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Discussions

Can riparian vegetation shade mitigate the expected rise in stream temperatures during heat waves in a pre-alpine river?

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Abstract. The influence of expected changes in heat wave intensity during the 21st century on the temperatures of an pre-alpine river are simulated and the mitigating effects of riparian vegetation shade on the radiant and turbulent energy fluxes analysed. Minor stream water temperature increases are modelled within the first half of the century, but a more significant increase is predicted for the period 2071–2100. The magnitude of maximum, mean and minimum stream temperature rises for a 20 year return period heat event was estimated to be in the region of 3 °C. Additional riparian vegetation is not able to fully mitigate the expected temperature rise caused by climate change, but can reduce maximum, mean and minimum stream temperatures by 1 to 2° C. Removal of existing vegetation amplifies stream temperature increases. Maximum stream temperatures could increase by more than 4 °C even in yearly heat events.

Keywords: stream temperature, modelling, riparian vegetation, shade, climate change

1 Introduction

Stream temperature is an important factor influencing the physical, chemical and biological properties of rivers and thus the habitat use of aquatic organism (Davies-Colley and Quinn 1998; Heino et al. 2009; Magnuson et al. 1979). Studies suggest that freshwater biodiversity is highly vulnerable to climate change with extinction rates exceeding those of terrestrial taxa (Heino et al. 2009). Stream temperature and assemblages of fish and benthic invertebrates along the river course are highly correlated. The duration and magnitude of especially the maximum summer stream temperatures are limiting factors for many species occurrence (Matulla et al. 2007, Melcher et al. 2014, Melcher et al. 2016).

Continuous warming of water temperatures induce changes in fish assemblages and slow altitudinal shifts of species, if the habitat is suitable and no migration barriers exist. River continuum disruption reduces the fish zone extent significantly.

Extreme events where lethal thresholds of stream temperature are exceeded can cause exchange of zoonoses or even extinction of species (Melcher et al. 2013, Pletterbauer et al. 2015). The largest uncertainties in forecasts of total suitable habitat are climate uncertainty followed by parameter uncertainty and model uncertainty (Wenger et al. 2013). Above that riparian ecosystems play a superior role in climate change adaptation in the 21st century (Capon et al. 2013).

Air temperatures have been rising and are expected to continue to rise globally within the next century (IPCC 2013). In eastern Austria in the period since 1880 mean air temperature has risen by 2 °C, which is more than double the 0.85 °C rise recorded globally (Auer et al. 2014). A further temperature increase within the 21st century is very likely (APCC 2014). A mean air temperature increase of 1.4 °C within the first half of the century is expected (Ahrens et al. 2014). Temperature development thereafter is strongly dependent on future greenhouse gas emissions. If emission scenario A1B is assumed, mean air temperature increases of 3.5 °C by the end of the 21st century are nearly certain (Gobiet et al. 2014). Other scenarios predict higher (A2) or lower (B1) increases (Gobiet et al. 2014).

Temperatures extremes have changed markedly and extreme high temperature events i.e. heat waves are very likely to increase in the 21st century (APCC 2014).

According to IPCC (2013) precipitation has the tendency to decrease in subtropical regions but increase in the middle latitudes on average. Austria lies between these two zones of opposing trends: Northern Europe, which shows an increasing trend and the Mediterranean which has a decreasing trend (IPCC 2013, Böhm 2006). In southeastern Austria a precipitation decrease of about 10–15% annually has been recorded over the last 150 years (APCC 2014, Böhm 2012). The decrease has been observed in summer and winter half-year (Böhm et al. 2009, 2012). A continuation of this trend might aggravate the danger of summer drought. In eastern Austria low flow discharge rate of rivers is likely to decrease by 10 to 15% for 2021–2050 compared to 1976–2007 during all seasons (Nachtnebel et al. 2014).

Heavy and extreme precipitation shows no clear increasing signal on average, but it is likely to increase from autumn to spring (APCC 2014). Long term increases of wind speeds or storm activity cannot be detected. An increase of sunshine hours in the Alps has been modelled, but no similar signal has been found for the low lands (Ahrens et al. 2014).

Stream temperature is controlled by advection of heat, dispersion and the net energy fluxes acting on the surface and river bed. While net short wave radiation is the dominant energy input causing diurnal fluctuations, longwave radiation flux as well as the turbulent fluxes evaporation and convection, which are controlled by air humidity, air temperature, wind and net radiation, play an important role (Caissie et al. 2007; Garner et al 2014; Hannah et al. 2008; Johnson 2004; Trimmel et al. 2016). Water temperature is sensitive to air temperature changes (Hannah et al. 2008) so that even if global radiation, air humidity and wind have no clear climate change signal, the change in air temperature alone will affect stream temperatures significantly (Nachtnebel et al. 2014; Settele et al. 2014; van Vliet et al. 2016). Apart from this soil temperature is expected to increase due to climate change and will influence stream temperatures via substrate heat conduction and groundwater flux (Kurylyk et al. 2015). For example, in Austria near surface groundwater body temperature is expected to rise by 0.5 to 1 °C

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on average by 2050 (BMLFUW 2011). Since 1980 Austrian river temperatures have increased on average by 1.5 °C during summer and 0.7 °C during winter (BMLFUW 2011). The annual mean temperature of the river Danube at the border to Slovakia has been rising (Webb and Nobilis 1995) and is likely to continue to rise to reach a value of between 11.1 and 12.2 °C by 2050 compared to around 9 °C at the beginning of the 20th century (Dokulil und Donabaum 2014; Nachtnebel et al. 2014).

Precipitation changes which affect discharge volume and velocity in general and the indirect effects of climate change on stream temperature like the percentage contributions of surface, subsurface, groundwater and/or snow melt still have to be analysed in more detail (Johnson and Wilby 2015). Apart from rising air temperatures and discharge changes, anthropogenic influences like discharge from waste water treatment plants and cooling water have to be taken into account. Another consequence of climate change is changes in sediment loads in river systems due to changes in mobilization, transport and deposition of sediment, which is expected to be very likely (APCC 2014). Sediment changes might alter the bed conduction flow as well as flow velocity.

One of the most influential factors regulating stream temperature is riparian vegetation (Caissie 2006, Groom et al. 2011; Johnson 2004; Moore et al. 2005; Rutherford et al. 1997). Streamside vegetation buffer width (Clark et al. 1999), vegetation density and average tree height all have a strong influence on stream temperature (Sridhar et al. 2004). Vegetation affects the sky view of the river and thereby short and long wave radiation flux, evaporation and convection heat flux, who are highly correlated to the openness of the sky, which can be evaluated using the view to sky value (VTS). The VTS can be influenced by factors other than vegetation such as topographic obstructions and bank shade (Boyd and Kasper 2003, Trimmel et al. 2016).

The main energy input during heat wave conditions is short wave radiation and the most significant output of stream energy is via evaporation. The reduction of short wave radiation can contribute significantly to reduce the heating of rivers during warmer summers (Sinokrot and Stefan 1993; Parker and Krenkel 1969; Rutherford et al. 1997; Trimmel et al. 2016). Vegetation affects the sky view of the river and can reduce the incoming global radiation of up to 95% (Holzapfel et al. 2013). Evaporation is dependent on the difference between water and air temperature, relative humidity, wind speed – which is affected by the roughness of the environment – and net radiation. An obstructed sky view reduces net incoming radiation, but it also reduces wind speed, air humidity and air temperature gradients and consequently evaporation. Long wave outgoing radiation and convective heat flux are dependent on the level of openness to the sky as well. During sunny conditions sky obstructed sites have reduced energy fluxes compared to open sites. Transpiration of the riparian vegetation causes additional energy loss of the system (Benyahya et al. 2012; Garner et al. 2014; Hannah et al. 2008; Trimmel et al. 2016, Webb et al. 2008).

Apart from its influence on average stream temperature vegetation shade can produce important microthermal gradients in the river profile which are of ecological significance (Clark et al. 1999). In particular, the maximum water temperatures during heat waves are reduced significantly by vegetation shade (Garner et al. 2014)

Though the influence of vegetation on water temperature is evident, its ability to mitigate climate change is not yet sufficiently understood.

There are different approaches to predicting stream temperature. Water temperature can be predicted using statistical functions (stochastic models) and its correlation (regression models) to known variables (e.g. air temperature, water temperature of the previous days or streamflow). Use of air temperature as a surrogate for future water temperature can lead to errors when linear (Erickson and Stefan 2000; Webb and Nobilis 1997) or non-linear (Mohseni et al. 1998) regression models are applied (Arismendi et al. 2014). Stochastic models used to determine the long term annual component of temperatures and their short term residuals separately yielded good results (Caissie et al. 2001). Including a discharge term in the regression model improves the model's performance during heat wave and drought (low flow) conditions, when water temperatures are most sensitive to air temperature (van Vliet et al. 2011).

Energy balance models resolving all energy fluxes affecting a river system are the best suited to predict stream temperature (Caissie et al. 2007) but demand the most input data. These models are able to simulate energy flux changes caused by increased or decreased river shade.

In this study the water temperature and all relevant influencing parameters of the rithron and upper potamal sections of the eastern Austrian river Pinka with a catchment size of 664km2 were recorded and subsequently simulated with the 1D energy balance model Heat Source (Boyd and Kasper 2003). Scenarios of complete riparian vegetation removal and maximum riparian vegetation were calculated for the conditions measured during the maximum heat wave, which took place in eastern Austria during summer 2013 and for those of future heat waves that, based on regional climate scenarios, are likely to occur by the end of this century.

The aim of this study is (1) to estimate the magnitude of stream temperature rise in a rithron to upper potamal river section during extreme heat events until the end of this century and (2) to investigate the ability of riparian vegetation to mitigate the expected water temperature rise.

Sections: In section 2 the study region, vegetation and climate scenarios as well as the method used to simulate stream temperature are explained. In section 3, first the influence of atmospheric energy fluxes on stream temperature in general are analysed along the study region during a heat wave in 2013. The influence of vegetation shade is discussed in this context. After this, the modelled future climate is described and finally the predicted water temperatures for different heat wave events for three future periods and three vegetation scenarios are presented. In section 4 the uncertainties of the presented results are outlined. In section 5 the results are discussed, taking into account the uncertainties of the predictions. Section 6 sums up the paper and points out the consequences of the papers findings.

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2 Methods

2.1 Study region

The river Pinka originates at 1480 meters above sea level (m.a.s.l.) in the eastern Austrian Alps and discharges about 100 kilometers downstream at 200 m above sea level into the river Raab. The study region covers the river Pinka from its most upstream gauge close to Pinggau at 13 km from the source (DFS 13) and 559 m.a.s.l. to the gauge at Burg 49 km downstream (DFS 62) at 240 m.a.s.l. (Fig. 1), before heavy modifications by water power plants start. In the first 10 km the river has a slope of 0.017 m m^{-1} whereas in the remaining section the slope is only 0.004 m m^{-1}. The meteorological reference station used is located at the centre of the study region at DFS 39.

In this region the highest temperature increases and the largest precipitation reductions in Austria have been observed (Böhm et al. 2009). The analysed period was an extreme heat wave that ran from 2 – 8 August 2013, which was the most intense heat wave of the year 2013. The mean air temperature of this episode was comparable to a 20 year return period 5 day event (see section 2.3) for the period 1981–2010. During the analysed period low flow conditions were prevailing. The river flow volume increased from 0.18 m^3s^{-1} at the upstream model boundary (DFS 13) to 0.76 m^3s^{-1} at the downstream model boundary (DFS 62). Main tributaries entered the river at DFS 16.5, 22 and 53.5. The mean flow velocity was 0.46ms^{-1} and it took the river water about 30 hours to traverse the studied length of the river. The river bankfull width varied from 4 to 10 m. The maximum depth of the different river sections varied between 0.1 and 0.5 m and was 0.17 m on average.

The riparian vegetation cover of this region and water temperature were investigated by Kalny et al. (2015), Holzapfel et al (2015) and Holzapfel and Rauch (2015). The vegetation composition ranges from commercial spruce (*Picea abies*) forest close to the source and near natural deciduous riparian vegetation sections with willows (*Salix sp*.), poplars (*Populus sp*.), maples *(Acer sp*.), ash (*Fraxinus excelsior*), alder (*Alnus glutinosa*) and wild cherry (*Prunus sp*.) to highly altered sections with only one-sided sparse tree plantations of e.g. maples (*Acer sp*.) or lime trees (*Tilia sp*.) lining the river course.

2.2 Vegetation scenarios

To estimate the influence of different shading elements the following scenarios were used: no vegetation cover (V0), maximum vegetation cover (V100) and actual vegetation cover (STQ).

STQ used the best available status quo input data for vegetation, bank and topographic shade as described in Kalny et al. (2015) and above.

For V0 all vegetation parameters (vegetation height, density and overhang) were set to 0 so that no vegetation shading occurs. V100 was defined as: 30 m height and 8 m overhang and 90 % vegetation density. This scenario ensures full vegetation shade. The fact that the density is below 100 % still enables some exchange with the atmosphere. River bank and topography were not changed in the vegetation scenarios. The average difference in stream temperature between no vegetation and maximum vegetation during the maximum heat wave of 2013 was calculated to be 3.81 °C by Trimmel et al. (2016).

The influence of bank shade on mean water temperature, not considering riparian vegetation, was calculated to be 0.31 °C, while the mere influence of topographic shade was calculated to be 0.44 °C. Existing vegetation on the other hand was found to be responsible for 4 times as much influence on temperatures (1.68 °C) (Trimmel et al. 2016). Although not negligible, topographic influences cannot be changed, and bank shade is more difficult to change than vegetation, especially because the river Pinka is mainly regulated with steep river banks of 73–90° or section wise 55–72° and runs through intensively managed cultural land.

While in Trimmel et al. (2016) the mean influence of vegetation along a 22.5 km long uniform reach was analysed, in this study the longitudinal changes from a more diverse section of 49 km including upstream forested regions and tributaries are examined.

2.3 Predicting stream temperature

To obtain future meteorological conditions data from the regional climate models (RCM) Aladin (driven by the global climate model ARPEGE), Remo andRegCM3 (both ECHAM 5 driven) for the location of the reference station were extracted. The aim was to estimate possible maximum temperature values, therefore data from Aladin, the climate model with the most extreme dry and hot summers, were used. The RCMs were bias corrected using the quantile mapping technique (Déqué 2007) based on the gridded data set of the ETHZ (Frei et al., 1998) for precipitation and the E-OBS data set (Haylock et al., 2008) for temperature. In a second step the data were spatially localized to a 1 km x 1 km grid for the area encompassing the area under investigation using the Austrian INCA data set (Haiden et al. 2011). In a third step the data were temporally disaggregated from a resolution of one day to one hour. Temperature was disaggregated based on the daily maximum and minimum temperatures using three piecewise continuous cosine curves, precipitation was disaggregated using stochastic functions whose distributions are based on 10 minute precipitation statistics from stations close to the target areas (Koutsoyiannis 2003, Goler & Formayer 2012). The temperature data were elevation corrected with a lapse rate of 0.65 °C per 100 m.

During the maximum heat wave event of 2013, field measurements were collected in the region. Global radiation, air temperature, air humidity and wind speed was measured at a reference station located at DFS 39 km 47° 16’ 11.055” N 16° 13’ 47.892” E, 300 m.a.s.l. (Trimmel et al. 2016). To link the measured micro scale meteorological data to topo scale meteorological data a systematic intercomparison between the local meteorological stations of the Austrian Weather Service (ZAMG) and the 1x1 km gridded observational data set INCA (Haiden et al., 2011) was done. These comparisons showed a high consistency, so the INCA data set was used to represent the local meteorological conditions within the catchment.

The model is very sensitive to discharge rates. A change in discharge of 0.1 m^3s^{-1} leads to a 4 times increase in stream temperature (0.4 °C) (Trimmel et al. 2016). Because the aim was to estimate the influence of vegetation shade, clear sky periods were chosen where no or only minor precipitation events occurred so discharge was fixed at low flow condition. The mean low flow conditions (MLF) of the gauging station Pinggau DFS 13 1981–2010 (MLF = 0.143 m^3s^{-1}), which is

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maintained by the Hydrographischer Dienst Österreich were used in the model. MLF is defined as the average discharge of all discharges below the 5% percentile discharge. At the other end of the study region at DFS 62 the corresponding flow volume is 0.795 m^3s^{-1}. The MLF lies slightly above the discharge level recorded during the heat wave event in 2013 both for DFS 13: 0.139 m^3s^{-1} and DFS 62: 0.759 m^3s^{-1}.
Topographic, vegetation, river morphology, hydrological and meteorological data were used to simulate future water temperature. Existing data sets and parameters obtained from Austrian authorities and the literature were completed with field surveys and measurements during 2012, 2013 and 2014. Vegetation height and density was sampled in a 50m buffer on both sides of the river. Vegetation overhang, morphology of the river bank and bed were all recorded at the whole river stretch (Kalny et al. 2015; Trimmel et al. 2016).

Stream temperature and flow volume were used as upstream boundary condition. For the 2013 episode these values rely on observations. To obtain equivalent data for future conditions first the maximum water temperature was modelled at DFS 13 km using the expected air temperature as input (Mohseni et al., 1998). The water temperature was split into two components: the long term seasonal component (or annual component) and the short term non seasonal component (or residuals series) (Caissie et al. 2001). The annual component was calculated according to Kothandaraman (1971) and the residuals were calculated with a stochastic second-order Markov model after Cluis (1972) and Salas et al. (1980). Observed water temperatures over the period 7 July 2012 to 9 September 2014 were used to fit the model. The coefficient of determination R^2 between observed and predicted water temperature for 7 July 2013 to 15 May 2014 is 0.96, the RMSE 0.08, for July 2013 R = 0.92. To take into account the climatic trend caused by the warming of the land surface (Kurylyk et al. 2015) the difference between the moving average of a 30 year climate period and the reference period 1981–2010 was added to the annual component.
The substrate temperature was initialized with the upstream model boundary temperature and calculated along the river using all available substrate information (Trimmel et al. 2016) and affects steam temperature via hyporheic flow and conduction flux. Deep alluvium temperature was not included in the calculation because it was assumed that during low flow conditions there is no deep groundwater influence. Furthermore the region is very inhomogeneous and the spatial distribution of the groundwater level is unknown (Pahr 1984).
Tributaries are defined by their water temperature and discharge values. The discharge and water temperature of the main inflows of the 2013 episode could be partly estimated using field measurements. The water temperature data of the remaining tributaries and their future values were synthesised using the daily fluctuations of the boundary station adding a fixed offset depending on the distance of the inflow to the boundary station. Missing discharge information was supplemented using percentages from the discharge at gauge Burg, as they were estimated during 2013.

Using the deterministic energy balance model Heat Source version 9 (Boyd and Kasper, 2003; Garner 2007) and the data sets described above, the energy fluxes along the river, hydraulics and stream temperature were simulated along the Pinka.

The model had been adapted and validated for usage at the Pinka during heat wave conditions by Trimmel et al. (2016). The sensitivity of Heat Source towards all meteorological and shading input parameters was tested and the influence of vegetation, bank and topographic shade analysed.

By fine tuning the morphological input (bottom width, roughness parameter Manning's n and sediment hyporheic thickness) and the wind parameterisation, the model's validity could be considerably improved. Tuning increased the coefficients of determination R^2 for stations analysed in Trimmel at al. 2016 from 0.87–0.91 (daily min), 0.90–096 (daily mean) and 0.86–0.92 (daily max) to 0.96–0.98(daily min), 0.96–0.99(daily mean) and 0.94–0.98 (daily max).

2.4 Selection of extreme heat events

The focus of this study was to estimate the change in water temperatures during extreme heat events caused by the expected rise in air temperature compared to the last observed period (1981–2010: "OBS"). Episodes were selected by choosing future heat wave events in three periods (2016–2045: "2030", 2036–2065: "2050", 2071–2100: "2085") in the summer months (June–August) that were simulated for the emission scenario A1B by the climate model Aladin (Radu et al. 2008). The events were chosen by selecting periods when the 5 day mean air temperature exceeded different thresholds using the percentiles of the 5 day mean air temperature of the three periods, which corresponded to an event with a 1 year (1a), 5 year (5a) or 20 year (20a) return period as well as the heat wave that represented the maximum event of the period (Max). The selection criteria are shown in Table 1. The start was 14 days prior to the end of the episode to allow spinup of the Heat Source model, so that all episodes have equal length of 14 days. Within this short time span during summer there are no significant changes in vegetation cover, as it was the case in other studies performed earlier in the year (e.g. Benyahya et al. 2012).

The heat wave 2013 as recorded in the permanent stations in this region and calculated according to Kysely at al. (2000) lasted from 23 July 2013 to 9.August 2013 (19 days). For comparison with the selected future episodes it was shortened to the 14 days prior to the last five days of maximum temperature: 25 July–8 August 2013. The last 5 days of the 2013 event were of the magnitude of a 20 year return period event of the OBS period.

3 Results

3.1 Influence of atmospheric energy fluxes and vegetation shade on stream temperature

The most important influences of atmospheric energy fluxes and vegetation shade on stream temperatures are depicted in Fig. 2. The mean view to sky (VTS) for the study region under current conditions (STQ) is 0.55. If all vegetation is removed (V0) there is still some remaining shade caused by topography and the river bank which reduces VTS to a value of 0.89. If maximum vegetation is assumed (V100), the value of VTS is strongly reduced, but still amounts to 0.16 on average because only 90% density was assumed. Peaks can be seen at broader river sections or sections oriented East-West.

The most important energy inputs on the river surface during the study period and

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For the study period and region the most important inputs on the river surface were short wave radiation flux with an average of 102 W m^{-2}, sensible heat flux with an average of 40W m^{-2} and long wave radiation with an average of 17 W m^{-2} .

The main energy output was latent heat flux. Latent heat flux was calculated using two different evaporation calculation methods. The Penman method led to high evaporation flux, with outputs even exceeding short wave radiation inputs at 120 W m^{-2} on average. The mass transfer method does not use the radiation balance and shows less pronounced peaks in open sky reaches. Evaporation calculated using the mass transfer method showed a much lower energy flux at 66 W m^{-2} on average leading to higher predicted water temperatures (+1.48 °C compared to Penman). The results of the Penman method for mean water temperature (21.8 °C) fitted better to the observed water temperatures (21.6 °C). The correlation coefficient R^2 exceeded 0.95 for the daily means and 0.90 for daily minimum and maximums for most of the 11 observation points if the whole 14 days spin up time span were considered. Because the Penman method performed better than the mass transfer method, the Penman method was chosen for further analyses.

Looking at the longitudinal distribution of energy fluxes along the river it can be seen that sensible heat flux and long wave radiation flux show their highest values close to the source. This leads to a rapid increase in the water temperature of the cool spring water.

All energy fluxes are dependent on the degree of openness to the sky, and show the same pattern along the river. Short wave radiation and latent heat flux in particular are strongly influenced by the value of the VTS and show distinct cutbacks where shading occurs.

Reductions in water temperature with other causes than variations in the value of the VTS are smaller and are caused by mixing with the water of incoming tributaries.

During heat waves the difference between air and water temperature increases, which triggers intensified evaporative flux that cools the river, but also causes increased sensible heat flux that heats the water column. Heat waves occur during high solar insolation episodes so while turbulent fluxes act in both directions, radiative energy fluxes are the main reason for increased heat input to the stream. Vegetation counteracts this effect during the day, which is also when maximum temperatures are reached. This reduction in energy input is not balanced by the reduced cooling at night caused by reduced sky view.

3.2 Future climate input

The selection criteria air temperature increases depending on the return period of the event (Table 1, 2). Apart from the 1a and 5a events of 2030 and the 1a event of 2050 all events are warmer than the 2013 heat wave. Air humidity during the selected events decreases slightly until the end of the century, but has a value below average during the 2013 event (Table 2). The reduction in humidity might lead to higher evaporation rates in the selected future events. The wind speed of 2013 also exceeds the wind speed of all future events (Table 2). Table 2 also shows the average global radiation received during each event per day. Reduced solar input during these events might cause lower maximum water temperatures. Future boundary water temperature increases by the end of the century by up to 4.1 °C (Table 2).

The extraction of the future climate data were based on the location of the INCA grid. INCA data for the heat event in 2013 could be compared with data measured directly at the river. The INCA data assume a greater distance to the river surface and show higher mean and maximum air temperatures, but also lower air humidity and higher wind speed. This difference in meteorological input data results in a 0.1 °C higher water temperature (Table 3). Maximum water temperature is affected also, showing a reduction of 0.3 °C. Minimum water temperature is 0.6 °C warmer when INCA data input were used.
To be able to directly compare the 2013 event with the future scenarios, henceforth the simulation using the INCA data of 2013 is referred to as “20a OBS”.

3.3 Future water temperatures

The stream temperatures increase from the upstream model boundary at DFS 13 to DFS 62 during the 2013 heat wave event was about 7 °C (Fig. 2). To analyse future changes along this longitudinal gradient, the location of the reference station, which is positioned in the centre of the study region at DFS 39 km, was used. As a temporal reference the focus was placed on the 20 year return period events of the 2071–2100 climate period as it represents the maximum expected temperature rise.
The mean water temperature (Fig. 3, Table 3) of the river Pinka and MLF at DFS 39 during the 20a heat wave event of the periods 2016–2045, 2036–2065 and 2071–2100 are predicted with 22.4 °C, 22.6 °C and 25.5 °C respectively. The corresponding predicted maximum water temperatures are 25.0 °C, 24.8 °C and 27.3 °C. These predictions represent a significant increase over the mean temperatures of the 20a event of the OBS period of 22.5 °C (maximum temperature: 24.4 °C) by the end of the century.
For mean temperatures a minor increase in water temperature is predicted for the first half of the century even for extreme heat events with a 20 year return period (Table 4). However, by the end of the century (2071–2100) a remarkable increase of +3 °C was modelled. Also maximum water temperatures show increases. For the period 2016–2045, maximum temperatures increase more than mean temperatures with a change over baseline conditions of +0.6 °C. By 2071–2100 the increase in maximum temperatures is predicted to be 2.9 °C compared to the OBS period, which is similar to the predicted increase in mean and minimum water temperatures (Table 4).
Supposed the existing vegetation were removed, the mean water temperature might reach 26.7 °C during 20 year return period heat events at the end of the century, which is 4.2 °C above the level of the STQ scenario of the OBS period. Maximum temperatures can even reach 28.9 °C, which is 4.5 °C more than in STQ scenario of the OBS period (Fig. 3, Table 3, 4).
Supposed maximum riverine vegetation was implemented the expected mean water temperature is predicted to reach only 23.9 °C, which is 1.4 °C above the level of 2013 (Fig. 3,Table 3,4). The maximum temperature reached in this scenario is 25.5 °C which is only 1.1 °C above the maximum event of the OBS period (Fig. 3, Table 3, 4).
Vegetation is not able to compensate fully the temperature increase expected by the end of the century. For the climate period 2036–2065 though, riverine vegetation has the potential to more than compensate for climate change during extreme

events and could even cause a reduced warming of –1.2 °C on average and –1.4 °C concerning maximum temperatures (Table 4).

Looking at the longitudinal distribution of water temperature along the river it can be seen that for the Pinka the benefit of additional vegetation becomes more distinct in the downstream sections. This can be explained by the slower flow velocities in comparison to the steeper upstream sections, which give short wave radiation in unshaded sections more time to heat the water column. In sections of greater river width or East–West orientation riparian vegetation has slightly less influence on the incoming solar radiation and which is reflected in the stream temperature during heat waves.

Water temperature is especially sensitive to the removal of vegetation between DFS 15 and DFS 25 where there are presently forests which prevent the cool headwaters from warming (Fig. 4).

4 Uncertainties in predicted stream temperature

In this study upstream model boundary stream temperature was initially predicted using air temperature using the method of Caissie et al. (2001). Using this methodology the air–water temperature difference increases until the end of the century and as the upstream model boundary influences sediment temperature and serves as surrogate for tributary temperatures, this error is able to cause a severe underestimation in the overall predicted stream temperature. A certain thermal lag could be explained by the dense snow cover in the headwaters during winter, which might retard groundwater warming (Kurylyk et al., 2015) and therefore also spring water warming. These effects are not modelled though. The depth of ground water and type of soil – especially humic soils with high heat capacity and low thermal conductivity – can cause an additional lag of ground water warming with respect to air temperature. A lagged temperature response in the order of up to 50% of the warming trend is feasible after 100 years (Kurylyk et al. 2015). In the case of the 1.7 °C/century increase of the IPCC B1 scenario, Kurylyk et al. (2015) simulated a temperature lag range of 0.94–1.6 °C/century. In our case the soils are inhomogeneous and have sandy as well as karstic regions and lags of minor dimensions are expected. Therefore a climate trend was added to the annual component to minimize the air–water temperature difference.

The predicted water temperature for the 49 km study region included full energy flux and hydrologic calculations. Air temperature was used next to other meteorological and morphological parameters in the calculation of latent and sensible heat flux as well as long wave radiation flux. The sensitivity of the model to changes in meteorological input parameters but also shading parameters within data precision was tested for 2–8 August 2013 on a 22.5 km long reach of the river Pinka by Trimmel et al. (2016). Air temperature uncertainties of ±0.2 °C were assumed in this sensitivity study. Variations of air temperature in this range led to a maximum change in mean water temperature of +/– 0.1 °C. Changes in vegetation height, density and overhang caused changes in water temperature of +/–0.40 °C, +0.44 /–0.46 °C and +0.01 /–0.05 °C respectively (Trimmel et al. 2016). Effects on maximum water temperatures showed to be very similar for most input parameters. Mainly global radiation and cloudiness affect maximum water temperatures to a greater extent than mean water temperatures. Using the model with a fixed cloudiness value for the calculation of the atmospheric emissivity does not give large errors regarding mean values, but does so regarding maximum stream temperature (+/– 0.7 °C).

In this study only the mitigating effects of vegetation shade during episodes of high solar irradiance are presented where shading can effectively reduce the increase of stream temperature, especially its maximum temperature. However, during overcast sky conditions the impediment of the nocturnal long wave back radiation and the reduced wind speeds at the river surface due to the higher roughness of vegetated river banks prevents cooling.

Not tackled were other aspects related to future development and climate change, such as potential heat sources or sinks as discharge of tempered waste water, changes of ground water level, possible changes in stream velocity and shading as sediment changes, impoundments, regulation and canalization as well as feasible discharge changes such as withdrawal of water for irrigation. The climate input is using only one possible emission scenario simulated by one regional climate model.

5 Discussion

As the air–water temperature difference – unlike the absolute temperature level – is not expected to increase, no increase in sensible heat flux can be predicted. Global radiation during heat waves has no climate change signal – so the radiative fluxes do not have an increasing trend. Thus the ability of vegetation to alter the stream's microclimate and water temperature will remain the same. Average heat wave temperature and daily maximum temperatures during heat waves show a similar warming trend as mean summer temperatures (Melcher et al. 2014).

In this study for a heat wave with 20 year return period in the climate period 2071–2100 with +3.8 °C increase in air temperature in respect to the observed period and MLF discharge, increases in maximum, mean and minimum stream temperatures of close to +3 °C in respect to the observed period were simulated. Considering a likely discharge decrease (Nachnebel et al. 2014) slightly higher temperature rise might be expected.

The relatively low values of water temperature predicted for the 20a 2050 heat wave might be explained by higher wind speeds and lower air humidity causing higher evaporation rates and lower solar radiation energy input compared to 2013. For the V0 scenario low water temperatures were also predicted, which would support the idea of increased evaporation. The maximum vegetation scenario shows comparably warm stream temperatures in respect to 2013.

The values predicted for the end of the century are clearly above the model uncertainty and in correspondence with values published by other studies.

For Austrian rivers, for example summer stream temperature increased by 1.5 ° C between 1980 and 2011 (BMLFUW 2011). An increase of up to 3.2 °C by 2050 in respect to 1900 for the river Danube was predicted by Dokulil and Donabaum (2014). Van Vliet et al. (2011) analysed 157 river temperature stations globally for the 1980–1999 period and predicted increases of annual mean river temperature of 1.3 °C, 2.6 °C and 3.8 °C under air temperature increases of 2 °C, 4 °C and 5 °C respectively.

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Vegetation scenarios were simulated. Removal of vegetation would magnify the stream temperature increases during 20 year return period events by the end of the century by up to 4.2 °C (mean) and 4.5 °C (daily maximum). Additional riparian vegetation on the other hand could mitigate part of the rise in maximum temperatures, so there would only be a 1.1 °C increase. The increase of mean temperatures is reduced to about 1.4 °C, so riparian vegetation management alone is not enough to compensate for the predicted warming caused by climate change. The water temperature difference between full and no vegetation shows no clear trend for future conditions. These reduction rates lie within the range of observed changes of pre- and postharvest situations (Cole and Newton 2013; Moore et al. 2005).

Although vegetation can have important effects on stream temperature, there will be river sections which will not be affected by the addition (or removal) of vegetation due to upstream or lateral, surface or subsurface advection of heat or topographic shade (Johnson and Wilby 2015).

Attention has to be given to the fact that vegetation mainly causes reduction of maximum stream temperatures by reducing the solar radiation input at the river surface by shading. This effect is strong during times of clear skies and high solar irradiation. During cloudy skies and during night time this effect is less pronounced while outgoing long wave radiation is still impeded by the sky obstruction caused by vegetation. This in turn could lead to higher mean and minimum temperatures, which can be also seen in the simulated events of low global radiation.

6 Conclusions

In this study the influence of expected changes in heat wave intensity during the 21st century on stream temperature in the rithron to upper potamal river section of the eastern Austrian river Pinka were simulated and the mitigating effect of riparian vegetation shade on the radiant and turbulent energy fluxes is analysed.

By the end of the century (2071–2100) in the study region there is predicted to be an air temperature increase of 3.8 °C to 5.6 °C during annual or less frequent extreme heat waves in comparison to the observed period of 1981–2010.

Minor stream water temperature increases are modelled for the first half of the century, but a strong increase is predicted for the period 2071–2100. The magnitude of maximum, mean and minimum stream temperature rises for a 20 year return period heat event is estimated to be in the range of 3 °C.

Vegetation can reduce maximum river temperature during heat waves, where high solar radiation is usual. Additional riparian vegetation is not able to fully mitigate the expected temperature rise caused by climate change, but can reduce maximum stream temperatures by 2.2 °C, mean by 1.6 °C and minimum by 0.9 °C on average during extreme heat waves. Removal of existing vegetation amplifies stream temperature increases, especially maximum temperatures can cause an increase by 1.8 °C in comparison with the actual vegetation scenario on average. Maximum stream temperatures could exceed a 4 °C increase compared to the observed period even in annual heat events. There might be counterproductive effects of full vegetation cover on stream water temperatures during periods of reduced solar radiation. Generally riparian vegetation can produce important microthermal gradients which are vital for many species (Clark et al. 1999).

This study shows that it is very likely that during extreme events an increase of 2 °C, which is the magnitude of the temperature differentiation of the local fish zones (Melcher et al. 2013, Pletterbauer et al. 2015), will be exceeded during this century. At a stream temperature of 20 °C, cold water adapted species reach their lethal phase (Melcher et al. 2014, Schaufler 2015). During a simulated annual heat wave event in the period 2016–2035 this threshold was never exceeded in the most upstream region (DFS13), which is presently populated by the cold adapted species brown trout (Guldenschuh 2015). At the end of the century during a heat wave event of a 20 year return period the threshold is likely to be exceeded for 72 of 120 h. At the lower boundary of the trout zone (DFS 20) 20°C during heat waves already is exceeded for 70 of the 120 h at the beginning of the century, but can be reduced by riparian vegetation shade during annual heat events to only last 9 h in total. The mitigation possibilities of vegetation are limited though, and cannot fully compensate for the whole predicted temperatures rise. At the end of the century in heat waves of a 5 year or less frequent return period, even if maximum vegetation is assumed, 20 °C will be exceeded during the whole heat wave event.

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Code availability: The last official version of the used software TTools and Heat Source are available online at: http://www.deq.state.or.us/WQ/TMDLs/tools.htm
The changes included into Heat Source within this study will be implemented in the next version, which will be available at the same location.

Data availability: The simulation input and result data sets for the present and future heat wave episodes used in this article are part of the research project BioClic and will be published together with the other vegetation, morphological and biological data sets produced in the project on the freshwater biodiversity data portal (http://data.freshwaterbiodiversity.eu/) and receive a doi.

Authors contributions: Weihs P. helped to better understand the energy fluxes of the riverine system. Formayer H. selected the climate episodes and helped to interpret the significance of the results. David L. produced the climate episode data and the upstream boundary water temperature. Kalny G. organized the field campaigns and built the basic vegetation and morphology data set. Trimmel H. further processed the data for the use of Heat Source, adapted and validated the model. She run the Heat Source simulations for all selected episodes and prepared the manuscript.

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	1a	5a	20a	Max
1981-2010 ("OBS")	23.1	25.0	27.2	27.4
2016-2045 ("2030")	23.4	26.6	27.2	29.0
2036-2065 ("2050")	24.2	27.2	28.4	28.8
2071-2100 ("2085")	28.1	30.6	31.0	32.0

Table 1: Mean 5 day air temperatures of future heat wave episodes used as selection criteria, shown with equivalent values from the observed period for comparison.

	OBS		2030				2050				2085			
	M.	I.	1a	5a	20a	max	1a	5a	20a	max	1a	5a	20a	max
Air temp. (mean) [°C]	26.2	27.2	23.3	26.6	27.2	29.0	24.2	27.2	28.4	28.8	28.1	30.6	31.0	32.0
Air temp (mean daily max) [°C]	34.5	35.7	30.0	33.7	34.6	37.5	29.5	33.7	35.9	36.9	34.8	38.2	39.6	39.0
Air humidity [%]	62	55	73	57	55	53	54	56	56	60	58	51	48	52
Wind speed [m s^{-1}]	0.6	1.4	0.7	0.9	0.9	1.0	1.3	1.1	1.1	0.8	1.3	1.2	0.8	0.9
Global rad. [MJ m^{-2} d^{-1}]	24.6	24.6	23.4	25.0	28.0	29.0	24.9	28.7	23.1	21.7	27.3	24.5	23.8	20.9
Boundary water temperature [°C]	16.3	16.3	14.1	15.9	16.0	16.8	15.6	16.2	17.0	17.5	17.5	19.4	20.4	20.3

Table 2: Mean and daily maximum air temperature, air humidity, wind speed, global radiation at the reference station and water temperature at the upstream model boundary averaged for the selected 5 day heat episodes in 2013 and the 1a, 5a, 20a and Max events of the climate periods centered on 2030, 2050 and 2085. For 2013 (OBS) measured values of the reference station 2 m above the river (M.) and interpolated measurement data from the INCA (I.) data set are shown.

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	(a) max			(b) mean			(c) min		
	V0	STQ	V100	V0	STQ	V100	V0	STQ	V100
Meas.	26.6	24.7	22.4	23.8	22.4	20.7	20.2	19.5	18.5
INCA	26.1	24.4	22.1	23.7	22.5	20.8	21.0	20.1	19.2
2030_1a	24.5	23.1	20.7	21.5	20.4	18.6	16.5	16.5	16.3
2030_5a	25.9	24.3	22.1	22.5	21.3	19.7	17.8	17.2	16.5
2030_20a	27.0	25.0	22.5	22.2	22.4	20.2	19.4	18.2	17.2
2030_max	27.2	25.7	23.5	24.8	23.4	21.6	21.9	20.8	19.5
2050_1a	24.3	22.6	20.0	21.6	20.4	18.9	19.0	18.2	17.3
2050_5a	26.5	24.8	22.2	23.7	22.3	20.5	20.4	19.5	18.4
2050_20a	26.6	24.8	23.0	23.7	22.6	21.3	20.2	19.9	18.9
2050_max	27.5	25.9	23.7	25.1	23.9	22.2	22.5	21.5	20.4
2085_1a	28.6	24.9	23.1	26.2	22.5	21.7	22.3	18.8	18.8
2085_5a	29.0	27.3	25.0	26.5	25.3	23.7	24.1	23.0	21.7
2085_20a	28.9	27.3	25.5	26.7	25.5	23.9	23.6	22.9	21.7
2085_max	29.3	27.8	25.7	27.1	26.0	24.6	25.0	24.1	23.0

Table 3: Daily minimum, mean and maximum 5 day mean water temperature of the 5 day episodes averaged over the river Pinka during the 1a, 5a and 20a episodes for the climate periods centered on 2030, 2050 and 2085 and mean low flow discharge at DFM 39. For 2013 (OBS), the measured values of the reference station 2 m above the river (Meas.) and interpolated measurement data from the INCA data set are compared.

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	(a) max			(b) mean			(c) min		
	V0	STQ	V100	V0	STQ	V100	V0	STQ	V100
OBS INCA	1.7	0	-2.3	1.2	0	-1.7	0.9	0	0.9
2030_1a	0.1	-1.3	-3.7	-1	-2.1	-3.9	-3.6	-3.6	-3.8
2030_5a	1.5	-0.1	-2.3	0	-1.2	-2.8	-2.3	-2.9	-3.6
2030_20a	2.6	0.6	-1.9	0.3	-0.1	-2.3	-0.7	-1.9	-2.9
2030_max	2.8	1.3	-0.9	2.3	0.9	-0.9	1.8	0.7	-0.6
2050_1a	-0.1	-1.8	-4.4	-0.9	-2.1	-3.6	-1.1	-1.9	-2.8
2050_5a	2.1	0.4	-2.2	1.2	-0.2	-2	0.3	-0.6	-1.7
2050_20a	2.2	0.4	-1.4	1.2	0.1	-1.2	0.1	-0.2	-1.2
2050_max	3.1	1.5	-0.7	2.6	1.4	-0.3	2.4	1.4	0.3
2085_1a	4.2	0.5	-1.3	3.7	0	-0.8	2.2	-1.3	-1.3
2085_5a	4.6	2.9	0.6	4	2.8	1.2	4	2.9	1.6
2085_20a	4.5	2.9	1.1	4.2	3	1.4	3.5	2.7	1.6
2085_max	4.9	3.4	1.3	4.7	3.5	2.1	4.9	4	2.9

Table 4: Difference of predicted maximum (a), mean (b) and minimum (c) water temperatures for the 1a, 5a, 20a and max event for the climate periods centered on 2030, 2050 and 2085 for vegetation scenario V0 (no vegetation), STQ (vegetation unchanged), V100 (maximum vegetation) to the 20a event of the OBS period (2013).

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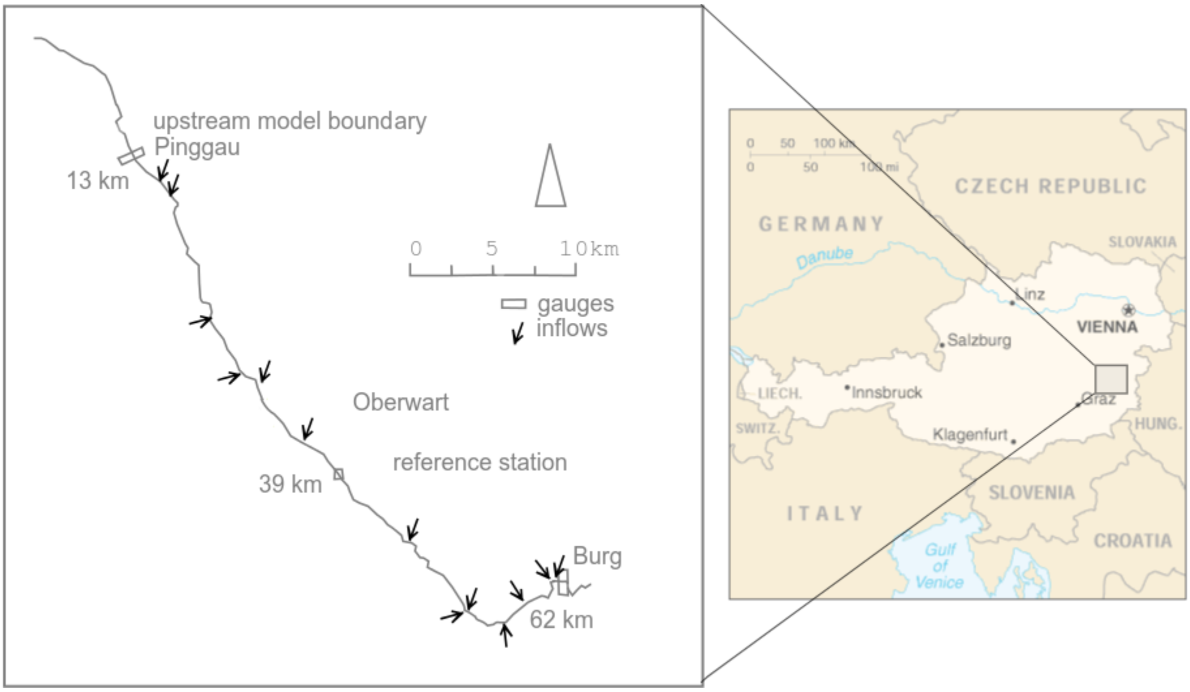

5 **Figure 1: The study region in Pinka showing gauges, tributaries and the reference station (km markers shown as distance from source).**

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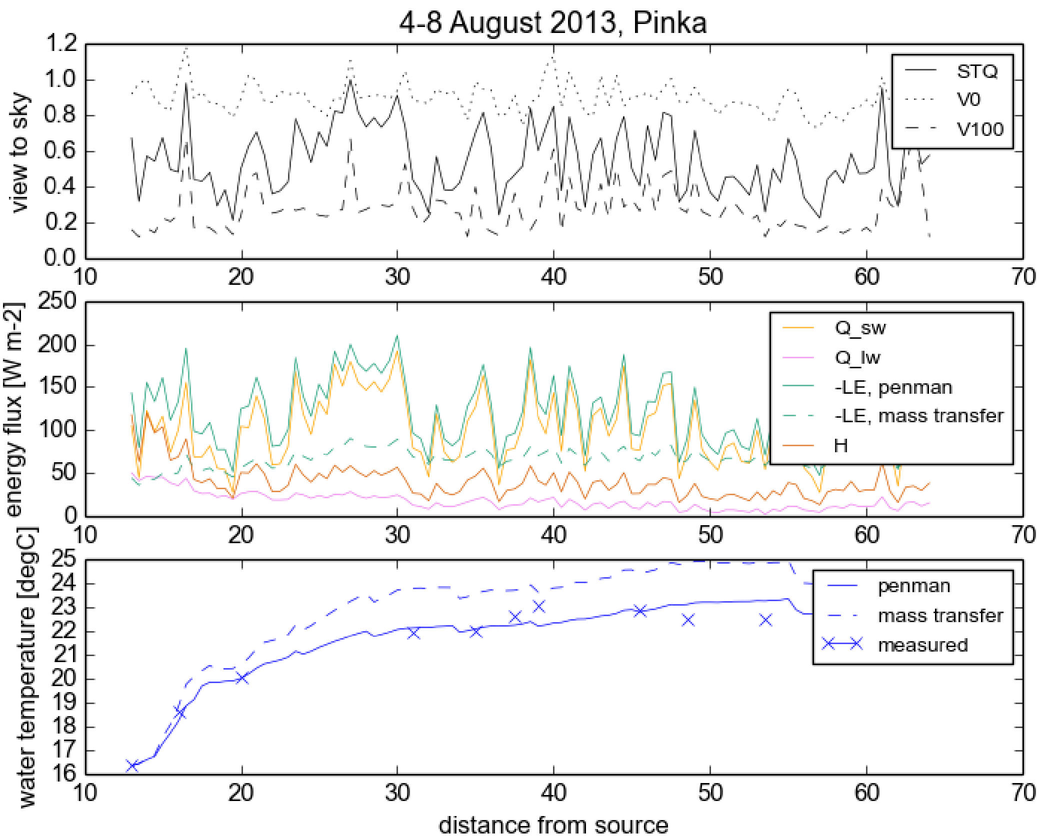

Figure 2: VTS levels for no vegetation (V0), existing vegetation (STQ) and maximum vegetation (V100), predicted energy fluxes: short wave (Q_sw), long wave (Q_lw), latent heat flux (LE) for mass transfer and penman method, sensible (H) and water temperature (WT) means for the heat wave episode of 4 - 8 August 2013.

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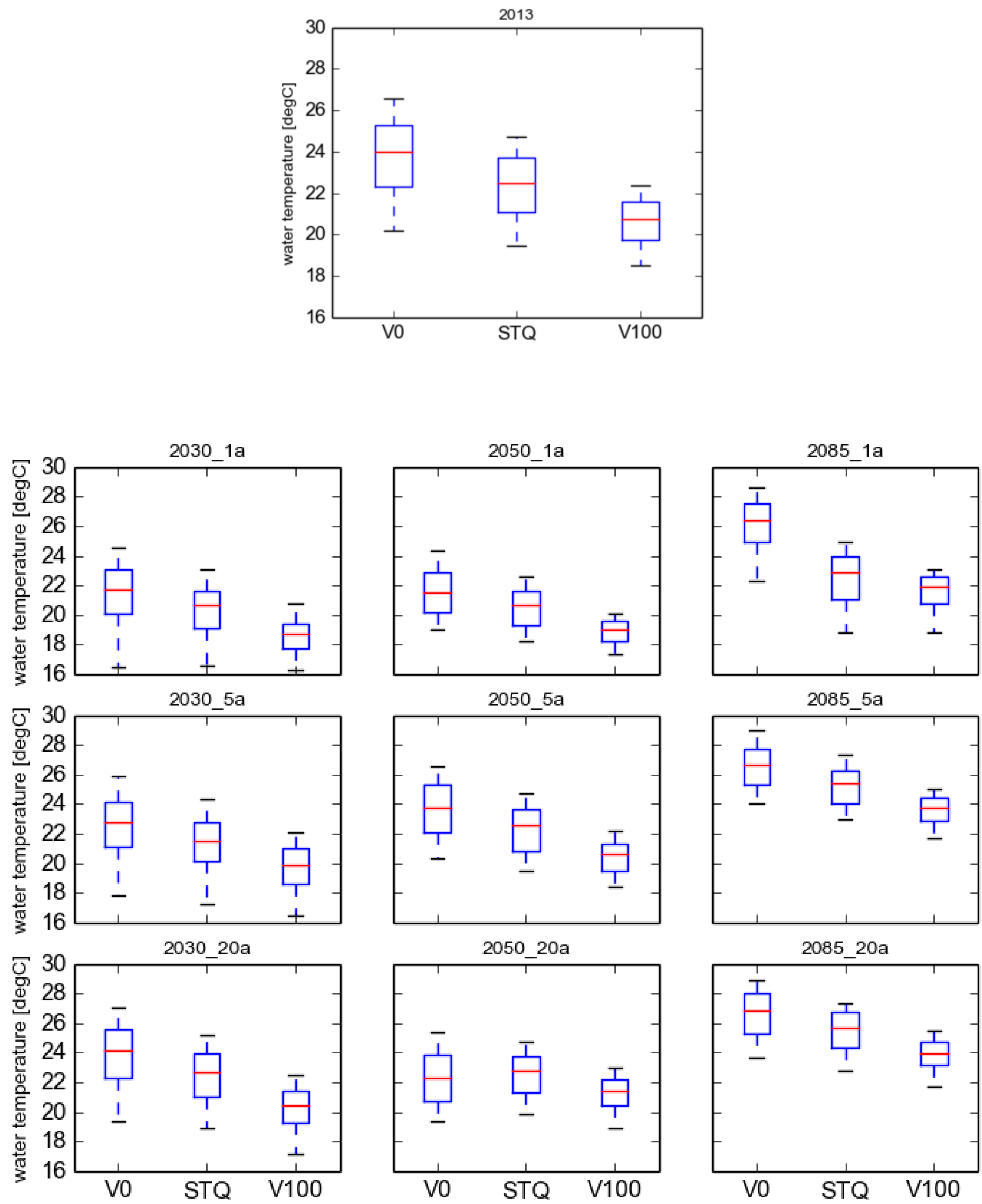

Figure 3: Box and whiskers chart showing the 5 day mean water temperature distribution during the 1a, 5a and 20a episodes for the climate periods centered on 2030, 2050, 2085 and mean low flow discharge at DFM 39.

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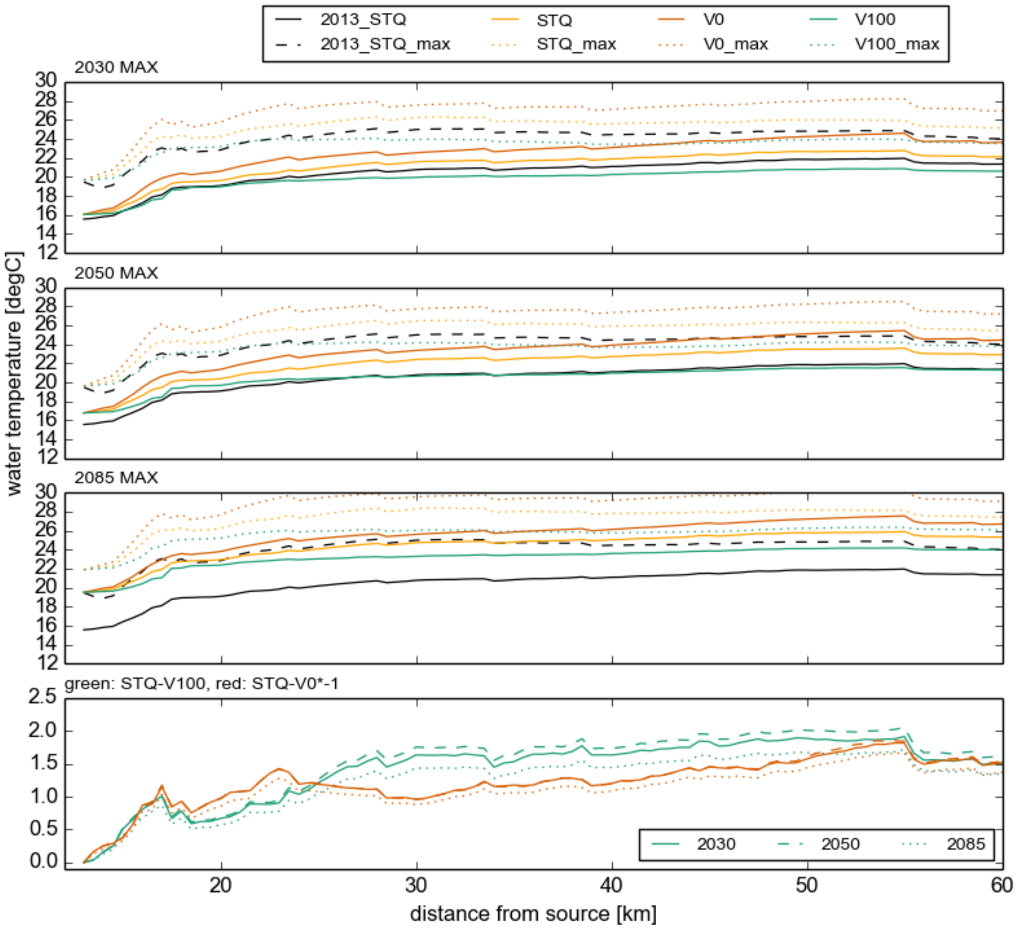

Figure 4: Mean and maximum water temperature averaged during the maximum events predicted for the climate periods centred on 2030, 2050 and 2085 along the river Pinka using vegetation scenarios V0, STQ and V100 in comparison to the maximum event recorded in 2013. The bottom panel shows the difference between STQ and V100 and STQ and V0.