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The influence of riparian vegetation shading on water temperature during low flow conditions in a medium sized river

Gerda Kalny^{1,*}, Gregor Laaha⁴, Andreas Melcher³, Heidelinde Trimmel², Philipp Weihs² and Hans Peter Rauch¹

¹ Institute of Soil Bioengineering and Landscape Construction, Department of Civil Engineering and Natural Hazards, University of Natural Resources and Life Sciences Vienna, Peter Jordan-Strasse 82, Vienna 1190, Austria

² Institute of Meteorology, Department of Water, Atmosphere and Environment, University of Natural Resources and Life Sciences Vienna, Gregor Mendel Strasse 33, Vienna 1180, Austria

³ Institute of Hydrobiology and Aquatic Ecosystem Management, Department of Water, Atmosphere and Environment, University of Natural Resources and Life Sciences Vienna, Gregor Mendel Strasse 33, Vienna 1180, Austria

⁴ Institute of Applied Statistics and Computing, Department of Landscape, Spatial and Infrastructure Science, University of Natural Resources and Life Sciences Vienna, Peter Jordan-Strasse 82, Vienna 1190, Austria

Abstract – Stream water temperature limits the growth and survival of aquatic organisms; whereby riparian shading plays a key role in inhibiting river warming. This study explains the effects of riparian shading on summer water temperatures at a pre-alpine Austrian river, during heatwave and non-heatwave periods at low flow conditions. A vegetation-shading index was introduced for the quantification of riparian vegetation effects on water temperature. For maximum water temperatures, a downstream warming of 3.9 °C was observed in unshaded areas, followed by a downstream cooling of 3.5 °C in shaded reaches. Water temperature directly responded to air temperature and cloudiness. For an air temperature change of 2 °C we modelled a water temperature change of 1.3 °C for unshaded reaches, but lower changes for intensively shaded reaches. Similar daily variations at shaded reaches were up to 4 °C lower than unshaded ones. This study gives clear evidence that for a medium-sized pre-alpine river, restoration practices should consider that discontinuity of riparian vegetation should be less than 6000 m; with more than 40% dense vegetation in order to minimize water temperature increases due to unshaded conditions.

Keywords: riparian vegetation / vegetation-shading index / water temperature / river vegetation management / restoration

Résumé – L'influence de la végétation rivulaire sur la température de l'eau pendant les conditions de faible débit dans une rivière de taille moyenne. La température de l'eau d'une rivière limite la croissance et la survie des organismes aquatiques ; de ce fait l'ombrage rivulaire joue un rôle clé dans la limitation du réchauffement des rivières. Cette étude analyse les effets de l'ombrage rivulaire sur les températures estivales de l'eau dans une rivière autrichienne préalpine, pendant les périodes de canicule et de non-canicule à faible débit. Un indice d'ombrage de la végétation a été introduit pour la quantification des effets de la végétation rivulaire sur la température de l'eau. Pour les températures maximales de l'eau, un réchauffement en aval de 3,9 °C a été observé dans les zones non ombragées, suivi d'un refroidissement en aval de 3,5 °C dans les zones ombragées. La température de l'eau a répondu directement à la température de l'air et à la nébulosité. Pour un changement de température de l'air de 2 °C, nous avons modélisé un changement de température de l'eau de 1,3 °C pour les zones non ombragées, mais des changements plus faibles pour les niveaux intensivement ombragés. Des variations quotidiennes semblables dans des zones ombragées étaient jusqu'à 4 °C inférieures à celles non ombragées. Cette étude montre clairement que pour une rivière préalpine de taille moyenne, les pratiques de restauration devraient considérer que la discontinuité de la végétation riveraine doit être

* Corresponding author: gerda.kalny@boku.ac.at

inférieure à 6 000 m, avec plus de 40 % de végétation dense afin de minimiser les augmentations de température de l'eau dues aux conditions non ombragées.

Mots clés : végétation riveraine / indice d'ombrage de la végétation / température de l'eau / gestion de la végétation des rivières / restauration

1 Introduction

Stream water temperature is an important and limiting parameter for a number of organisms such as fish or aquatic invertebrates (Broadmeadow and Nisbet, 2004; Matulla *et al.*, 2007; Rahel and Olden, 2008; Logez and Pont, 2013; Pletterbauer *et al.*, 2014). It results from the multiple processes, which influence the gains and losses of thermal energy in streambeds, depending on the amount of stream discharge, topography and atmospheric conditions along the river course (Caissie, 2006). Upstream water temperature and discharge, hyporheic exchange, ground water inflow, bed heat conduction, tributary inflow and its water temperature, turbulent exchange (sensible and latent heat), solar radiation (incident, reflected), and long wave radiation are components of these processes (Moore *et al.*, 2005; Caissie, 2006). Taking into consideration atmospheric conditions, air temperature and incoming short-wave radiation are mentioned as major influencing factors on water temperatures by Evans *et al.* (1998). They recorded total energy gains dominated by a net short-wave radiation of 97.6%. Solar radiation reaching the stream is influenced by different topographic factors, including the prevailing riparian vegetation buffer, which can decrease incoming energy by up to 95% (Rutherford *et al.*, 1997; Moore *et al.*, 2005; DeWalle, 2010). During summer heatwave periods in particular, solar energy plays a key role in influencing stream energy heat budget, and consequently stream water temperature (Johnson, 2004; Leach and Moore, 2010; Groom *et al.*, 2011). Hence shading through riparian vegetation, primarily in small to medium sized and slowly flowing lowland rivers, is often most relevant to avoid excessive heating in order to mitigate adverse effects on the ecosystem (Ghermandi *et al.*, 2009; He *et al.*, 2011; Holzapfel *et al.*, 2013).

Some studies were undertaken to quantify the influence of riparian vegetation on river water temperature, however, they have mainly explored small rivers, with a discharge of up to only 30 l/s (Story *et al.*, 2003; Johnson, 2004; Rutherford *et al.*, 2004; Moore *et al.*, 2005; Gomi *et al.*, 2006). The most widely discussed vegetation parameters of these studies are buffer width, vegetation height and its density. For instance DeWalle (2010) specifies varying minimum buffer widths for sufficient shading, and corresponding water temperature influence, depending on stream orientation. Buffer widths for east–west oriented rivers necessitate a minimum buffer width of 6–7 m, whereas for north–south orientated rivers the buffer width needs to be 18–20 m, and for meandering rivers no more than 12 m. According to Sridhar *et al.* (2004), vegetation width exceeding 30 m distance has hardly any further influence on stream water temperature. However, the height and density of the riparian vegetation have an equal or even higher impact on water temperature (Sridhar *et al.*, 2004; DeWalle, 2010). Davies-Colley *et al.* (2009) and DeWalle (2008) showed that the ratio of canopy height to stream width has particular high influence on stream light exposure and is therefore notably relevant.

Apart from riparian vegetation structures, also the temperature conditions of river and atmosphere determine the cooling effect of vegetation. Cooling occurs when energy gains are reduced by riparian vegetation, which minimizes water temperature increase, so that the influence of cooler water is prevalent (Garner *et al.*, 2014). The cooling effect is greater at high water temperatures, typically occurring during heatwaves and at daily temperature peaks (Moore *et al.*, 2005) whereas there is only a minor effect of vegetation shading on daily temperature minima (Rutherford *et al.*, 2004).

However, these findings primarily apply to smaller rivers, which are usually shallow, so they adjust quickly to incoming solar radiation. Consequently, water temperature changes are rather fast (Moore *et al.*, 2005), and riparian vegetation influence can be high (Poole and Berman, 2001). The effect of shading might be different for larger rivers where water temperature fluctuations are normally lower (Poole and Berman, 2001) and solar radiation may play a different role, but these effects are not fully explored yet. Moreover, studies investigating riparian shade and its impact on stream water temperatures have been carried out in most temperate regions of the world, but up to date only a few studies have been conducted in Europe (Ghermandi *et al.*, 2009; Broadmeadow *et al.*, 2011; Garner *et al.*, 2014; Johnson and Wilby, 2015). So far, studies, focusing on effects of riparian vegetation on water temperature of medium sized rivers are missing, especially for Central European climates where climate change impacts are predicted to be high (Kovats *et al.*, 2014; Laaha *et al.*, 2016).

The aim of this study is to analyse the effects and mitigation evidence of different river type specific riparian vegetation on summer river water temperature, under heatwave and non-heatwave conditions at a medium sized river in Central Europe. The specific objectives are (i) to describe the summer temperature regime during heatwave and non-heatwave periods (ii) to better understand longitudinal riparian vegetation shading impacts on water temperature by introducing a new vegetation-shading index (VSI), (iii) to explore the sensitivity of VSI to the section length used in its calculation and (iv) to validate the effects of shaded and unshaded river reaches on water temperature variations. The findings will be discussed in the light of riparian vegetation management.

2 Materials and methods

2.1 Study site

The study was conducted at the river Pinka, located in the south-east of Austria (Fig. 1). In this area, in particular, climate change impacts are predicted to be high, in terms of an increase of heatwaves and exacerbation of low flow conditions (Kovats *et al.*, 2014; Laaha *et al.*, 2016). The river source is at an altitude of about 1480 m.a.s.l, and it discharges into the river Raab at about 200 m.a.s.l. Along the river, mean discharge increases up to 2.0 m³/s. The study area belongs to the trout,

Fig. 1. Study site—the river Pinka from distance from source (DFS) 0–DFS 62 including river course, tributaries, gauge stations, water temperature (WT) measuring stations and climate stations.

grayling and barbel fishzone, bearing 24 fish species and 140 benthic taxa (Melcher *et al.*, 2016).

The catchment is situated at a transition zone of alpine, illyric and continental climate. It is characterised by a mean annual rainfall of about 800 mm, frequent thunderstorms, heavy rainfalls (Cejka *et al.*, 2005) and high temperature amplitudes between summer and winter (Fink *et al.*, 2000). The river Pinka exhibits sound hydro-morphological sections with near natural riparian vegetation and minor land use, as well as highly impacted sections in terms of vegetation cover, in total twelve urban/settlement areas, river geometry and continuity. Substrates are dominated by late tertiary sedimentary rocks and, to a lesser extent, by volcanic rocks (Wimmer *et al.*, 2012). The main hydrological characteristics are summarized in Table 1.

While the entire Austrian river stretch (source to distance from source 62.55 km (DFS 62.55)) was the object of investigations, the river stretch between DFS 30.00 and DFS 50.00 was chosen for detailed analysis. This river stretch has no remarkable tributaries and a rather uniform flow direction. Discharge records were available at four gauges situated at DFS 12.45, 37.75, 58.65 and 62.55 (Fig. 1). For describing the meteorological situation, records of air temperature (AT), hours of sunshine, global radiation and precipitation at two near-by stations Kleinzicken (1.5 km to DFS 52.00) and Bad Tatzmannsdorf (3 km to DFS 38.00) were used.

2.2 Vegetation-shading index (VSI)

Vegetation mapping was performed based on aerial photographs and field measurements. Following DeWalle (2010), Moore *et al.* (2005) and Sridhar *et al.* (2004) we

considered a buffer zone of 50 m from the centreline of the river as being relevant for stream temperature. From aerial photographs we delineated polygons that were homogeneous in terms of land use, vegetation cover and vegetation composition. The polygons were refined by evidence from intensive site visits, where also vegetation height in the form of Koch classes (<5, –10, –20, >20 m), and vegetation density clustered as Braun Blanquet (<5, –25, –50, –5, –100%), see (Traxler, 1997), were recorded. In a following step, the results were transferred from area to point information, using the Arc View sampling extension “TTools” (Kasper and Boyd, 2002). During the process, the information was assigned to cross-sections, every 50 m along the river, perpendicular to the river axis. Ten points were generated every 5 m orographically left and right from the centerline, with vegetation parameters being assigned at each of these cross-sections.

For each 50 m cross-section, VSI was calculated that integrates the parameters vegetation height (h_R), vegetation width (w), and vegetation density (d), as these parameters were found to influence water temperature (WT) most (DeWalle, 2010; Holzapfel *et al.*, 2013). For the VSI of a northwards or southwards flowing river, all vegetation parameters were calculated as mean values of the orographic left and right river bank. When the river was flowing eastwards, the orographically right bank was used for calculations, and when it was flowing westwards the orographically left bank was used. Based on this guideline the VSI is computed as:

$$\text{VSI} = \left(\frac{h_R}{h_{\max}} + \frac{w}{w_{\max}} + \frac{d}{d_{\max}} \right) \div 3, \quad (1)$$

Table 1. Hydrological data describing different sites along the river Pinka. Abbreviations: DFS = distance from source, MQ = mean discharge; WT = water temperature measuring point.

DFS (km)	MQ (m ³ /s)	Flow direction (–)	Catchment (km ²)	Strahler order number (–)	Altitude (m.a.s.l.)	Gradient (‰)	River width (m)	Distance from last WT (km)	Minutes from last WT (min)	Average time 500 m (min)
2.3		East		2			2			
10.97	0.4	South	36	3	559	0.036	5			
15.28	1.0	South		4	515	0.014	8	4.49	116	12
19.79	1.0	South	134	5	414	0.008	10	4.51	140	14
30.69	1.0	North		5	342	0.004	13	10.9	336	15
34.86	1.2	East		5	319	0.006	7	4.17	132	13
37.23	1.2	East	172	5	306	0.004	7	2.37	60	12
39.01	1.2	South		5	299	0.004	7	1.78	47	9
44.26	1.2	East		5	279	0.002	10	5.25	235	21
45.39	1.2	East		5	276	0.003	10	1.13	55	14
45.55	1.2	East		5	275	0.003	10	0.16	8	8
48.4	1.2	South		5	266	0.004	10	2.85	125	18
53.04	1.2	North		5	257	0.001	8	4.64	224	22
53.22	2.0	East		6	256	0.001	8	0.18	11	11
55.09	2.0	East		6	249	0.002	6	1.87	76	15
58.79	2.0	East	417	6	244	0.001	6	3.7	139	17
61.51	2.0	North	664	6	240	0.002	5	2.72	119	17

where h_R (%), relative vegetation height, weighted ratio of vegetation height and river width, which is calculated as:

$$\text{if } \frac{\text{vegetation height} * 100}{\text{river width} * 1.5} \leq 100; \text{ then } h_R = \frac{\text{vegetation height} * 100}{\text{river width} * 1.5}; \text{ else } h_R = 100. \quad (2)$$

Note: That multiplication of the river width with 1.5 is due to the fact that a tree height of 15 m generates, at this geographic position, a shade length of 10 m, from 10 a.m. to 2 p.m., and can fully shade the present river width. $h_{\max}$ (%) – maximum vegetation height (=100 %); w (m) – width of the woody riparian vegetation buffer; $w_{\max}$ (m) – maximum vegetation width, (=50 m, as this is defined as maximum width influencing the WT); d (%) – vegetation density = vegetation cover related to ground area; $d_{\max}$ (%) – maximum vegetation density (=100%).

The obtained VSI values range between 0 (no vegetation) and 1 (full vegetation). Because of river flow, WT at a river site will depend on the upstream situation but it is unclear at what section length vegetation will have most influence. We therefore calculated mean VSI values for upstream sections of WT measurement points of various lengths, ranging between 50 m and 10000 m (VSI_{50} to VSI_{10000}). For validating these VSI indices we used the Global Site Factor (GSF), computed from hemispherical photographs (Rich *et al.*, 1999) that were taken at 43 sites between DSF 0.05 and DFS 62.81.

2.3 Selection of the study period

Heatwave events were of particular interest in this project. Hence, the analysis was carried out for the summer of 2013

(1 June–31 August) when record temperatures of 40.5 °C were measured by public meteorological stations in this region. The days were classified into non-heatwave periods (NK), heatwave periods (K) and extreme heatwave days (K+) following Kysely *et al.* (2000). According to this definition, a heatwave period (K) is characterised by at least three subsequent days with maximum air temperatures ($AT_{\max}$) ≥ 30 °C and continues until the $AT_{\max}$ drops below 25 °C or the mean $AT_{\max}$ of the period is below 30 °C. Extreme heatwave days (K+) additionally have clear sky conditions ($\geq 80\%$ of possible sun hours – defined by (MeteoSchweiz)), precipitations below 1 mm/day and discharges of a maximum of 75% of the mean discharge (used as a threshold for low flow conditions).

For comparison of sunny and cloudy days additionally, single consecutive days with clear sky conditions ($\geq 80\%$ of possible sun hours) and cloudy conditions ($\leq 50\%$ of possible sun hours), with no intermediate rain, were selected (Tab. 2).

2.4 Measurement and analysis of water temperature

Data sets concerning river WT were collected at a spatially distributed network of 17 HOBO Pendant Temperature Data Loggers 8K*UA-002-08 along the river Pinka (Tab. 1 and Fig. 1). Data was sampled hourly, from June 2013 until August 2013. We analyse the relationships between water temperature along the river with meteorological variables and with the VSI by means of Spearman's rank correlation (r_s). In addition, we analysed the relationships between impotent parameters by linear regression.

2.5 Numerical water temperature model

In order to gain a better understanding of the influence of riparian shading on the change in $WT_{\max}$ the energy balance

Φ_{total} along the river was calculated using the model HEAT SOURCE version 9 (Boyd and Kasper, 2003). The model is based on the following energy balance equation:

$$\Phi_{\text{Total}} = \Phi_{\text{Evaporation}} + \Phi_{\text{Convection}} + \Phi_{\text{Longwave}} + \Phi_{\text{Solar}} + \Phi_{\text{Conduction}}, \quad (3)$$

where Φ_{Total} is the energy balance, $\Phi_{\text{Evaporation}}$ the evaporation flux, $\Phi_{\text{Convection}}$ the convection flux, Φ_{Longwave} the long wave radiation balance (all referring to the stream surface), Φ_{Solar} is the short wave energy, which is absorbed by the water column,

Table 2. Two 5-day periods with consecutive days of clear sky and cloudy conditions and the according maximum air temperatures (AT_{max}). Abbreviations: DFS=distance from source; NK=non-heatwave period; K=heat wave period.

Date	% possible sun	Discharge (DFS 37.75)	AT_{max} (°C)	Period
13.07.2013	58	0.69	24.8	NK
14.07.2013	72	0.68	26.4	NK
15.07.2013	28	0.68	25.5	NK
16.07.2013	92	0.6	26	NK
17.07.2013	92	0.63	28.6	NK
29.07.2013	86	0.44	36.9	K
30.07.2013	48	0.43	27.9	K
31.07.2013	36	0.43	28.7	K
01.08.2013	82	0.42	30.6	K
02.08.2013	92	0.41	34.3	K

and $\Phi_{\text{Conduction}}$ the conduction flux. The model was validated for use in the research area in a study by Trimmel *et al.* (2016).

WT increase (ΔT) caused by energy gains was calculated by using the following formula:

$$\Delta T = \frac{Q}{c \cdot m}, \quad (4)$$

where Q is the heat energy input (W/m^2) into the river, m the water mass (kg) and c the specific heating capacity of water.

Possible ground water (GW) influences were analysed in the area between DFS 37.75 (38) to DFS 58.65, by considering the discharge volume (WV) of the tributaries Zickenbach (Zick), Teichbach (Teich) and Gerentbach (Ger). The WT of these assumed inflows was then incorporated, and the resulting WT (WT_R) of the river Pinka was estimated using the formula as follows:

$$WT_R = \%WV_{38} * WT_{38} + \%WV_{Zick} * WT_{Zick} + \%WV_{Teich} * WT_{Teich} + \%WV_{Ger} * WT_{Ger} + \%WV_{GW} * WT_{GW}, \quad (5)$$

where $\%WV_{38}$ = percentage of the water volume at DFS 37.75.

3 Results

3.1 Riparian vegetation

In the upper reaches of the river Pinka (from source to DFS 20.00), the mean VSI_{50} was 0.69, which reveals a high level of shading, and points to areas of rather high, wide and dense riparian vegetation, often featured by commercial forests (Fig. 2a). Downstream of DFS 20.00, the river flows through

Fig. 2. (a) Distribution of the longitudinal vegetation-shading index (VSI) values of the river Pinka, referring 50 m sections upstream of the water temperature measuring points, as well as 6000 m sections. The scatter plots show the ratio of Global Site Factors (GSF) and VSI_{50} s (b), as well as the vegetation parameters width (c), height (d) and density (e).

settlement areas and agricultural lands. The VSIs for these middle and lower reaches were more diverse, 16% of the river stretch showed a VSI_{50} below 0.2 and 62% had a VSI_{50} above 0.6. Particularly notable was the very low mean VSI_{50} of 0.15 from DFS 37.00 to DFS 39.65. This section had almost no riparian vegetation and consequently no vegetation shading effect (Fig. 2). In terms of longer stretches, the VSI_{6000} showed two deep depressions between DFS 20.00 and DFS 50.00, dropping down to 0.35 and 0.34.

The VSI values were compared with GSF values from the hemispherical photographs. The correlation coefficient (r_s) between GSF and VSI (Fig. 2b) was 0.8 during times of highest sun elevation, and 0.9 for the GSF over the whole day ($p < 0.01$). The high correlation coefficients underline the appropriateness of the newly proposed VSI for characterising vegetation shading. Vegetation parameters height, width and density (Fig. 2c–e) cannot reach higher correlations.

3.2 Hydro-meteorological conditions

Figure 3 shows the hydro-meteorological conditions of summer 2013 for the study area. According to the Kysely classification the summer of 2013 is characterised by two heatwave periods (K): from 17th June 2013 to 23rd June 2013, and from 23rd July 2013 to 9th August 2013, which amounted, in total, to 25 days (Fig. 3a). These two periods included 16 clear sky days and 20 days without any precipitation. Extreme heatwave days (K+) were defined on 2nd, 3rd, 6th, 7th and 8th August 2013 additionally taking into account days with a discharge of less than 75% of the mean flow.

The temporal patterns of precipitation and discharges at DSF 12.45 and 37.75 km are presented in Figure 3b. There were only few and mostly minor precipitation events during the summer of 2013. Consequently, the discharges steadily decreased and reached a minimum at 3rd August 2013, corresponding to a low flow event. WT shows temporal development that is reverse to the discharge (Fig. 3c) as would be expected.

Figure 4 shows the distribution of WT along the river. On average, daily mean water temperatures (WT_{mean}) increased, from about 9.4 °C to 18.7 °C, WT_{max} increased from 10.4 °C to 20.4 °C. During heatwave periods (K), average WT_{max} increased much stronger, up to 24.4 °C at DFS 62.55, and even to 26 °C during the extreme heatwave days (K+). However, there was no steady increase in WT from source to DFS 62.55. Especially noticeable is the decrease of WT_{max} in the extreme heatwave days (K+) of 4.7 °C, from DFS 39.01 to DFS 53.22. This decrease was much lower during the non-heatwave period (NK) it was only 3 °C. Such increases and decreases were mainly observed for WT_{max} and daily water temperature range (WT_{range}), whereas variations were small in WT_{mean} (Fig. 4c,d). The highest WT values in all periods were measured at DFS 39.01; a low shaded area, where at extreme heatwave days (K+), on average, values of $WT_{range} = 6.9$ °C and $WT_{max} = 28.2$ °C, were reached. This issue will further be explored in a later section.

For the middle reaches (DFS 30.00 to DFS 50.00), which represent conditions without considerable inflows, we assessed the dependence of WT on meteorological parameters. Spearman correlations coefficients (r_s) point to a strong

relationship between WT_{max} and AT_{max} , with values between 0.85 and 0.94 ($p < 0.01$). In addition, we observed significant, but lower correlations (about 0.5) with global radiation, and with sun hours as well.

3.3 Effects of VSI section length on water temperature

Figure 5 illustrates the VSI as a function of WT_{max} , WT_{range} , WT_{mean} and daily minimum water temperatures (WT_{min}), during the extreme heatwave days (K+) in the middle reaches (DFS 30.00 to DFS 50.00), for the different river section lengths from 50 m and up to 10000 m upstream of the WT measuring points. Mostly negative correlations are observed, illustrating that a higher VSI is related with lower WT. The strengths of the correlation strongly depended on the section lengths and the WT parameters. WT_{max} and WT_{range} were the most highly correlated parameters (Fig. 5). Correlations for these parameters increased when increasing the considered river section length for VSI calculation from 50 m to 6000 m, from -0.34 to -0.73 for WT_{range} , and from -0.5 to -0.82 for WT_{max} . However, larger river section lengths again led to a decrease of the correlations. The calculated VSIs for river section lengths from 4000 m to 7000 m, showed the highest correlations with values of about -0.7 . The statistically best performing VSI value was calculated for a section length of 6000 m with -0.82 for WT_{max} and -0.73 for WT_{range} . Consequently, VSI_{6000} were considered as most representative in this study. In contrast, much lower correlations were observed for WT_{min} and WT_{mean} with a correlation coefficient of -0.05 (WT_{min}) and -0.42 (WT_{mean}) for VSI_{6000} . They represent more the night conditions; hence, they do not depend so much on radiation and shading effects. We will therefore focus on WT_{max} and WT_{range} in the subsequent analyses.

Similar relationships were also observed between WT_{max} and selected vegetation parameters with correlations coefficients (r_s) between -0.77 (vegetation width) to -0.84 (vegetation density). Vegetation height showed a lower correlation with a coefficient of -0.55 .

3.4 Impact of shading and cloudiness on water temperature

Observing successive days with differing cloud cover conditions (Tab. 2), but same discharges, WT_{max} reacted in different ways. During the heatwave period (K) greatest increases and decreases in WT could be seen from DFS 34.86 to DFS 53.22 (Fig. 6a). On the 29th July 2013, a clear day, WT_{max} rose from DFS 34.86 to DFS 39.01, by 3.9 °C to WT_{max} values of 28.8 °C. The river morphology of this stretch is heavily impacted by river regulations and low amount of riparian vegetation which results in a mean VSI_{50} of 0.31. The 14.21 km long river stretch downstream of DFS 39.01, has a more natural appearance with dense riparian vegetation buffers (mean $VSI_{50} = 0.61$). Henceforth, WT_{max} decreased from 28.8 °C down to 23.8 °C. On the 30th July 2013, a mean cloudy day, WT_{max} at DFS 39.01 had a lower peak of 25.1 °C with lower warming (1.1 °C) and cooling (2.6 °C) gradients. These gradients decreased even more on the 31st July 2013, a cloudy

Fig. 3. Hydro-meteorological characteristics of the summer of 2013 at the Pinka region: (a) daily maximum air temperature (AT_{max}), and sun hours per day measured at the climate stations Kleinzicken and Bad Tatzmannsdorf, (b) daily precipitation (precip.) at the same climate stations, and the resulting discharges at two gauges (DFS 12.45 and 37.75), and (c) daily maximum and mean water temperatures (WT max and WT mean) at selected sites along the river Pinka (DFS = distance from source). The heat wave periods (Kysely) are shaded in grey.

day. On 1st August 2013, and 2nd August 2013, two clear days, WT_{max} rose back to precloud conditions. Figure 6b shows the same tendencies in the non-heatwave periods (NK). Daily WT_{min} remained stable during both periods. Since no precipitation occurred during these periods, and discharge volume remained at the same level, we anticipated that the influence of ground water on WT is similar on all days. Consequently the key element for changing WTs is the

incident solar radiation influenced by the appearance of riparian vegetation.

3.5 Daily variations of water temperature

Considering the VSI₆₀₀₀ of the river sections, there was a clear difference in WT behaviour. In the extreme heatwave

Fig. 4. Distribution of water temperature (WT) at the different WT stations along the river Pinka during summer 2013, for periods of non-heatwave periods (non-Kysely), heatwave periods (Kysely) and extreme heatwave days (Kysely+) respectively. With (a) WT maximum, (b) WT ranges, (c) WT minimum and (d) WT mean.

Fig. 5. Absolute spearman correlation coefficients of the vegetation-shading index (VSI) to the daily water temperature (WT) parameters, related to the specific VSI section lengths. The data from WT stations is related to distance from source (DFS) 30.00 and DFS 50.00 on extreme heatwave (K+) days.

days (K+) a WT_{max} of $28.1^{\circ}C$ was reached earliest at 1 p.m. at DFS 39.01, a very sparsely shaded section (VSI_{6000} 0.37). Opposed the most shaded areas (VSI_{6000} above 0.6) reached mean WT_{max} of $23.6^{\circ}C$ from 6 p.m. to 9 p.m. (Fig. 7). The WT_{range} amounted to $7.6^{\circ}C$ for the unshaded, to an average of $5.3^{\circ}C$ for medium shaded and to an average of $3.6^{\circ}C$ for highly shaded upstream conditions. In the heatwave and non-heatwave periods, the temporal curve progression was quite

similar, except that the entire curve had a temperature offset. In the extreme heatwave days (K+) mean WT_{max} was $6.7^{\circ}C$ higher than in non-heatwave periods (NK).

3.6 Correlation of water and air temperature

WT_{max} and AT_{max} are highly correlated. Figure 8a shows scatter-plots for selected WT stations. The slopes of the WT_{max} - AT_{max} regression line is low in the upstream reaches, whereas the slopes much higher at locations between DFS 30.69 and DFS 61.51. However, the slopes of the regression lines also depend on the VSI value (Fig. 8b). The analysis of the interrelationship between different slopes of the WT_{max} - AT_{max} regression line and the riparian vegetation (Fig. 8c-f) revealed that steeper slopes indicate a lower VSI and therewith a higher impact of the AT on the WT. Considering these correlations, Table 3 shows the calculated WT changes due to an AT increase of $2^{\circ}C$.

3.7 Field data validation by a numerical river temperature model

The energy balance of two sites with different vegetation structures (full vegetation DFS 46.00/no vegetation DFS 39.01), was simulated by HEAT SOURCE, using formula (3). Energy balance never dropped below $0 W/m^2$ during the daytime in both cases, independent of cloudiness (Fig. 9). At the time of highest sun elevation on a clear day, the maximum values of the energy balance varied from $194 W/m^2$ (Fig. 9a), for areas without vegetation, to $35 W/m^2$ (Fig. 9b) for fully vegetated areas. Vegetation structures had less impact during cloudy conditions with a difference of just $39 W/m^2$.

Fig. 6. Distribution of the longitudinal vegetation-shading index (VSI 50) and water temperature (WT) values of two 5-day periods with differing cloudiness conditions. Periods describe (a) heatwave (Kyselý) and (b) non-heatwave (non-Kyselý) conditions.

The calculated energy gains on a 1 km long river stretch, with dimensions such as DFS 39.01, and no riparian vegetation, increased river WT by 0.4 °C (Formula (4)). This results in an increase of 3.3 °C for a river section of 9 km. Under the same conditions, but with less energy due to dense vegetation, the WT increased just by 0.1 °C. Consequently, other cooling influences could have a stronger impact in shaded areas.

Observing the time period with the lowest discharge values, DFS 39.01 amounted to 60% of the water mass achieved on DFS 58.79. Above ground tributaries added another 24% of water mass. The WT of the Zickenbach, the biggest tributary showed no significant differences in WT in comparison to the river Pinka. Therefore, 16% of the water mass was ground water and assumed to be the reason for the WT decrease. Ground water temperatures from nearby stations showed mean values of 12 °C. Formula (5) was used to calculate the WT of 1 m³ water along the 19.78 km long river

stretch. WT decreases of 3.6 °C were calculated whereas the observed reduction of WT_{max} was 5 °C.

4 Discussion

4.1 VSI and its spatial scale in terms of water temperature

In the present study, VSI was calculated as an integral parameter, taking into account vegetation height, width and density, whereby all three have a verifiable impact on the solar radiation situation input on a stream surface. These are the parameters most commonly studied concerning global radiation reduction (Zwieniecki and Newton, 1999; DeWalle, 2010; Sridhar *et al.*, 2004) but there are no clear results concerning the ranked importance of these. The VSI results in a significant correlation which had the same or even better correlation coefficients with WT as the

Fig. 7. Overview of the mean daily water temperature (WT) variations from non-heat wave (non-Kyselý), heat wave (Kyselý) and extreme heat days (K+), as well as mean WT variations for a cloudy day (31.7.2013) and a clear sky day (2.8.2013) at seven selected WT stations between distance from source (DFS) 30.00 and DFS 50.00.

Fig. 8. Maximum water temperatures (WT_{max}) shown as a function of air temperature (AT) at selected WT stations along the whole river stretch (a), and for selected WT stations between distance from source (DSF) 30.00 and DFS 50.00 (b) for summer 2013. (c–f) Show the regressions of vegetation-shading indexes (VSI) to the slopes of the AT to WT regression lines.

Table 3. Water temperature (WT) change according to an air temperature (AT) change of 2 °C. Abbreviations: DFS = distance from source, VSI = vegetation shading index.

DFS (km)	VSI ₆₀₀₀	Slope	R ² AT/WT	AT change (°C)	AT from (°C)	AT to (°C)	WT from (°C)	WT to (°C)	WT change (°C)
2.3		0.245	0.66	2	30	32	11.3	11.8	0.5
10.97	0.72	0.155	0.19	2	30	32	15.3	15.6	0.3
15.28	0.6	0.452	0.72	2	30	32	19.5	20.4	0.9
19.79	0.64	0.577	0.8	2	30	32	20.9	22.1	1.2
30.69	0.52	0.503	0.81	2	30	32	21.7	22.7	1
34.86	0.66	0.439	0.84	2	30	32	21.3	22.2	0.9
37.23	0.53	0.543	0.8	2	30	32	21.8	22.9	1.1
39.01	0.37	0.635	0.83	2	30	32	23.5	24.7	1.3
44.26	0.47	0.589	0.88	2	30	32	22.6	23.8	1.2
45.55	0.52	0.502	0.87	2	30	32	22.7	23.7	1
48.4	0.64	0.416	0.78	2	30	32	21.7	22.6	0.8
53.22	0.69	0.325	0.61	2	30	32	20.5	21.2	0.6
58.79	0.69	0.512	0.82	2	30	32	22.6	23.6	1
61.51	0.68	0.511	0.84	2	30	32	22.7	23.8	1

Fig. 9. Daily variations of energy balances for a cloudy (31.7.2016) and a clear sky day (2.8.2016), without vegetation (NV) and with vegetation (V).

individual vegetation parameters. Additionally, it was highly correlated to the GSF with a coefficient of 0.9 ($p < 0.01$). Depending on river size, different lengths are of relevance, in order to heat the water to a specific temperature. In the present study, the influence of the mean VSIs of different lengths on WT was tested for a stream with 1–1.2 m³/s discharge and points to 4–7 km (peak correlation coefficient for WT_{max} of −0.82 at 6 km VSI length) as being an appropriate length. The results are not directly comparable to those of most existing studies which deal with smaller streams with a discharge of up to 0.03 m³/s (Story *et al.*, 2003; Johnson, 2004; Rutherford *et al.*, 2004; Moore *et al.*, 2005; Gomi *et al.*, 2006). Rutherford *et al.* (1997) mentioned 1st order streams need 250 m to 500 m; 2nd order 500 m to 1.5 km and 3rd order 1.5 km to 5 km unshaded sections in order to heat the water by 5 °C. Johnson and Wilby (2015) stated that around 0.5 km of complete shade is necessary to decrease WT by 1 °C in July at a headwater site; whereas 1.1 km shade is needed 25 km downstream. Accordingly,

larger rivers need a longer distance to reach the same WT changes than smaller ones.

In the present study, WT_{min} and WT_{mean} showed a steadily increasing curve from source to DFS 62.55, unaffected by riparian vegetation conditions. However, WT_{max} and WT_{range} had peaks at unshaded reaches, of up to approximately 4 °C difference to shaded ones, which followed a steadily increasing curve. These findings correlates well with the findings of Bowler *et al.* (2012), Johnson (2004) and Webb *et al.* (2008) which show that if a riverine reach is fully clear cut, the daily WT_{max} and WT_{range} are particularly affected.

4.2 Heatwave periods, VSI and their impact on water temperature

We focused on the comparison between non-heatwave periods (NK) and extreme heatwave days (K+), as well as clear sky and cloudy days. Only considering AT to divide the

summer into non-heatwave (NK) and heatwave (K) days, differences in WT_{max} of $4.3^{\circ}C$ were found at all WT stations. Additionally, taking into account cloudiness and discharge conditions, extreme heatwave days (K+) were selected. Differences in WT_{max} to the non-heatwave periods (NK) increased by another $1.2^{\circ}C$. Many other studies have analysed WT behaviour after clear cut, especially on clear sky and hot days (*i.e.*, Story *et al.*, 2003; Moore *et al.*, 2005; Quinn and Wright-Stow, 2008). Increases of daily WT_{max} , on non-vegetated sites, of up to $13^{\circ}C$ were found (Moore *et al.*, 2005).

Additionally, we also analysed the differences between consecutive clear sky and cloudy days to have the same hydrological boundary conditions. The only changing parameter was the radiation input through different cloudiness conditions. On a clear day, the maximum values of the energy balance differed by $159 W/m^2$ between areas without vegetation and fully vegetated areas, whereas on cloudy days differences decreased to $39 W/m^2$. Garner *et al.* (2014) also recorded the dramatically reduced energy gains of the river at vegetated sites compared to open sites.

These differing energy inputs to the river were reflected in the different WT_{max} during the clear sky days. Open sites with hardly any vegetation showed a WT_{max} of up to $27.8^{\circ}C$, while densely shaded ones showed, on the same day, a WT_{max} of $24.9^{\circ}C$. The lowest WT_{max} with $22.7^{\circ}C$ occurred on a heavily shaded river stretch (mean $VSI_{50} = 0.61$). The shading effects of the vegetation have caused a reduction of incoming solar radiation, resulting in a reduction of the increase of WT. Ground water and other potential inflows are acting as cooling factors. Story *et al.* (2003) concluded from their study that ground water inflow in a shaded reach caused 40% of the $3^{\circ}C$ cooling effect in daily WT_{max} , whereas bed heat conduction and hyporheic exchange caused 60% of this effect. In our study, ground water influence for a 19.78 km long river stretch was numerically modelled with a WT_{max} decrease of $3.6^{\circ}C$, neglecting energy exchange with the atmosphere or soil.

4.3 Water temperature variations

When considering daily WT variations, the most relevant parameters were daily WT_{max} and WT_{range} . The results of the present study showed differences between shaded and unshaded sites of up to $4.2^{\circ}C$ for daily WT_{max} . The correlation between VSIs and WT changes is high. It is specifically most apparent up to VSI_{6000} of 0.4, when the vegetation cover is generally very low. The unshaded areas showed up to $2.6^{\circ}C$ higher daily WT_{max} in the extreme heatwave days (K+) than fully or patchy shaded ones (VSI_{6000} above 0.4) in the processed area did. This is consistent with Bowler *et al.* (2012) who concluded that mean WT_{max} are up to $4.9^{\circ}C$ lower at forested riversides than at pasture riversides.

Disregarding all these different conditions and parameters, DFS 39.01, the WT measuring point with the lowest vegetation density ($VSI_{50} = 0$; $VSI_{6000} = 0.37$) showed the highest WT_{max} in all periods. This highlights the importance and possibilities of riparian vegetation management and the need for at least a degree of riparian vegetation as previously stated in Holzapfel *et al.* (2013). Rutherford *et al.* (1997) also emphasizes that a natural shading of 95–99% radiation reduction is not necessary and 70% is sufficient. In the present study, sites with VSI_{6000} of about 0.4 (40% density) had a significant effect on preventing

WT increase in pre-alpine conditions. Similarly, Correll (2005) stated that from an ecological point of view continuous buffers are more important than wider but fragmented ones.

4.4 Water temperature influenced by air temperature dependent on VSI

We found a relationship between WT_{max} and AT_{max} with an R^2 of 0.8–0.9 in summer. Based on this correlation an increase of $2^{\circ}C$ AT_{max} , results in an increase of WT_{max} of $1.3^{\circ}C$ for an unshaded reach and $0.8^{\circ}C$ for a shaded reach. Following a WT increase at an AT change is always dependent on the riparian vegetation situation. Webb and Nobilis (1997) recorded a R^2 of 0.97 between AT and WT for monthly mean values over the entire year. In the summer, between June and August, R^2 was only between 0.47 and 0.7.

5 Conclusion

WT is a very important and limiting parameter for the development of riverine life, which is driven by meteorological variables, but also influenced by riparian vegetation stands and many other abiotic factors. This paper focuses explicitly on the impact of different riparian vegetation stands on WT. Most sensitive to changes caused by riparian vegetation is the daily WT_{max} followed by the daily WT_{range} .

In particular, during extreme meteorological events such as heatwave periods, when the river system suffers from highest WTs, vegetation has an impact on WT. In this case, our study has shown that sparse riparian vegetation is sufficient, in order to avoid a WT increase in pre-alpine conditions. VSIs of above 0.4 already achieved good results. On cloudy days the existence of riparian vegetation has no further effects due to solar radiation decrease.

The VSI is a representative parameter which characterises the shading effects of riparian vegetation by its height, width and density. The most relevant considered VSI section length is dependent on specific local boundary conditions. Since the highest correlation between WT and VSI was registered for vegetation stretches of 6000 m, we conclude that for a medium-sized pre-alpine river, restoration practices should consider that discontinuity of riparian vegetation should be less than 6000 m, with more than 40% dense vegetation in order to minimise WT increases due to unshaded conditions.

The cooling of WT directly by riparian vegetation was not possible, as the energy balance on a clear sky day never dropped below 0. The findings have shown that riparian vegetation can prevent the WT from an additional increase, and therefore effects such as ground water inflow can have higher impacts. WT directly reacted to changes in AT, riparian vegetation significantly influenced this relationship.

The present study confirmed findings of other studies regarding the influence of riparian vegetation on WT. Each river, however, is a unique system and highly dependent on size, predominant meteorological situations and geographical position. Climate change effects, in particular, put an additional pressure on river ecosystems and its inhabitants, such as fish and benthic invertebrates. To ensure the preservation of habitats for aquatic organisms, riparian vegetation management should be a not dispensable sector in future river planning and management,

particularly at low water conditions to buffer extreme WT peaks in heatwave periods.

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