been geographically restricted to meltwater-dominated streams, Scottish upland streams and lowland rivers in mid and south-west England and no research exists on the energy exchanges occurring upon hydrologically dynamic upland streams in Wales. Furthermore, previous research on river heat budgets has revealed that thermal exchange processes are highly variable in time. Despite this fact, there is still a paucity of medium to long-term studies that include data for more than one year and allow a detailed and reliable examination of seasonal and sub-seasonal thermal patterns. In addition, studies of river energy budgets have been restricted to the determination of seasonal and diurnal patterns of river heat fluxes and no studies exist that include the analysis of stream temperature and energy balance parameters with respect to changes in hydrological conditions related to storm events (Table 1).

1.3 Purpose of this study

Despite long-standing interest, the understanding of processes and factors that determine river thermal behaviour provides an ongoing challenge. There remains a need for basic research integrating distinct temporal and spatial scales which have been rather neglected in previous studies. On a spatial scale, only a few studies examined microthermal gradients of water temperatures within small streams, though they are of ecological relevance with respect to thermal refugia for freshwater organisms. Even more rare are studies involving ground-based infrared thermometry to monitor spatial temperature patterns with broad and detailed coverage. With regard to research on river energy budgets, long-term studies including high-resolution data of more than one calendar year are still scarce and have been restricted to distinct stream types and specific climatic conditions. Furthermore, there is a paucity of studies that focus on changes in river heat fluxes in response to distinct hydrological conditions and storm events.

To address these research gaps, this study combines the examination of spatial and temporal patterns of river thermal processes of a Welsh upland stream. The study includes a long-term analysis of the river energy balance components at different temporal scales as well as the investigation of spatial water temperature patterns at a microscale. To gain insight into temporal temperature and heat flux dynamics, detailed measurements of water column and streambed temperatures at 0.05, 0.20 and 0.40 m depth as well as high-resolution hydrometeorological data were used to calculate energy budgets for the respective study site. The variables had been monitored at 15 min intervals between December 2000 and May 2002 and therefore provided a long-term perspective upon local river heat exchange processes. Calculated energy balances were investigated based on different time scales with a focus on annual, seasonal, diurnal patterns and response to storm events. In order to detect spatial stream temperature variability, water column temperatures were measured at different sites along the channel over a 10-weeks time period during the summer of 2010. The positions of the miniature temperature recorders covered different morphological features along the course of the stream such as pools and riverbanks. This setup provided the possibility to study the impact of these channel features on in-stream temperature variability. The *in situ* measurements were complemented by spatially continuous, ground-based thermal imaging of the stream on two individual days during the summer.

The determination of the heat fluxes that occur at the air-water and water-streambed interfaces together with the examination of the spatial stream temperature distribution is conducive to an improved understanding of the processes and factors driving the thermal behaviour of streams. As the examined stream is representative for running waters in the upper catchments of the Plynlimon massif in Mid-Wales which include the headwaters of the Severn, findings of this investigation may be applicable to other upland streams with comparable catchment features such as a similar land use and topography. Furthermore, the heat exchange patterns for a small upland stream presented herein can be compared to the outcomes of earlier studies which concentrated on other types of streams, e.g. moorland streams. These comparisons might in turn reveal coherencies between catchment characteristics and the dominant heat exchange processes of a channel.

Overall, the broader aim of this study is to gain an improved understanding of the fundamental processes and factors determining the spatiotemporal stream temperature patterns. The specific objectives of this study to achieve the above aim are threefold:

(1) to characterise dynamics of microclimate, stream temperatures and energy exchange processes over one and a half years

(2) to detect potential spatial heterogeneity of stream temperatures within the study reach

(3) to explain spatiotemporal dynamics of water temperatures and heat fluxes with reference to hydrometeorological conditions and reach characteristics

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In order to achieve the study aim and objectives this research is designed to test the following hypotheses:

(1) Stream temperatures are driven by energy and hydrological fluxes which in turn are determined by the prevailing hydrometeorological conditions

(2) Spatial temperature patterns are driven by local energy and hydrological fluxes which are influenced by channel characteristics

1.4 Theoretical background

The following subchapter provides an overview of the various processes and factors controlling the stream temperature of running waters and outlines the potential impacts of human activities on stream thermal regimes. Given its relevance to this study, the different components of the river energy budget are described in more detail.

1.4.1 Processes and factors determining stream temperature

The water temperature of a stream is a measure of the amount of heat energy in a distinct water volume which may be illustrated by the following equation (Poole and Berman, 2001):

$$\text{Water temperature} \approx \text{heat energy/ water volume}$$

Hence, water temperature is determined by both the heat energy added to the stream and the stream discharge. Changes in either the heat load or the volume of water flowing in the channel will influence water temperatures. It is important to consider that changes in water temperature only occur when the concentration of heat energy in the stream is changed. The concentration of the heat energy in a stream may thereby either be changed by an increase or decrease in the stream discharge with the heat load staying constant or by an increase/decrease of the heat load applied to the same stream discharge. Factors that determine the net heat energy and water delivered to a stream therefore have the potential to raise or lower water temperature and have been defined as “drivers” of stream temperature by Poole and Berman (2001). Stream temperature drivers include external climatic parameters such as air temperature, wind speed and precipitation which are in turn determined largely by latitude, altitude and continentality (Figure 1). Air temperature has been considered the most important of the climatic factors due to its strong direct influence on stream temperature and groundwater temperature (Ward, 1985). Therefore, the relationship between air and water temperature has been subject to various studies in the last decades. Early studies revealed that streams with small groundwater influence tracked air temperatures closely (Johnson 1971; Grant 1977; Walker and Lawson 1977). Other studies have focused on the nature of the air- water temperature relationship and have shown a departure from linearity not only at low but also at high air temperatures (Crisp and Howson, 1982; Mohseni et al., 2002) and for streams which are affected by anthropogenic influence. However, air temperature is just one of many climatic variables acting as a driver of stream temperature and the investigation of individual heat fluxes occurring at the water column provides a more detailed insight into natural processes determining water temperature. Given its importance to the present study, the energy budget of streams is described in a separate paragraph (see below, 1.4.2). Apart from climatic conditions, geographic components such as topography, lithology and groundwater temperature as well as the thermal signatures of the various sources contributing to runoff such as snowfields, glaciers, tributary inflows or (sub-) surface flow are considered external drivers of stream temperature as they directly affect the heat or water load of a stream (Poole and Berman, 2001). Torgersen et al. (1999) have demonstrated that in terms of the longitudinal stream temperature pattern large volume tributaries, lateral groundwater inflows and topographical shading caused a cooling of channel water. Brown and Hannah (2008) have investigated the thermal variability across an alpine river system and documented the considerable effect of water source and landscape factors such as altitude, azimuth and stream length on water temperatures.

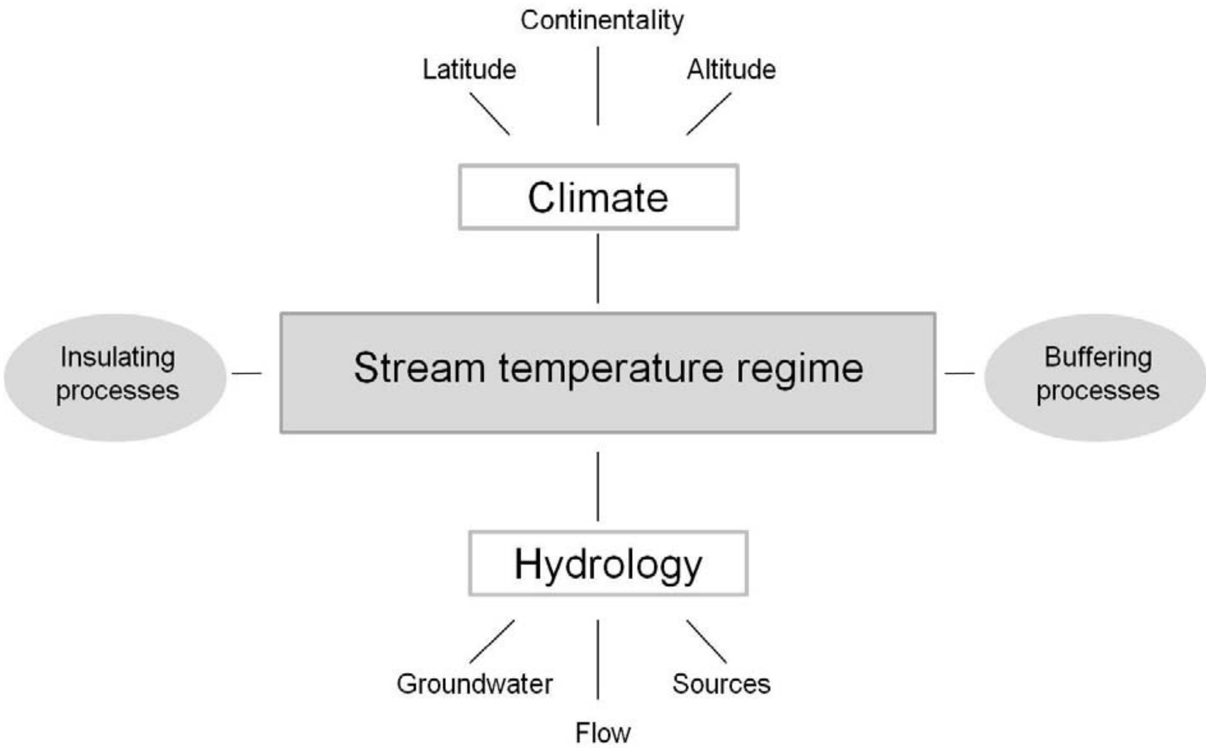


Figure 1. Major factors and processes determining the natural stream temperature regime.

Overall, the interaction of the climatic and hydrological drivers of stream temperature generates temporal and spatial temperature patterns of water temperature (Figure 1). The longitudinal temperature profile of a stream reflects the regulation of water temperatures by different drivers at the macrospatial scale. At the source water temperature generally corresponds to groundwater temperature while in a downstream direction, daily water temperature tends to increase as the influence of atmospheric conditions increases via occurring heat exchanges between the water column and the atmosphere (Benson, 1953; Torgersen et al., 1999). However, in terms of the generally observed overall downstream warming trend, external drivers and the internal structure of the stream interact to determine the actual spatial temperature distribution within the channel. Accordingly, the rate of the downstream temperature increase but also micro-scale temperature variability depend on buffering and insulating processes which are determined by the internal structure of the stream (Poole and Berman, 2001). Unlike the external drivers of temperature, buffering and insulating processes are internal regulators of stream temperature. Insulating processes determine the rate of heat fluxes towards or away from the water column. Channel width and riparian shading are two main factors that insulate the stream because they affect the surface area where heat exchange processes take place and determine the amount of solar radiation reaching the water column.

Furthermore, riparian vegetation influences the magnitude of convective heat fluxes by affecting micrometeorological parameters such as wind speed and relative humidity. Buffering of stream temperatures is often associated with processes that control the transfer of stored heat between different channel components and moderate water temperatures during periods of extreme thermal or hydrological conditions. Exchange processes between channel water and groundwater are considered the most important buffering processes in streams (Poole and Berman, 2001). Interactions between groundwater and surface-water may occur directly below the streambed at the interface between streambed and alluvial aquifer which is generally referred to as hyporheic exchange, or by lateral flow of stream water through the alluvial aquifer, underlying adjacent floodplains. Various studies have focused on the thermal impact of alternating pool/riffle sequences at the streambed and the thermal behaviour at riffles was reported to be very complex and variable with season (Evans and Petts, 1997; Hannah et al., 2009). In general, the rate of hyporheic exchange processes is determined by groundwater levels, stream flow and, as for all buffering and insulating processes, by internal stream system features such as the channel morphology and substratum characteristics.

Like the spatial temperature patterns within streams, water temperature variability at different temporal scales is determined by the interaction between the external stream temperature drivers and the internal structure of the fluvial system. In general, the thermal regime of running waters exhibits diel fluctuations and an annual temperature cycle (reviewed by Caissie, 2006). Diel fluctuations are determined basically by the diel air temperature cycle and include the occurrence of daily minimum temperatures in the early morning and daily maximum temperatures in the late afternoon. Daily variations in water temperature are highly variable among different stream types and climatic conditions (Ward, 1985). For instance, the diurnal temperature variation is generally smaller in cold headwater streams when compared with larger streams. This reflects the fact that with increasing stream order channels become less dominated by groundwater and become instead more influenced by meteorological conditions because surface area for heat exchange processes increases associated with increased channel width in the downstream direction (reviewed by Caissie, 2006). However, at some distance downstream, the increasing heat capacity of the river renders the stream less responsive to fluctuations in atmospheric parameters revealing that the interaction between the different stream temperature drivers such as meteorological and hydrological factors finally determines the actual river thermal behaviour. The annual temperature cycle of running waters resembles a sinusoidal curve (Ward, 1963). The amplitude and phase of the annual temperature periodicity pattern are largely determined by the geographical location. Various long-term studies have shown that the annual cycle of running waters in warmer climates is extended throughout the summer and winter period while in colder regions the seasonal cycle is restricted to the summer period with temperatures being close to 0 °C during the winter period (Webb and Walling, 1993; Caissie et al., 2005; Hannah et al., 2008). On a smaller, regional scale the annual thermal pattern of water temperatures is determined by channel morphology, riparian shading and local groundwater influx. For instance annual ranges in groundwater-dominated streams are markedly smaller when compared to streams which are dominated by surface-runoff (Ward, 1985).

Human impacts

Any significant alterations of the factors and processes that determine the thermal regime of running waters may cause thermal anomalies along the longitudinal temperature profile or modify the temporal dynamics of river and stream temperatures (Ward, 1985). Three main types of human modifications that may have an impact on the river temperature regime have been identified and examined over the last decades (reviewed by Webb et al., 2008): Stream regulation, thermal effluents and changes in land use via forestry and urbanisation. Changes in natural river flow patterns through the construction of reservoirs and dams have been investigated by early studies in the 1950´s until today (reviewed by: Smith 1972; Ward 1985; Webb et al. 2008). Impoundment affects the downstream river thermal regime mostly through the alteration of the natural flow conditions and the associated changes of the river heat capacity and modifies the annual as well as the diurnal temperature cycle of downstream water temperatures (Webb and Walling, 1996; Lowney, 2000). The thermal pollution from thermal effluents such as industrial cooling water and condenser water released by the electricity-generating industry has also been studied in detail and heated effluents are known to have a considerably negative effect on aquatic habitat quality (Langford, 1990; Wright et al., 1999). The elevating effect of forest harvesting on river and stream temperatures is well-known (Brown and Krygier 1970; Beschta et al. 1987; Brosofske et al. 1997) and is mainly related to changes in microclimatic conditions associated with the removal of vegetation (reviewed by Moore et al., 2005). Urbanisation is also considered a land use change resulting in a warming of water temperatures due to the associated deforestation and the increase of heated runoff from impervious surfaces (Nelson and Palmer, 2007). However, in their review on human-caused thermal degradation Poole and Berman (2001) reported that the impact of human modifications depends on the sensitivity of the stream. Accordingly, the dominant mechanism controlling water temperature differs among different streams and only human activities that affect the dominant factors and processes will alter the stream temperature.

1.4.2 The river energy budget

To gain a detailed understanding of the temperature dynamics of running waters, the heat exchange processes in the river environment have to be taken into consideration (Figure 2). In general, the energy balance for a stream reach without tributary inflow is given by (Webb and Zhang, 1997):

$$Q_n = Q^* + Q_h + Q_e + Q_b + Q_f + Q_a$$

where Q_n = total energy available, Q^* = net (all-wave) radiation, Q_h = sensible heat flux, Q_e = latent heat flux, Q_b = bed conduction, Q_f = friction at the streambed and river banks, Q_a = heat advection by precipitation and groundwater. Hence radiative, convective, conductive as well as advective fluxes together determine the water temperature within a stream reach. Basically, heat transfers occur at the air-water column and at the water column-streambed interfaces with the relative importance of the interfaces depending on the channel exposure and potential groundwater influence at the streambed (Sinokrot and Stefan, 1994; Evans et al., 1998; Hannah et al., 2004). At the air-water interface, energy exchange is dominated by radiative and convective heat transfers. Net radiation, which has been reported to account for the highest proportion of the total energy flux in most studies, is the sum of net short-wave and net long-wave radiation. The amount of incoming solar short-wave and atmospheric long-wave radiation depends thereby on the atmospheric conditions such as sunshine and cloud cover and the channel exposure (channel width, riparian shading) while outgoing short-wave and long-wave radiation depend on the respective incoming fluxes, the albedo of the water surface and the water column temperature, respectively, and also on the channel exposure. Convective heat fluxes generally refer to the vertical interchange of air masses by the transfer of sensible and latent heat (Oke, 1987). The transfer of sensible heat is the addition or subtraction of energy that is sensed as a change in temperature. Heat gains/ losses at the air-water column interface that are related to sensible heat flux are determined by the temperature gradient between the water surface and the air directly above the water surface and the wind speed at the air-water interface. Accordingly, heat losses through sensible heat take place when water temperatures are higher than air temperature above the water surface. Conversely, the atmosphere warms the water column when the temperature gradient is inversed. Latent heat flux, which is commonly referred to as evaporation, is the transfer of heat via water vapour that is not sensed as a temperature change. Energy is removed from the water column when liquid water transforms into vapour. In the opposite direction, energy is added from the atmosphere to the water column via condensation. Evaporation rates are determined by the vapour pressure gradient between air and water surface and wind speed. Evaporation from the water surface is favoured by low humidity and high wind speed as these conditions increase the vapour pressure gradient between air and water surface and remove moisture-laden air above the water surface.

At the interface between streambed and water column heat exchange may occur via bed conduction, bed friction, advection through groundwater flow and also, although to a lesser extent than at the air-water interface, via radiation. The importance of the different heat fluxes has been shown to vary across the year and between different stream reaches depending on the specific characteristics of the channel and the surrounding environment. Bed conduction refers to the heat transfer that is caused by the temperature gradient within the streambed. This temperature gradient is mainly influenced by the conductivity of the bed material and by the amount of radiation absorbed by the streambed which again is determined by water depth and the streambed albedo. Advective heat exchanges at the streambed take place when groundwater of different temperature mixes with the water column. Heat is added to the water column through up-welling of relatively warmer groundwater and heat is lost from the main stream flow when colder groundwater mixes with the water column. The importance of advective heat fluxes at the streambed-water column interface differs between different streams and may even differ along the longitudinal stream profile as the influence of groundwater depends on the characteristic channel morphology. In some studies, radiative, conductive and advective transfers at the streambed are considered together as bed heat flux as they all together result in the streambed thermal profile (Hannah et al., 2004). Heat gains through friction at the streambed are generally low and depend on the channel slope and river discharge. However, friction at the streambed was shown to be important for specific streams in autumn and winter periods (Webb and Zhang, 1997). Heat advection by precipitation was found to be negligible even during heavy rain storms (Evans et al., 1998) and therefore remains unconsidered in most studies on river energy budgets.

Overall, the importance of the different heat fluxes at the air-water column and water column-streambed interfaces varies in time and space. The temporal variability is thereby mainly related to changes in atmospheric and (micro-) meteorological conditions whereas the spatial heterogeneity of energy exchange processes depends also on the channel morphology and reach characteristics. For example, wide streams have a wider surface for energy exchange processes at the air-water column interface than narrow streams and may therefore receive a higher energy input via radiation but may at the same time lose more energy via evaporation. Finally, stream discharge influences heat transfer processes directly by attenuation of incoming radiation to the streambed, by affecting bed friction and groundwater exchange processes, and in general, by determining the heat capacity of the water column.

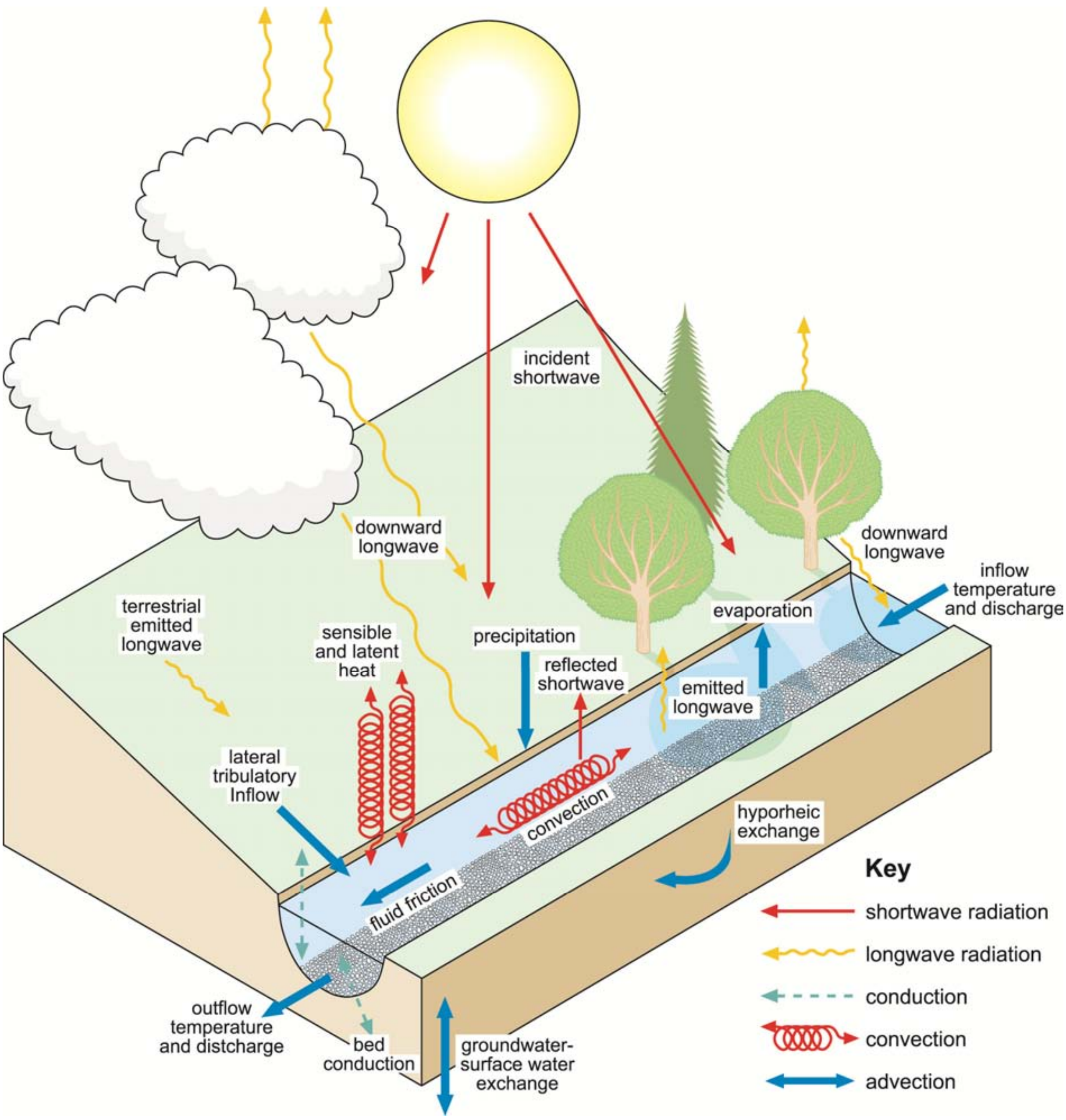


Figure 2. Energy fluxes and hydrological processes determining stream temperature. Chemical and biological processes are not shown as they are assumed to be negligible (Hannah et al., 2008).

2 Methods

2.1 Study area and site

The study catchment is located in the Plynlimon massif, mid-Wales, UK, and is part of the upper basin of the river Severn (Figure 3). The study site is located at 298 m above sea level (asl) with catchment elevations varying from 620 m asl in the south-west to 290 m asl in the east. The catchment is underlain by Ordovician and Silurian mudstones, shales and greywackes (Neal et al., 1997). The soil is generally made up of stagno-podzols but peats, brown earths and gleys are also present. The predominant land use is pasture, moorland and forestry where coniferous plantation is mainly located in the southern part of the catchment. In terms of the catchment climate, rainfall averages about 2500 mm yr^{-1} and mean annual air temperature is 7.3 °C.

The Afon Llwyd is a small upland tributary of the Afon Clywedog which is dammed by the Clywedog Reservoir. The study site on the Afon Llwyd is located approximately one kilometre upstream of its entrance to the reservoir. However, impacts on the flow regime related to the downstream impoundment are negligible due to the steep gradient of the channel which accounts for 0.6 %. At the study site, the average bankfull channel width is around 5 m while the distance of the Afon Llwyd to its source is about 5 km with a drained catchment size of 7.5 km^2. The mean annual runoff is 0.42 m^3 s^{-1}. However, the flow regime is flashy with peak flows > 5 m^3 s^{-1} which is common for the headwater catchments in Plynlimon (Neal et al., 1997).

The Afon Llwyd study reach has been integrated in two previous studies. In one earlier work the effects of gravel-bed riffle pool sequences on riparian hydrology were investigated (Emery, 2003) while the second study examined the flow paths of saturated and unsaturated water in the adjacent floodplain (Bradley et al., n.d.). However, no stream temperature research has been conducted in this reach until now. From the late 1960s much research was conducted in the adjacent Plynlimon catchments with a focus on water balance differences between forested and deforested catchments (Kirby et al., 1991). As part of this research the impact of clearfelling on stream temperature in the Plynlimon catchments has been analysed (Neal et al., 1992; Crisp, 1997; Stott and Marks, 2000). Following marked increases of maximum stream temperatures from the pre- to the post-clearfelling years, it was concluded that forest cover lowers stream temperature mainly through depression of maximum temperatures (Stott and Marks, 2000). Since the mid-1980s research on water quality of Plynlimon streams gained importance as the acidification of streams related to acid rain and forest harvesting received greater attention. In this context, the understanding of stream flow generation in the Plynlimon catchments became a major research focus over the last two decades.

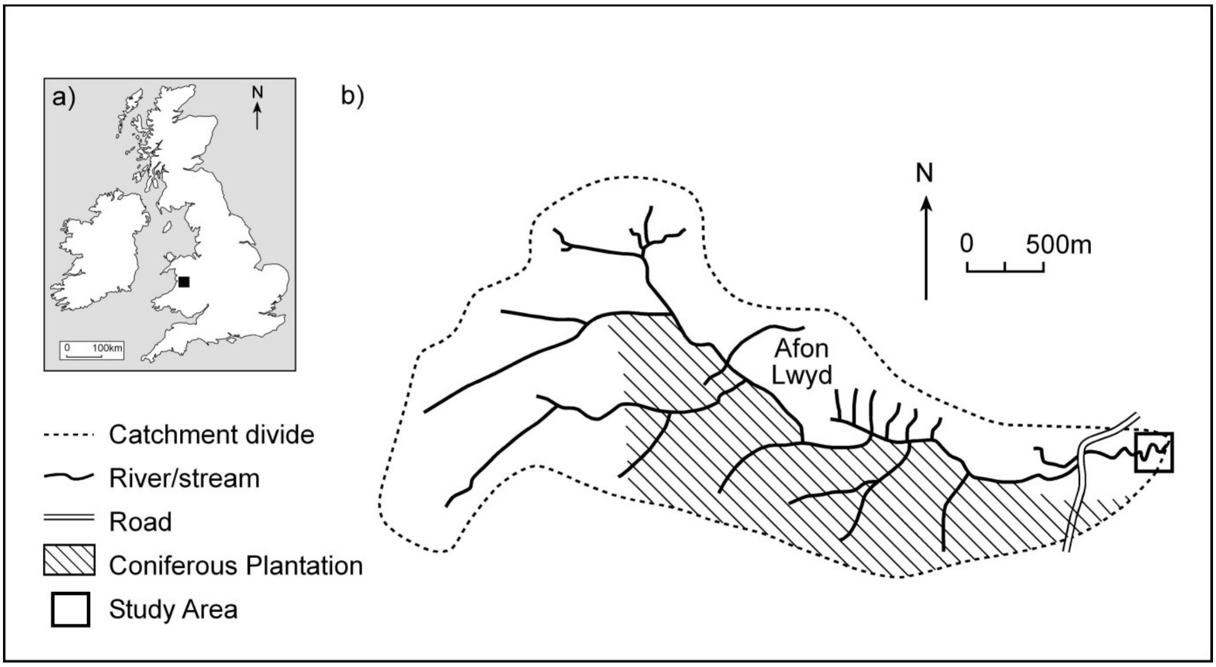


Figure 3. Location map of Afon Llwyd, Plynlimon, mid-Wales, UK.

2.2 Examination of temporal dynamics

2.2.1 Data collection

Analysis of stream temperature and energy budgets was based on water column and streambed temperature recordings as well as micrometeorological data collected from 12/12/2000 until 17/05/2002 within the study reach (Figure 4). Microclimate data and water/streambed temperatures were recorded at an automatic weather station (AWS) every 10 s and averaged over 15 min intervals by a Campbell Scientific CR10X datalogger except for precipitation data which were recorded at hourly intervals (Figures 5 and 6). Table 2 includes details on instruments and measurements. Atmospheric pressure data were derived from MIDAS station 1190 (National Grid Reference: SJ012187) operated by the Met Office which is located about 20 miles north-east of the study reach at 360 m asl. Precipitation data were obtained from Tanllwyth automatic weather station located 10 miles south-west of the study reach at 348 m asl (National Grid Reference: SN84277 87682).

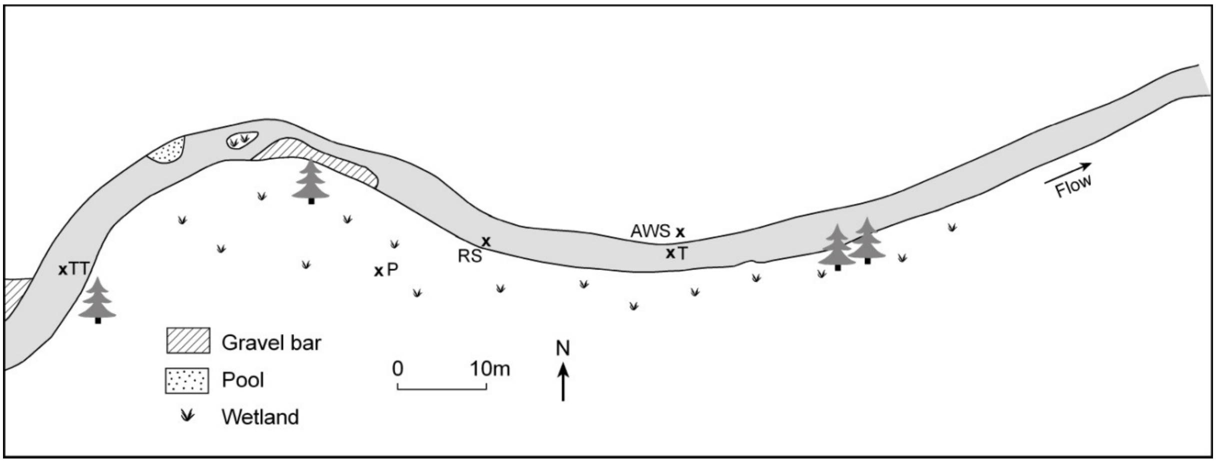


Figure 4. Study reach on Afon Llwyd with locations of automatic weather station (AWS), water column and streambed temperature sensors (T), upstream temperature sensors (TT), rain gauge (P) and river stage sensor (RS).

Stream water levels were recorded at 15 min intervals by a GE sensing 1830- level pressure sensor. A local stage-discharge relationship was constructed based on discharge derived from linear down-scaling of data monitored at the Centre for Ecology and Hydrology (CEH)- operated gauging station 54022 Plynlimon flume (SN 853 872) according to the catchment areas of the Afon Llwyd (7.5 km^2) and the Plynlimon flume (8.7 km^2). Estimated discharge was consistent with observed water levels (r = 0.99). However, the relationship was undefined for high flows. Therefore, discharge > 4 $m^3 s^{-1}$ was approximated by linear regression with discharge derived from the down-scaling procedure described above.

Table 2. Location and instrumentation of hydrometeorological variables.

Parameter	Instrument	Location	Accuracy
Air temperature	Campbell HMP35AC temperature and humidity probe	2 m above water surface (w.s.)	0.2 °C
Water column temperature	Campbell 107 thermistor	0.05 m above streambed	0.2 °C
Streambed temperatures	Campbell 107 thermistor	0.05, 0.20 and 0.40 m below streambed	0.2 °C
Net radiation	REBS net radiometer	~ 1.75 m above w.s.	± 5 %
Incoming short-wave radiation	Skye 1110 pyranometer	~ 1.75 m above w.s.	< 3 %
Reflected short-wave radiation	Skye 1110 pyranometer	~ 1.75 m above w.s.	< 3 %
Short-wave to streambed	Skye 1110 pyranometer	Streambed surface	< 3 %
Bed heat flux	REBS heat flux plate	0.05 m below streambed	± 5 %
Wind speed	Vector A100R 3-cup anemometer	~ 2 m above w.s.	0.25 $m s^{-1}$
Relative humidity	Campbell HMP35AC temperature/ humidity probe	~ 2 m above w.s.	1–3 %
Water level	GE sensing 1830- level pressure sensor	0. 10 m above streambed	0.1 %

Figure 5. Housing for Campbell 107 thermistor recording streambed temperatures at 0.05 m, 0.20 m and 0.40 m depth.

Figure 6. Automatic weather station recording micrometeorological data at 1.75 m above water surface.

Data were checked for inconsistencies and data gaps through visual inspection of time series plots or generation of cumulative plots and differences plots for comparable data. Occasional spurious values were removed and when possible the gaps were filled with average values calculated from the preceding value and the following value or, for larger gaps, through linear interpolation or linear regression derived from a corresponding time series where correlation analysis between time series exhibited $r > 0.9$. Data checking identified inconsistent data for streambed temperatures measured at 20 cm depth from 27th of September 2001 onwards. Therefore available streambed temperature data which had been recorded approximately 40 m upstream by a Tinytag temperature data logger at the same depth (Figure 4) were applied for the time period from 27th of September 2001 until 13th of March 2002 when the Tinytag measurements terminated. Temperature data obtained by Campbell 107 thermistors and Tinytag temperature loggers at 20 cm depth within the streambed were highly correlated for the preceding time period ($r > 0.99$) and the root-mean-square error (RMSE) was 0.76 °C. Furthermore, water column temperature data showed inconsistencies from January 2002 onwards and were replaced by values obtained via linear regression with streambed temperatures at 5 cm depth. Data gaps affecting microclimate and water/bed temperatures occurred between 20/09/2001 and 26/09/2001 due to datalogger failure. During this time period the access to the study site was prohibited because of the outbreak of the Foot and Mouth Disease (Anderson, 2002).

2.2.2 Estimation of energy balance components

In the present study, the stream energy balance definition by (Webb and Zhang, 1997) was applied. Accordingly, the heat budget of a stream is expressed as:

$$Q_n = Q^* + Q_h + Q_e + Q_b + Q_f + Q_a \qquad (1)$$

where Q_n = total energy available, Q^* = net (all-wave) radiation, Q_h = sensible heat flux, Q_e = latent heat flux, Q_b = bed conduction, Q_f = friction at the streambed and river banks, Q_a = heat advection by precipitation and groundwater. Throughout this study, energy fluxes directed towards (away from) the water column were defined as positive (negative) fluxes as these heat fluxes were supposed to add (remove) heat from the stream water. The different energy balance components have either been measured directly or estimated based on empirical equations (see below) and are expressed as daily flux totals in MJ m^{-2} d^{-1}.

The total energy available at the air-water interface (Q_{sn}) is the sum of the following components (Evans et al., 1998):

$$Q_{sn} = Q^* + Q_h + Q_e + Q_p \qquad (2)$$

where Q_p = heat advection by precipitation.

Net radiation at the air-water interface

Net (all-wave) radiation at the air-water interface (Q^*) was monitored above the water surface. Additionally, accuracy of measured net radiation was checked by calculating Q^* based on the following equation:

$$Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow \qquad (3)$$

where $K\downarrow$ = incoming short-wave radiation, $K\uparrow$ = outgoing short-wave radiation, $L\downarrow$ = incoming long-wave radiation, $L\uparrow$ = outgoing long-wave radiation.

Therefore, $K\downarrow$ and $K\uparrow$ were measured above the water surface while $L\downarrow$ was estimated based on the Stefan-Boltzmann law with an emissivity of 0.97 (Oke, 1987). $L\uparrow$ was calculated by rearrangement of equation 3. Net short-wave radiation (K_s*) and net long-wave radiation (L_s*) at the water surface were derived from differences between outgoing and incoming short-wave and long-wave radiation fluxes, respectively.

Net radiation at the streambed- water column interface

Incoming short-wave radiation at the streambed ($K_b\downarrow$) was measured while outgoing short-wave radiation at the channel bed ($K_b\uparrow$) was computed as follows:

$$K_b\uparrow = K_b\downarrow \times \alpha \qquad (4)$$

where α = albedo of the streambed (0.10: Evans et al., 1998; Webb and Zhang, 1997). Incoming long-wave radiation to the bed ($L_b\downarrow$) was calculated using the Stefan-Boltzmann law with the water column as the effective atmosphere and an emissivity of 0.97 while outgoing long-wave radiation from the bed ($L_b\uparrow$) was estimated based on the streambed temperature at 0.05 m and an emissivity of 0.98 (Oke 1987). Net short-wave radiation (K_b*) and long-wave radiation at the bed (L_b*) were calculated from differences between $K_b\downarrow$ and $K_b\uparrow$ and $L_b\downarrow$ and $L_b\downarrow$, respectively while net (all-wave) radiation at the streambed (Q_b*) was computed as sum of K_b* and L_b*.

Evaporation/ condensation rate at the water surface

The evaporation/condensation rate (mm d^{-1}) at the air-water column interface (E_v) was estimated using an empirical Penman-style equation according to Webb and Zhang (1997):

$$E_v = 0.165 \text{ x } (0.8 + \frac{ws}{100}) \text{ x } (E_w - E_a) \qquad (5)$$

where ws = wind speed at 2 m above the water surface (km d^{-1}), E_w = saturated vapour pressure at water surface temperature (mbar), and E_a = vapour pressure at air temperature (mbar). Vapour pressures were calculated based on the following equations (McIlveen, 1992):

$$E_w = 6.1 + (0.27 \text{ x } T_w) + (0.034 \text{ x } T_w^2) \qquad (6)$$

$$E_a = \frac{\mathrm{RH}}{100} \, x \, E_{Ta} \qquad (7)$$

where T_w = water column temperature (℃), RH = relative humidity (%) and E_{Ta} = saturated vapour pressure at air temperature (mbar).

Latent heat of vaporisation

Latent heat of vaporisation (L_v) (℃ J g^{-1}) was estimated based on the following empirical equation (Webb and Zhang, 1997):

$$L_v = 2499.64 - 2.336 \text{ x } T_a \qquad (8)$$

where T_a = air temperature (℃).

Latent heat flux

The latent heat flux at the air-water column interface (Q_e) (W m^{-2}) was calculated based on the following equation (Webb and Zhang, 1997):

$$Q_e = E_v \times L_v \times \gamma \qquad (9)$$

where γ = specific weight of water (g cm^{-3}).

Sensible heat flux

As sensible heat flux (Q_h) is the product of latent heat flux and the Bowen ratio (β), Q_h was estimated by calculating the Bowen ratio according to Bowen (1926):

$$\beta = (0.61 \times P \times \frac{(Tw - Ta)}{(Ew - Ea)}) / 1000 \qquad (10)$$

where P = atmospheric pressure (mbar).

Bed heat flux

Heat exchange within the bed including conductive, advective, convective and radiative heat transfer was characterised by bed heat flux (Q_{bhf}) rather than bed conduction (Q_b) as it was not possible to sample the streambed gravels to determine thermal conductivity of the bed. Q_{bhf} was measured just below the streambed at 0.05 m depth (Hannah et al., 2004).

Fluid friction

Heat gained by fluid friction at the streambed and channel banks was estimated using this empirical equation according to Theurer et al. (1984):

$$Q_f = 9805 \times \frac{F}{W} \times S \qquad (11)$$

where F = flow volume entering the study reach (m^3 s^{-1}), W = average channel width (m) and S = slope of the channel (m m^{-1}). However, this term was omitted from the energy balance due to the fact that estimations yielded unrealistically high values compared with other energy flux components.

Other energy fluxes

Heat transfer by precipitation was assumed to be negligible as it has been demonstrated that heat transfer by precipitation was negligible even during heavy rainstorms (Evans et al., 1998). Chemical and biological processes were also assumed to be insignificant for the energy balance. Heat fluxes related to groundwater were captured by measuring thermal profiles within the streambed. No tributaries flow into the stream within the study reach.

Accuracy check of energy balance estimations

Bed heat flux and radiative fluxes have been monitored directly or have been calculated using well-proven equations. Latent and sensible heat fluxes have been calculated using equations 9 and 10 and have been estimated additionally by the bulk aerodynamic approach (Oke, 1987). Therefore the water level and height of instruments above the water surface were taken as respective lower and upper boundary for the estimation of heat flux gradients. According to Hannah et al. (2004), it was assumed that water surface temperature equals water column temperature, saturated vapour pressure at water surface temperature equals water surface humidity, and wind speed at the water surface equals zero. The surface roughness length was set to 5 x 10^{-5} m which is a value in the mid-range of published values for water surfaces (Oke, 1987). The comparison of latent and sensible heat fluxes estimated by the two different approaches yielded a good agreement of values with correlations being high for both latent (r = 0.98) and sensible heat (r = 0.94) and root mean square errors for latent (RMSE = 6.72 W m^{-2}) and sensible heat (RMSE = 8.02 W m^{-2}) being similar to those reported by Hannah et al. (2004). Hence, turbulent heat fluxes estimated by equations 9 and 10 were considered reliable and were used for energy balance estimations.

Stream temperature prediction

To check the accuracy of the estimated energy balance, water temperature was predicted based on the total energy available derived from equation 1. Therefore a deterministic model according to Moore (2005) which allows calculating the change of temperature with time at a specific location was used.

$$\frac{\partial T_w}{\partial t} = \frac{Q_n}{d \times \rho \times \theta} \qquad (12)$$

where Q_n = total energy available (W m^{-2}), d = water depth (m), ρ = water density (1000 kg m^{-3}), and θ = specific heat of water (4.19 x 10^{-3} MJ kg^{-1} $°C^{-1}$). Therefore it has been assumed that the stream is vertically well-mixed and that changes in temperature along the stream are relatively small compared to temporal changes (Caissie et al., 2007). Daily changes in water temperature calculated by equation 12 were added to (subtracted from) observed daily water temperatures to calculate the respective water temperature of the following day. To assess the model fit between simulated and observed water temperatures over the year 2001 the Mean Error (ME) was calculated (Hannah and Gurnell, 2001). The ME reflects the overall tendency of the model to underestimate (positive values) or overestimate (negative values) the temperature. Furthermore, the model performance was evaluated by calculating the Nash Coefficient (NASH) and root- mean- square error (RMSE) which are given by (Nash and Sutcliffe, 1970; Hannah and Gurnell, 2001):

$$ME = \frac{\sum_{i=1}^{N} (Oi - Pi)}{df} \qquad (13)$$

$$NASH = 1 - \frac{\sum_{i=1}^{N} (O_i - P_i)^2}{\sum_{i=1}^{N} (O_i - O_M)^2} \qquad (14)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(O_i\text{-}P_i\right)^2}{df}} \qquad (15)$$

where O_i = observed daily water temperature, P_i = predicted daily water temperature, O_M = observed mean daily water temperature over the period N and df = degrees of freedom.

2.2.3 Data analysis

Data were analysed at annual, seasonal and sub-seasonal timescales such as diurnal and storm-event scale. Data analysis included the calculation of summary statistics such as (averages of) daily mean, daily minimum/maximum values and daily ranges. Furthermore, water column/streambed temperatures and microclimate parameters were correlated among each other. Pearson´s product moment correlation coefficient (r) was used as a measure of correlation. Statistics are only presented if significant at $p < 0.05$. Unless stated otherwise, all correlations were significant at $p < 0.03$ level.

For seasonal analysis, summary statistics were calculated for the centre months of the four seasons (January, April, July, October) as seasonal differences are generally expected to be most pronounced in the middle of the season. For diurnal analysis, individual 15 min values were averaged at 24-hour intervals over monthly time series to create composites for January, April, July and October 2001.

To examine the impact of storm flows on stream thermal processes heat budgets, water column and streambed temperatures have been analysed with respect to selected storm flow events. In total four exemplary events were selected according to the following procedure. One event in each season was selected that allowed for a clear separation between pre-event and main event (peak flow) time periods based on the discharge hydrograph. To quantify thermal changes over the events, averages of microclimate parameters, heat budget components, discharge and water column/ bed temperatures were calculated over the main event peak and compared with respective averages over the time period immediately before the event. For water/streambed temperatures and microclimate parameters the differences between pre-event and concurrent event values of the parameters were calculated.

2.3 Examination of spatial dynamics

2.3.1 Data collection

Water temperatures, air temperature as well as water levels were measured from 21/05/2010 to 05/08/2010. Table 3 includes details on instruments and measurements. Water temperatures were recorded *in situ* every 5 min by Tinytag TG-1400 temperature data loggers at 12 distinct positions within the study reach (Figure 7). The 12 positions are subsequently referred to as positions 1, 2, 3a, 3b, 3c, 4a, 4b, 5a, 5b, 6a, 6b, 6c. Temperature loggers were placed into and attached to white plastic housings which were open at two ends (Figure 8). The housings were fixed to the streambed via road pins with the openings oriented parallel to the stream flow direction enabling unhindered water flow through the housing. To mark the locations of the 12 temperature loggers white marker pegs were installed at the respective channel banks. Position 1 was installed at the inlet of the study reach while position 2 was positioned within a small pool (Figure 7). Positions 3a, 3b and 3c comprised a stream section where the stream is temporarily split up by a small island in the middle of the channel. Loggers at positions 4a and 4b were installed to capture potential shading effects from the north-facing and south-facing channel bank. Loggers at positions 5a and 5b lay within a stream section where the flow velocity is generally reduced compared to other stream sections. Loggers at position 6a, 6b and 6c were installed to monitor potential shading effects of coniferous trees standing at the south-sided channel bank in line with logger position 6b.

Air temperature was recorded every 5 min with a Tinytag TG-1400 temperature data logger at the northern riverbank in close vicinity to position 6a. Water levels were measured every 15 min by a TruTrack WT-HR 1500 water height data logger close to position 1 at the study site inlet. A stage-discharge relationship was generated as described in 2.2.1. However, this relationship did not work for river flows > 1.5 m^3 s^{-1}. Thus, discharge was estimated by downscaling data recorded at the CEH gauging station 54022 Plynlimon flume according to the catchment areas of the Afon Llwyd (7.5 km^2) and Plynlimon flume (8.7 km^2). Estimated runoffs were highly correlated with observed water levels at Afon Llwyd over the study period ($r = 0.936$). Precipitation was measured by a tipping bucket at the environment agency-operated weather station Dolydd, which is located about 250 m south west of the study site.

Data were checked for inconsistencies and gaps through visual inspection of time series plots or generation of cumulative and differences plots for comparable data. Occasional spurious values were removed and when possible the gaps were filled through linear interpolation or by linear regression derived from a corresponding time series where correlation analysis between time series exhibited $r > 0.9$.

The study reach was surveyed with a LEICA TC800 total station according to the manufacturer´s manual. The survey covered the different positions of the temperature loggers and the water level sensor as well as the shape of the channel and *in stream* structures such as gravel bars and pools.

Table 3. Monitored variables and instrumentation.

Parameter	Instrument	Location	Accuracy
Air temperature	Tinytag TG-4100 temperature data logger	riverbank, 0.75 m above water surface	0.2 ℃
Water temperatures	Tinytag TG-4100 temperature data logger	0.05 m above streambed	0.2 ℃
Water level	TruTrack WT-HR 1500 water height data logger	0.015 m above streambed	0.001 m

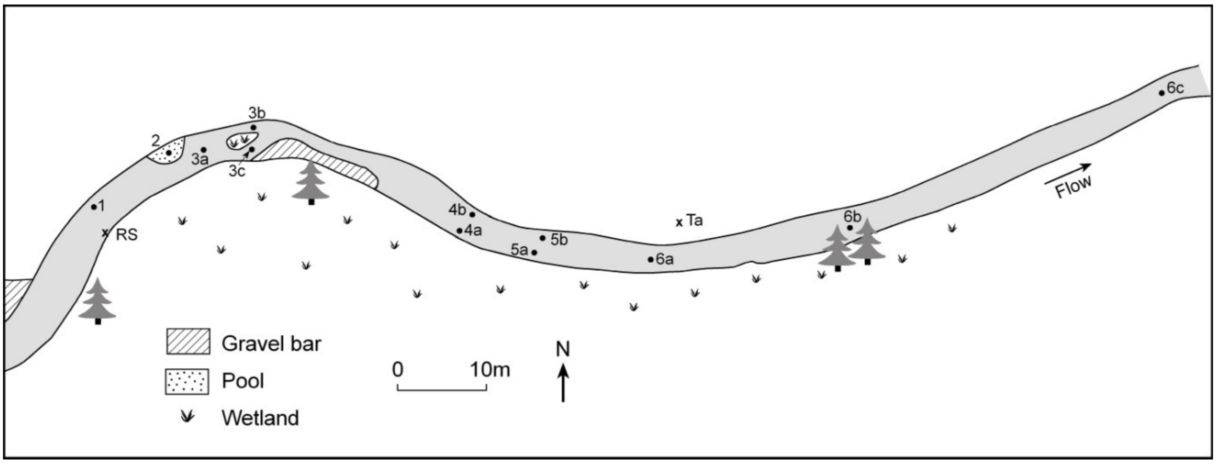


Figure 7. Study reach on Afon Llwyd with respective positions of water temperature loggers 1 to 6c, air temperature logger (Ta) and water level sensor (RS).

Figure 8. White plastic housing containing Tinytag temperature logger.

2.3.2 Data analysis

Water temperatures measured at the different positions within the channel were compared via visual inspection of time series, by comparison of statistical values and by generating box-and-whisker plots. For statistical analysis summary statistics such as daily mean water temperatures, daily minimum/maximum values and daily ranges of water temperatures were computed. Box-and-whisker plots allowed inter-site comparison by summarising the median, minimum, maximum, upper and lower quartiles based on 5-min temperature data. Water temperatures were analysed additionally on a diurnal basis to examine potential spatial temperature patterns in the course of the day. To determine the effect of stream thermal capacity on spatial temperature variation, summary statistics individually calculated for an extended low-flow period from 18 until 28 June 2010 and a high-flow period from 15 July until 25 July 2010 were compared. The respective low-flow and high-flow period were chosen based on the discharge hydrograph of the study period. To set the stream thermal dynamics in a hydrometeorological context, daily water temperatures were correlated with daily air temperature and discharge. Pearson´s product moment correlation coefficient (r) was used as a measure of correlation. Statistics are only presented if significant at $p < 0.05$. Unless stated otherwise, all correlations were significant at $p < 0.03$ level.

2.3.3 Thermal imaging

Thermal radiation emitted from surfaces can be remotely detected by specific sensors (Anderson and Wilson, 1984). For water surfaces the infrared (IR) imaging technique is sensitive to the upper 0.1 mm of the water column. In this study, the water surface temperature within the study reach was monitored via ground-based IR thermography using the portable thermographic system INFRATEC VarioCAM hr. Thermal images included 640 x 480 pixels and covered a spectral range of 7.5 – 14 µm. The detected radiant temperature had an absolute accuracy of 1.5 K and the resolution of temperature was 0.08 K. In addition to the infrared pictures, corresponding visual images of the monitored sections were taken (1.3 MP). Measurements were conducted between 13:30 and 15:30 on 21 May 2010 and from 14:30 until 16:30 on 16 June 2010. The camera was either hand-held or mounted on a tripod located at the bank of the stream. The main cross-sections of *in situ* stream temperature measurements as well as various structures within the stream such as vegetation or riffles and gravel bars have been monitored. As the main focus of image interpretation was the distribution of water temperature the emissivity in all the images was considered constant at 0.96 which is a value in the mid-range of published values for water surfaces (Anderson and Wilson, 1984). Meteorological conditions were similar on both recording days and were characterised by dry and mostly sunny conditions which were interrupted by just a few cloudy spells. Effects on temperature measurements related to air temperature and relative humidity were taken into account in that air temperature and relative humidity data were input into the camera. Therefore air temperature, relative humidity and wind speed were measured on site using a Kestrel 3000 pocket weather meter. Radiant water temperatures are only representative of the water column temperature when the water column is sufficiently mixed (Torgersen et al., 2001). Measurements of vertical thermal profiles within the water column at different stream sections using a Casella whirling hygrometer (± 0.1 °C accuracy) revealed no thermal stratification. To estimate the accuracy of the measured radiant temperatures, monitored stream temperatures were compared against manual spot measurements of water temperature (kinetic water temperature) below the water surface. Differences between radiant and kinetic water temperature were less than 0.2 °C. For image review InfraTec IRBIS 3 software was used.

3 Results

3.1 Examination of temporal stream temperature dynamics

3.1.1 Annual and seasonal patterns

Water column and streambed temperatures

Mean daily water column and stream bed temperatures displayed a clear annual cycle over the study period (Figure 9). In the course of the year 2001 mean daily water column and bed temperatures increased from March onwards and reached their highest values in the middle of June. During the summer, water temperatures ranged between 10°C and 20 °C and declined gradually from September onwards. The lowest daily water column and streambed temperatures ranged at 0 °C and occurred during winter months with more temperature depressions taking place in winter 2000/2001 when compared to the subsequent winter period 2001/2002. However, no icing periods occurred in either of the winter periods. During the course of the year, diurnal and seasonal fluctuations in water column and bed temperatures mirrored one another and were significantly correlated with each other. Accordingly, water column temperature was highly correlated with stream bed temperatures at 0.05 m ($r = 0.998$), 0.20 m ($r = 0.992$) and 0.40 m ($r = 0.980$) depth. In addition, bed temperatures at different depths were strongly positively correlated among each other with all values exceeding $r = 0.983$. However, streambed temperatures at 0.40 m depth slightly lagged temperatures of overlying streambed and water column (Figure 9). In 2001, mean daily water column temperature (T_w) averaged 9 °C and was about 0.27 °C (0.23 °C) higher than in the streambed at 0.05 m (0.20 m) depth and 0.42 °C warmer than the underlying streambed at 0.40 m depth (Table 4). Mean daily streambed temperatures at 0.05 m and 0.20 m depth did not differ significantly from each other and were intermediate to the water column and the streambed at 0.40 m depth ($T_{b\_0.40}$). Hence, the streambed at 0.40 m depth displayed on average the lowest mean daily temperatures (Table 4).

Table 4. Summary statistics for temperatures (°C) and discharge ($m^3 s^{-1}$) with daily means, standard deviation, mean daily minimum/maximum values, mean daily range in 2001.

Variable	Mean	Std	Min	Max	Range
Water column temperature	9.00	4.66	7.55	10.61	3.06
Bed at 0.05 m depth temperature	8.73	4.54	7.42	10.2	2.78
Bed at 0.20 m depth temperature	8.77	4.50	7.83	9.78	2.36
Bed at 0.40 m depth temperature	8.58	4.18	8.2	9.04	1.62
Stream discharge	0.42	0.44	0.03	3.03	0.39

However, vertical streambed-water column temperature gradients showed a highly variable pattern throughout the year. As shown in Figure 10, temperature differences between T_w and $T_{b\_0.40}$ varied considerably over the year. Compared to the water column, the streambed at 0.40 m depth tended to be periodically warmer in winter but cooler in summer. Maximum differences between T_w and $T_{b\_0.40}$ were approximately 1 °C and occurred in June. Towards the end of summer, water column and

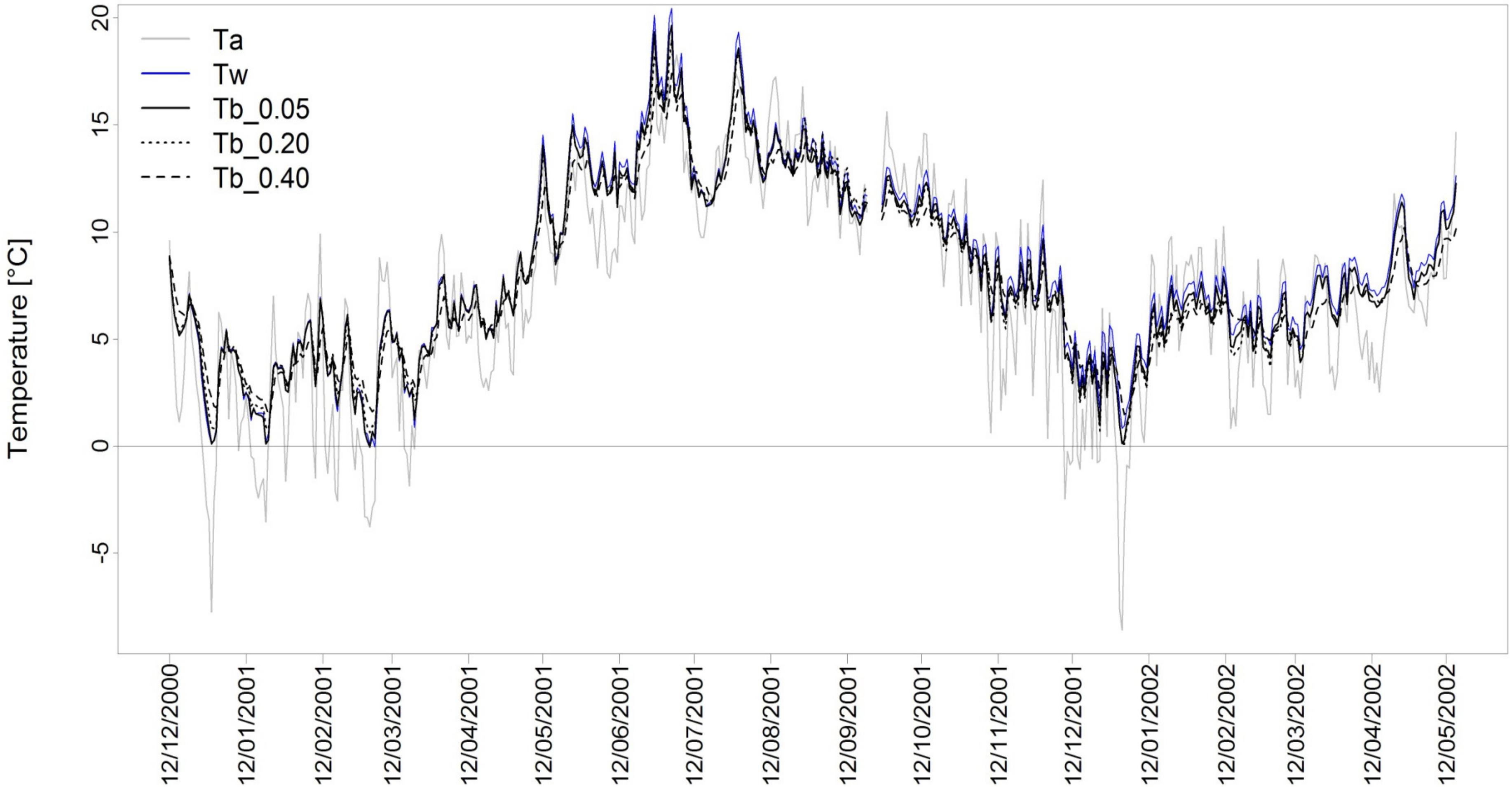


Figure 9. Mean daily air and water column temperatures and streambed temperatures at 0.05 m, 0.20 m and 0.40 m depth over the monitoring period.

streambed at 0.40 temperatures started to converge gradually until winter, except for the month of October where the T_w minus $T_{b\_0.40}$ difference was enhanced again. In winter and early spring, differences between T_w and $T_{b\_0.40}$ were relatively small accounting for less than 0.2 °C.

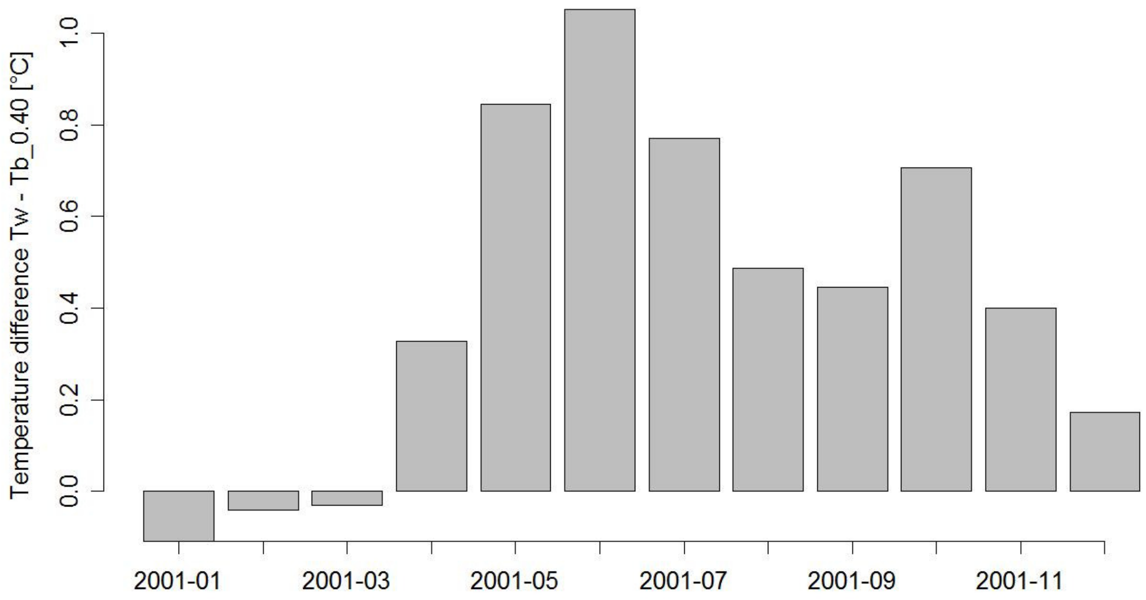


Figure 10. Mean daily water column temperature (T_w) minus bed temperature at 0.40 m depth ($T_{b\_0.40}$) over every month of the year 2001.

Daily maximum temperatures in 2001 were on average greatest in the water column and decreased with depth, while daily minimum temperatures tended to increase with depth (Table 4). Averaged over the year 2001, both daily minimum temperature was highest and daily maximum temperature was lowest at 0.40 m depth. Accordingly, daily temperature range and standard deviation was lowest for $T_{b\_0.40}$. The highest standard deviation and greatest daily differences between minimum and maximum temperatures were found for the water column which showed a mean daily range of 3 °C in 2001. Hence, the diel temperature range was highest in the water column and was dampened with increasing depth.

Discharge

Mean daily river flow over the monitoring period was 0.48 $m^3\ s^{-1}$ while absolute minimum and maximum discharge were 0.03 $m^3\ s^{-1}$ and 4.53 $m^3\ s^{-1}$, respectively. The respective averages over the year 2001 are shown in Table 4. The discharge hydrograph closely tracked patterns in precipitation over the monitoring period (Figure 11). Accordingly, daily flows were significantly correlated with precipitation ($r = 0.816$) which accounted for in total 2379 mm in 2001. During the study period, peak flows took place mainly in February 2001 and 2002 as well as in November 2001, while the main low flow periods occurred from May - June 2001 and in April 2002 (Figure 11).

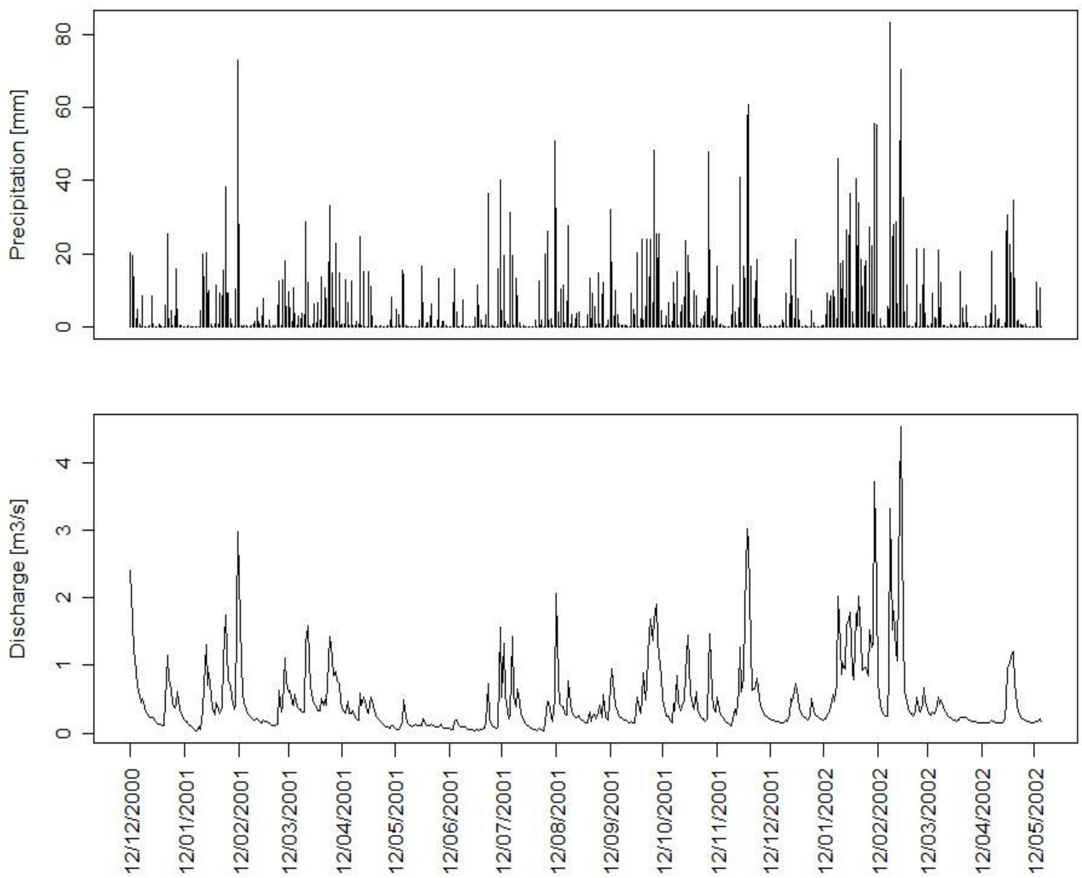


Figure 11. Mean daily river discharge of Afon Llwyd and precipitation within the study reach over the monitoring period.

As thermal capacity of stream water is highly determined by runoff conditions correlations between discharge and water temperatures were examined. Daily stream flows were weakly negatively correlated with water column (r = -0.134) and streambed temperatures at 0.05 m (r = -0.121), 0.20 m (r = -0.140) and 0.40 m (r = -0.157), respectively. Since a coarse annual analysis may mask potential impacts of changing thermal capacity on stream temperature, correlations for single months have also been included. Respective correlation coefficients for centre months of every season (January, April, July and October 2001) displayed a clear seasonal variability in correlation. In January 2001, correlations were significantly positive between daily river flows and water column temperature (r = 0.724), bed temperature at 0.05 m (r = 0.721), 0.20 m (r = 0.698) and 0.40 m (r = 0.523) depth, respectively. In contrast to this, daily discharge was negatively correlated with channel temperature (r = -0.538), bed temperature at 0.05 m (r = -0.551) and 0.20 m (r = -0.537 m) but not significantly correlated with streambed temperature at 0.40 m in July 2001. For April and October 2001 no significant correlations were found.

Riparian microclimate

Air temperature. Mean daily air temperature exhibited a clear annual cycle with diurnal fluctuations being higher than those for water column or streambed temperatures (Figure 9). Accordingly, the mean daily range of air temperature was approximately 7.90 °C, while water column and streambed temperatures only showed daily differences of about 3 °C (cf. Table 4 and 5). The mean daily air temperature in 2001 was 7.82 °C and therefore was considerably lower than mean daily water column temperature (9.0 °C). The lowest air temperatures including periods of frost occurred at the end of the year and persisted up to March in the year 2001 (Figure 9). Over the year, water and streambed temperatures tracked seasonal patterns of air temperature without any apparent lag.

Table 5. Summary statistics for riparian microclimate variables including air temperature (T_a) and vapour pressure at air temperature (E_a). Mean values and standard deviation (Std) are presented.

Variable	Mean	Std
T_a daily average (°C)	7.82	5.36
T_a daily minimum (°C)	3.53	5.67
T_a daily maximum (°C)	11.43	5.78
T_a daily range (°C)	7.90	4.16
Relative humidity daily average (%)	89.66	6.48
E_a daily average (mbar)	10.12	3.63
Wind speed daily average (m s^{-1})	1.64	0.97

Daily air temperatures were highly correlated with the water column temperature (r = 0.934). The slope for the air-water temperature relationship was 0.8 (Figure 12). The discrepancy between air and water temperatures was highest at relatively low air temperatures (Figure 12). In addition to the high correlation with water column temperatures, air temperature was strongly positively correlated with streambed temperatures at 0.05 (r = 0.934), 0.20 m, (r = 0.921) and 0.40 m depth (r = 0.881), respectively, with the correlation decreasing with depth.

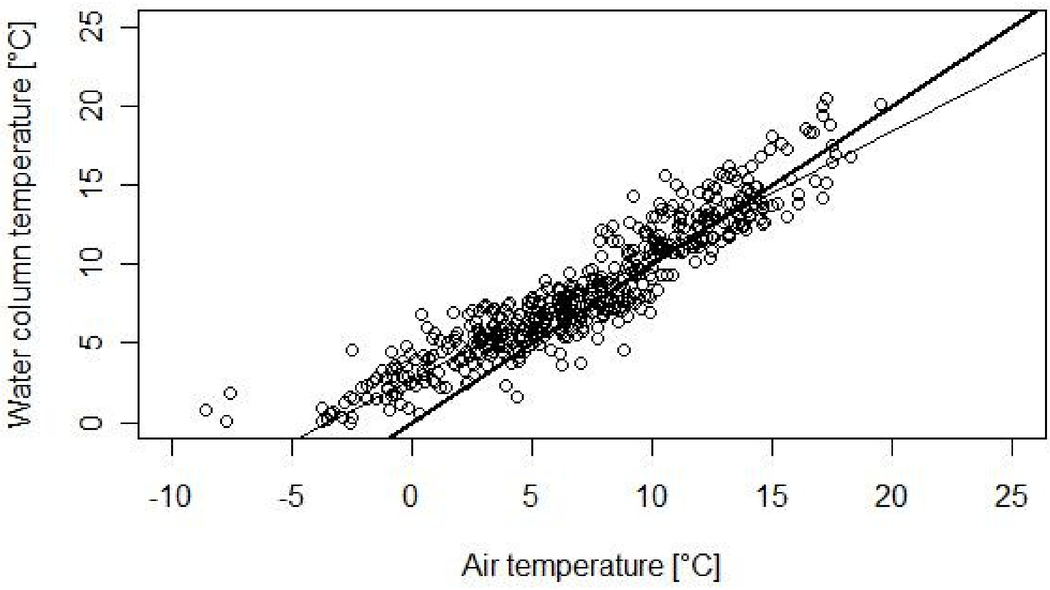


Figure 12. Relationship between air and water column temperatures based on mean daily values over the monitoring period with respective regression line (thin black line). Broader black line has a slope equal to 1.

Humidity, vapour pressure and wind speed. Relative humidity (RH) affects evaporation directly and is therefore an important variable with regard to heat exchange processes in streams. RH exhibited a relatively weak annual cycle over the monitoring period and the daily average in 2001 was 89.66 % (Figure 13, Table 5). Over the study period, RH was lowest in spring and increased throughout the summer and autumn before the values reached a stable level of fluctuation in winter and declined again gradually at the end of winter.

Vapour pressure at air temperature (E_a), which was calculated based on RH and air temperature, displayed a more apparent intra-annual variation and closely resembled the annual air temperature pattern (Figure 13). E_a was highly correlated with air temperature ($r = 0.935$). Values of E_a peaked during summer, declined in autumn and remained low in winter. The daily average was 10.12 mbar in 2001 (Table 5).

Together with E_a and the saturated vapour pressure at water surface temperature (E_w), wind speed determines the evaporation rate and is therefore a considerable micrometeorological variable. Over the monitoring period wind speed fluctuated on average around 1.64 m s^{-1} with no clear seasonal variation (Table 5 and Figure 13). Wind speed was slightly negatively correlated with relative humidity ($r = -0.150$).

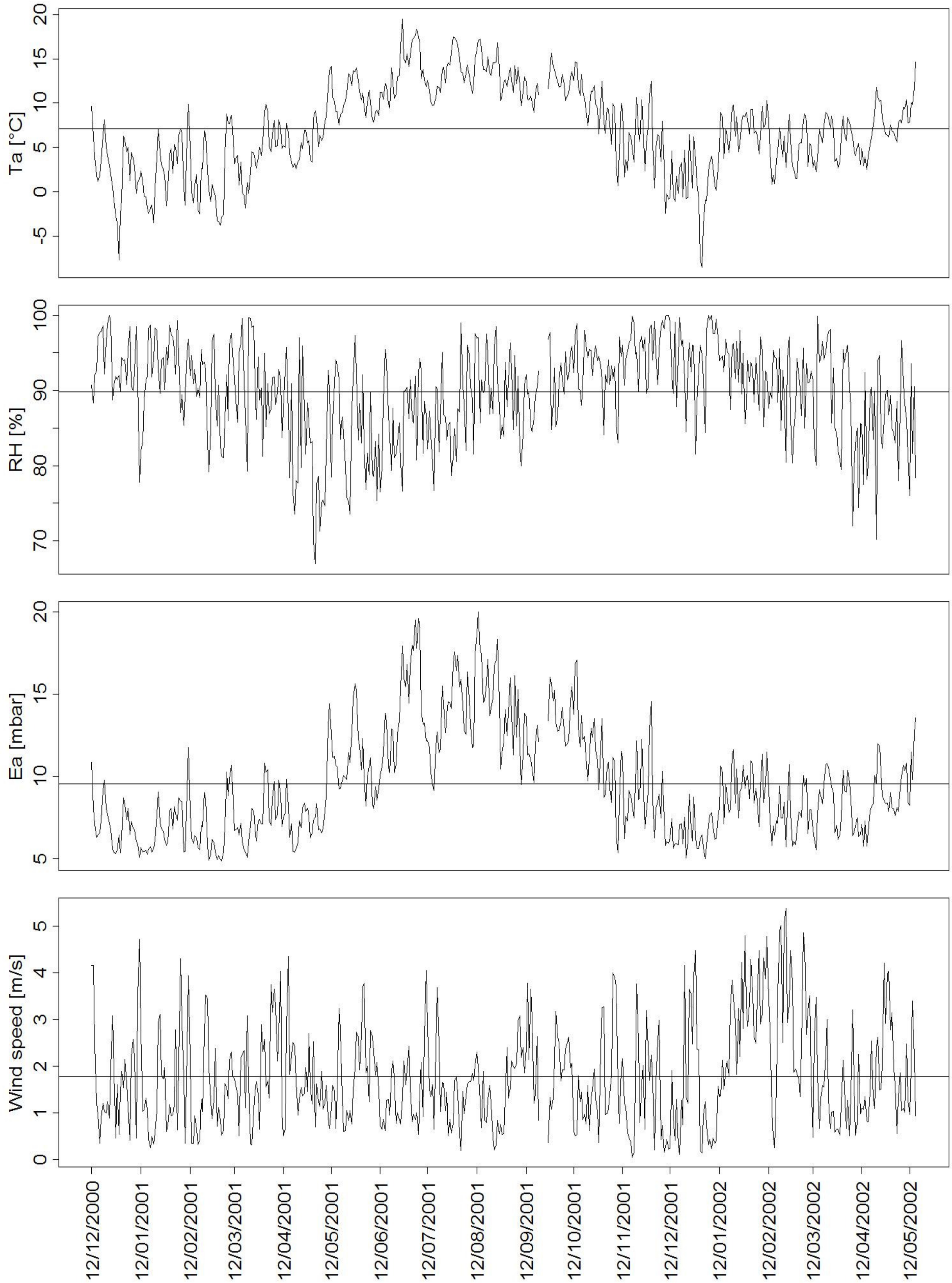


Figure 13. Mean daily air temperature (T_a), relative humidity (RH), vapour pressure at air temperature (E_a) and wind speed over the monitoring period. Horizontal lines correspond to respective mean daily averages over the study period.

Heat and energy exchange processes

Energy exchange processes at the air-water and water-streambed interfaces largely determine river thermal dynamics, especially where advective heat or water sources are negligible. Therefore, energy budgets of the Afon Llwyd have been examined on different temporal scales. Energy flux sign convention adopted herein considers energy fluxes to be positive (energy gains) when they are directed toward the water column to heat the stream. Conversely, fluxes directed away from the water column, which cool the stream, are considered negative (energy losses).

Air-water interface. Net (all-wave) radiation (Q*), which is the sum of net short-wave (K*) and net long-wave (L*) radiation, displayed a clear annual pattern (Figure 14). Averaged over the year 2001, mean daily net radiation was 5.72 MJ m^{-2} d^{-1} and was in total the only daily heat source for the stream (Table 6). Maximum values for net radiation were about 20 MJ m^{-2} d^{-1} and occurred in summer, while in winter values of Q* were low and approximately 0 MJ m^{-2} d^{-1} (Figure 14). Hence, energy gain for the water column through radiation was highest in summer and low during winter. Low energy input through Q* coincided with low energy gain through short-wave radiation, as shown in Figure 14. In general, the contribution of net long-wave radiation to the net radiation term was small compared to net short-wave radiation (Table 6, Figure 14). Accordingly, correlation between Q* and K_s* was higher (r = 0.978) than between Q* and L_s* (r = -0.574). In relation to the radiation parameters, sensible heat flux (Q_h) was relatively small with daily flux totals ranging between -3.85 and 2.77 MJ m^{-2} d^{-1} (Figure 14, Table 6). Averaged over the year 2001, mean daily Q_h was -0.31 MJ m^{-2} d^{-1} and therefore Q_h was in total a heat loss. Annual patterns in sensible heat flux were weak. However, Q_h tended to be temporary slightly positive in autumn 2001 and January/February 2002 whereas Q_h appeared to be rather negative in June/July 2001 and December 2001 (Figure 14). Daily flux totals of Q_h were strongly positively correlated with mean daily air minus daily water column temperature differences (r = 0.878) and slightly positively correlated with mean daily wind speed (r = 0.256). Latent heat flux (Q_e) displayed a more distinct annual cycle with mainly negative values throughout spring and summer and values around zero during the rest of the year (Figure 14). Daily energy flux totals ranged between -9.24 and 3.17 MJ m^{-2} d^{-1}. Mean daily latent heat flux in 2001 was -1.53 MJ m^{-2} d^{-1} and was therefore in total a greater heat loss to the stream than sensible heat flux (Table 6). Q_e was highly correlated with relative humidity (r = 0.651).

Total energy available at the air-water interface (Q_{sn}) is the sum of Q*, Q_h and Q_e and demonstrated a clear annual cycle over the monitoring period (Figure 14). Q_{sn} increased in spring and reached maximum values in summer. In autumn the available energy at the air-water interface decreased and tended to zero or below zero values in winter. Daily energy flux totals ranged between -8.40 and 16.17 MJ m^{2} d^{-1} (Table 6). Averaged over the year 2001, heat exchange processes at the air-water interface were an energy gain to the stream with a mean daily total energy input of 3.88 MJ m^{-2} d^{-1} (Table 6). In total, daily energy fluxes related to net all-wave radiation were the only daily energy gain and also the greatest contributor to the energy balance at the air-water interface, while energy fluxes through latent and sensible heat transfer were smaller and in total a daily heat sink. Accordingly, Q_{sn} largely mirrored the pattern of net all-wave radiation across the year.

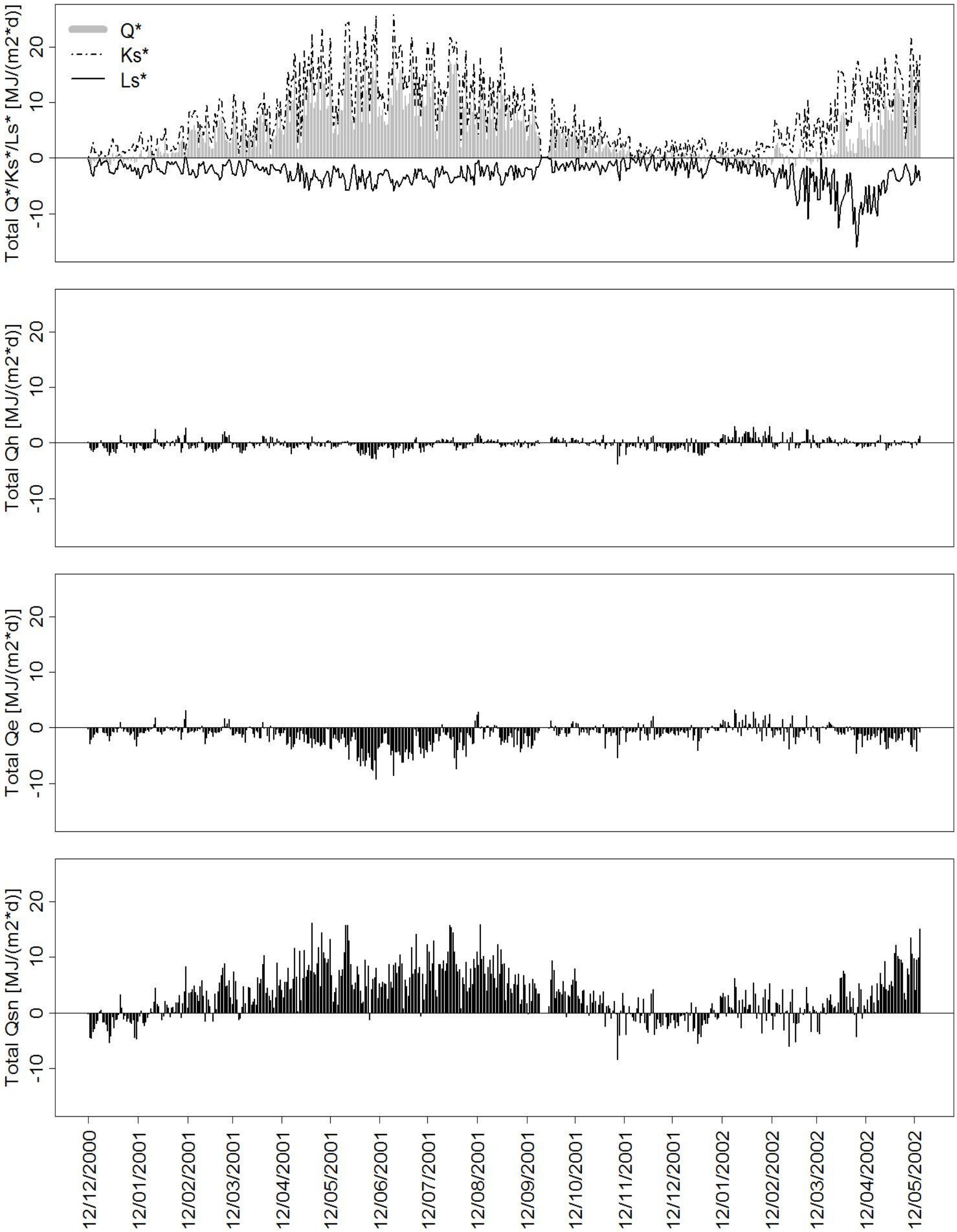


Figure 14. Total daily net all-wave (Q*), short-wave (K_s*) and long-wave radiation (L_s*) at the air-water interface, sensible heat (Q_h), latent heat (Q_e) and total energy available at the air-water interface (Q_{sn}) over the monitoring period.

Table 6. Summary statistics for daily energy flux totals (MJ m^{-2} d^{-1}) towards the water column in 2001. Percentages correspond to the proportion of all heat gains (+ %) or all heat losses (- %), respectively.

Variable	Mean	Std	Minimum	Maximum	%
Air-water interface					
Q^*	5.72	5.09	-0.75	20.21	+ 100.00
K_s^*	7.96	6.31	-0.24	25.84	
L_s^*	-2.24	1.42	-5.93	0.56	
Q_h	-0.31	0.87	-3.85	2.77	- 15.98
Q_e	-1.53	1.84	-9.24	3.17	- 78.87
Q_{sn}	3.88	4.39	-8.40	16.17	
Water-channel bed interface					
Q_b^*	5.0	5.72	-0.12	25.21	
K_b^*	5.19	5.72	0.04	25.32	
L_b^*	-0.19	0.11	-0.56	0.14	
Q_{bhf}	-0.10	0.51	-2.34	1.23	- 5.15
Total energy available					
Q_n	3.79	4.21	-8.39	15.60	
Water column temperature (°C) and river discharge (m^3s^{-1})					
T_w	9.0	4.66	7.55	10.61	
Discharge	0.42	0.44	0.03	3.03	

Water column-streambed interface. Net all-wave (Q_b^*) and net short-wave radiation (K_b^*) at the streambed both showed a clear seasonal variation with maximum radiative fluxes during summer and values around zero during autumn and winter months (Figure 15). In contrast, net long-wave radiation at the streambed (L_b^*) largely remained close to zero throughout the year. Q_b^* was an energy source in 2001 as it yielded in total 5 MJ m^{-2} d^{-1} with K_b^* and L_b^* accounting for 5.19 MJ m^{-2} d^{-1} and -0.19 MJ m^{-2} d^{-1}, respectively (Table 6). Daily ranges in Q_b^* were on average between -0.12 MJ m^{-2} d^{-1} and 25.21 MJ m^{-2} d^{-1}. Q_b^* was highly negatively correlated with mean daily discharge (r = -0.404).

Averaged over one year, bed heat flux (Q_{bhf}) was relatively small compared to energy fluxes at the air-water interface with daily minimum and maximum values ranging between -2.34 and 1.23 MJ m^{-2} d^{-1}, (Table 6). In the year 2001, Q_{bhf} was in total a heat sink with a mean daily energy flux of -0.10 MJ m^{-2} d^{-1}. The annual pattern of Q_{bhf} was relatively weak (Figure 15). However, bed heat flux tended to be a heat source in winter 2000/2001 and a heat sink in summer and in spring 2002. In spring 2001 and autumn there was no clear tendency and values equalled zero. Q_{bhf} which was measured directly, was significantly positively correlated with streambed at 0.05 m minus streambed at 0.40 m temperature differences (r = 0.234). Furthermore, the correlation between bed heat flux and the total energy available (r = -0.311), the net all-wave radiation at the bed (r = -0.503) and the water column temperature (r = -0.429) was significantly negative. However, daily bed heat flux was weakly positively correlated to daily discharge (r = 0.119).

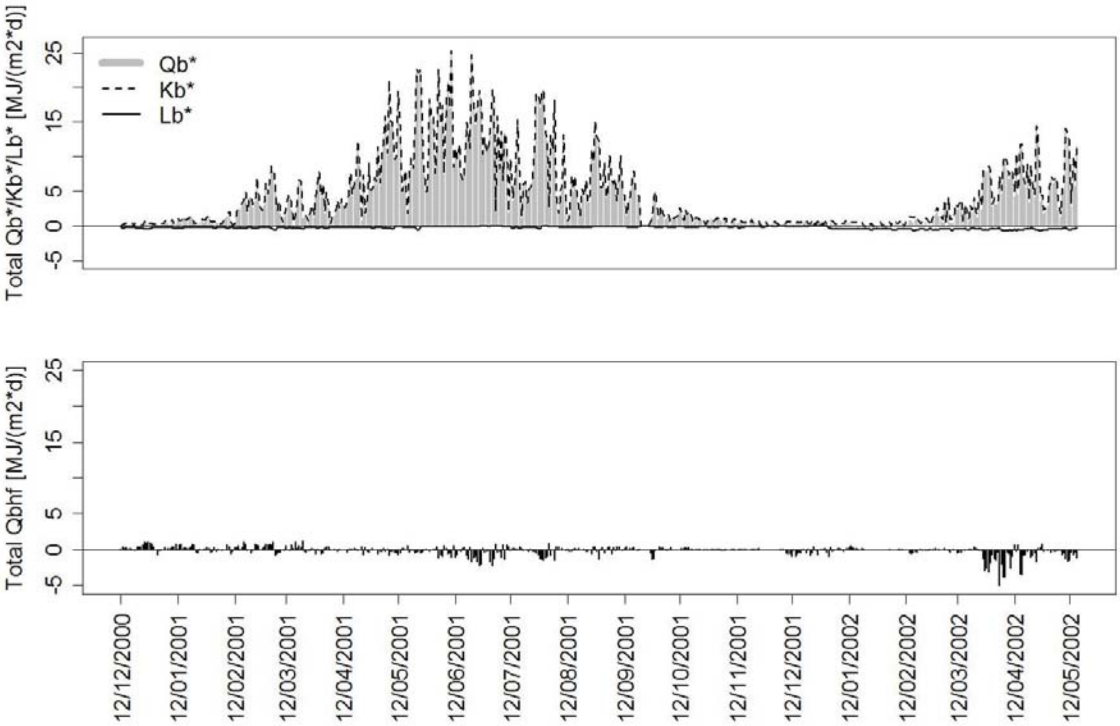


Figure 15. Total daily net all-wave (Q_b*), short-wave (K_b*) and long-wave (L_b*) radiation at the streambed and bed heat flux (Q_{bhf}) over the monitoring period.

Total energy available. Averaged over the year 2001, total energy available (Q_n) yielded an energy gain by the water column with daily energy flux totals accounting for 3.79 MJ m^{-2} d^{-1} (Table 6). Mean daily minimum and maximum values accounted for on average -8.39 and 15.60 MJ m^{-2} d^{-1}, respectively. As shown in Figure 16, Q_n followed a clear annual cycle with maximum positive values during summer and main energy losses in winter. In terms of the relative contribution of energy balance terms to Q_n, net all-wave radiation (Q*) at the air-water interface represented on average the only energy input (Table 6). Latent heat flux, sensible heat flux and bed heat flux were, in order of decreasing importance, all energy sinks. Averaged over the year, all heat gains and 94.85 % of heat losses took place at the air-water interface, while only 5.15 % of heat losses occurred at the streambed. Accordingly, Q_n yielded high correlation with Q_{sn} (r = 0.995) and roughly tracked seasonal patterns in the latter (cf. Figures 14 and 16). In total and irrespective of flux direction, 98.71 % of energy exchange processes occurred at the air-water interface while 1.29 % of heat transfers took place at the channel-bed.

Visual inspection of Figure 16 shows that mean daily water column temperature (T_w) roughly tracked total energy available across the year with daily fluctuations being higher for Q_n than for T_w. Maximum water temperatures and maximum total energy available took place during summer months while low water temperatures coincided with negative or zero values of total energy available in winter. In late summer and autumn, decrease in Q_n slightly leads the seasonal decline in T_w. Mean daily water column temperatures were significantly correlated with mean daily total energy available (r = 0.565) and correlations were slightly increased when Q_n led T_w by 1 day (r = 0.599).

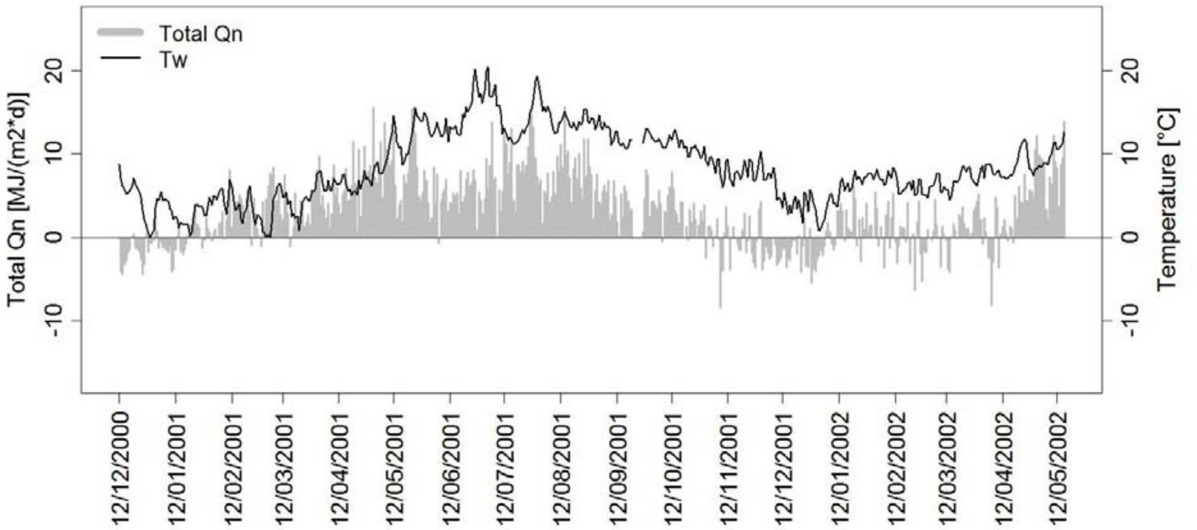


Figure 16. Total daily stream energy available (Q_n) with water column temperature (T_w) line graph overlay over the monitoring period.

Seasonal patterns in heat flux partitioning

To characterise seasonal patterns in more detail, centre months of every season in 2001 (January, April, July, October) were selected for heat budget partitioning. Table 7 and Figure 17 demonstrate a high seasonal variability in mean daily flux totals of different heat budget components. Q* was the major heat source for the study reach throughout all seasons accounting for +78.22 %, +100 %, +100 % and +91.04 % of all heat gains in January, April, July and October, respectively. Latent heat flux (Q_e) was the major heat sink throughout the year and in fact the only energy sink in autumn. According to this, Q_e accounted for -66.67 %, -84.36 %, -82.39 % and -100 % of heat losses in winter, spring, summer and autumn of 2001, respectively. Heat losses through sensible heat flux (Q_h) were -33.33 % in January, -15.08 % in April and -5.07 % in July. In contrast, Q_h represented a minor heat source in October contributing +6.65 % of all heat gains within the water column. Bed heat flux (Q_{bhf}) was the second largest energy source in winter (+21.78 %) and a minor one in autumn (+2.31 %). In spring, bed heat flux was a small heat sink (-0.56 %) while in summer Q_{bhf} was the second biggest energy sink behind latent heat transfer accounting for -12.54 % of all energy losses. Altogether, heat budget partitioning revealed considerable seasonal variations in energy flux contributions at the air-water and water-streambed interfaces over the study period.

Table 7. Summary statistics for daily energy flux totals (MJ m^{-2} d^{-1}) towards stream water in a) January, b) April, c) July and d) October 2001. Percentages correspond to the proportion of all heat gains (+ %) or all heat losses (- %), respectively.

a) January 2001

Variable	Mean	Std	Min	Max	%
Air-water interface					
Q*	0.50	0.84	-0.75	3.00	+78.22
K_s*	2.25	1.40	0.54	5.73	
L_s*	-1.75	0.93	-3.72	-0.02	
Q_h	-0.28	0.83	-1.65	2.44	-33.33
Q_e	-0.56	0.88	-3.20	1.84	-66.67
Q_{sn}	-0.34	1.97	-4.70	4.50	
Water-channel bed interface					
Q_b*	0.50	0.37	-0.06	1.29	
K_b*	0.76	0.37	0.19	1.56	
L_b*	-0.26	0.04	-0.36	-0.16	
Q_{bhf}	0.14	0.36	-0.75	0.78	+21.78
Total energy available					
Q_n	-0.20	1.78	-4.05	4.01	
T_w (°C) and Discharge (m^3 s^{-1})					
T_w	3.03	1.37	0.21	5.47	
Discharge	0.41	0.32	0.03	1.30	

b) April 2001

Variable	Mean	Std	Min	Max	%
Air-water interface					
Q*	7.48	3.83	0.62	15.30	+100
K_s*	10.22	5.01	1.79	19.44	
L_s*	-2.74	1.28	-5.81	-0.88	
Q_h	-0.27	0.71	-1.96	1.16	-15.08
Q_e	-1.51	1.14	-3.85	0.37	-84.36
Q_{sn}	5.71	3.04	0.23	11.62	
Water-channel bed interface					
Q_b*	4.40	2.78	0.02	12.08	
K_b*	4.67	2.78	0.29	13.34	
L_b*	-0.27	0.03	-0.36	-0.21	
Q_{bhf}	-0.01	0.26	-0.68	0.45	-0.56
Total energy available					
Q_n	5.70	2.86	0.58	11.44	
T_w (°C) and Discharge (m^3 s^{-1})					
T_w	6.44	0.85	5.04	8.02	
Discharge	0.52	0.30	0.18	1.43	

c) July 2001

Variable	Mean	Std	Min	Max	%
Air-water interface					
Q*	11.67	3.99	3.34	17.45	+100
K_s*	15.02	4.86	4.96	21.86	
L_s*	-3.34	1.04	-5.42	-1.45	
Q_h	-0.17	0.74	-1.73	0.98	- 5.07
Q_e	-2.76	1.93	-7.42	0.60	-82.39
Q_{sn}	8.74	3.80	-0.60	15.80	
Water-channel bed interface					
Q_b*	10.40	5.99	1.06	19.69	
K_b*	10.58	5.95	1.35	19.70	
L_b*	-0.18	0.13	-0.42	0.02	
Q_{bhf}	-0.42	0.77	-2.34	0.69	-12.54
Total energy available					
Q_n	8.32	3.59	0.04	15.31	
T_w (°C) and Discharge (m^3 s^{-1})					
T_w	14.86	2.91	11.22	20.45	
Discharge	0.36	0.41	0.05	1.57	

d) October 2001

Variable	Mean	Std	Min	Max	%
Air-water interface					
Q*	3.15	1.57	0.15	7.31	+91.04
K_s*	4.58	1.99	0.83	9.68	
L_s*	-1.43	0.73	-2.95	0.09	
Q_h	0.23	0.52	-0.99	1.33	+6.65
Q_e	-0.53	0.94	-3.71	1.10	-100
Q_{sn}	2.86	2.18	-2.46	7.88	
Water-channel bed interface					
Q_b*	1.08	0.64	0.09	2.65	
K_b*	1.26	0.64	0.26	2.86	
L_b*	-0.12	0.05	-0.28	-0.07	
Q_{bhf}	0.08	0.12	-0.15	0.43	+2.31
Total energy available					
Q_n	2.94	2.18	-2.44	7.84	
T_w (°C) and Discharge (m^3 s^{-1})					
T_w	11.08	0.90	9.25	12.89	
Discharge	0.77	0.50	0.14	1.90	

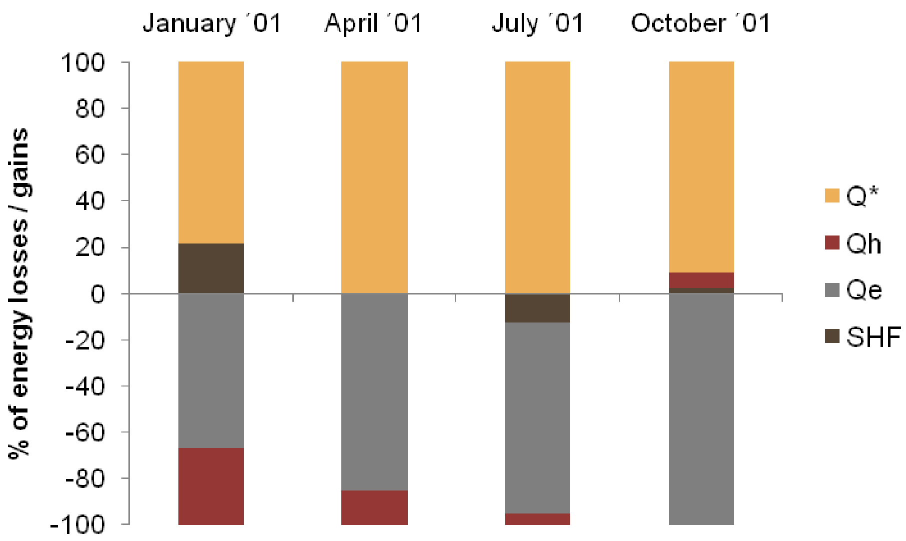


Figure 17. Heat flux partitioning for single months of 2001. Negative (positive) values refer to heat losses (gains) by the water column contributed by bed heat flux (Q_{bhf}), latent heat flux (Q_e), sensible heat flux (Q_h) and net radiation (Q*), respectively.

Stream temperature prediction

To check the accuracy of the total energy available (Q_n) computed in the present study, daily water column temperature was predicted based on daily energy totals. Figure 18 reveals a generally good fit of simulated values (T_{w_sim}) with measured values (T_{w_obs}) as seasonal and daily fluctuations in water temperatures were mirrored well by the model and correlations between T_{w_sim} and T_{w_obs} were high (r = 0.972). The Root Mean Square Error between observed and predicted values was 1.70 °C while the Mean Error was -1.07 °C. The calculated Nash-Sutcliffe coefficient accounted for 0.87. Particularly daily temperature peaks were slightly overestimated by the model, as clearly shown in Figure 18. Accordingly, water temperatures above 10 °C were slightly overpredicted compared to measured temperatures while temperatures below 10 °C did not show a preferential direction of deviation (Figure 19). Furthermore, the fit between predicted and observed water column temperature varied seasonally as demonstrated by the T_{w_sim} minus T_{w_obs} differences in Figure 18. Root Mean Square Error between simulated and measured values was on average 1.86 °C in spring, 2.21 °C in summer, 1.29 °C in autumn and 1.15 °C in winter. Water temperatures were overestimated by the model throughout the seasons as the Mean Error accounted for -1.40 °C, -1.79 °C, -0.72 °C and -0.23 °C in spring, summer, autumn and winter, respectively.

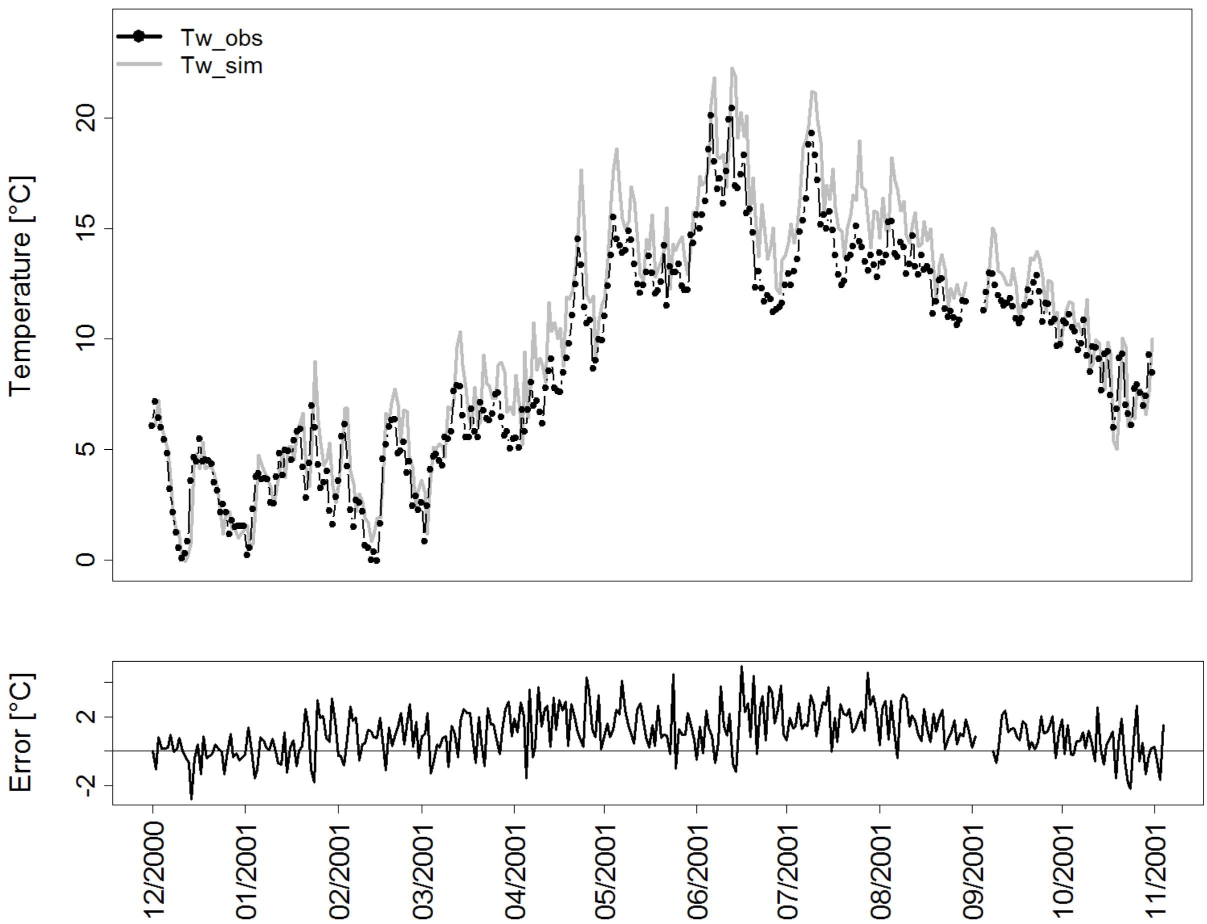


Figure 18. Mean daily observed (T_{w_obs}) and simulated water column temperature (T_{w_sim}) over one year within the monitoring period and respective T_{w_sim} minus T_{w_obs} differences (Error).

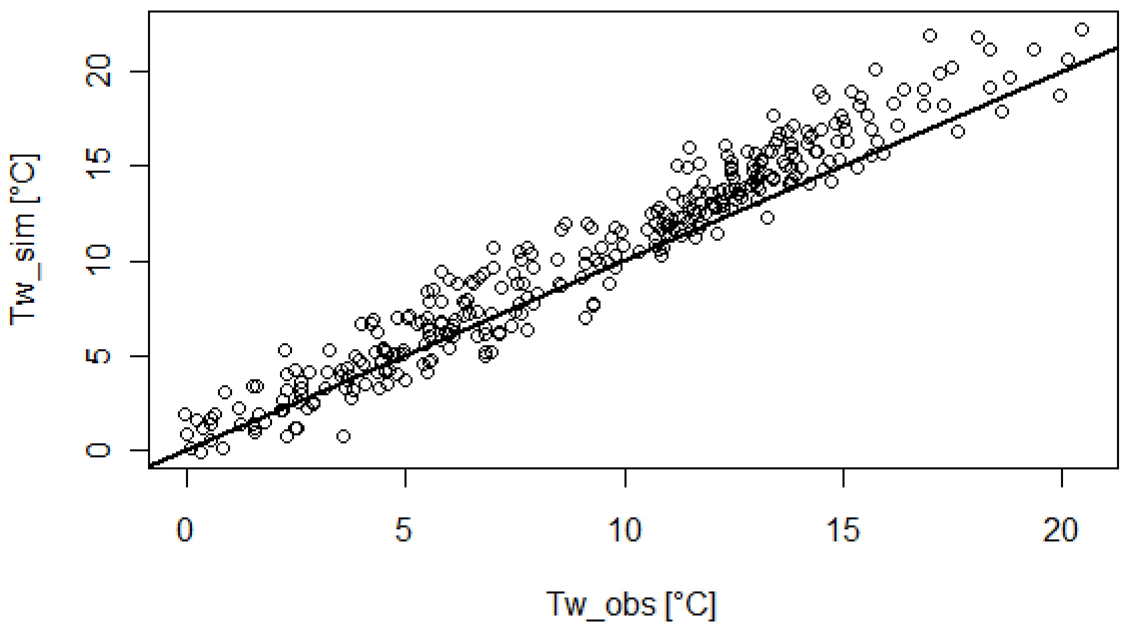


Figure 19. Relationship between simulated (T_{w_sim}) and observed (T_{w_obs}) water temperature. Black line represents a 1:1 relationship.

3.1.2 Sub-seasonal patterns

Diurnal variations in water temperature and energy fluxes

To further highlight the relationship between energy fluxes and stream temperature, diurnal patterns of temperature and energy components have been analysed. To detect potential seasonal variation in diurnal patterns, these were examined for the different seasons by averaging diurnal cycles over the centre month of each season. In winter, neither water column nor bed temperatures showed a pronounced diurnal cycle and water column as well as bed temperatures ranged around 3 °C across the day (Figure 20). In spring and summer, water column and, in decreasing order of magnitude, streambed temperatures at 0.05 m and 0.20 m depth displayed a clear diurnal cycle with maximum temperatures around 15:00 and 16:00 and minimum values around 6:00 and 7:00 in the early morning. The diel temperature cycle in the streambed, particularly at 0.20 m depth was thereby slightly delayed when compared with the water column. Daily fluctuations of bed temperature at 0.40 m depth were much weaker and daily temperature depressions at this depth coincided with daily temperature peaks in the water column and the above lying streambed. Diurnal patterns in autumn were similar to those in spring and summer but much weaker.

In winter, the total energy balance of the stream (Q_n) was positive from about 9:00 in the morning until 15:00 in the afternoon and remained constantly slightly below zero during the rest of the day and night (Figure 21). The diurnal pattern of Q_n coincided with respective energy inputs and losses through net all-wave radiation (Q^*) across the day. Bed heat flux (Q_{bhf}) as well as latent heat flux (Q_e) showed no apparent diurnal fluctuation and were close to zero all day. Furthermore, sensible heat flux (Q_h) tended to be zero during most time of the day but yielded temporarily slightly positive values just after midday.

In spring and summer, maximum values of Q_n around midday were more than twice as high as in winter and the part of the day seeing a total energy gain by the water column was extended from around 6:00 until 19:00. At night, the total energy budget in April and July remained negative with minimum values occurring in the evening at about 19:00 and 20:00, respectively. In comparison with the wintertime, negative values were slightly more negative during the night. Values for Q_n started to get positive in the early morning, at the same time when the net all-wave radiation term exceeded zero. Afterwards the increase in Q_n totally correlated with the increase in Q^* over the morning. However, from about 10:00 on Q_n remained slightly below Q^* and also declined towards zero more rapidly in the afternoon. The divergence of Q_n and Q^* at this daytime coincided with an increased heat loss through bed heat flux and latent heat flux. The energy loss through Q_{bhf} started around 8:00 in the morning and reached a maximum at around 14:00 in the afternoon. Q_e represented a small but constant energy sink at night-time and became even more negative around 9:00 with minimum values occurring around 16:00. Sensible heat flux (Q_h) equalled zero throughout the day.

In autumn, the daytime where the stream was undergoing an energy gain was shorter than in spring/summer and lasted from around 7:30 until 16:30. As in winter, Q_n was highly correlated with diurnal variations of Q^*. Hence, Q^* and Q_n remained constantly slightly negative at night and in the evening and Q_n became positive in the morning when Q^* exceeded zero. However, Q_n slightly exceeded Q^* just before and around midday, at the same time when the sensible heat flux was slightly positive. During the rest of the day, Q_h equalled zero. Values of Q_{bhf} did not show a clear diel pattern and were close to zero. Q_e was slightly negative most of the day but temporarily became zero just before midday. In general, diurnal peaks of total energy available preceded the diurnal peaks of water column temperature by about 3 hours.

Overall, diurnal cycles of energy fluxes and water/bed temperatures were most pronounced in spring and summer. Water column and streambed temperatures followed a diurnal pattern in summer, spring and autumn, in order of decreasing magnitude. In winter, diurnal patterns in temperatures were negligible. Water column and bed temperatures at 0.05 and 0.20 m depth showed similar diurnal fluctuations with the diurnal temperature peaks getting smaller with depth. In contrast, bed temperatures at 0.40 m depth showed an inverted temperature cycle with diurnal temperature depressions in the early afternoon coinciding with temperature peaks in the upper streambed and water column. Q* displayed a clear diurnal pattern throughout the seasons. Bed heat fluxes, latent and sensible heat fluxes did not show a clear diurnal cycle in winter and autumn. Particularly for Q_h, diurnal fluctuations were almost non-existing, irrespective of the season. Of all the energy balance parameters, total energy available and net all-wave radiation displayed the strongest diurnal pattern with occurrence throughout the year.

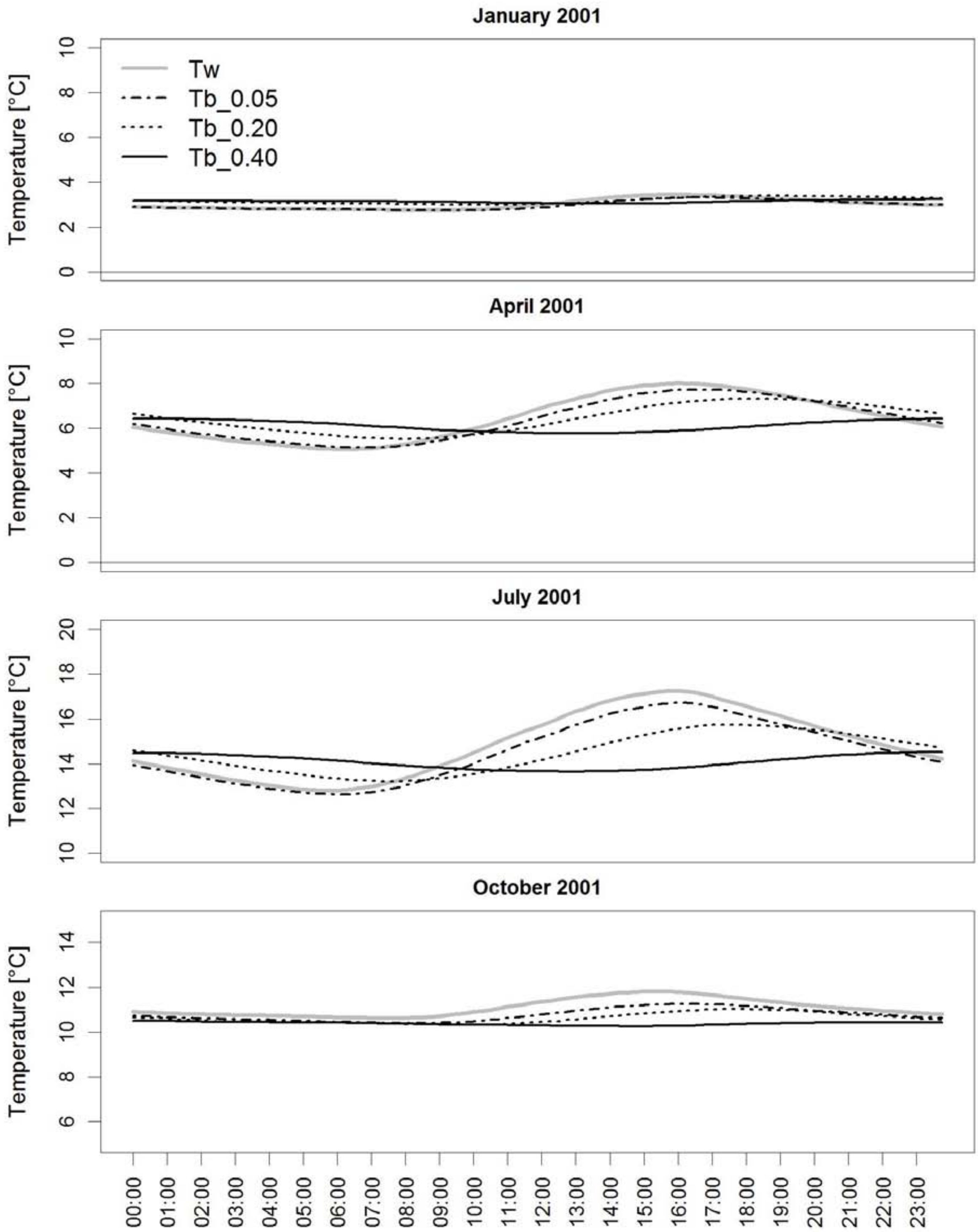


Figure 20. Diurnal patterns of water column (T_w) and streambed temperatures at 0.05 m ($T_{b\_0.05}$), 0.20 m ($T_{b\_0.20}$) and 0.40 m ($T_{b\_0.40}$) depth in the four seasons. Note that temperature levels at y-axis differ between the different seasonal plots.

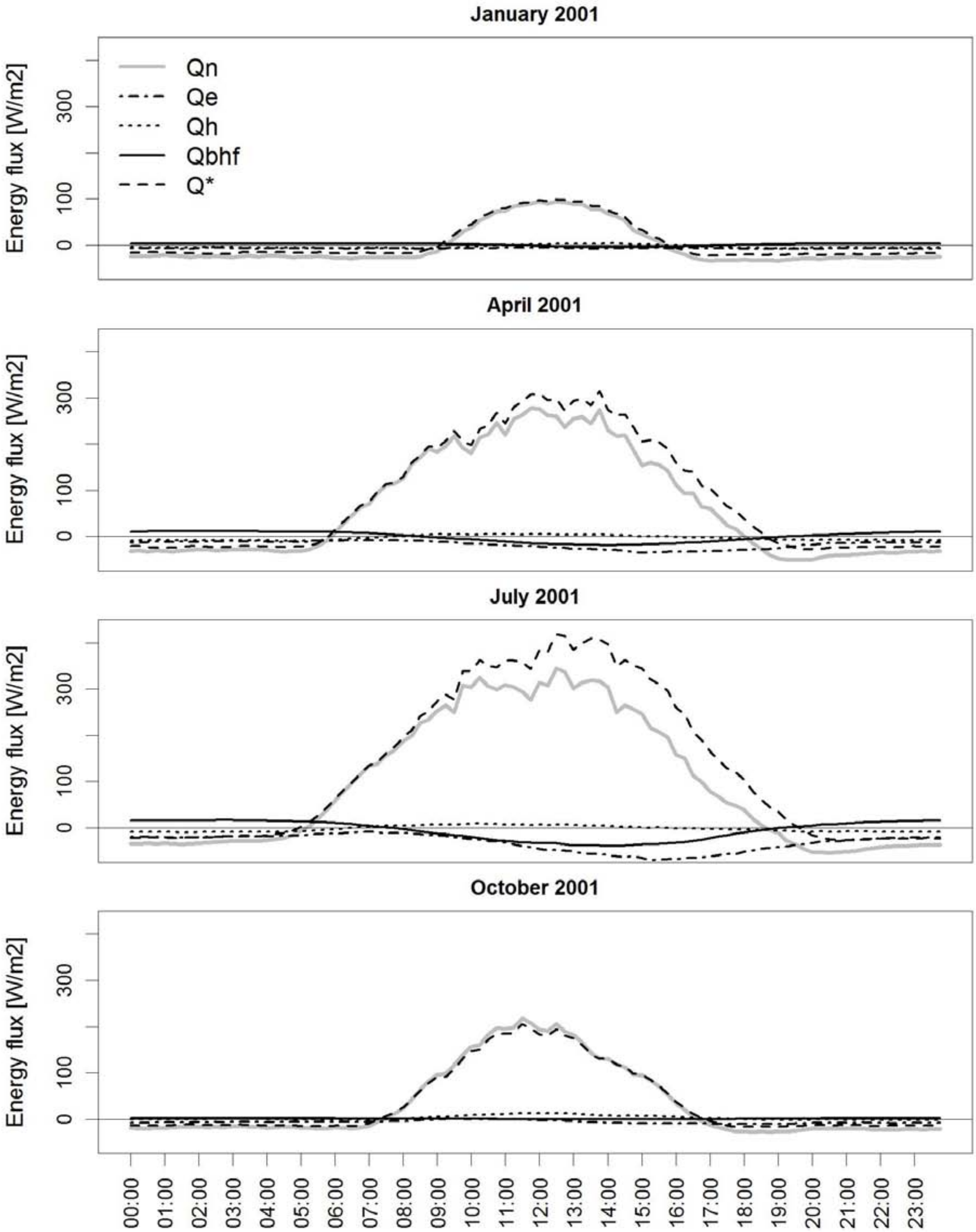


Figure 21. Diurnal patterns of total energy available (Q_n), latent heat flux (Q_e), sensible heat flux (Q_h), bed heat flux (Q_{bhf}) and net all-wave radiation (Q^*) in the different seasons.

Thermal response to storm events

To determine the impact of storm flows on thermal processes, particularly those at the streambed, water column and streambed temperatures occurring directly before and during selective storm events in every season were compared. Those storm events have been selected which allowed for a clear division into pre-storm and concurrent storm conditions (Figure 22). Water column and streambed temperatures have been averaged over the days which had been directly preceding a storm and over the storm period itself. To set the temperature response in a wider context, potential changes in energy budget components before and during storm flow have been examined additionally. Figure 23 displays the variations in water column and streambed temperatures at 0.05, 0.20 and 0.40 m depth that occurred during the individual storm events. Water column and bed temperatures showed a clear response to storm events in spring, summer and autumn as they visibly dropped to lower values with occurrence of the peak flow (Figure 23 b, c, d). The temperature response in the streambed appeared generally more dampened, especially at 0.40 m depth. For the examined winter storm flow, no clear temperature response was visible (Figure 23 a).

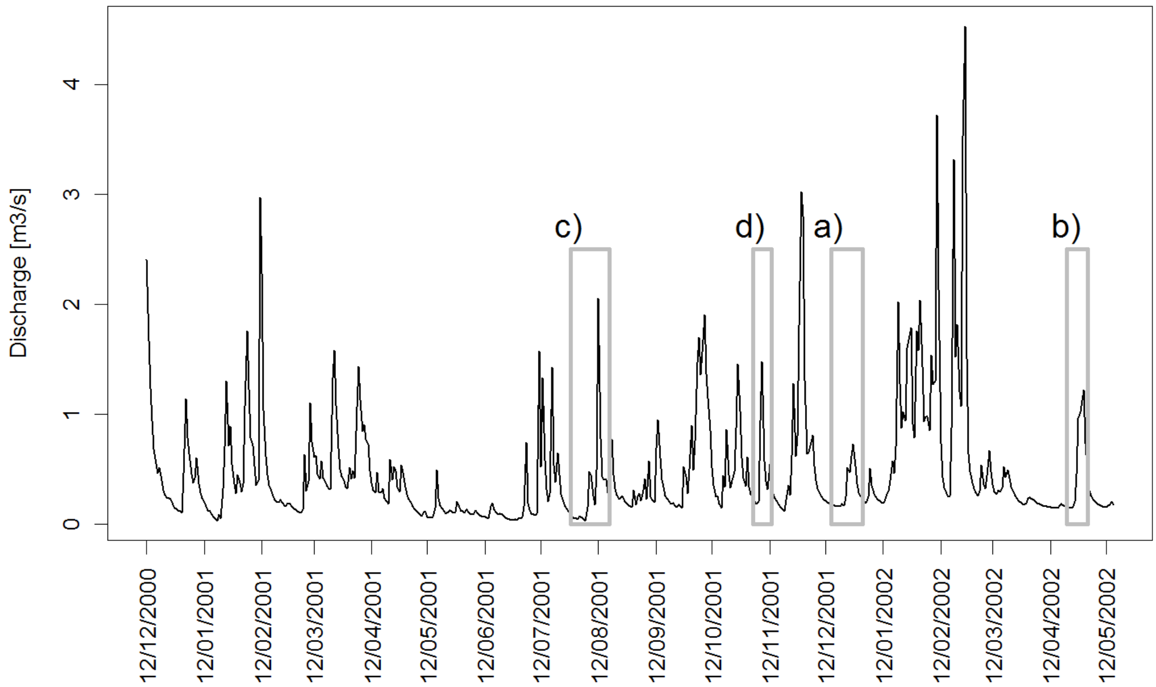
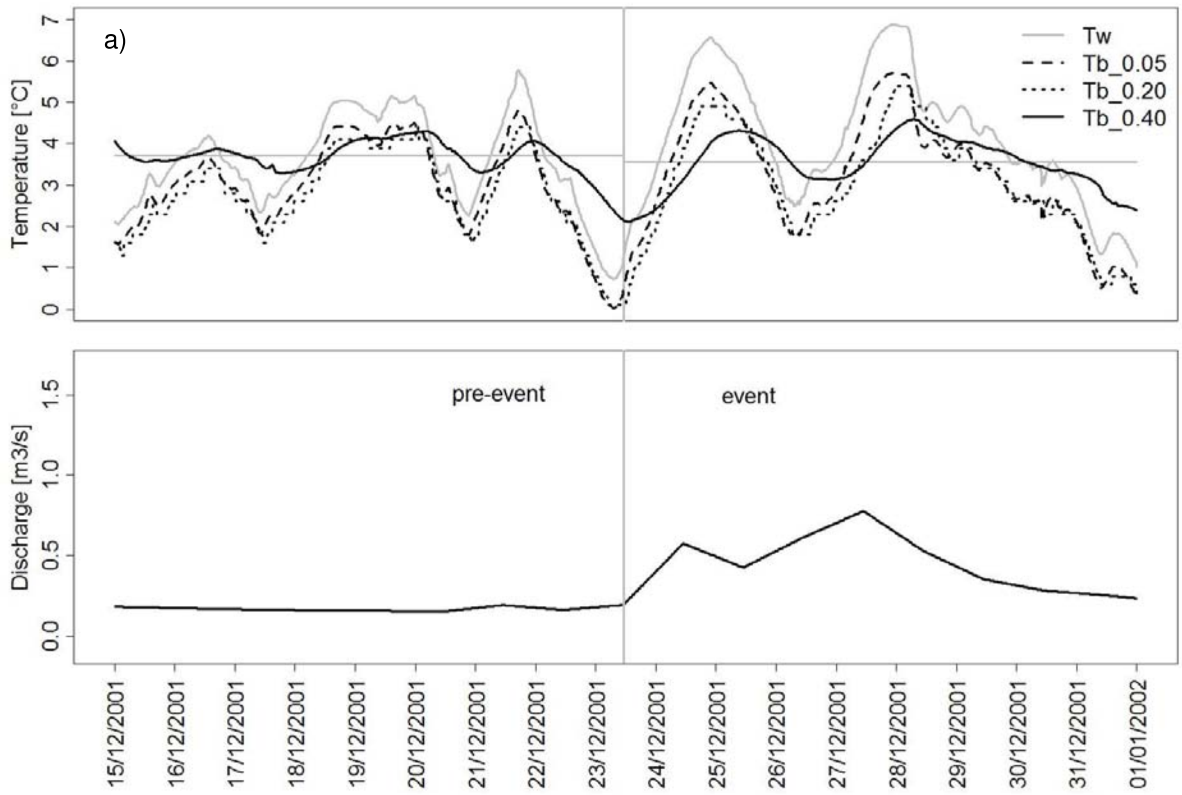


Figure 22. Mean daily discharge over the monitoring period. Rectangles refer to selected storm events in winter (a), spring (b), summer (c) and autumn (d), respectively.


a)
Temperature [°C]
Tw
Tb_0.05
Tb_0.20
Tb_0.40
Discharge [m3/s]
pre-event
event
15/12/2001
16/12/2001
17/12/2001
18/12/2001
19/12/2001
20/12/2001
21/12/2001
22/12/2001
23/12/2001
24/12/2001
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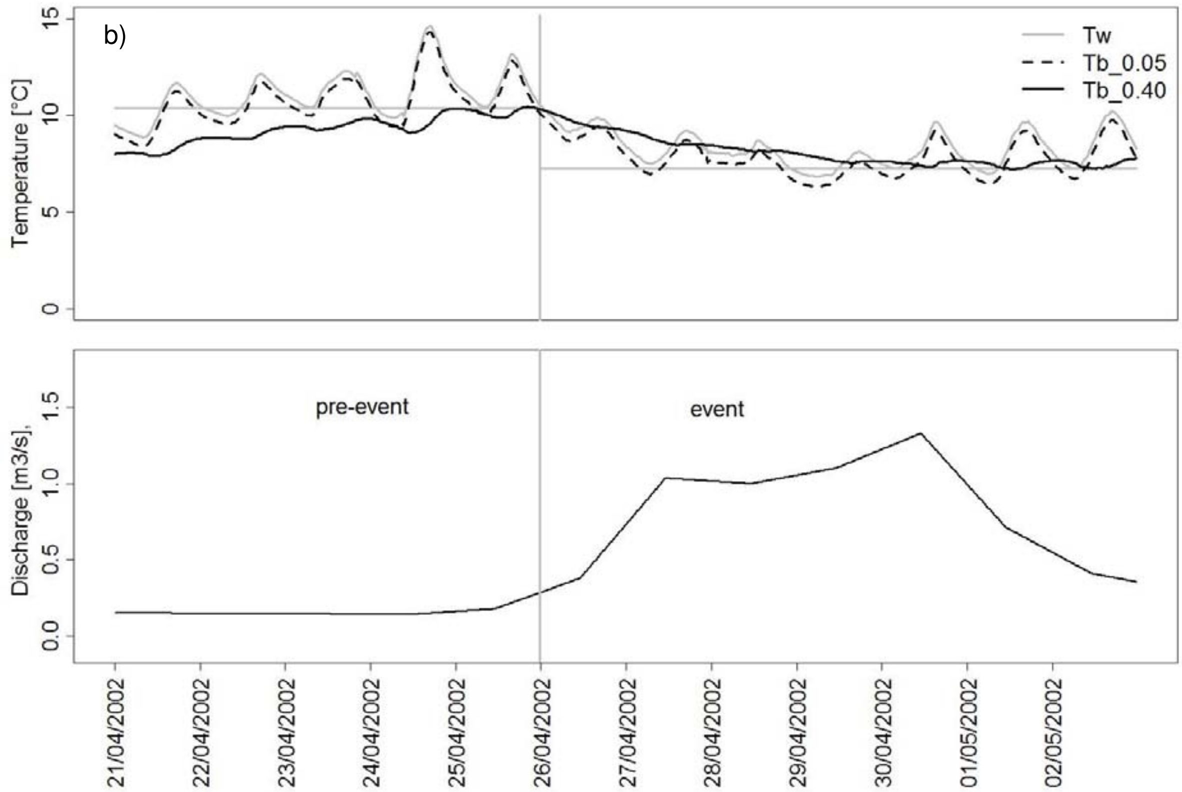
31/12/2001
01/01/2002


b)
Temperature [°C]
Tw
Tb_0.05
Tb_0.40
Discharge [m3/s],
pre-event
event
21/04/2002
22/04/2002
23/04/2002
24/04/2002
25/04/2002
26/04/2002
27/04/2002
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01/05/2002
02/05/2002

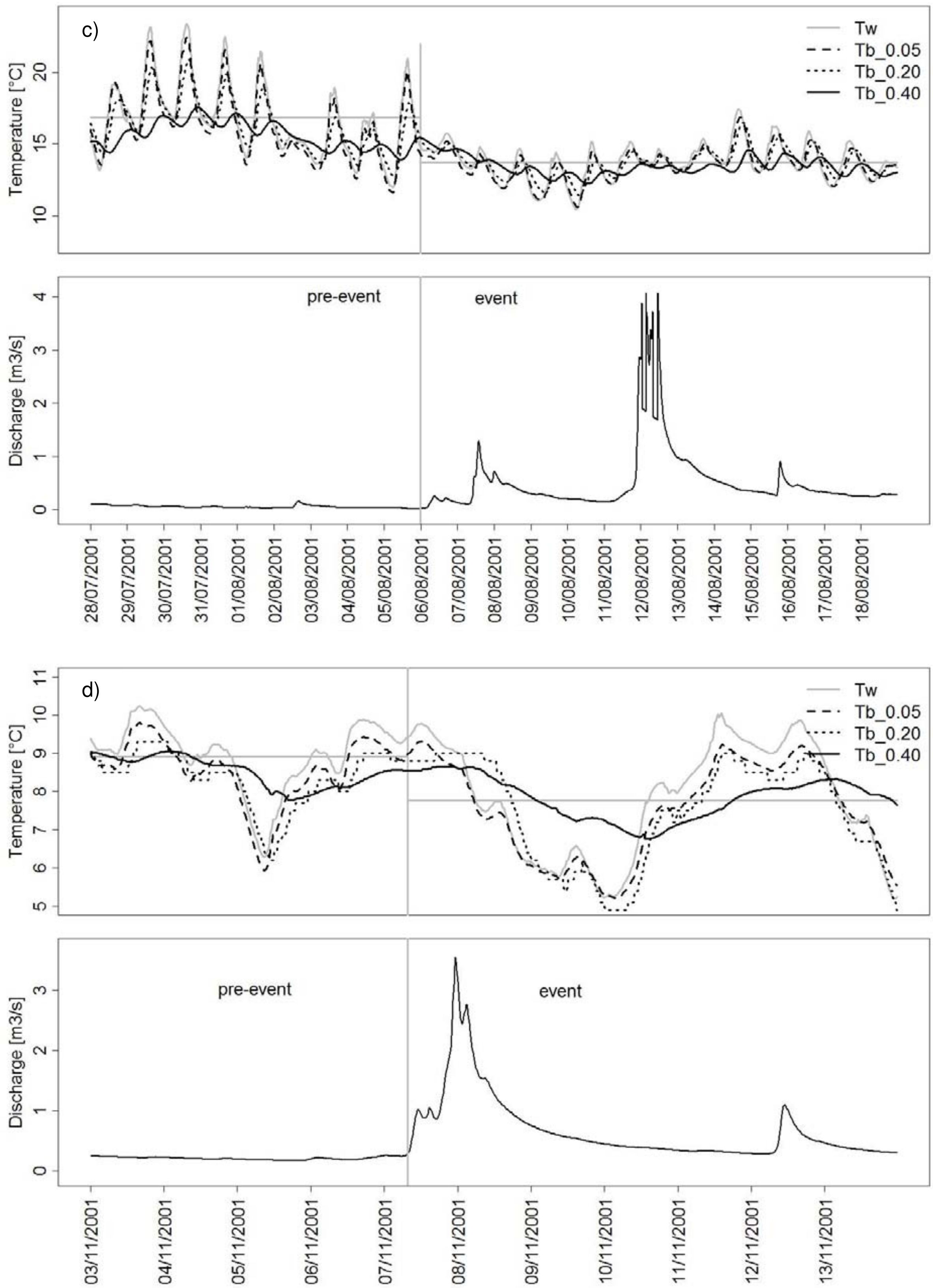

Figure 23. Water column (T_w) and streambed temperatures at 0.05 m ($T_{b\_0.05}$), 0.20 m ($T_{b\_0.20}$) and 0.40 m depth ($T_{b\_0.40}$) and discharge directly before and during selected storm events in winter (a), spring (b), summer (c) and autumn (d), respectively. Note that no $T_{b\_0.20}$ data was available from 14th of March 2002 onwards (b).

Water column temperatures (T_w) during any storm event were consistently lower when compared to temperatures that had occurred directly before the storm (Figure 24). A similar temperature reducing effect by the sudden increase in runoff was found for the streambed temperatures at 0.05 m ($T_{b\_0.05}$), 0.20 ($T_{b\_0.20}$) and 0.40 m depth ($T_{b\_0.40}$) with the amplitude of the reduction decreasing with depth. However, an exception to this tendency was the winter event. Here, the storm-induced temperature decline was greatest at 0.40 m depth and lowest in the water column (Figure 24). Overall, reductions in water column and streambed temperatures in response to storm events were most pronounced in spring and summer and lowest in winter which also coincided with the relative magnitude of the respective storm events. In terms of microclimate, air temperature always decreased with the occurrence of storm events, especially in spring and autumn (Figure 24). Relative humidity was lower during storm events than before storm events in winter and autumn but higher in spring and summer. Conversely, vapour pressure at air temperature (E_a) increased with occurrence of storm events in winter and autumn and decreased at storm events in spring and summer. Wind speed was always higher during storm events when compared with pre-event conditions.

Net all-wave radiation at the water surface (Q*) was slightly higher during than directly before storm events with respect to winter and spring events whereas during the summer and autumn event Q* was clearly or slightly reduced compared to the pre-storm days, respectively (Table 8). Heat losses by sensible heat flux (Q_h) were enhanced in association with peak flows at winter, spring and autumn events but Q_h became an energy source with occurrence of the peak flows during the summer event. In a similar way, more heat was lost due to latent heat fluxes (Q_e) during storms compared to pre-storm days for winter, spring and autumn events but not for the summer event where heat losses by Q_e were reduced with occurrence of the storm flow.

With regard to the water-streambed interface, net all-wave radiation at the bed (Q_b*) was always higher before events than during storms, particularly at spring and summer storm events (Table 8). The same was true for net short-wave radiation at the streambed (K_b*). Heat losses through net long-wave radiation at the channel bed (L_b*) were enhanced through the sudden increase in runoff at spring, summer and autumn events. For the winter event, L_b* was almost zero both before and during the examined storm. Bed heat flux (Q_{bhf}) represented a heat sink during the days preceding the storm flows and became a small heat source with occurrence of the peak flow at spring, summer and autumn events but not in winter, where heat losses through Q_{bhf} became just smaller during the peak flow. Total energy available (Q_n) was enhanced with occurrence of storm flows in spring and summer. On the contrary, Q_n was a net heat loss in winter which increased associated with peak flows. In autumn, Q_n represented a small heat gain by the water column before the storm but was a heat loss during the peak flow period.

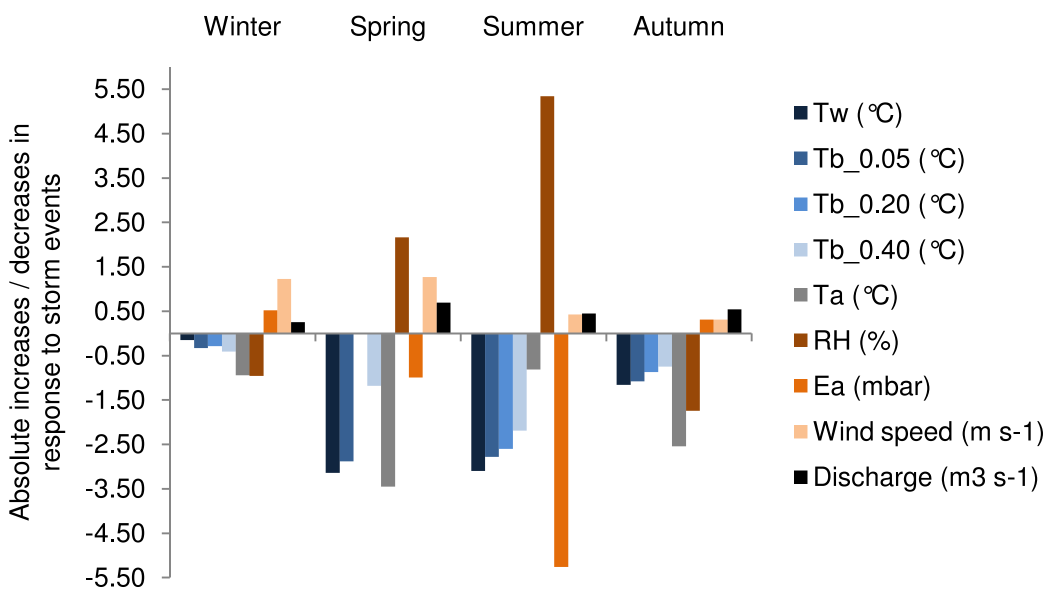

Figure 24. Absolute increases (positive values) and decreases (negative values) in water column temperature (T_w), streambed temperature at 0.05, 0.20, 0.40 m depth and air temperature (T_a); relative humidity (RH); vapour pressure at air temperature (E_a); wind speed and discharge in response to storm events.

Table 8. Summary statistics of daily energy flux totals (MJ m^{-2} d^{-1}) and discharge for pre-event and event periods in winter (a), spring (b), summer (c) and autumn (d). Diff refers to absolute differences of event minus pre-event energy flux totals/discharge.

a) Winter

Variable	Pre-Event	Event	Diff
Air-water interface			
Q^*	0.18	0.34	+0.16
K_s^*	1.55	2.07	+0.52
L_s^*	-1.37	-1.74	-0.37
Q_h	-0.67	-1.23	-0.56
Q_e	-0.77	-1.18	-0.41
Q_{sn}	-1.26	-2.08	-0.82
Water-channel bed interface			
Q_b^*	0.47	0.46	-0.01
K_b^*	0.52	0.43	-0.09
L_b^*	-0.05	0.03	+0.08
Q_{bhf}	-0.34	-0.19	+0.15
Total energy available			
Q_n	-1.6	-2.27	-0.67
Flow			
Discharge (m^3s^{-1})	0.17	0.42	+0.25

b) Spring

Variable	Pre-Event	Event	Diff
Air-water interface			
Q^*	8.13	9.8	+1.67
K_s^*	13.59	12.60	-0.99
L_s^*	-5.45	-2.81	+2.64
Q_h	0	-0.22	-0.22
Q_e	0.07	-2.09	-2.16
Q_{sn}	6.09	7.49	+1.40
Water-channel bed interface			
Q_b^*	9.07	3.71	-5.36
K_b^*	9.52	4.26	-5.26
L_b^*	-0.45	-0.55	-0.10
Q_{bhf}	-0.81	0.04	+0.85
Total energy available			
Q_n	5.28	7.52	+2.24
Flow			
Discharge (m^3s^{-1})	0.16	0.85	+0.69

c) Summer

Variable	Pre-Event	Event	Diff
Air-water interface			
Q^*	12.21	8.08	-4.13
K_s^*	15.59	10.33	-5.26
L_s^*	-3.38	-2.25	+1.13
Q_h	-0.56	0.41	+0.97
Q_e	-3.76	-0.39	+3.37
Q_{sn}	7.88	8.1	+0.22
Water-channel bed interface			
Q_b^*	13.99	4.64	-9.35
K_b^*	14.09	4.87	-9.22
L_b^*	-0.1	-0.24	-0.14
Q_{bhf}	-0.86	0.06	+0.92
Total energy available			
Q_n	7.02	8.17	+1.15
Flow			
Discharge (m^3s^{-1})	0.06	0.51	+0.45

d) Autumn

Variable	Pre-Event	Event	Diff
Air-water interface			
Q^*	1.56	1.45	-0.11
K_s^*	2.59	2.9	+0.31
L_s^*	-1.04	-1.44	-0.40
Q_h	-0.08	-1.22	-1.14
Q_e	-0.92	-1.97	-1.05
Q_{sn}	0.55	-1.73	-2.28
Water-channel bed interface			
Q_b^*	0.83	0.46	-0.37
K_b^*	0.96	0.62	-0.34
L_b^*	-0.13	-0.16	-0.03
Q_{bhf}	-0.03	0.03	+0.06
Total energy available			
Q_n	0.53	-1.7	-2.23
Flow			
Discharge (m^3s^{-1})	0.2	0.74	+0.54

3.1.3 Summary

Water column and streambed temperatures at 0.05 m, 0.20 m and 0.40 m depth all displayed clear annual cycles with temperature maxima occurring during summer months. Temperature gradients between water column and streambed were generally small but varied highly with season. In winter, the streambed was warmer than the water column while the gradient was inversed in summer. Averaged over a full year, water column and bed temperatures were negatively correlated with discharge but correlations varied between different seasons. Air temperature showed a clear annual cycle with stronger diurnal fluctuations than water column temperature and was highly correlated with water column and streambed temperature, respectively ($r > 0.9$). Vapour pressure at air temperature also displayed a clear annual pattern while periodic patterns in relative humidity and wind speed were weaker and absent, respectively.

Averaged over a year, energy exchange processes at the air-water column interface resulted in a total available energy (Q_{sn}) at the water surface that accounted for 3.88 MJ m^{-2} d^{-1}. Q_{sn} followed a clear annual cycle which mirrored that of net radiation at the water surface (Q^*) and showed maximum energy gains during summer and energy fluxes close to zero in winter. Averaged over the year 2001, Q^* was the only energy source by the water column and also the greatest energy flux that occurred at the air-water column interface. Latent (Q_e) and sensible heat fluxes (Q_h) as well as bed heat flux (Q_{bhf}) were relatively small compared to net radiation, displayed relatively weak annual patterns and in total were all energy sinks. Averaged over the year, total energy available (Q_n), which is the sum of Q^*, Q_e, Q_h and Q_{bhf}, yielded a small energy gain for the study reach which accounted for 3.79 MJ m^{-2} d^{-1}. Almost 100 % of energy exchange processes over the study period took place at the air-water interface with the bed energy fluxes being relatively small. Heat budget partitioning revealed clear seasonal variations in the contributions of the different energy fluxes. Net radiation was the major energy source across the year and also the sole energy gain in spring and summer. In winter and autumn bed heat flux and sensible heat transfer added additional energy to the water column. Irrespective of the season, major heat losses were related to latent heat flux with minor contributions of bed heat flux (sensible heat flux) in spring and summer (winter, spring, summer).

Analysis of diurnal patterns of energy fluxes and water column/bed temperatures revealed that diel fluctuations were most pronounced during spring and summer. The diurnal cycle of Q^* was the most pronounced when compared with those of Q_h, Q_e and Q_{bhf} and diel fluctuations of Q_n largely coincided with those of Q^*. Diurnal water column temperature peaks in the early afternoon were about 3 hours delayed when compared with daily maxima of Q_n.

With respect to storm events, water column and streambed showed a clear decrease in temperatures with the occurrence of peak flows. Responses of microclimate and energy balance components to storm events varied between the individual events in the different seasons. At the streambed, net radiation was consistently reduced during peak flows while bed heat flux was found to add more energy to the water column with the occurrence of peak flows during the selected spring, summer and autumn storm events.

3.2 Examination of spatial water temperature patterns

3.2.1 Hydroclimatological context

Total amount of rainfall during the study period in summer 2010 was 262 mm which is approximately one-tenth of total annual precipitation accounting for 2500 mm. The highest daily totals in precipitation were observed on 20 July with in total 55.6 mm rainfall occurring during a period where high rainfall events occurred (Figure 25). A dry period without any rainfall took place from 15 June until 23 June. The discharge hydrograph of the monitoring period reflects the precipitation pattern (Figure 25). Consequently, most of the study period was characterized by low-flows followed by maximum flows with up to > 8 $m^3 s^{-1}$ occurring from 15/07/2010 until 23/07/2010. One major low-flow and high-flow period each have been defined for further analysis with the low flow period occurring from 18 until 28 June 2010 (mean daily discharge: 0.07 $m^3 s^{-1}$) and the high flow period taking place from 15 July until 25 July 2010 (mean daily discharge: 0.77 $m^3 s^{-1}$). Mean daily discharge over the monitoring period was 0.20 $m^3 s^{-1}$ and therefore about half the magnitude of the mean annual discharge which is 0.43 $m^3 s^{-1}$. Over the full study period, discharge was significantly inversely correlated with water temperatures at all sites yielding r-values of around -0.242. When considered separately according to the defined low-flow and high-flow period, negative correlation between discharge and water temperatures was only significant over the low-flow period but not during the high-flow period. However, negative correlation between water temperature and discharge during the low-flow period was considerably greater ($r < -0.831$) when compared with the correlation over the full study period. Hence, the inverse relationship between discharge and water temperatures was considerably enhanced during the low-flow period.

Air temperature showed clear diurnal fluctuations and averaged 13.88 °C over the study period with a standard deviation of 2.02 °C (Figure 25). Mean daily minimum (maximum) air temperatures accounted for 7.35 °C (19.42 °C) yielding a mean diurnal temperature range of 12.07 °C. Absolute minimum air temperature occurred on 27 May while the highest air temperatures were recorded on 21 May 2010. Air temperatures were significantly correlated with water temperatures at all sites with $r > 0.713$ and were even greater under low-flow and high-flow conditions with $r > 0.894$ and $r > 0.898$, respectively. Figure 26 illustrates the relationship between daily water column temperature at position 1 and air temperature and reveals that water column temperatures generally exceeded air temperatures over the study period. The slope of the relationship was 0.59.

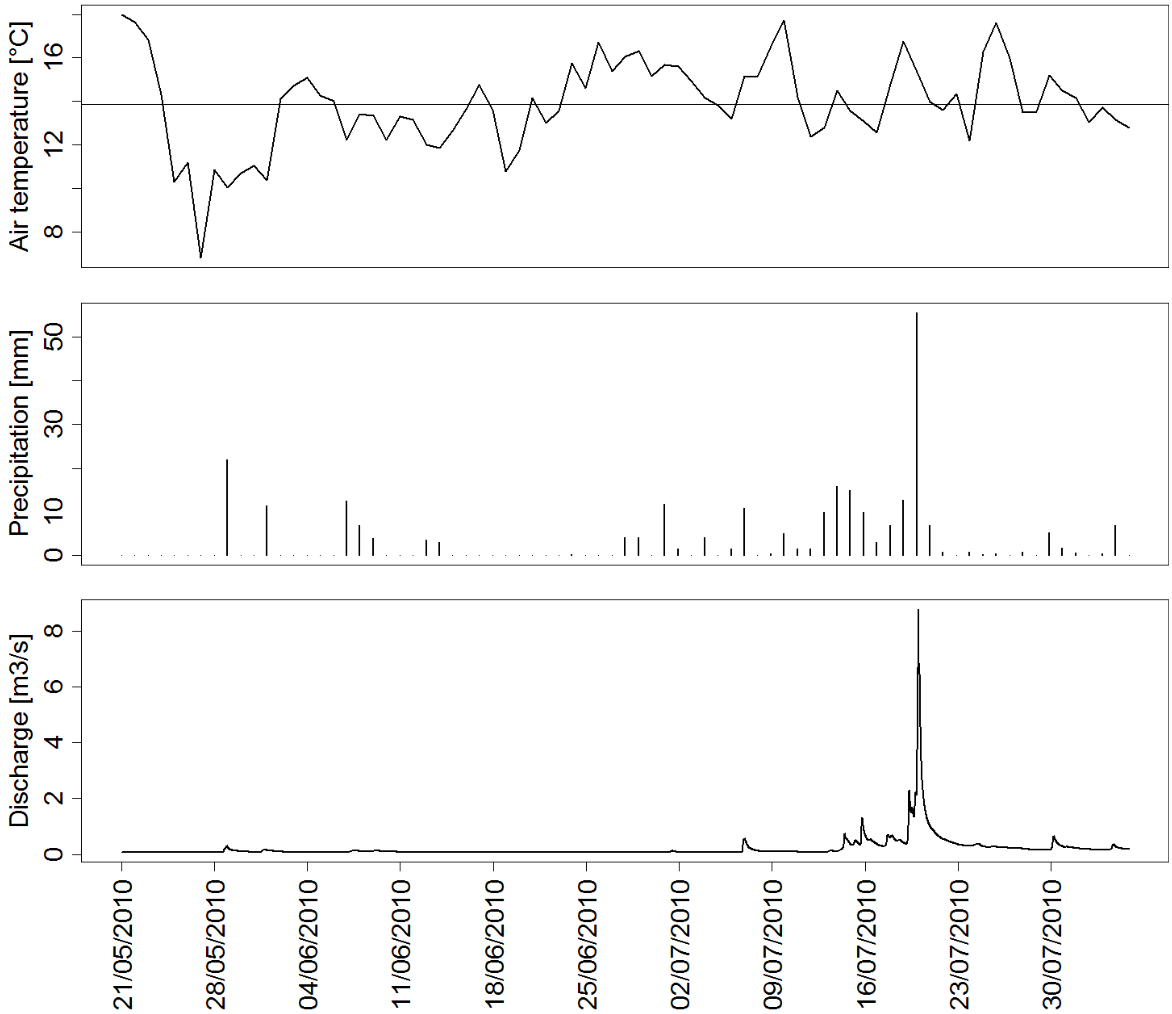

Figure 25. Mean daily air temperatures, daily precipitation and discharge during the 10- week study period in summer 2010.

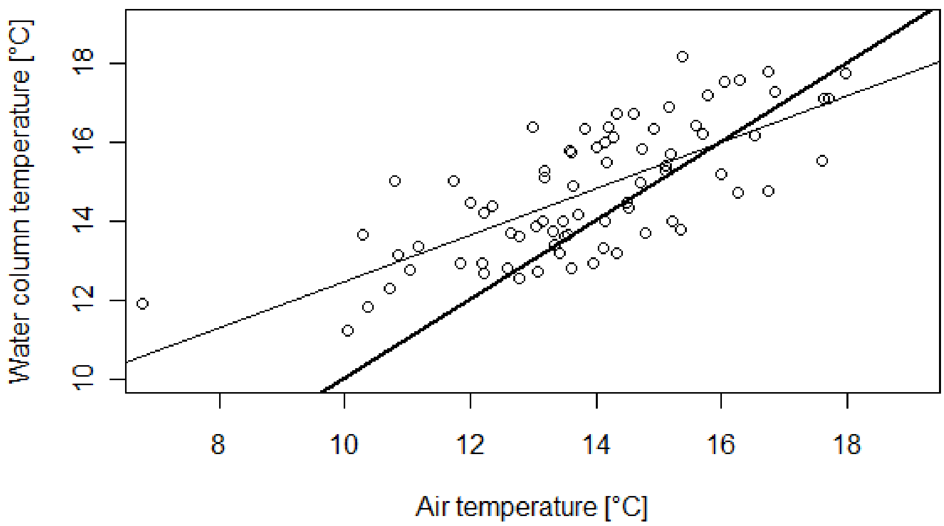

Figure 26. Relationship between water and air temperatures based on mean daily values in summer 2010 with regression line (thin black line). Broader black line has a slope equal to 1.

3.2.2 *In situ* measurements of water temperature

To detect potential spatial temperature patterns within the stream, water temperature was measured at different positions within the study reach over a period of 10 weeks during the summer 2010. Positions of temperature loggers included different channel features such as pools, riffles and riparian shading. Daily minimum, maximum and mean water temperatures at position 4a were consequently below other recorded temperatures from about 20/07/2010 onwards while temperatures did not show any deviations earlier in the recordings. As there was no physical explanation for this drop in temperature, position 4a was excluded from further analysis. Figure 27 shows daily maximum, mean and minimum water temperatures at the different positions within the stream and the discharge over the study period. Fluctuations of daily minimum water temperatures measured at the different channel positions mirrored each other over the study period. Cycles of daily mean and maximum water temperatures also mostly coincided between all temperature loggers. However, mean and maximum temperatures at position 5a were slightly lower than temperatures at other positions throughout the time period from about 20/06/2010 until 01/07/2010. This time period was within an extended low-flow period occurring from the beginning of June until the middle of July.

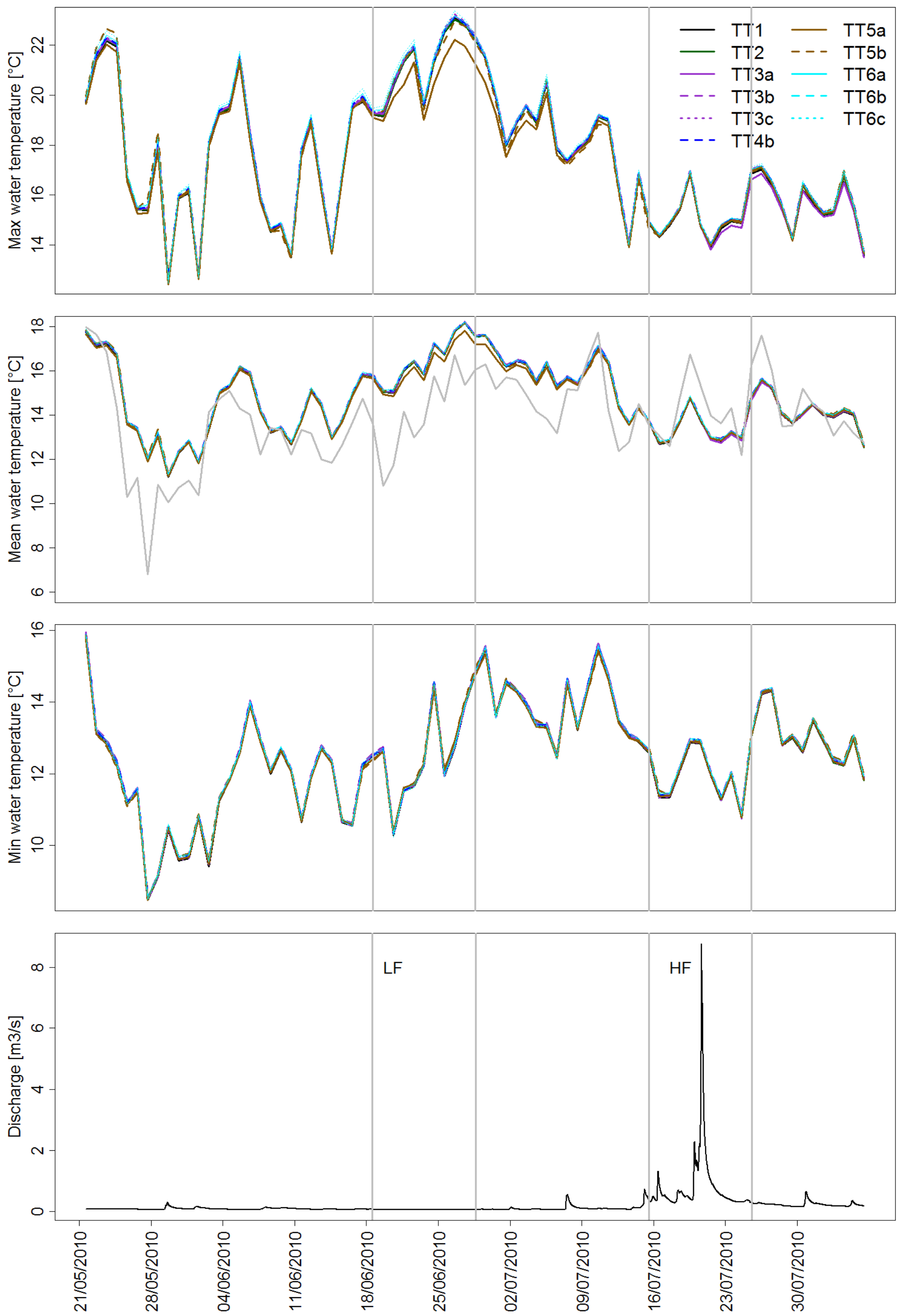

Figure 27. Daily maximum, mean and minimum water temperatures recorded with temperature loggers at different positions within the channel and discharge over the study period. High- (HF) and low-flow (LF) periods are mapped.

Averaged over the study period, measured water temperatures were highly similar with great significant correlations between all sites (r > 0.980) (Table 9). Mean daily water temperatures fluctuated, averaged over all temperature loggers, around 14.81 °C with a standard deviation of 0.05 °C. Daily minimum water temperature was on average 12.51 °C with a standard deviation of 0.03 while daily maximum water temperature averaged 17.60 (± 0.10) °C. Averaged over all sites, daily range in water temperatures was 5.08 °C with a standard deviation of 0.09 °C. Hence, minimum and maximum water temperatures displayed a similar low spatial variability as registered for mean water temperatures with temperature variations below the accuracy of measurement (0.2 °C). Box-and-whisker plots allowed comparison of 5 min data between sites and confirmed the homogeneity between the recorded temperatures that was found for daily temperature data (Figure 28). Accordingly, medians of water temperatures as well as minimum and maximum temperatures did not differ between sites. However, maximum temperatures measured at position 5a were slightly lower which reflected the lower daily maximum temperatures at this site around the low-flow period in June (Figure 28, Table 9). Every boxplot shows the presence of outliers which represent the diel maximum temperatures around the low-flow period in the mid of June.

Table 9. Mean daily water temperatures (°C) and air temperature (TTTa) measured *in situ* with Tinytag temperature loggers over the study period (21/05/2010 – 05/08/2010). Min, max and range refer to mean daily minimum, maximum temperatures and temperature range, respectively.

Tinytag	Mean	Min	Max	Range
TT1	14.76	12.48	17.53	5.05
TT2	14.79	12.49	17.56	5.06
TT3a	14.80	12.51	17.56	5.05
TT3b	14.86	12.56	17.64	5.08
TT3c	14.80	12.48	17.62	5.14
TT4b	14.84	12.53	17.64	5.10
TT5a	14.70	12.48	17.37	4.90
TT5b	14.80	12.53	17.55	5.02
TT6a	14.87	12.56	17.69	5.13
TT6b	14.83	12.51	17.66	5.15
TT6c	14.87	12.52	17.75	5.23
TTTa	13.88	7.35	19.42	12.07

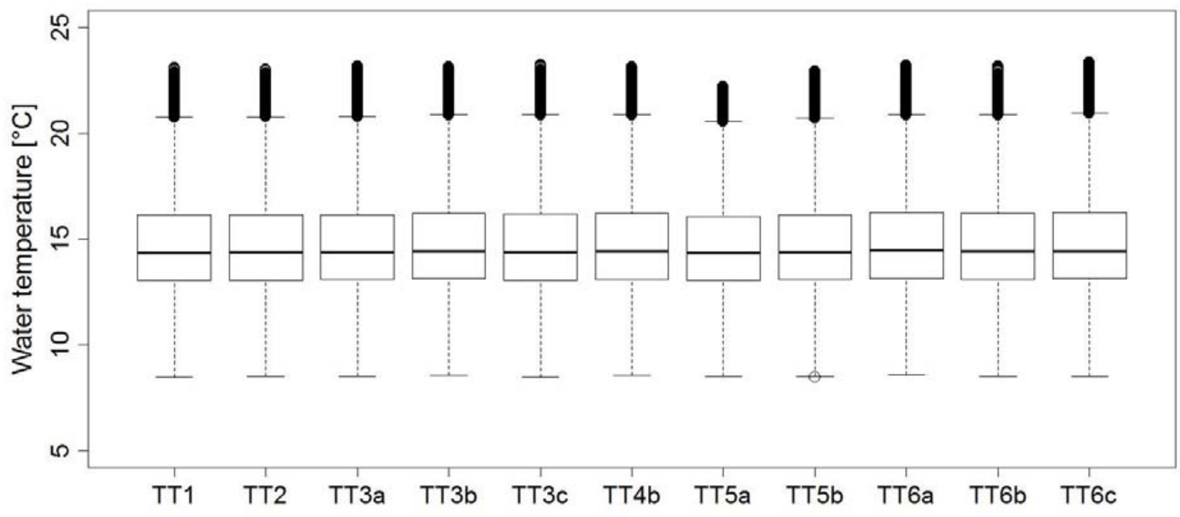

Figure 28. Box- and- whisker plots of water temperature measured over the study period in summer 2010 at the different positions within the stream.

To determine the effect of hydrological conditions and stream thermal capacity on spatial stream temperature variability, water temperatures were studied explicitly for the extended low-flow period from 18 until 28 June 2010 and the high-flow period occurring from 15 July until 25 July 2010 (Figure 27). Averaged over all temperature loggers, mean daily water temperature during the low-discharge period was 16.51 °C with a standard deviation of 0.10 °C. Mean daily water temperature measured over the high-flow period was considerably lower accounting for 13.49 °C while standard deviation was just slightly smaller (0.08 °C) when compared to low-flow conditions. Hence, also under high- and low-flow conditions no significant spatial variations in stream temperature were detected. Again, box-and-whisker plots of water temperatures based on the recorded 5 min data showed slightly reduced maximum temperatures at position 5a at least during the low-flow period and confirmed the homogeneity between sites with no significant differences in medians of water temperatures (Figure 29). Similar to mean daily temperatures, mean daily maximum and minimum temperatures, accounting for 21.25 °C and 12.63 °C respectively, were higher under low-flows compared to the high-flow period where mean daily maximum and minimum water temperatures were 15.18 and 12.06 °C, respectively. Standard deviation of minimum daily temperatures accounted for 0.03 °C and 0.04 °C under low-flow and high-flow conditions, respectively, and was therefore as low as for mean daily water temperatures. The spatial variability of daily maximum temperatures appeared to be greater, particularly under low-flow conditions as the standard deviation of maximum daily temperatures for the low-flow (high-flow) period was 0.25 °C (0.06 °C). However, the greater standard deviation was mainly related to temperature deviations at position 5a. Averaged over all positions, daily ranges of stream temperature were considerably lower during the high-flow (3.13 °C) compared to the low-flow (8.62 °C) period which becomes clearly visible by the boxplots shown in Figure 29 a and b. Overall, the comparison between the high- and low-flow periods revealed that the spatial variability of stream temperature was comparably low, irrespective of the flow-conditions. Furthermore, averaged over all sites, daily water temperatures as well as daily temperature ranges were relatively higher during the low discharge when compared to water temperatures during high discharge period (Figure 29).

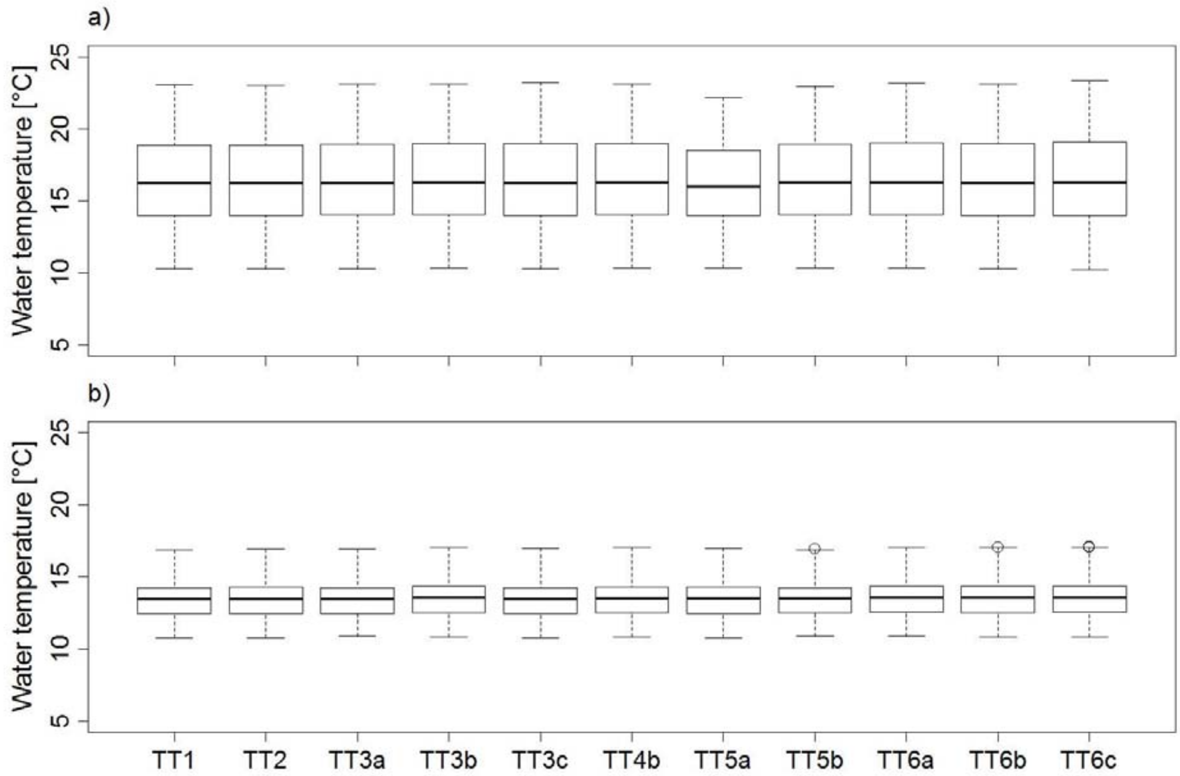

Figure 29. Box-and-whisker plots of water temperatures measured during the low- (a) and high-flow (b) period in summer 2010.

Measured water temperatures have further been analysed on a diurnal basis to investigate potential spatial temperature variability in the course of the day. As Figure 30 demonstrates, water temperatures along the channel were most similar during the night and morning. From midday onwards, temperatures measured at position 5a did not increase as strongly as the temperatures registered at the other channel positions and daily maximum values at this position remained below those of the remaining loggers. The maximum divergence of the logger at position 5a from the remaining ones occurred between 16:00 and 17:00. During this time period a temporary small divergence between the other temperature loggers is also visible. Towards the evening and throughout the night, water temperatures at the different sites were consistent.

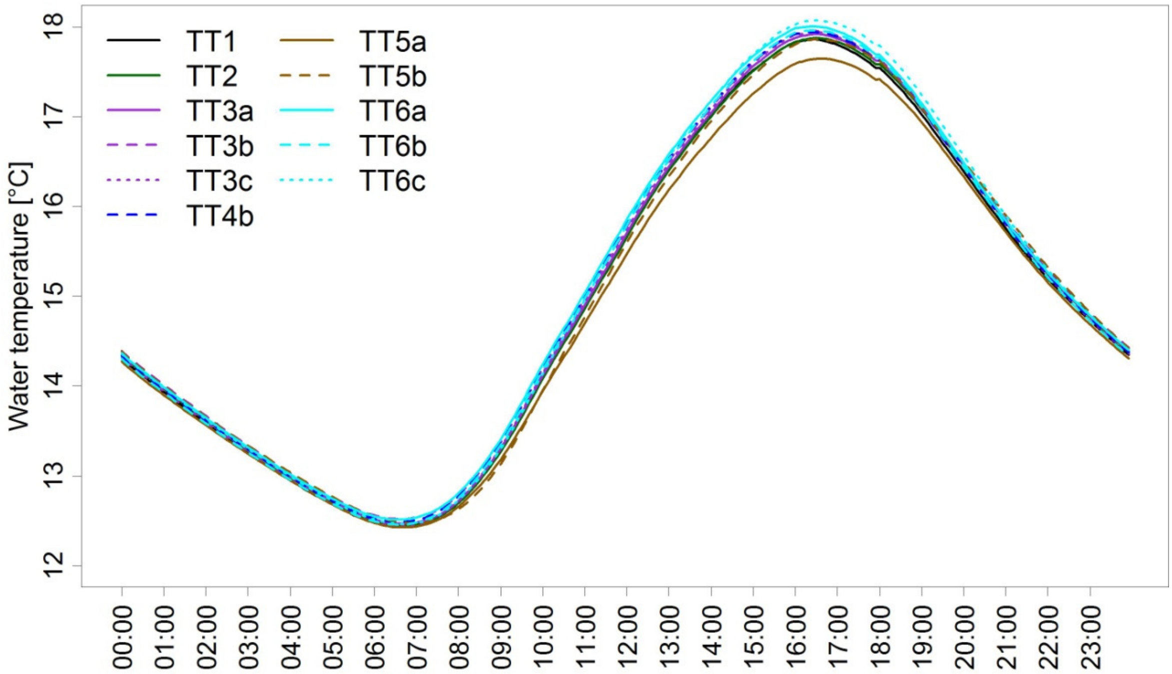

Figure 30. Mean diurnal cycles of water temperatures measured with Tinytag loggers (TT) at different channel positions over the study period in summer 2010.

3.2.3 Thermal imaging of stream water

To complement *in situ* measurements of stream temperature at discrete points, thermal images have been collected at two single days within the study period using a handheld infrared camera. Thermal pictures were taken of stream sections within the study reach in the early afternoon on 21 May 2010 and again on June 16, 2010. In addition to the infrared pictures, corresponding visual images of the sections were taken subsequently. Areas which were examined via infared thermometry included the main cross-sections of *in situ* stream temperature measurements as well as various structures within the stream such as vegetation or small sand and gravel bars. Meteorological conditions were similar on both recording days and were characterised by dry and mostly sunny conditions which were interrupted by just a few cloudy spells. Figure 31 shows a thermal image which is representative for most of the recorded images. The image was taken just downstream of position 6a where the channel width is about 4 metres. The picture demonstrates that water temperatures were uniform across and along the channel ranging between 20 °C and 21 °C. Light blue patches at the top left indicate slightly lower water temperatures but values were still almost 20 °C. Flashy bright green and orange patches at the right riverbank are related to shaded riverbank structures and do not represent stream water. The thermal image clearly displays that channel water flowing along the riverbank or around *in stream* vegetation had the same temperature as stream water in the middle of the channel.

However, at a riffle section where the stream was relatively shallow with larger stones protruding from the water surface, some small heterogeneity of stream temperature was spotted via infrared thermometry (Figure 32). This section was located about 5 metres downstream of logger position 6c. At this site, channel width is about 4 metres and water level was about 13 cm at the time of the infrared measurements. Figure 32 shows that near the stones, particularly at the top left part of the accumulation of stones, the water surface appeared slightly cooler (about 0.5 – 1 °C) than at other parts within the channel. However, this remained the only spotted temperature variation over the study reach.

Figure 33 gives an impression of difficulties which have been faced in association with thermal infrared imaging. For the reason of time and for organisational reasons, infrared pictures had to be taken in the early afternoon during the summer time. Therefore, shading effects, mainly arising from the right (south-side) riverbank, were recorded as apparent temperature differences at the water surface. Furthermore, direct insolation of the channel resulted in strong reflectance of solar radiation from the water surface and therefore partly appeared as a virtual variation in stream temperature as seen at the top left of Figure 33. However, apparent temperature variabilities were set apart from substantial heterogeneity of stream temperature comparing infrared and corresponding visual images.

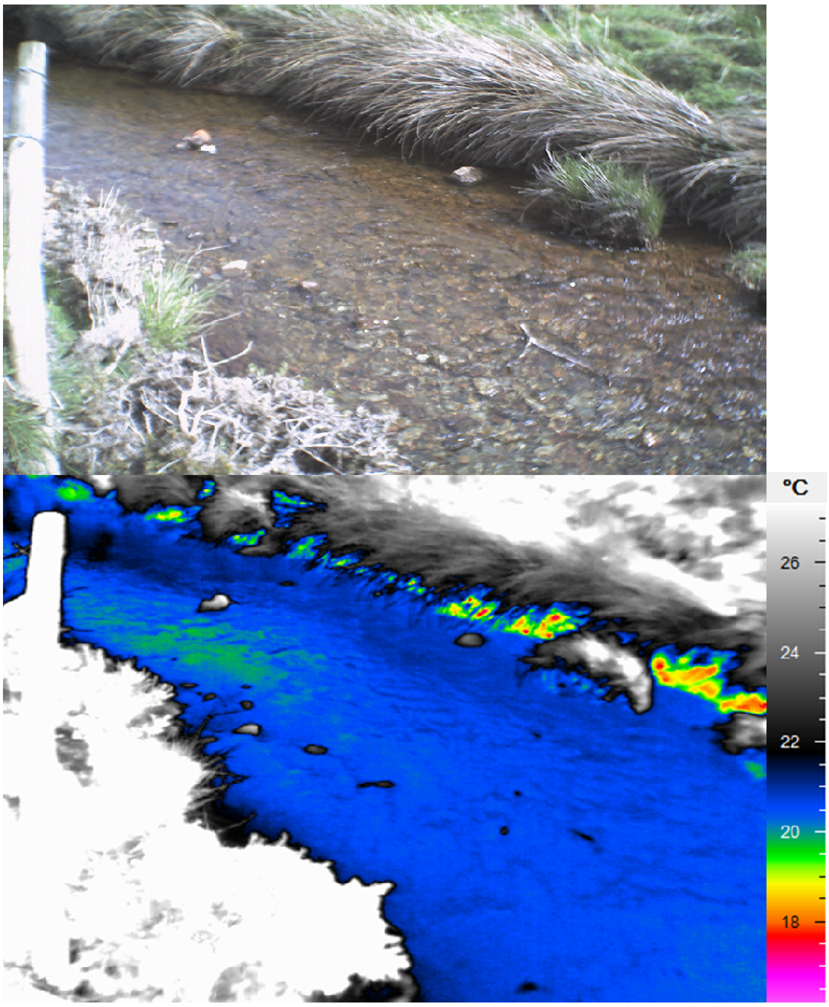

Figure 31. Visual (top) and corresponding infrared image (bottom) taken on 21 May 2010 15:02 just downstream of site 6a. Channel width is about 4 m and flow is from right to left. Vantage point and scale of visual and infrared pictures are not exactly the same.

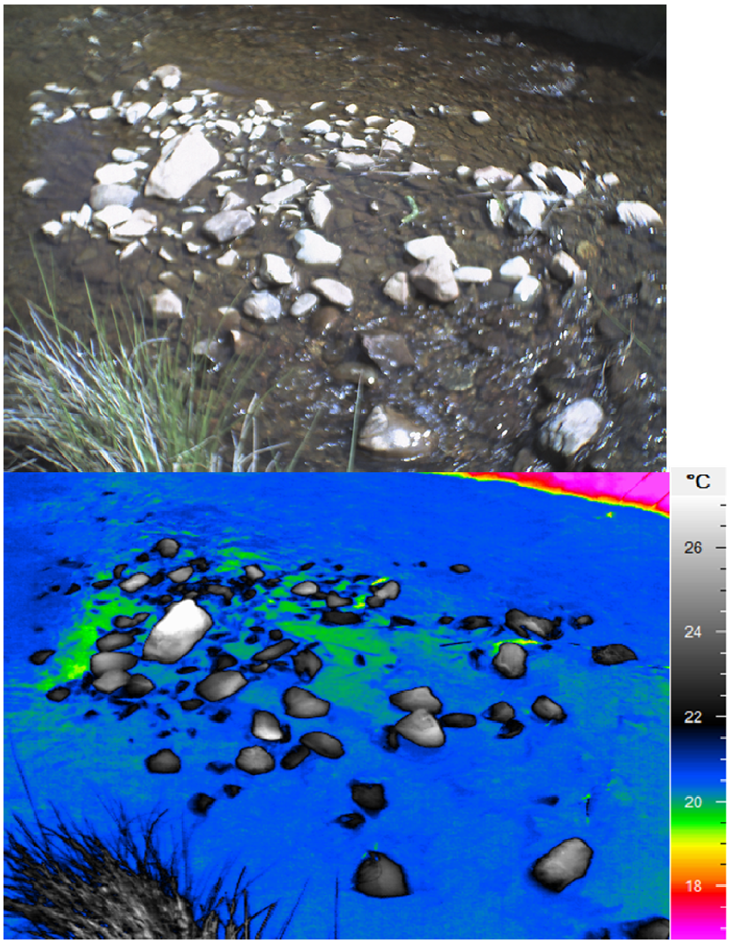

Figure 32. Visual (top) and corresponding infrared image (bottom) taken on 16 June 2010 15:09 downstream of site 6c. Channel width is about 4 m and flow is from right to left. Vantage point and scale of visual and infrared pictures are not exactly the same.

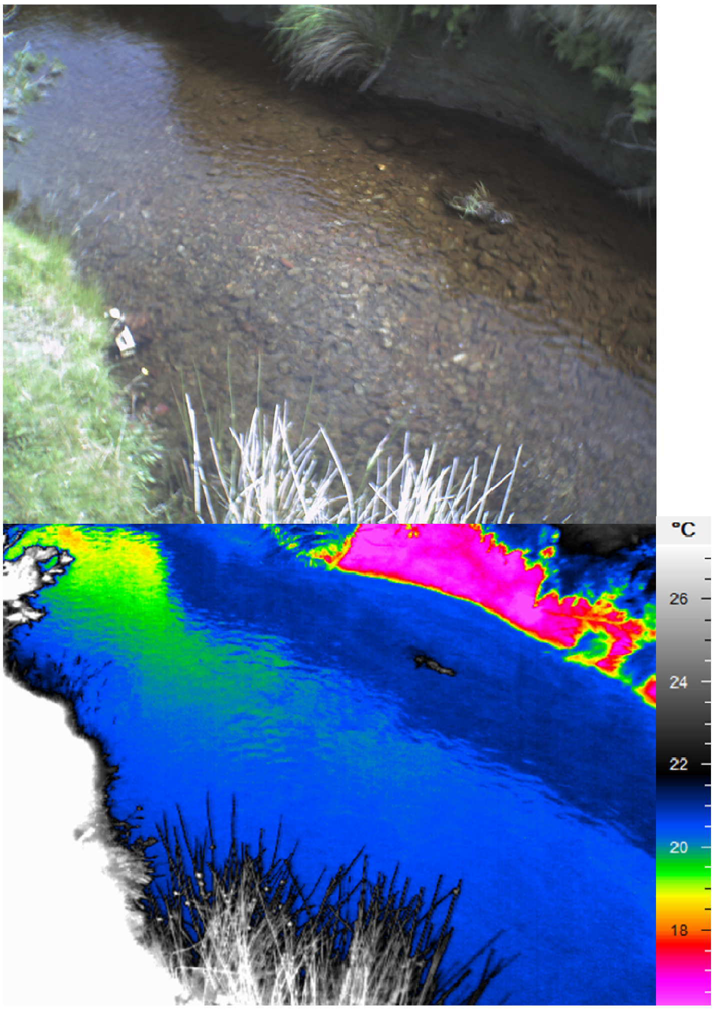

Figure 33. Visual (top) and corresponding infrared image (bottom) taken on 16 June 2010 15:18 at cross-section 4a/b. Channel width is about 4 m and flow is from right to left. Visual image shows positions of temperature loggers at this section (white housings at the streambed close to the riverbank). Vantage point and scale of visual and infrared pictures are not exactly the same.

3.2.4 Summary

Analysis of spatial stream temperature variability via *in situ* measurements and thermal infrared imaging revealed that water temperature distribution within the study reach was highly uniform throughout the full study period, irrespective of the prevailing flow conditions. However, daily maximum water temperatures at logger position 5a were found to be lower when compared to other positions with the discrepancy being enhanced during a low-flow period but being absent during a high-flow period. Thermal imaging identified a small cold water patch within a riffle sequence downstream of logger position 6c where water surface temperatures were about 0.5 – 1 °C cooler than in the adjacent channel areas. Over the study period, water column temperatures at all sites were positively correlated with air temperatures but negatively correlated with discharge.

4 Discussion

The purpose of this study was to provide insight into the dynamic processes that drive the water temperature of running waters with focus on the relationship between stream temperature, energy fluxes and hydrometeorological conditions. Therefore, both spatial and temporal stream temperature and energy flux patterns of a Welsh upland stream have been characterized within a hydrological and meteorological context. High-resolution stream temperature and micrometeorological data were available for more than one and a half years and facilitated the examination of river heat dynamics in a long-term perspective. The study included annual, seasonal and even more detailed sub-seasonal analyses in order to provide an improved understanding of the relationship between hydrometeorological conditions and stream thermal behaviour. To find out more about the factors and processes that determine the spatial variability of stream temperature at micro-scale, spatial water temperature patterns have been investigated related to morphological channel features and hydrological conditions. This part of the study included *in situ* water temperature measurements at different sections along the study reach during 10 weeks of summer. In addition, thermal imaging via portable infrared camera allowed for a spatially continuous monitoring of stream temperature.

4.1 Factors and processes determining the temporal variability of stream thermal behaviour

Interactions between microclimate, hydrology, energy transfer processes and stream temperature are highly complex as, for instance, microclimate sets boundary conditions for energy exchanges that affect stream temperature whereas the stream temperature is in turn a boundary condition for microclimate (Moore et al., 2005). To facilitate the understanding of the study results, the following discussion was structured by the responses of stream temperature and energy fluxes to the two main drivers of thermal behaviour as defined in Chapter 1.4.1 (Figure 1): the prevailing atmospheric and hydrological conditions. The respective paragraphs include discussions about the different scales at which the main drivers may affect thermal behaviour.

4.1.1 Atmospheric conditions

Atmospheric conditions are considered a major driver of channel water temperature (Poole and Berman, 2001; Caissie, 2006) and in particular microclimate is known to determine energy fluxes at the water column of streams (Hannah et al., 2008). In turn, the various energy fluxes that occur at the water surface through the transfer of latent (Q_e) and sensible heat (Q_h) and by net radiation (Q^*) as well as bed heat flux (Q_{bhf}) fundamentally control the water temperature of running waters (Stevens et al., 1975).

Over the study period from 12/12/2000 until 17/05/2002, water column (T_w) and streambed temperatures at 0.05 m ($T_{b\_0.05}$), 0.20 m ($T_{b\_0.20}$) and 0.40 m ($T_{b\_0.40}$) depth all displayed a clear annual cycle with maximum temperatures in the summer and minimum temperatures in winter. Accordingly, total energy available (Q_n), which is the sum of the various energy fluxes that occur at the water column, showed a clear annual cycle with total heat gains by the water column taking place in spring and summer and total heat losses taking place in autumn and winter. Water column temperature tracked total energy available across the year with a certain delay and showed smaller daily and seasonal fluctuations compared with Q_n. The delayed response of T_w to Q_n and the dampened fluctuations in T_w both reflect the generally high heat capacity of water. Correlation analyses attest to the lag between T_w and Q_n as they revealed that T_w and Q_n were slightly stronger correlated when Q_n led water temperature by one day. Analysis of diurnal patterns in water temperatures and energy fluxes were also consistent with this finding as they revealed that daily temperature peaks tracked daily maximum values of Q_n by about 3 hours. The findings conformed to previous studies provided by Hannah et al. (2004, 2008). Therein the energy and temperature dynamics of moorland and forest upland streams had been examined and the determined correlation coefficients for the concurrent (r = 0.500) and lagged correlations (r = 0.565) between T_w and Q_n were of the same magnitude as those reported herein (r = 0.575 and r = 0.607, respectively).

Given that the total energy available by the water column is the sum of net radiation, sensible heat flux, latent heat flux and bed heat flux, seasonal and diurnal variations in Q_n are driven by respective changes in these subcomponents (Hannah et al., 2004, 2008). Of all the individual energy balance components, energy fluxes by net radiation (Q*) were greatest and showed the most pronounced seasonal and diurnal patterns with maximum fluxes up to 20 MJ m^{-2} d^{-1} during summer and minimum fluxes close to zero MJ m^{-2} d^{-1} in winter. Accordingly, variations in total energy available at the air-water interface (Q_{sn}) largely mirrored Q* across the year. Q* was the main energy gain by the water column throughout the year, irrespective of the season. This indicates that energy gains by incoming short-wave (solar) radiation exceeded on average the energy losses by skyward emittance of long-wave radiation. In spring and summer, Q* was even the only heat source by the water column. The great contribution of Q* to the stream energy budget is consistent with the rather exposed character of the channel within the study reach which is largely free from riparian vegetation and associated shading. It should be noted that comparison with previous studies is hampered by the fact that the time periods between the studies vary. Apart from this study only a few studies exist that include a study period of more than one calendar year (see Chapter 1.2, Table 1). Nevertheless, the results of this study should be set within a wider context. The findings presented herein are consistent with the outcomes of previous river heat budget studies in that they also found the net radiation term to be the most dominant energy flux (Webb and Zhang, 1997, 1999; Evans et al., 1998; Hannah et al., 2004, 2008). However, in terms of the energy gains or losses related to Q* results of the different studies vary among each other. In this study, Q* provided a heat gain by the water column throughout the full year while Hannah et al. (2004) demonstrated that over their study period which covered the salmon-spawning hatch season from late-October to mid-April, Q* was a heat sink rather than a heat source. This finding was related to the fact that during this time of the year incoming short-wave radiation from the sun was too low to exceed the constant skyward emittance of long-wave radiation from the water column in the subarctic study environment at a relatively high latitude site (57°02´N). In comparison, the Welsh study reach on Afon Llwyd is located at lower latitude (52°30´N) and receives therefore a higher short-wave (solar) radiation input over the year which resulted in the mostly positive net radiation term during the study period.

Compared to net radiation, the transfer of latent and sensible heat as well as bed heat flux were relatively small over the study period and were just minor contributors to the energy budget of the Afon Llwyd. The transfer of latent heat is related to the energy transfer through evaporation or condensation of water/water vapour (Oke, 1987). Thereby, energy is added to the water column when water vapour condensates at the water surface while energy is removed from the water column when liquid water turns into water vapour and evaporates from the water surface. Seasonal patterns for Q_e were relatively weak but showed that evaporation was predominantly an energy sink throughout the year with energy losses being greatest during spring/summer and lowest in late autumn/winter. Diurnal analyses were consistent with these findings as latent heat flux was an energy sink throughout the day, irrespective of the season, with maximum energy losses occurring in the afternoon and being most pronounced in spring and summer. Energy gains by condensation were rather negligible as they occurred only at very few days during the study period. As latent heat flux is determined by prevailing atmospheric conditions such as relative humidity and wind speed above the water surface (Webb and Zhang 1997), patterns in Q_e reflect changes in these micrometeorological parameters. Hence, annual maximum losses through Q_e during summer months generally reflect the relatively low relative humidity in summer combined with a high saturation vapour pressure associated with higher air temperatures during this time of the year. Accordingly, latent heat flux was significantly correlated with relative humidity over the study period. Previous research also found Q_e to be a predominant heat sink by the water column, although relative contribution of Q_e to the total energy loss from the water column varies between the different studies which may be related to the different time periods considered in the studies (Webb and Zhang, 1997; Evans et al., 1998; Cozzetto et al., 2006).

Sensible heat flux reflects the prevailing air-water temperature gradient (Webb and Zhang, 1997). This implies that energy is lost via Q_h when water temperature exceeds air temperature whereas energy is gained by the water column when the air above the water column is warmer than the water. Accordingly, daily fluxes of sensible heat were strongly positively correlated with mean daily air minus daily water column temperature differences. Seasonal patterns in Q_h were very weak in the Afon Llwyd study reach. Nevertheless, analysis of the centre month of each season revealed that Q_h was predominantly a heat loss but yielded a small energy gain by the water column in autumn 2001 and January 2002 when mean daily air temperatures mainly exceeded mean daily water temperatures. For other UK rivers it has been reported that sensible heat transfer was rather a heat sink in spring/summer and during frost periods and predominantly a heat source in autumn/winter (Webb and Zhang, 1997; Hannah et al., 2004, 2008). In general, variations in the air-water temperature gradient between reaches are also dependent on the individual water sources and the associated distinct thermal signatures that contribute to the stream flow leading to a site-specific air-water temperature gradient.

Bed heat flux is a measure of heat conduction, advection and radiative processes that occur at the channel bed and reflects the prevailing temperature gradient within the streambed (Hannah et al., 2004). Accordingly, Q_{bhf} was correlated well with streambed at 0.05 m minus streambed at 0.40 m depth temperature differences over the study period. Diurnal patterns reflected the relationship between Q_{bhf} and the streambed temperature gradient as the daily Q_{bhf} depression in the afternoon coincided with the greatest vertical temperature gradient at this daytime. Like Q_e and Q_h, energy fluxes related to Q_{bhf} were rather small compared with Q* and displayed a weak annual pattern. However, Q_{bhf} tended to be a heat source during winter months and was predominantly a heat sink during summer 2001 and spring 2002 suggesting that in winter the deeper streambed was warmer than the above lying channel bed leading to an upward temperature gradient and the warming of the channel water. Conversely, in summer the upper streambed was warmed through the incoming solar radiation which resulted in a downward heat transfer away from the water column into the cooler underlying streambed. Bed heat flux was positively correlated with discharge and negatively correlated with water column temperature indicating that within the study reach heat transfer at the bed was sensitive to changes in river flow and water column temperature. Accordingly, at higher flows and lower water column temperature, Q_{bhf} tended to warm the water column while during lower flows and higher water column temperature, this trend was reversed leading to a downward heat loss from the water column into the bed. Although absolute values of the net radiation term at the streambed were almost as high as at the water surface, net bed radiation accounted only for 25 % of the variation in Q_{bhf} and was therefore rather a minor contributor to the total bed heat flux. Hence, advective and convective rather than radiative bed heat exchanges characterised Q_{bhf} within the study reach with the contribution of Q_b* to Q_{bhf} being comparable to that reported for a Scottish upland stream (24 %: Hannah et al., 2004) and intermediate to those reported for a forest and moorland reach (cf. 14 % and 53 %, respectively: Hannah et al., 2008). However, Evans et al. (1998) demonstrated that on average 81 % of the variation in the recorded bed heat flux were attributable to incoming short-wave radiation. The great discrepancies between Q_b* contributions to Q_{bhf} in different streams or even between different sections within one stream reflect differences in streambed morphology and groundwater influence. For instance, the nature of the substratum determines the conductivity within the channel bed. Hence, bed conduction at the streambed of the Afon Llwyd appeared to be rather low when compared to the UK lowland river which was investigated in Evans et al. (1998). Though, to finally quantify the actual thermal conductivity of a streambed, sampling of the streambed would be indispensable.

When compared to energy exchanges at the air-water interface, relative contribution and magnitude of energy exchanges at the underlying streambed were relatively small within the study reach. Averaged over the year 2001, all energy gains and 94.85 % of heat losses took place at the air-water interface. In terms of total energy transfers irrespective of flux direction, 98.71 % of energy transfer processes took place at the air-water interface averaged over one year. Comparison of relative contribution of bed heat flux processes to total energy fluxes between different reaches is again hampered by the fact that the respective studies focused on different time periods or seasons. Given the highly variable results of various previous studies, it can be generally reasoned that the magnitude and relative contribution of thermal processes at the streambed strongly depends on reach-specific characteristics such as sub-surface hydrology and channel exposure (Webb and Nobilis, 1997; Hannah et al., 2004; Cozzetto et al., 2006). For instance, Hannah et al. (2008) found considerable differences in the relative contribution and magnitude of Q_{bhf} between a forest and moorland reach over the same time period which they attributed to contrasting groundwater-surface water interactions. Accordingly, Q_{bhf} was a small heat gain throughout the year for the channel water dominated forest reach whereas it accounted for more than half of all heat gains in autumn-winter and almost 20 % of heat losses in summer for the groundwater-influenced moorland reach. Hence, the relatively small contribution and magnitude of bed heat flux processes found within the study reach of Afon Llwyd suggests that the stream is rather unaffected by groundwater fluxes.

Altogether, energy exchange processes within the study reach displayed a high seasonal variation which was largely related to seasonal variation in atmospheric conditions. Figure 34 shows schematically the seasonal variation in the different stream energy balance components in the year 2001. The present findings are in agreement with results from previous river heat budget studies wherein long-term analysis of energy fluxes and micrometeorology revealed that the contribution of the different heat fluxes varied with season (Webb and Zhang, 1997; Hannah et al., 2004, 2008). Added together, net radiation was the major energy input throughout the year while energy gains by sensible heat and bed heat flux were seasonally limited. Energy losses were mainly caused by evaporation and to a smaller extent by sensible heat transfer. In spring and summer bed heat flux was also a heat loss. These findings reflect the rather open and unsheltered nature of the channel including a high width-depth ratio which provides an exposed surface area for energy exchange processes at the air-water interface, especially for radiative fluxes.

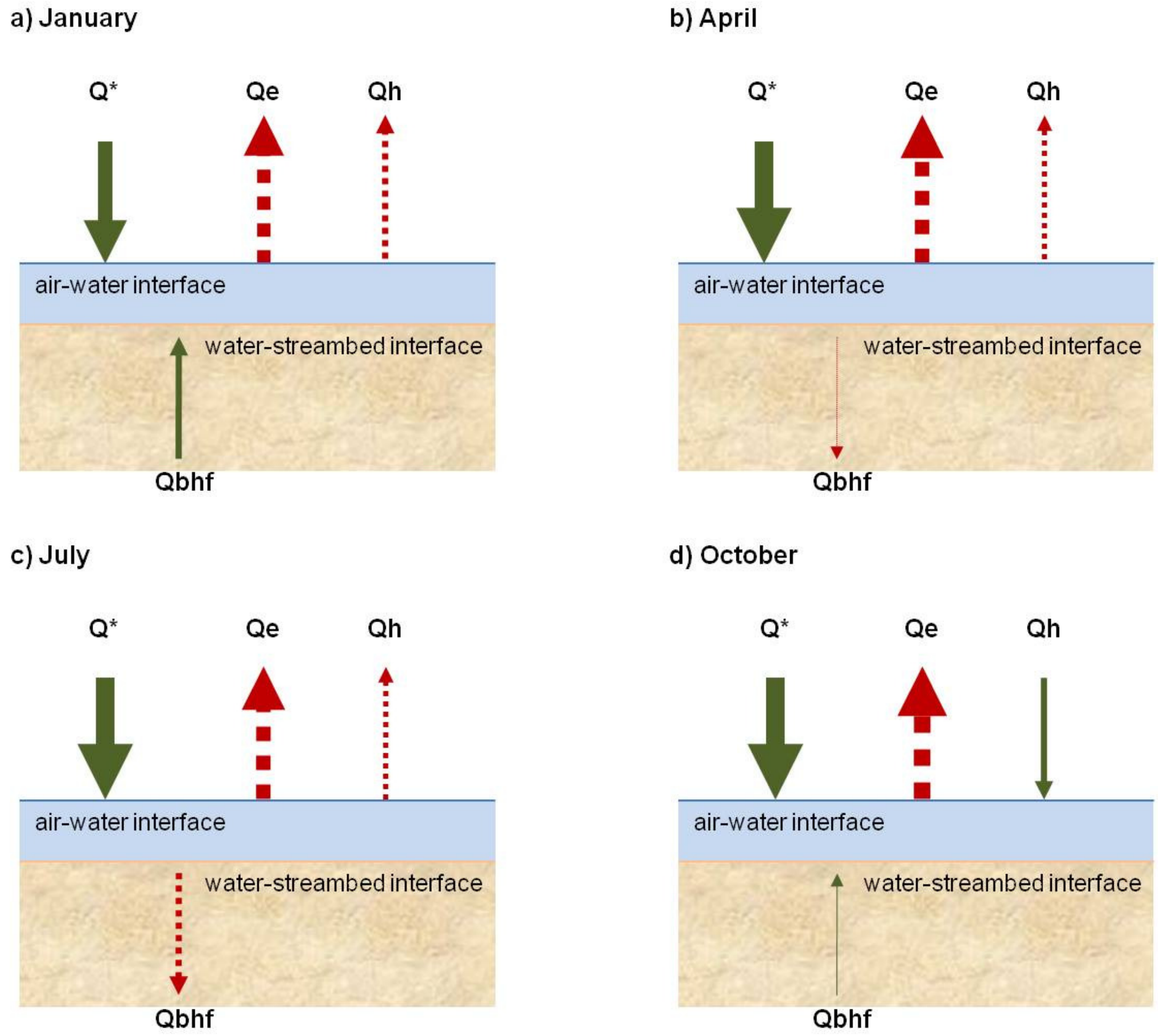

Figure 34. Schematic representation of seasonal heat budget partitioning with Q*, Q_e, Q_h, Q_{bhf} referring to net radiation, latent heat, sensible heat and bed heat flux, respectively. Solid green arrows relate to heat gains while dashed red arrows represent heat losses. Weight of arrows shows relative contribution of components to respective heat gains/losses.

4.1.2 Hydrological conditions

Stream flow

In general, changes in river flow imply changes in the heat capacity of the water column (Poole and Berman, 2001). Assuming that the energy input is the same, low discharge consequently promotes a faster heating of the water column whereas a high water volume associated with high runoff implies a relatively slower heating of the water column. To examine the effect of changing flow conditions on stream temperatures, the relationship between discharge and water temperature has been examined. Considering daily discharge and water column temperatures over a full year, correlations yielded slightly negative values which reflected partially the above mentioned physical relationship between discharge and heat capacity of the water column. Discharge was also negatively correlated with streambed temperatures at 0.05 m, 0.20 m and 0.40 m. These findings indicate the potential downwelling of cooler channel water into the streambed associated with the increased hydraulic pressure at higher flows. Similar results were found for a forest and moorland stream in the subarctic Scottish upland (Hannah et al., 2004, 2008). However, effects of changing discharge on water temperature were found to be variable throughout the year. Correlations that were conducted for the centre month of every season in the year 2001 revealed specific and complex shorter-timescale associations between discharge and water temperature. Accordingly, highly negative correlations between daily discharge and water/streambed temperatures were found for the month of July whereas considerably positive correlations were found for January. The strongly inverse correlation in July suggests that changes in thermal capacity have a strong influence on water temperatures in summer. This may be related to the fact that at this time of the year stream water temperature is mainly determined through solar radiation and is therefore rather sensitive to changes in thermal capacity. Accordingly, high flows in summer enhance the thermal capacity of the stream and are generally associated with cloudy conditions. Furthermore, high flows in summer may be associated with an enhanced contribution of relatively cooler water sources. Hence, higher flows in summer appear to be closely linked with both the reduced heating of the water column and the cooling via advective water sources and consequently lower stream temperature. In contrast to this, correlation between discharge and water temperature in January were converse and yielded a considerably positive correlation. This may be explained as follows. In winter, changes in water source contributions with different thermal signatures may be the dominant thermal effect associated with higher flows rather than changes in the thermal capacity as energy input through solar radiation during this period of the year is rather low anyway. Hence, higher flows in winter may have been associated with a greater contribution of relatively warmer groundwater to the stream flow and therefore may have resulted in enhanced stream temperatures associated with higher flows within the study reach.

Storm events

Storm events refer to the occurrence of hydrograph peaks during and immediately after a significant rainfall event (Davie, 2008). To date only a few studies exist that focus on the thermal impact of storm events and results provided by these studies are contradictory due to differences in the examined study basins and study periods (Chutter, 1970; Pluhowski and Arlington, 1972; Smith and Lavis, 1975; Kobayashi et al., 1999). A recent comprehensive study on the stream temperature response to storm events has been provided by Brown and Hannah (2008). They demonstrated clear spatial and temporal differences in water column and streambed temperature responses to storm events. However, their study was focused on alpine streams. To gain insight into the thermal response to storm flows in the Afon Llwyd study reach, stream temperatures and energy fluxes directly before and during selected storm flow events have been examined. Water column temperature showed a consistent decrease in response to runoff events in terms of any examined event, whereby the intensity of temperature declines reflected the relative magnitude of the respective storm events. These findings are consistent with some of the previous studies (Smith, 1972; Brown and Hannah, 2007) which reported water temperature decline associated with storm flows but are contradictory to others wherein a temperature increase in response to peak flows was documented (Kobayashi et al., 1999; Langan et al., 2001). The reduction of stream temperatures during peak flows is likely attributable to changes from warmer to colder water source contributions related to the occurrence of storm flows; it has been shown before that the temporary advection of distinct water sources during storm flows can have a considerable impact on stream temperatures (Kobayashi et al., 1999; Langan et al., 2001; Brown and Hannah, 2007). Runoff generation processes in Plynlimon catchments were found to be very complex (Neal et al., 1988; Haria and Shand, 2004, 2006). Nevertheless, it is known that pre-storm water, particularly bedrock groundwater, is dominating the storm hydrograph in the nearby Hafren catchment (Haria and Shand, 2006). Therefore, the influx of relatively colder groundwater during storm events may have had a temperature lowering effect within the study reach. The incorporation of measurements of groundwater temperature and detailed studies on stream flow generation within the study reach, e.g. including the application of tracer techniques, would help to elucidate the actual reasons for storm flow associated temperature depressions. Direct cooling of the stream through relatively colder precipitation during events is unlikely to have contributed to water temperature decline as previous studies considered precipitation inputs to be negligible in the energy balance (Webb and Zhang, 1997; Evans et al., 1998).

Temperature reductions in response to the examined peak flows were also found for streambed temperatures at 0.05 m, 0.20 m and 0.40 m depth with the response getting damped with depth during the spring, summer and autumn storm events. The dampening of the thermal response with increasing depth into the streambed indicates a greater thermal attenuation with depth (Hondzo and Stefan 1994). As both water column and streambed temperatures declined, downwelling of colder channel water into the streambed during storm events is suggested. This finding conforms also to the above discussed negative correlation between discharge and bed temperatures. Dampening of storm-associated streambed temperature reduction with depth was not found for the winter storm event. Instead, storm flow related temperature reductions were more pronounced at 0.40 m depth than in the water column and the overlying streambed. This is attributable to the inversed temperature gradient in winter with higher temperatures in the streambed at 0.40 m depth and relatively colder water column temperatures. Accordingly, the downwelling of colder channel water into the streambed during peak flows in winter resulted in a cooling of the previously warmer bed at 0.40 m depth.

As stream temperature is determined by prevailing energy exchange processes at the air-water and water column-streambed interface, the impacts of storm events on stream energy fluxes have been analysed as well. To the author´s knowledge no similar studies exist until now. Sensible heat flux (Q_h) represented a heat loss before and during examined winter, spring and autumn storm events reflecting generally warmer water column than air temperatures. Heat losses by Q_h were increased with occurrence of the storm events in these seasons while in summer Q_h turned from a pre-storm heat sink to a heat source during the event. The increase in heat losses by Q_h during winter, spring and autumn events, coincided with a relatively stronger cooling of air temperature compared with water temperature in association with storm events. Hence, the water column to air temperature gradients increased with the occurrence of peak flows, therefore yielding increased heat losses via Q_h. During the summer storm event, the water to air temperature gradient switched from higher water than air temperatures to the opposite. This was due to a relatively stronger decline of water than air temperatures related to the storm event. Latent heat flux (Q_e) at the air-water interface showed a similar seasonal pattern in response to storm events. Accordingly, heat losses by Q_e increased with occurrence of the storm events in winter, spring and autumn but not in summer. In terms of the summer storm event heat losses by Q_e were reduced during storm flow when compared with pre-storm losses. These findings reflect microclimate conditions during the storm events. Correspondingly, occurrence of storm events in winter, spring and autumn was always associated with a change towards conditions that favour evaporation such as higher saturation vapour pressures at the water surface (E_a), lower relative humidity (RH) and enhanced wind speed. Instead, during the summer event, RH was higher and E_a was lower compared to pre-storm conditions leading to reduced evaporation. In terms of thermal processes at the streambed, uniform responses in bed heat flux and bed radiation parameters to storm events were found for all seasons except for winter. This may be the result of anyhow relatively low streambed energy fluxes in winter. Therefore, the winter event was excluded from the subsequent discussion. The occurrence of storm events resulted in a reduction of the net radiation and short-wave radiation at the streambed. This reflects the generally increased attenuation of radiation at the water column associated with enhanced water levels. Bed heat flux (Q_{bhf}) was a heat sink during pre-storm periods and became a heat source during storm events. The conversion of Q_{bhf} from a heat sink to a heat source reflects the conversion of the water column-streambed temperature gradient occurring with the relatively greater decrease in water column temperature than streambed temperatures in response to storm events.

Altogether, this analysis revealed that water column as well as streambed temperatures declined in response to storm events due to changes in the relative contribution of advective water sources. Apart from water and streambed temperatures, energy fluxes at the air-water and water-streambed interfaces were considerably changed by the occurrence of storm flow events. Changes in turbulent heat fluxes at the air-water interface were thereby mainly related to changes in microclimate and water column temperatures associated with the storm event while changes in energy exchange processes at the streambed were the result of both altered short-wave radiation penetration to the bed and changes in the water column- streambed temperature gradient. These findings highlight the complexity of the relationship between microclimate, energy fluxes and stream temperature. For instance, they show that sensible heat flux is not simply one of the processes that control stream temperature but in a sense depends on the water temperature itself as the air-water temperature gradient is influenced by the prevailing water column temperature. Given that no studies on the impact of storm flow on stream energy exchanges have been published until now and that the present study focused on the examination of four individual events, there remains a need for further research on the complex relationship between storm flow, microclimate, energy fluxes and stream temperature, both for the Welsh study reach and for other running waters.

Interaction of groundwater and surface water at the streambed

Apart from atmospheric and hydrological flow conditions, the advective exchange between groundwater and channel water at the streambed can be an important driver of stream water temperature. For instance, Holmes (2000) reported on the moderating effect of phreatic groundwater inputs on water temperatures throughout the year and Story et al. (2003) showed that groundwater inflow considerably contributed to the cooling of daily maximum temperatures in a small stream which passed from an open into a shaded reach. In another study O´Driscoll and DeWalle (2006) included investigations on the impact of groundwater inputs on energy fluxes such as the transfer of latent and sensible heat. In the present study, the thermal effect of potential groundwater influence within the Afon Llwyd study reach is illustrated on the basis of the observed bed heat flux dynamics which have been addressed above and based on the measurements of vertical temperature gradients within the streambed. Furthermore, the relationship between air and water temperatures is discussed as an indicator for groundwater exchange processes at the channel bed.

Over the study period, seasonal and diurnal fluctuations of water column and bed temperatures were highly consistent and correlated among each other and showed no time lag between temperatures of the water column and the streambed at 0.05 m and 0.20 m. Only the streambed temperatures at 0.40 m depth appeared slightly retarded compared to the overlying streambed and the water column. In accordance with the similar temperature dynamics over the course of the year, the vertical temperature gradient between water column and streambed and therefore also the bed heat flux was found to be very small. Averaged over a full year, mean daily temperatures in the water column were just slightly higher than in the channel bed and decreased less than 0.5 °C with depth into the bed. Highly similar temporal dynamics of water column and streambed temperatures without a considerable time lag or gradient between water column and streambed temperatures suggest that, at least within the study reach, the Afon Llwyd is a losing stream according to the definition of Silliman and Booth (1993). The relatively small thermal gradient supports the hypothesis that the stream is channel-water dominated rather than influenced by upwelling groundwater (Malcolm et al., 2002; Brown et al., 2006; Hannah et al., 2009) as vertical gradients for groundwater-influenced streams were found to be considerably greater (Evans and Petts, 1997; Clark et al., 1999; Hannah et al., 2004). Furthermore, the analysis of the thermal response to stream flow dynamics including storm flows is consistent with this model as discharge was negatively correlated with streambed temperatures and peak flows resulted in temperature declines within the streambed (discussed above). However, no explicit investigations on groundwater- surface water interactions in the Afon Llwyd catchment exist so far that could corroborate this conclusion. Nevertheless, a study on water movement through the adjacent floodplain of the Afon Llwyd has been conducted and the outcomes may support the above proposal of a losing stream (Bradley et al., n.d.). In this study it was suggested that water seepage from the Afon Llwyd into the floodplain occurs at distinct sections and that river levels may control groundwater levels in the adjacent floodplains. To finally confirm the above assumptions, groundwater exchange processes at the streambed and within the hyporheic zone should be investigated in a detailed study including stream flow measurements at the study reach inlet and outlet to compute net gains or losses, the determination of hydraulic heads within the streambed, the application of hydrochemical tracers or other techniques such as applied in Cey et al. (1998).

It has been reported that water temperature is less sensitive to air temperature when streams are groundwater dominated (Mohseni and Stefan, 1999). Therefore, the nature of the air-water temperature relationship can be used as indicator for potential groundwater influence (O´Driscoll and DeWalle, 2006). The following discussion focuses on the air-water column temperature relationship over the study period from 12/12/2000 until 17/05/2002 as the second study period during summer 2010 included only 10 weeks of measurements and results may therefore be less significant. Over the study period fluctuations were considerably higher for air temperatures than for water column or streambed temperatures. This trend reflects the much higher thermal capacity of water compared to air. Daily air temperatures were highly correlated with water and also with streambed temperatures and linear regression between daily air and water temperatures yielded a regression slope of 0.8. Departures from linearity were apparent at low air temperatures and were consistent with the outcomes of previous studies (Mohseni and Stefan, 1999; Mohseni et al., 2002). However, comparison of the regression slope with other works is hampered by the fact that most previous studies focused on the air-water temperature relationship at a weekly, monthly or annual scale rather than a daily scale. When compared with previous findings nevertheless, the slope of the relationship found herein is relatively high (Webb and Nobilis, 1997; O´Driscoll and DeWalle, 2006) and suggests that the stream within the study reach is largely unaffected through groundwater, lateral inflows, river regulation or strong riparian shading (Webb and Nobilis, 1997). This is consistent with the fact that the stream at the study site is approximately just 5 km from its source, displays a natural flow regime and is mainly unshaded in this area. Furthermore, this finding conforms to the above assumption that the stream is channel-water dominated rather than groundwater-influenced.

4.1.3 Accuracy of the estimated stream energy balance

The prediction of stream temperatures can be used as a tool to check the accuracy of calculated energy balances (Webb and Zhang, 1997). Therefore, a deterministic model which includes the estimated total energy available as input and considers changes in thermal capacity has been applied herein (Moore, 2005). A similar deterministic model has been used by Caissie et al. (2007) and Benyahya et al. (2010). Results for temperature simulation showed a generally good fit of simulated and measured water column temperatures. Measured and predicted values were highly correlated with each other ($r = 0.972$) with a root mean square error of 1.70 °C and a Nash-Sutcliffe coefficient of 0.87. The relationship between predicted and observed temperatures revealed that particularly water temperatures above 10 °C were overpredicted through the model. Accordingly, mean daily water temperatures were mostly overestimated in spring and summer when temperatures exceeded this value more frequently. However, seasonal and daily fluctuations in water temperatures were mirrored well by the model and correlations between measured and predicted values were high (see above). This indicates that the water level/heat capacity of the water column which was one of two input variables was generally too low and resulted in the overprediction of the heating of the water column in response to the prevailing energy conditions. Furthermore, inaccuracies could be related to the negligence of the advective heat transfer by groundwater, lateral inflows and precipitation. However, neglected cooling by precipitation is rather unlikely to be the reason because heat fluxes through precipitation have been shown to be negligible (Evans et al., 1998). The omission of heat flux related to bed friction is also unlikely to represent a reason for temperature overestimation as bed friction adds energy to the water column; therefore consideration of bed friction would have resulted in even more enhanced water column temperatures. The calculation of energy budget components based on micrometeorological data may have led to inaccurate estimations of heat gains or losses and is therefore a potential source of error. However, attempts to minimise errors of estimation have been made by using high resolution micrometeorological data that had been recorded directly above/in the stream. Only data for atmospheric pressure which is generally considered a large-scale meteorological condition have been derived from a remote meteorological station. Therefore estimation errors related to the use of remote meteorological data such as reported by Benyahya et al. (2010) can be largely ruled out herein. Benyahya et al. (2010) noted that particularly solar radiation and wind speed, which affects both latent and sensible heat fluxes, were the most site specific microclimate conditions. Accordingly, a deterministic temperature model performed better when microclimate rather than meteorological station data were used. To further minimise errors of estimation of energy balance components in the present study, sensible and latent heat fluxes had been estimated by two different calculation approaches. Estimations derived from the different approaches yielded similar estimations for evaporative and sensible heat fluxes.

4.2 Factors and processes determining spatial temperature variability

Spatial heterogeneity of stream temperature can be found at different spatial scales including the reach and catchment scale and has significant ecological implications as, for example, cold water patches within streams can be used as thermal refugia for some motile aquatic organisms (Clark et al., 1999; Danehy et al., 2005; Moore et al., 2005). The following discussion highlights the impact of channel morphology, groundwater influence and hydrological flow conditions on stream temperature distribution at a small spatial scale.

4.2.1 Channel morphology and groundwater influence

Channel morphology includes characteristics such as channel incision, channel width-depth ratio, riparian vegetation at the channel bank and the structure of the streambed which determines the exchange between channel water and groundwater. As all these channel characteristics influence local energy and hydrological fluxes, they interact to determine the spatial distribution of water temperature within channels. Temporal fluctuations of stream temperature that were measured *in situ* at different positions within the study reach during a 10-week study period in summer 2010 mirrored each other highly and differences between mean daily water temperatures recorded at the distinct locations accounted for less than 0.1 °C. Given the accuracy of measurements of 0.2 °C, mean daily stream temperatures did therefore not differ significantly between the different monitoring sites. Similarly, daily maximum and minimum temperatures did not differ spatially except for maximum temperatures at logger position 5a which were about 0.23 °C lower than the mean daily maximum temperatures averaged over all positions and the full study period. This finding was confirmed by the diurnal analysis of water temperatures which showed that only water temperatures at position 5a were slightly diverging from the other temperature recordings during the diurnal temperature peak in the afternoon. Since this logger was positioned about 40 cm away from the south-facing channel bank which rises approximately 1 m above the channel surface at this section, the slightly reduced temperature maxima at this site are likely to be related to the reduced solar insolation during midday/afternoon associated with shading from the channel bank. Although temperature divergence at position 5a was relatively small and exceeded the error of measurement just slightly, temperature variation is unlikely to have been caused by an instrument error as all temperature loggers had been cross-calibrated in advance and the observed temperature deviations occurred temporarily and were limited to maximum water temperatures at the respective position.

The thermal infrared (IR) images of different sections within the study reach confirmed the generally low spatial heterogeneity of water temperature within the channel and did not show considerable cross-sectional or longitudinal temperature gradients overall. However, pictures that had been taken of a riffle section about 5 m downstream of logger position 6c, presented some small patches of water column that appeared to be about 0.5 to 1 °C cooler than the surrounding water column. Since the *in situ* measurements did not include this riffle sequence the IR monitored temperature variability could not be confirmed by the *in situ* temperature monitoring. However, in general, temperatures measured via infrared thermometry corresponded well with those measured by a hand-held thermometer. The slightly lower water temperature at the riffle section may have resulted from the local up-welling of relatively cooler groundwater as reported in a previous study wherein ground-based thermal infrared imagery was considered a valuable and promising method to detect local groundwater inflow into small streams (Schuetz and Weiler 2010). The upwelling of groundwater associated with riffles is consistent with the findings of previous studies which reported that riffles exhibit complex thermal behaviour and may cause local alterations of groundwater-surface water interactions (Evans and Petts 1997; Hannah et al. 2009). The exchange between channel water and groundwater was apparently limited to this section of the study reach as *in situ* measurements and infrared images of other stream sections, including also another riffle sequence, did not show any further coldwater patches. However, it should be mentioned that the upwelling of groundwater might have been masked by equal groundwater and channel water temperatures.

4.2.2 Stream flow conditions

The prevailing stream flow conditions may influence the spatial heterogeneity of stream temperatures by determining the heat capacity of the water column (Poole and Berman, 2001). Spatial temperature distribution along the study reach was uniform, irrespective of the different hydrological conditions that occurred during the study period. Accordingly, mean daily stream temperatures at the different sites did not differ significantly from each other, neither during the examined low-flow period from 18 until 28 June 2010, nor during the high-flow period from 15 July until 25 July 2010. The same was true for daily maximum and minimum temperatures under the respective flow conditions. However, only during the low-flow period but not under the high-flow conditions, daily maximum temperatures were slightly lower at position 5a than temperatures at the other sites. This finding is consistent with the outcomes of a study provided by Cardenas et al. (2008) wherein a reduction in spatial stream temperature variability associated with an increase in runoff was reported. The diminished temperature heterogeneity related to higher flows reflects the increased thermal capacity and the relatively higher turbulence and better mixing of the water column associated with enhanced runoff. Conversely, low flows are generally expected to promote the occurrence of thermal variability as heat capacity of the water column is relatively low under these conditions. Given the fact that the study period comprised a considerable low flow period and thermal heterogeneity was low, spatial variability of stream temperature is unlikely to be more pronounced during other times of the year.

Apart from the associated changes in stream heat capacity stream flow may influence spatial temperature distribution indirectly by affecting the vertical hydraulic gradient at the streambed (Curry et al., 1994; Arntzen et al., 2006) which in turn determines whether groundwater discharge or recharge dominates the hyporheic exchange. Accordingly, previous studies have shown that increased water levels and flow velocities associated with high discharge yielded hydraulic gradients that promoted downwelling of channel water into the streambed while up-welling of thermally different groundwater was facilitated under lower flow conditions (Hannah et al., 2004; Malcolm et al., 2004). The monitoring period of the present study included a considerable flow depression in summer but yet, apart from one exception, no groundwater up-welling within the study reach occurred. Hence, upwelling of thermally different groundwater contributing to enhanced spatial temperature variability is also unlikely to take place during other times of the year.

4.2.3 Conclusions

Overall, the high spatial homogeneity of stream temperature within the study reach that was captured by both *in situ* temperature measurements and thermal infrared imaging led to the following conclusions. Firstly, apart from one exception, no considerable groundwater influx at the streambed existed under the examined hydrological conditions as this would have been expected to result in cold water patches due to the generally lower groundwater than water column temperature in summer (Ebersole et al., 2003; Schuetz and Weiler, 2010). This is consistent with the findings of the temporal stream temperature analysis discussed in 4.1.2. Accordingly, temporal temperature dynamics within the streambed and water column suggested that within the study reach the Afon Llwyd is a channel water- rather than groundwater-dominated stream. A further conclusion of the spatial stream temperature analysis is that apparently no large confluences, tributaries or springs flow into the stream within the study reach as stream temperatures downstream of lateral inflows would have been shifted towards the thermal signature of the joining water source (Torgersen et al., 2001; Cristea and Burges, 2009). Selker et al. (2006) demonstrated the considerable impact of groundwater inflow and confluences on the longitudinal temperature pattern of running waters and Lowry et al. (2007) showed that focused groundwater discharge via soil pipes caused local temperature anomalies above the streambed of a peat-dominated wetland stream. A further outcome from the analysis of spatial temperature distribution is that channel water temperatures within the study reach were relatively insensitive to morphological channel features as stream temperature showed no variability related to channel structures. It appears that the occurrence of spatial temperature patterns was prevented through the relatively high flow velocities and the associated high turbulence within the water column.

Comparison of small-scale stream temperature variability with previous research is hampered by the fact that studies with focus on local, micro-scale temperature variations, including distances of a few centimetres to a few metres, are scarce. In contrast, a lot of research on longitudinal stream temperature distribution at the reach scale exists and the factors and processes that control the spatial variability at the catchment and reach scale have been discussed at length (Torgersen et al., 2001; Malcolm et al., 2004; Loheide and Gorelick, 2006; Cristea and Burges, 2009). For instance, a conceptual model provided by Malcolm et al. (2004) outlined that particularly the catchment topography and the channel geometry, e.g. channel incision, orientation and width, exert substantial control on the thermal regime of running waters at the reach scale. However, at the micro scale the above factors are considered rather constant and other processes and factors may be more important to control spatial temperature distribution. To the author´s knowledge, the study provided by Clark et al. (1999) is the only study with focus on microthermal stream temperature patterns so far. Clark et al. (1999) showed that particularly water depth and shading by riparian vegetation and river banks yielded considerable lateral temperature gradients of up to 7 °C associated with the respective impacts on water heat capacity and incoming solar radiation. However, their study was focused on groundwater dominated streams which had generally lower stream gradients (0.3 to 0.5 %) and a greater channel width compared with the Welsh upland stream examined in the present study whose average channel gradient and channel width are 0.6 % and 4 to 5 m, respectively. Given the relatively steep channel gradient within the study reach the stream flow is rather fast and turbulent and yields a strong mixing of the water column. Hence, morphological channel features showed no considerable effect on the spatial distribution of water temperature over the study period. Furthermore, in contrast to the channel which was examined by Clark et al. (1999), water depth across the channel was relatively uniform within the study reach and prevented strong lateral temperature gradients. At the reach scale, Malcolm et al. (2004) found that spatial variability of stream temperatures was most apparent during summer months when stream temperatures are generally rather high. Lateral temperature contrasts at the micro scale are also expected to be pronounced in summer due to the lower flow depths and the associated low thermal capacity combined with a stronger solar heating during this season. It can be consequently reasoned that spatial temperature variability which was examined in summer and found to be low is unlikely to be enhanced or more pronounced during another time of the year.

5 Conclusions and future research

The thermal behaviour of running waters is highly complex as both atmospheric and hydrological conditions influence stream temperature. The purpose of the present study was therefore to gain an improved understanding of the processes and factors that determine spatiotemporal water temperature dynamics using the example of a Welsh upland stream.

Water column as well as streambed temperatures displayed clear seasonal cycles across the year. Accordingly, the different energy fluxes that occurred at the air-water and water-streambed interfaces showed, to a greater or lesser extent, seasonal patterns in response to intra-annual variations in atmospheric conditions. Net radiation, which followed the most pronounced annual cycle, was the dominant heat source for heating the channel water while latent heat flux was the dominant heat sink throughout the year. When compared with heat transfer that took place at the air-water column interface heat exchange processes between the water column and the streambed were of minor importance indicating that the thermal dynamics within the open study reach are dominated by atmospheric conditions rather than by upwelling groundwater. This is consistent with both the strong relationship between air and water temperature and the examination of spatial temperature patterns by thermal IR imaging as, apart from one exception, no coldwater patches related to local groundwater influx were detected. Furthermore, streambed temperatures, like water column temperature, were negatively correlated with discharge indicating that thermal dynamics within the streambed were dominated by channel water. To confirm these findings detailed examination of the potential exchange between groundwater and surface water within the study reach, e.g. by hydrometric and hydrochemical methods, is necessary. Apart from atmospheric conditions and the respective energy fluxes within the water column hydrological conditions were shown to have a considerable effect on stream temperature. Thermal impacts were largely related to stream flow- induced alterations in heat capacity and to changes in water source contributions associated with storm flow events. To further highlight the thermal impact of variations in water source contributions, runoff generation processes within the catchment and the respective thermal signatures of the different water sources should be investigated in future studies.

Spatial analysis of stream temperatures showed that local temperature anomalies were limited to a coldwater patch associated with upwelling groundwater at a riffle section and to local reductions in daily maximum temperatures due to shading from the channel bank. In general, spatial temperature variability within the study reach was very low in that no significant lateral or longitudinal temperature gradients were found. It appears that the occurrence of spatial temperature patterns is prevented through the generally high flow velocities and the associated high turbulence within the water column. As low-flow conditions during summer generally favour the formation of lateral temperature gradients temperature variability within the study reach is expected to be even lower during other periods and seasons of the year. Given the high thermal homogeneity in space it can be reasoned that energy fluxes, which have been estimated based on micrometeorological measurements at one distinct position within the reach, are spatially uniform as well. Consequently, results of the first part of the study should be representative for the whole study reach.

Overall, both hypotheses that have been introduced in Chapter 1.3 can be corroborated. Accordingly, stream temperature was sensitive to hydrological conditions and also highly correlated with energy flux patterns which in turn were found to be associated with fluctuations in atmospheric conditions. Furthermore, stream temperature anomalies in space, although scarcely present, were shown to be related to respective changes in energy fluxes and hydrological processes.

The dominant role of prevailing atmospheric conditions in controlling stream thermal dynamics within the study reach may have some considerable implications for the future water temperature dynamics of the Afon Llwyd and comparable streams in the nearby Plynlimon catchments. Arnell (1998) noted that the rise in stream temperatures of UK rivers related to global warming will be enhanced for small sensitive headwater streams and less pronounced for groundwater dominated catchments. It can be consequently reasoned that the increase in air temperature associated with global climate change is likely to cause a relatively strong increase in water temperature of the Afon Llwyd. This in turn might affect the habitat quality of the stream, especially for populations of brown trout (*Salmo trutta* L.) which are known to be endemic in Plynlimon headwater streams (Crisp and Beaumont, 1997). Additionally, the strong influence of atmospheric conditions on stream temperature dynamics suggests that changes in local microclimate associated with forestry, which is widely practised in the Plynlimon catchments, might significantly affect stream thermal behaviour. It has been demonstrated before, that water temperatures of Plynlimon streams are affected by forest clearfelling (Stott and Marks, 2000).

With respect to future stream temperature research, this study highlights the demand for further long-term studies that investigate the complex relationship between water temperature, energy fluxes and hydrological processes within different reaches. The results reinforce observations by others that the importance of individual energy fluxes to the stream thermal budget can vary considerably between the different seasons and between different reaches depending on site characteristics such as sub-surface hydrology (Webb and Zhang, 1997; Evans et al., 1998; Hannah et al., 2008). Furthermore, the findings highlight the importance of hydrological conditions such as stream flow dynamics and contribution of different runoff water sources for stream temperature behaviour. In terms of the spatial analysis of stream temperature, there remains a need for further small-scale studies exploring the microthermal impact of hydrometeorological conditions and *in stream* structures. In general, thermal imaging provided a useful tool to monitor temperature distribution within the channel in a spatially continuous way even though shading from the river bank and reflectance of solar radiation from the water surface hampered the detection of actual temperature variation. Future studies should therefore include techniques that allow a spatially continuous monitoring such as ground-based IR thermography.

Many studies have demonstrated that surface-subsurface water exchanges vary spatially (Malard et al., 2002; Payn et al., 2009) suggesting that the related energy exchange processes at the streambed may also vary considerably in space. Hence, the integration of temporal and spatial analysis of stream temperature and heat fluxes holds promise for future research. In this respect, modelling approaches which consider both spatial and temporal dynamics of stream energy budgets may represent a helpful tool. Just recently, Leach and Moore (2010b) analysed stream temperature variability along a stream in relation to both heat exchanges and reach-scale hydrology using a Lagrangian stream temperature model.

6 Bibliography

AHMADI-NEDUSHAN, B. ET AL. 2007. Predicting river water temperatures using stochastic models: case study of the Moisie River (Québec, Canada). *Hydrological Processes* 21: 21-34.

ANDERSON, I. 2002. Foot and mouth disease 2001: lessons to be learned inquiry. The Stationery Office, London, UK.

ANDERSON, J.M., AND S.B. WILSON. 1984. The physical basis of current infrared remote-sensing techniques and the interpretation of data from aerial surveys. *International Journal of Remote Sensing* 5: 1.

ANDERSON, R. 1969. Temperature and rooted aquatic plants. *Chesapeake Science* 10: 157-164.

ARNELL, N.W. 1998. Climate Change and Water Resources in Britain. *Climatic Change* 39: 83-110.

ARNTZEN, E.V., C.R. GEIST, AND P.E. DRESEL. 2006. Effects of fluctuating river flow on groundwater/surface water mixing in the hyporheic zone of a regulated, large cobble bed river. *River Research and Applications* 22: 937-946.

BENSON, N.G. 1953. The importance of groundwater to trout populations in the Pigeon River, Michigan. Wildlife Management Institute, Washington DC.

BENYAHYA, L., D. CAISSIE, N. EL-JABI, AND M.G. SATISH. 2010. Comparison of microclimate vs. remote meteorological data and results applied to a water temperature model (Miramichi River, Canada). *Journal of Hydrology* 380: 247-259.

BENYAHYA, L., A. ST-HILAIRE, T.B.M.J. QUARDA, B. BOBÉE, AND B. AHMADI-NEDUSHAN. 2007. Modeling of water temperatures based on stochastic approaches: case study of the Deschutes River. *Journal of Environmental Engineering and Science* 6: 437-448.

BESCHTA, R.L., R.E. BILBY, G.W. BROWN, L.B. HOLTBY, AND T.D. HOFSTRA. 1987. Stream temperature and aquatic habitat; fisheries and forestry interactions. *Streamside Management Forestry and Fishery Interactions* 57: 191-232.

BOTT, T.L., L.A. KAPLAN, AND F.T. KUSERK. 1984. Benthic bacterial biomass supported by streamwater dissolved organic matter. *Microbial Ecology* 10: 335-344.

BOWEN, I.S. 1926. The ratio of heat losses by conduction and by evaporation from any water surface. *Physics Review* 27: 779-787.

BRADLEY, C., A. CLAY, N.J. CLIFFORD, J. GERRARD, AND A.M. GURNELL. Variations in saturated and unsaturated water movement through an upland floodplain wetland, mid-Wales, UK. *Journal of Hydrology* In Press, Accepted Manuscript: . Available at: http://www.sciencedirect.com/science/article/B6V6C-50YK884-4/2/614ef956ab66e887bedbda06d37e2dc6 [Accessed September 14, 2010].

BROSOFSKE, K.D., J. CHEN, R.J. NAIMAN, AND J.F. FRANKLIN. 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. *Ecological Applications* 7: 1188-1200.

BROWN, G.W. 1969. Predicting Temperatures of Small Streams. *Water Resources Research* 5: PP. 68-75.

BROWN, G.W., AND J. KRYGIER. 1970. Effects of clear-cutting on stream temperature. *Water Resources Research* 6: 1133-1139.

BROWN, L.E., AND D.M. HANNAH. 2007. Alpine Stream Temperature Response to Storm Events. *Journal of Hydrometeorology* 8: 952.

BROWN, L.E., AND D.M. HANNAH. 2008. Spatial heterogeneity of water temperature across an alpine river basin. *Hydrological Processes* 22: 954-967.

BROWN, L.E., D.M. HANNAH, AND A. MILNER. 2006. Hydroclimatological influences on water column and streambed thermal dynamics in an alpine river system. *Journal of Hydrology* 325: 1-20.

CADBURY, S.L., D.M. HANNAH, A.M. MILNER, C.P. PEARSON, AND L.E. BROWN. 2008. Stream temperature dynamics within a New Zealand glacierized river basin. *River Research and Applications* 24: 68-89.

CAISSIE, D. 2006. The thermal regime of rivers: a review. *Freshwater Biology* 51: 1389-1406.

CAISSIE, D., N. EL-JABI, AND M.G. SATISH. 2001. Modelling of maximum daily water temperatures in a small stream using air temperatures. *Journal of Hydrology* 251: 14-28.

CAISSIE, D., N. EL-JABI, AND A. ST-HILAIRE. 1998. Stochastic modelling of water temperatures in a small stream using air to water relations. *Canadian Journal of Civil Engineering* 25: 250-260.

CAISSIE, D., M.G. SATISH, AND N. EL-JABI. 2005. Predicting river water temperatures using the equilibrium temperature concept with application on Miramichi River catchments (New Brunswick, Canada). *Hydrological Processes* 19: 2137-2159.

CAISSIE, D., M.G. SATISH, AND N. EL-JABI. 2007. Predicting water temperatures using a deterministic model: Application on Miramichi River catchments (New Brunswick, Canada). *Journal of Hydrology* 336: 303-315.

CARDENAS, M.B., J.W. HARVEY, A.I. PACKMAN, AND D.T. SCOTT. 2008. Ground-based thermography of fluvial systems at low and high discharge reveals potential complex thermal heterogeneity driven by flow variation and bioroughness. *Hydrological Processes* 22: 980-986.

CENTRE FOR ECOLOGY AND HYDROLOGY. 2010. UK Gauging station network. Available at: http://www.nwl.ac.uk/ih/nrfa/station_summaries/054/022.html.

CEY, E.E., D.L. RUDOLPH, G.W. PARKIN, AND R. ARAVENA. 1998. quantifying groundwater discharge to a small perennial stream in southern Ontario, Canada. *Journal of Hydrology* 210: 21-37.

CHERKAUER, K.A., S.J. BURGES, R.N. HANDCOCK, J.E. KAY, S.K. KAMPF, AND A.R. GILLESPIE. 2005. Assessing satellite-based and thermal infrared remote sensing for monitoring pacific northwest river temperature. *Journal of the American Water Resources Association* 41: 1149-1159.

CHUTTER, F.M. 1970. Hydrobiological studies in the catchment of Vaal Dam, South Africa. Part 1. River zonation. *Int. Revue ges. Hydrobiol.* 55: 445-494.

CLARK, E., B.W. WEBB, AND M. LADLE. 1999. Microthermal gradients and ecological implications in Dorset rivers. *Hydrological Processes* 13: 423-438.

CLUIS, D.A. 1972. Relationship between stream water temperature and ambient air temperature. *Nordic Hydrology* 3: 65-71.

COUTANT, C. 1977. Compilation of Temperature Preference Data. *Journal of the Fisheries Research Board of Canada* 34: 739-745.

COX, B.A., AND P.G. WHITEHEAD. 2009. Impacts of climate change scenarios on dissolved oxygen in the River Thames, UK. *Hydrology Research* 40: 254 p.

COZZETTO, K., D. MCKNIGHT, T. NYLEN, AND A. FOUNTAIN. 2006. Experimental investigations into processes controlling stream and hyporheic temperatures, Fryxell Basin, Antarctica. *Advances in Water Resources* 29: 130-153.

CRISP, D.T. 1997. Water temperature of Plynlimon streams. Available at: http://hal-sde.archives-ouvertes.fr/hal-00304422/ [Accessed September 6, 2010].

CRISP, D.T., AND W.R.C. BEAUMONT. 1997. Fish populations in Plynlimon streams. *Hydrology and Earth System Sciences* 1: 541-548.

CRISP, D.T., AND E.D. CREN. 1970. The temperature of three different small streams in northwest England. *Hydrobiologia* 35: 305-323.

CRISP, D.T., AND G. HOWSON. 1982. Effect of air temperature upon mean water temperature in streams in the north Pennines and English Lake District. *Freshwater Biology* 12: 359-367.

CRISTEA, N.C., AND S.J. BURGES. 2009. Use of Thermal Infrared Imagery to Complement Monitoring and Modeling of Spatial Stream Temperatures. *Journal of Hydrologic Engineering* 14: 1080-1090.

CUMMINS, K.W. 1974. Structure and Function of Stream Ecosystems. *BioScience* 24: 631-641.

CURRY, R.A., J. GEHRELS, D.L.G. NOAKES, AND R. SWAINSON. 1994. Effects of river flow fluctuations on groundwater discharge through Brook Trout, Salvelinus-Fontinalis, spawning and incubation habitats. *Hydrobiologia* 277: 121-134.

DANEHY, R.J., C.G. COLSON, K.B. PARRETT, AND S.D. DUKE. 2005. Patterns and sources of thermal heterogeneity in small mountain streams within a forested setting. *Forest Ecology and Management* 208: 287-302.

DAUFRESNE, M., AND P. BOET. 2007. Climate change impacts on structure and diversity of fish communities in rivers. *Global Change Biology* 13: 2467-2478.

DAVIDSON, B., AND R. BRADSHAW. 1967. Thermal Pollution of Water Systems. *Environmental Science & Technology* 1: 618-630.

DAVIE, T. 2008. Fundamentals of hydrology. Routledge.

DAVIS, J.C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: A review. *Journal of the Fisheries Research Board of Canada* 32: 2295-2331.

DURANCE, I., AND S.J. ORMEROD. 2007. Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology* 13: 942-957.

EBERSOLE, J., W. LISS, AND C.A. FRISSELL. 2003. Cold water patches in warm streams: physicochemical characteristics and the influence of shading. *Journal of the American Water Resources Association* 39: 355-368.

EDWARDS, R.W., J.W. DENSEM, AND P.A. RUSSELL. 1979. An Assessment of the Importance of Temperature as a Factor Controlling the Growth Rate of Brown Trout in Streams. *Journal of Animal Ecology* 48: 501-507.

ELLIOTT, J.M. 1975. The Growth Rate of Brown Trout (Salmo trutta L.) Fed on Maximum Rations. *Journal of Animal Ecology* 44: 805-821.

EMERY, J.C. 2003. Characteristics and controls of gravel-bed riffle-pool sequences for habitat assessment and river rehabilitation design. Doctor of Philosophy. University of Birmingham, Birmingham.

EVANS, E.C., G.R. MCGREGOR, AND G.E. PETTS. 1998. River energy budgets with special reference to river bed processes. *Hydrological Processes* 12: 575-595.

EVANS, E.C., AND G.E. PETTS. 1997. Hyporheic temperature patterns within riffles. *Hydrological Sciences Journal* 42: 199.

FAUX, R.N., H. LACHOWSKY, C.E. TORGERSEN, AND M.S. BOYD. 2001. New approaches for monitoring stream temperature: Airborne thermal infrared remote sensing. US Department of Agriculture Forest Service Engineering.

FICKE, A.D., C. MYRICK, AND L.J. HANSEN. 2007. Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries* 17: 581-613.

GIBSON, R.J. 1966. Some factors influencing the distribution of brook trout and young Atlantic salmon. *Journal of the Fisheries Research Board of Canada* 23: 1977-1980.

GRANT, P.J. 1977. Water temperatures of the Ngaruroro river at three stations. *Journal of Hydrology (N. Z.)* 16: 148-157.

HANDCOCK, R.N., A.R. GILLESPIE, K.A. CHERKAUER, J.E. KAY, S.J. BURGES, AND S.K. KAMPF. 2006. Accuracy and uncertainty of thermal-infrared remote sensing of stream temperatures at multiple spatial scales. *Remote Sensing of Environment* 100: 427-440.

HANNAH, D.M., AND A.M. GURNELL. 2001. A conceptual, linear reservoir runoff model to investigate melt season changes in cirque glacier hydrology. *Journal of Hydrology* 246: 123-141.

HANNAH, D.M., I.A. MALCOLM, AND C. BRADLEY. 2009. Seasonal hyporheic temperature dynamics over riffle bedforms. *Hydrological Processes* 23: 2178-2194.

HANNAH, D.M., I.A. MALCOLM, C. SOULSBY, AND A.F. YOUNGSON. 2008. A comparison of forest and moorland stream microclimate, heat exchanges and thermal dynamics. *Hydrological Processes* 22: 919-940.

HANNAH, D.M., I.A. MALCOLM, C. SOULSBY, AND A.F. YOUNGSON. 2004. Heat exchanges and temperatures within a salmon spawning stream in the Cairngorms, Scotland: seasonal and sub-seasonal dynamics. *River Research and Applications* 20: 635-652.

HARIA, A.H., AND P. SHAND. 2004. Evidence for deep sub-surface flow routing in forested upland Wales: implications for contaminant transport and stream flow generation. *Hydrology and Earth System Sciences* 8: 334-344.

HARIA, A.H., AND P. SHAND. 2006. Near-stream soil water-groundwater coupling in the headwaters of the Afon Hafren, Wales: Implications for surface water quality. *Journal of Hydrology* 331: 567-579.

HARRIS, D.D. 1977. Hydrologic changes after logging in two small Oregon coastal watersheds. *U.S. Geological Survey Water-Supply Paper* 2037: .

HASSAN, J.A. 1985. The Growth and Impact of the British Water Industry in the Nineteenth Century. *The Economic History Review* 38: 531-547.

HAWKINS, C.P., J.N. HOGUE, L.M. DECKER, AND J.W. FEMINELLA. 1997. Channel Morphology, Water Temperature, and Assemblage Structure of Stream Insects. *Journal of the North American Benthological Society* 16: 728-749.

HESTER, E.T., M.W. DOYLE, AND G.C. POOLE. 2009. The influence of in-stream structures on summer water temperatures via induced hyporheic exchange. *Limnology and Oceanography* 54: 355-367.

HOLMES, R.M. 2000. The importance of ground water to stream ecosystem function. *In* Streams and ground waters, 137-148. Academic Press, San Diego.

HONDZO, M., AND H.G. STEFAN. 1994. Riverbed heat conduction prediction. *Water Resources Research* 30: PP. 1503-1513.

HYNES, H.B.N. 1970. Ecology of running waters. University of Toronto, Toronto. Available at: http://bases.bireme.br/cgi-bin/wxislind.exe/iah/online/?IsisScript=iah/iah.xis&src=google&base=REPIDISCA&lang=p&nextAction=lnk&exprSearch=166220&indexSearch=ID [Accessed August 31, 2010].

JENSEN, A.J. 1990. Growth of Young Migratory Brown Trout Salmo trutta Correlated with Water Temperature in Norwegian Rivers. *Journal of Animal Ecology* 59: 603-614.

JOHNSON, F.A. 1971. Stream temperatures in an alpine area. *Journal of Hydrology (Netherlands)* 14: 322-336.

JOHNSON, S.L. 2004. Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. *Canadian Journal of Fisheries and Aquatic Sciences* 61: 913-923.

KIRBY, C., M.D. NEWSON, AND K. GILMAN. 1991. Plynlimon research: The first two decades. Institute of Hydrology, Wallingford, UK.

KISHI, D., M. MURAKAMI, S. NAKANO, AND K. MAEKAWA. 2005. Water temperature determines strength of top-down control in a stream food web. *Freshwater Biology* 50: 1315-1322.

KOBAYASHI, D., Y. ISHII, AND Y. KODAMA. 1999. Stream temperature, specific conductance and runoff process in mountain watersheds. *Hydrological Processes* 13: 865-876.

KOTHANDARAMAN, V. 1971. Analysis of water temperature variations in large rivers. *Journal of the Sanitary Engineering* 97: 19-31.

LANE, E.W., E.J. CARLSON, AND O.S. HANSON. 1949. Low temperature increases sediment transport in Colorado River. *Civil Engineering* 19: 45-46.

LANGAN, S.J., L. JOHNSTON, M.J. DONAGHY, A.F. YOUNGSON, D.W. HAY, AND C. SOULSBY. 2001. Variation in river water temperatures in an upland stream over a 30-year period. *The Science of The Total Environment* 265: 195-207.

LANGFORD, T.E. 1990. Ecological effects of thermal discharges. Springer.

LEACH, J.A., AND R.D. MOORE. 2010a. Above-stream microclimate and stream surface energy exchanges in a wildfire-disturbed riparian zone. *Hydrological Processes* 9999: n/a.

LEACH, J.A., AND R.D. MOORE. 2010b. Stream temperature dynamics in two hydrogeomorphologically distinct reaches. *Hydrological Processes*.

LEBOSQUET, M., AND E.C. TSIVOGLOU. 1950. Simplified dissolved oxygen computations. *Sewage and Industrial Wastes* 22: 1054-1061.

LOHEIDE, S.P., AND S.M. GORELICK. 2006. Quantifying Stream−Aquifer Interactions through the Analysis of Remotely Sensed Thermographic Profiles and In Situ Temperature Histories. *Environmental Science & Technology* 40: 3336-3341.

LOWNEY, C.L. 2000. Stream temperature variation in regulated rivers: Evidence for a spatial pattern in daily minimum and maximum magnitudes. *Water Resources Research* 36: PP. 2947-2955.

LOWRY, C.S., J.F. WALKER, R.J. HUNT, AND M.P. ANDERSON. 2007. Identifying spatial variability of groundwater discharge in a wetland stream using a distributed temperature sensor. *Water Resources Research* 43: .

LYONS, J. 1996. Patterns in the species composition of fish assemblages among Wisconsin streams. *Environmental Biology of Fishes* 45: 329-341.

MACAN, T.T. 1958. The temperature of a small stony stream. *Hydrobiologia* 12: 89-106.

MADEJ, M., C. CURRENS, V. OZAKI, J. YEE, AND D. ANDERSON. 2006. Assessing possible thermal rearing restrictions for juvenile coho salmon Oncorhynchus kisutch through thermal infrared imaging and in-stream monitoring, Redwood Creek, California. *Canadian Journal of Fisheries and Aquatic Sciences* 63: 1384-1396.

MALARD, F., K. TOCKNER, M.J. DOLE-OLIVIER, AND J.V. WARD. 2002. A landscape perspective of surface-subsurface hydrological exchanges in river corridors. *Freshwater Biology* 47: 621-640.

MALCOLM, I.A., D.M. HANNAH, M.J. DONAGHY, C. SOULSBY, AND A.F. YOUNGSON. 2004. The influence of riparian woodland on the spatial and temporal variability of stream water temperatures in an upland salmon stream. Available at: http://hal-insu.archives-ouvertes.fr/hal-00304936/ [Accessed July 5, 2010].

MALCOLM, I.A., C. SOULSBY, AND A.F. YOUNGSON. 2002. Thermal regime in the hyporheic zone of two contrasting salmonid spawning streams: ecological and hydrological implications. *Fisheries Management and Ecology* 9: 1-10.

MARKARIAN, R.K. 1980. A study of the relationship between aquatic insect growth and water temperature in a small stream. *Hydrobiologia* 75: 81-95.

MCILVEEN, R. 1992. Fundamentals of weather and climate. Chapman and Hall, London.

MILNER, A.M., J.E. BRITTAIN, E. CASTELLA, AND G.E. PETTS. 2001. Trends of macroinvertebrate community structure in glacier-fed rivers in relation to environmental conditions: a synthesis. *Freshwater Biology* 46: 1833-1847.

MILNER, A.M., AND G.E. PETTS. 1994. Glacial rivers: physical habitat and ecology. *Freshwater Biology* 32: 295-307.

MOHSENI, O., T.R. ERICKSON, AND H.G. STEFAN. 2002. Upper Bounds for Stream Temperatures in the Contiguous United States. *Journal of Environmental Engineering* 128: 4-11.

MOHSENI, O., AND H.G. STEFAN. 1999. Stream temperature/air temperature relationship: a physical interpretation. *Journal of Hydrology* 218: 128-141.

MOHSENI, O., H.G. STEFAN, AND T.R. ERICKSON. 1998. A Nonlinear Regression Model for Weekly Stream Temperatures. *Water Resources Research* 34: PP. 2685-2692.

MOORE, R., D.L. SPITTLEHOUSE, AND A. STORY. 2005. Riparian microclimate and stream temperature response to forest harvesting: A review. *Journal of the American Water Resources Association* 41: 813-834.

MOORE, R.D. 2005. Stream temperatures in British Columbia: Regional patterns and prediction. Department of Geography and Department of Forest Resources Management, The University of British Columbia, Vancouver, B. C.

MOORE, R.D., P. SUTHERLAND, T. GOMI, AND A. DHAKAL. 2005. Thermal regime of a headwater stream within a clear-cut, coastal British Columbia, Canada. *Hydrological Processes* 19: 2591-2608.

MORRILL, J.C., R.C. BALES, AND M.H. CONKLIN. 2005. Estimating Stream Temperature from Air Temperature: Implications for Future Water Quality. *Journal of Environmental Engineering* 131: 139-146.

NASH, J.E., AND J.V. SUTCLIFFE. 1970. River flow forecasting through conceptual models part I - A discussion of principles. *Journal of Hydrology* 10: 282-290.

NEAL, C., N. CHRISTOPHERSEN, R. NEALE, C.J. SMITH, P.G. WHITEHEAD, AND B. REYNOLDS. 1988. Chloride in precipitation and streamwater for the upland catchment of River Severn; some consequences for hydrochemical models. *Hydrological Processes* 2: 155-165.

NEAL, C. ET AL. 1997. The occurrence of groundwater in the Lower Palaeozoic rocks of upland Central Wales. Available at: http://hal-insu.archives-ouvertes.fr/hal-00304371/ [Accessed August 25, 2010].

NEAL, C., C.J. SMITH, AND S. HILL. 1992. Forestry impact on upland water quality.

NELSON, K.C., AND M.A. PALMER. 2007. Stream temperature surges under urbanization and climate change: Data, models and responses. *Journal of the American Water Resources Association* 43: 440-452.

NORTH, E. 1980. The effects of water temperature and flow upon angling success in the river Severn. *Aquaculture Research* 11: 1-9.

O´DRISCOLL, M.A., AND D.R. DEWALLE. 2006. Stream-air temperature relations to classify stream-ground water interactions in a karst setting, central Pennsylvania, USA. *Journal of Hydrology* 329: 140-153.

OKE, T.R. 1987. Boundary layer climates. 2. ed. Methuen & Co:, London.

PAYN, R.A., M.N. GOOSEFF, B.L. MCGLYNN, K.E. BENCALA, AND S.M. WONDZELL. 2009. Channel water balance and exchange with subsurface flow along a mountain headwater stream in Montana, United States. *Water Resources Research* 45: W11427.

PILGRIM, J.M., X. FANG, AND H.G. STEFAN. 1998. Stream temperature correlations with air temperatures in Minnesota: Implications for climate warming. *Journal of the American Water Resources Association* 34: 1109-1121.

PLUHOWSKI, E.J., AND V. ARLINGTON. 1972. Unusual temperature variations in two small streams in northern Virginia. *U.S. Geological Survey Professional Papers* 800-B: .

POOLE, G.C., AND C.H. BERMAN. 2001. An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-CausedThermal Degradation. *Environmental Management* 27: 787-802.

RANEY, F. 1963. Rice water temperature. *California Agriculture* 17: 6-7.

RAPHAEL, J.M. 1962a. Prediction of temperature in rivers. *ASCE, Journal of the Power Division* 88: 157-181.

RAPHAEL, J.M. 1962b. Prediction of temperature in rivers and reservoirs. *Journal of the Power Division* 88: 157-181.

SCHMIDT, C., M. BAYER-RAICH, AND M. SCHIRMER. 2006. Characterization of spatial heterogeneity of groundwater-stream water interactions using multiple depth streambed temperature measurements at the reach scale. Available at: http://hal-sde.archives-ouvertes.fr/hal-00298728/ [Accessed September 2, 2010].

SCHUETZ, T., AND M. WEILER. 2010. Detection and quantification of localized groundwater inflow in small streams using ground-based infrared thermography. *In* Geophysical Research Abstracts,

SELKER, J.S. ET AL. 2006. Distributed fiber-optic temperature sensing for hydrologic systems. *Water Resources Research* 42: .

SILLIMAN, S.E., AND D.F. BOOTH. 1993. Analysis of time-series measurements of sediment temperature for identification of gaining vs. losing portions of Juday Creek, Indiana. *Journal of Hydrology* 146: 131-148.

SINOKROT, B.A., AND H.G. STEFAN. 1994. Stream Water-Temperature Sensitivity to Weather and Bed Parameters. *Journal of Hydrologic Engineering* 120: 722-736.

SMITH, B.P., D.M. HANNAH, A.M. GURNELL, AND G.E. PETTS. 2001. A hydrogeomorphological context for ecological research on alpine glacial rivers. *Freshwater Biology* 46: 1579-1596.

SMITH, K. 1972. River water temperatures - an environmental review. *Scottish Geographical Magazine* 88: 211-220.

SMITH, K. 1975. Water temperature variations within a major river system. *Nordic Hydrology* 6: 155-169.

SMITH, K., AND M.E. LAVIS. 1975. Environmental Influences on the Temperature of a Small Upland Stream. *Oikos* 26: 228-236.

STEFAN, H.G., AND E.B. PREUD´HOMME. 1993. Stream temperature estimation from air temperature. *Journal of the American Water Resources Association* 29: 27-45.

STEVENS, H., J.F. FICKE, AND G. SMOOT. 1975. Water temperature- influential factors, field measurement, and data presentation. *Techniques of Water-Resources Investigations of the US Geological Survey TW II - D5*.

STORY, A., R. MOORE, AND J. MACDONALD. 2003. Stream temperatures in two shaded reaches below cutblocks and logging roads: downstream cooling linked to subsurface hydrology. *Canadian Journal of Forest Research* 33: 1383-1396.

STOTT, T., AND S. MARKS. 2000. Effects of plantation forest clearfelling on stream temperatures in the Plynlimon experimental catchments, mid-Wales. *Hydrology and Earth System Sciences* 4: 95-104.

TASKER, G.D., AND A.W. BURNS. 1974. Mathematical generalization of stream temperature in central New England. *Journal of the American Water Resources Association* 10: 1133-1142.

THEURER, F.D., K.A. VOOS, AND W.J. MILLER. 1984. Instream water temperature model. *Instream Flow Information Paper, US Fish and Wildlife Service* 16: .

TORGERSEN, C.E., R.N. FAUX, B.A. MCINTOSH, N.J. POAGE, AND D.J. NORTON. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment* 76: 386-398.

TORGERSEN, C.E., D. PRICE, H. LI, AND B. MCINTOSH. 1999. Multiscale thermal refugia and stream habitat associations of Chinook Salmon in northeastern Oregon. *Ecological Applications* 9: 301-319.

UEHLINGER, U., F. MALARD, AND J.V. WARD. 2003. Thermal patterns in the surface waters of a glacial river corridor (Val Roseg, Switzerland). *Freshwater Biology* 48: 284-300.

VANNOTE, R.L., AND B.W. SWEENEY. 1980. Geographic Analysis of Thermal Equilibria: A Conceptual Model for Evaluating the Effect of Natural and Modified Thermal Regimes on Aquatic Insect Communities. *The American Naturalist* 115: 667.

VIS, C., C. HUDON, R. CARIGNAN, AND P. GAGNON. 2007. Spatial Analysis of Production by Macrophytes, Phytoplankton and Epiphyton in a Large River System under Different Water-Level Conditions. *Ecosystems* 10: 293-310.

VOGT, T., P. SCHNEIDER, L. HAHN-WOERNLE, AND O. CIRPKA. 2010. Estimation of seepage rates in a losing stream by means of fiber-optic high-resolution vertical temperature profiling. *Journal of Hydrology* 380: 154-164.

WALKER, J.H., AND J.D. LAWSON. 1977. Natural stream temperature variations in a catchment. *Water Research* 11: 373-377.

WARD, J.V. 1963. Annual variation of stream water temperature. *Journal of the Sanitary Engineering* 89: 3710-3732.

WARD, J.V. 1994. Ecology of alpine streams. *Freshwater Biology* 32: 277-294.

WARD, J.V. 1985. Thermal characteristics of running waters. *Hydrobiologia* 125: 31-46.

WEBB, B.W., D.M. HANNAH, R.D. MOORE, L.E. BROWN, AND F. NOBILIS. 2008. Recent advances in stream and river temperature research. *Hydrological Processes* 22: 902-918.

WEBB, B.W., AND F. NOBILIS. 1997. Long-term perspective on the nature of the air-water temperature relationship: a case study. *Hydrological Processes* 11: 137-147.

WEBB, B.W., AND D.E. WALLING. 1993. Longer-term water temperature behaviour in an upland stream. *Hydrological Processes* 7: 19-32.

WEBB, B.W., AND D.E. WALLING. 1996. Long-term variability in the thermal impact of river impoundment and regulation. *Applied Geography* 16: 211-223.

WEBB, B.W., AND Y. ZHANG. 1997. Spatial and seasonal variability in the components of the river heat budget. *Hydrological Processes* 11: 79-101.

WEBB, B.W., AND Y. ZHANG. 1999. Water temperatures and heat budgets in Dorset chalk water courses. *Hydrological Processes* 13: 309-321.

WEHRLY, K.E., M.J. WILEY, AND P.W. SEELBACH. 2003. Classifying Regional Variation in Thermal Regime Based on Stream Fish Community Patterns. *Transactions of the American Fisheries Society* 132: 18-38.

WRIGHT, S.A., F.M. HOLLY JR, A.A. BRADLEY, AND W. KRAJEWSKI. 1999. Long-Term Simulation of Thermal Regime of Missouri River. *Journal of Hydraulic Engineering* 125: 242-252.

Appendices

Appendix 1 – Abbreviations and symbols

asl	above sea level
AWS	automatic weather station
CEH	Centre for Ecology and Hydrology
cm	centimetre
DTS	distributed fibre-optic temperature sensor
IR	infrared
K	Kelvin
kg	kilogram
km	kilometre
m	metre
mbar	millibar
ME	mean error
min	minute
MJ	megajoule
mm	millimetre
MP	megapixel
NASH	Nash coefficient
RMSE	root-mean-square error
s	second
Std	standard deviation
TIR	thermal infrared
UK	United Kingdom
µm	micrometre

E_a	vapour pressure at air temperature [mbar]
E_v	evaporation/condensation rate [mm d^{-1}]
E_w	saturated vapour pressure at water surface temperature [mbar]
F	flow volume entering the study reach [m^3 s^{-1}]
$K\downarrow$	incoming short-wave radiation [MJ m^{-2} d^{-1}]
$K\uparrow$	outgoing short-wave radiation [MJ m^{-2} d^{-1}]

$K_b\downarrow$	incoming short-wave radiation at the streambed [MJ m^{-2} d^{-1}]
$K_b\uparrow$	outgoing short-wave radiation at the streambed [MJ m^{-2} d^{-1}]
$L\downarrow$	incoming long-wave radiation [MJ m^{-2} d^{-1}]
$L\uparrow$	outgoing long-wave radiation [MJ m^{-2} d^{-1}]
$L_b\downarrow$	incoming long-wave radiation to the bed [MJ m^{-2} d^{-1}]
$L_b\uparrow$	outgoing long-wave radiation from the bed [MJ m^{-2} d^{-1}]
L_v	latent heat of vaporisation [°C J g^{-1}]
P	atmospheric pressure [mbar]
Q*	net radiation [MJ m^{-2} d^{-1}]
Q_a	heat advection by precipitation and groundwater [MJ m^{-2} d^{-1}]
Q_b	bed conduction [MJ m^{-2} d^{-1}]
Q_b*	net radiation at the streambed [MJ m^{-2} d^{-1}]
Q_{bhf}	bed heat flux [MJ m^{-2} d^{-1}]
Q_e	latent heat flux [MJ m^{-2} d^{-1}]
Q_f	friction [MJ m^{-2} d^{-1}]
Q_h	sensible heat flux [MJ m^{-2} d^{-1}]
Q_n	total energy available [MJ m^{-2} d^{-1}]
Q_{sn}	total energy available at the air-water interface [MJ m^{-2} d^{-1}]
RH	relative humidity [%]
S	slope of the channel [m m^{-1}]
T_a	air temperature [°C]
$T_{b\_0.05}$	streambed temperature at 0.05 m depth [°C]
$T_{b\_0.20}$	streambed temperature at 0.20 m depth [°C]
$T_{b\_0.40}$	streambed temperature at 0.40 m depth [°C]
T_w	water temperature [°C]
W	average channel width [m]
ws	wind speed [m s^{-1}]
α	albedo
β	Bowen ratio
ρ	water density [kg m^{-3}]
γ	specific weight of water [g cm^{-3}]

Appendix 2 – Study reach

Figure A 1. Overview of study reach. a) View to the East of the site, b) stream section including loggers 3a, 3b, 3c and c) study site inlet.

Figure A 2. Brown Trout (*Salmo trutta* L.) in the Afon Llwyd.

Figure A 3. Meteorological station "Dolydd", operated by the Enviornment Agency, located about 250 m south-west of the study reach.

Appendix 3 – Data collection / Equipment

Figure A 4. LEICA TC800 total station used for surveying.

Figure A 5. TruTrack WT-HR 1500 water height data logger installed at the river bank close at the study site inlet.

Appendix 4 – Stage-discharge relationship for Afon Llwyd

The stage-discharge relationship for the study period from 12/12/2000 until 21/05/2002 was constructed based on measured water levels and discharge derived from linear downscaling of data monitored at CEH gauging station Plynlimon flume according to the respective catchment sizes of the Afon Llwyd (7.5 km^2) and the Plynlimon flume (8.7 km^2). The gauging station at Plynlimon flume was selected due to the similar catchment characteristics and discharge conditions compared with Afon Llwyd. The relationship is undefined for high flows. Therefore, discharge > 4 $m^3 s^{-1}$ was approximated by linear correlation with discharge derived from the down-scaling procedure described above.

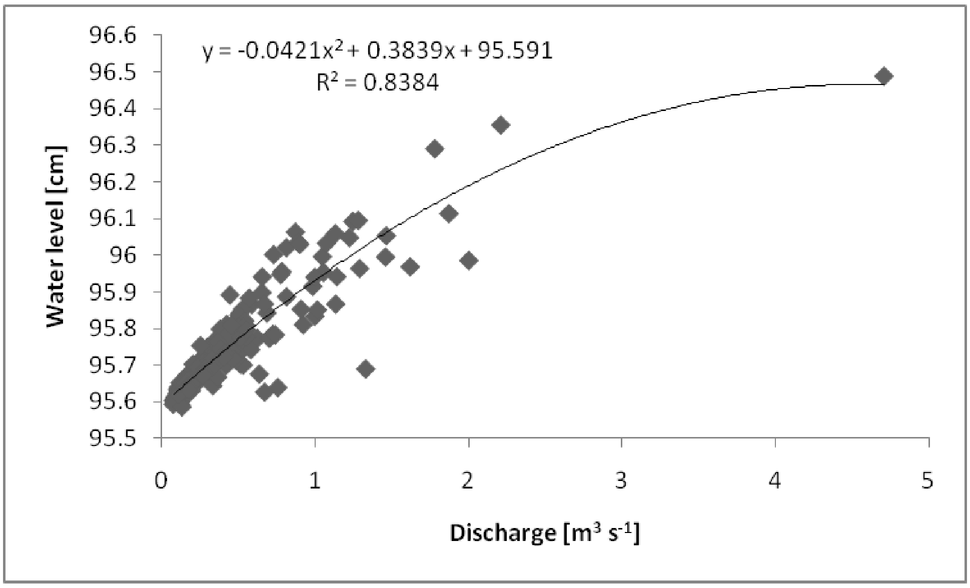

Figure A 6. Stage- discharge relationship for Afon Llwyd for the study period from 12/12/2000 until 17/05/2002

Details on CEH gauging station Severn at Plynlimon flume (54022)

Grid Reference: 22 (SN) 853 872
Operator: IH
Local number: 2103
Catchment Area: 8.7 km^2
Level of Station: 331.0 mOD
Max. Altitude: 740.0 mOD

Catchment Description

High relief, very wet (2400 mm) catchment developed on Palaeozoic shales, grits and mudstones. 67% of catchment afforested up to 1985 when some clear felling took place. Forest slopes very steep, peat moorland hilltops (Centre for Ecology and Hydrology, 2010).

Ehrenwörtliche Erklärung

Hiermit versichere ich, dass ich die vorliegende Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Birmingham, Oktober 2010