Authors response:

We thank both reviewers for their useful comments and feedback and for your valuable time spent reviewing our manuscript. We gave careful consideration to all comments provided by the reviewers. Both reviewers commented that the objectives were not well presented and the structure of the paper difficult to follow. We worked on a clearer overview and hope we could facilitate readability. We have now completed the revisions and are happy to provide a updated response to all comments. Below you find a summary of the most relevant changes made in the manuscript and a marked up version of the revised manuscript for your consideration.

Response to Reviewer 1:

Some responses to your general and specific comments we gave to you have changed during the preparation of the revised manuscript. These are marked yellow. Figure 2 including caption has changed as well. Mostly the response is only clarified in correspondence with the revised version. We hope you recognize all changes as improvements.

General remarks

No.	Comment	Response
1+2	In general, this paper was difficult to read and review because it lacked focus and clear explanation of the research actually carried out. The objectives of the study were not clearly presented;	We agree and tried to improve this throughout the paper. We left the aim of the present article at the end of the Introduction following a paragraph about the scientific novelty where from the objectives of the present article are derived and hope this makes the objectives much clearer to the reader. The delimitation between preliminary work and the present article is described in the Methods now. " Preliminary work has been done and published by Holzapfel and Rauch (2015), Holzapfel et al. (2015) and during a different article by Trimmel et al. (2016). Vegetation cover and river morphology was recorded continuously along the river, stream temperatures were recorded at 12 sites as well as main tributaries of the eastern Austrian river Pinka (Holzapfel and Rauch 2015, Holzapfel et al. 2015). This data was used to set up and validate the 1D energy balance and hydraulic model Heat Source (Boyd and Kasper 2003) for the river Pinka (Trimmel et al. 2016). Further Heat Source was used to analyse the mean influence of different meteorological, hydrological and shading parameters during heat wave conditions along a 22.5 km long uniform reach (Trimmel at al. 2016).

		In the present article stream temperature was simulated with the 1D energy balance and hydraulic model Heat Source (Boyd and Kasper 2003) for 51 km along a section including upstream forested regions and tributaries for each 500m along the river, which amounts to a total of 103 sites. First the longitudinal changes of energy fluxes were analysed during the maximum heat wave, which took place in eastern Austria during summer 2013. Future heat wave episodes, which are likely to occur during the climate periods 2016-2045, 2036-1065 and 2071-2100 in the study region, were selected. Regional climate scenarios, which have been produced within the ENSEMBLE project (Hewitt et al. 2004) were further processed and the meteorological data extracted. The future upstream model water temperature was simulated according the methodology of Caissie et al. (2001). Heat Source was used to simulate the stream temperature of the river Pinka for 12 future episodes and three vegetation scenarios."
3	this was a climate change type study (and the title should have reflected this)	We agree. To make it clearer the title is extended to: "Can riparian vegetation mitigate the expected rise in stream temperature due to climate change during heat waves in a pre-alpine river?"
4	A lot of results and discussion material focused around a model which was not described within the present study. As such, this aspect was not evaluated. Nevertheless, authors presented R2, RMSE and model uncertainties, etc., which was somewhat confusing to the reviewer.	The authors agree that the description of the model was not sufficient and the methods section is not well organized and difficult to follow. We included several subheadings and restructured some paragraphs to make it easier to read. We tried to include all aspects necessary to understand the results and discussion. An exhaustive description of Heat Source cannot be given though, because this is not the scope of the article.
5	The heat fluxes presented in this study were all positive, (section 3.1) which is clearly not the case in reality (not sure how authors could model river temperatures with such fluxes)	The authors fully agree that not all the energy fluxes are positive. There is a subsection called "Energy fluxes during heat waves" included in the discussion now. On this issue we also responded within our first short comment: "In this figure the latent, sensible, short- and long wave energy flux averaged over the heat wave episode 4-8. August 2013 are shown. Extreme heat events as treated in this study are outlined by high minimum and maximum air temperatures. High minimum air

		temperatures limit radiative cooling at night, also higher air temperatures increase the sensible heat flux from the atmosphere towards the river. Under these extreme conditions long wave radiation and sensible heat flux became positive on average. Evaporation was the only energy flux, which was negative on average. The intention of Figure 2B was to better compare the magnitude of the negative latent heat flux with the magnitude of the short wave radiation balance, the magnitude of the other energy fluxes and the view to sky. This is why the latent energy flux was multiplied with (-1) and a minus sign added in the legend. In the text the term "input" and "output" was used to indicate the positive or negative direction of the energy flux. The authors however understand that this representation of the energy fluxes is misleading and will clarify this aspect."
6	The result section was difficult to follow, as authors presented both results from the present study and results from Trimmel et al. (2016). The text was almost presented as a part 2 of that paper, so reviewer was not always able to follow in the results presented were from this study or from the previous study.	We agree that the position of the section "Uncertainties" after the "Results" section was misleading. A subsection treating with the uncertainties was included at the end of the Methods section. A delimitation to preliminary work presented in a previous publication by Trimmel et al. 2016 is given in the Methods.
7	The results section also contained discussion material, and then separate discussion section was also presented.	Results are described more thoroughly now and discussion material was moved to the Discussion.
8	Finally, the reviewer is not sure of the scientific novel contribution which this present brings	We agree that a clear presentation of the scientific novelty would enhance the article. We propose to insert following paragraph following the description of the state of the art (as already posted within our second short comment): "Many studies have already addressed the influence of riparian vegetation on stream water temperature using field measurements. Other studies coped with different methods to predict stream

		temperature and few tried to answer the question on how climate change might increase stream water temperature. Mainly air temperature was used as a surrogate for stream temperature and energy flux variations at different river sections are not considered. One result or trend may however not be transferred from one river to other. Statements of the riparian vegetation's potential to mitigate influence of climate change are only reliably valid for a given type of stream and for a given climate zone. The novel aspect of the present study is to investigate the influence of climate change and of riparian vegetation on the same river and attempt to make a realistic forecast of the riparian vegetation's potential to mitigate climate change in a specific river."

Specific comments:

No.	Comment	Response
9	Pg. 1, line 13-14: "and turbulent energy fluxes analysed". Not clear, something is missing here.	Referee 1 is correct, here is one word missing. It should be "and turbulent energy fluxes **were** analysed"
10	Pg. 1, line 14: "Minor stream water temperature increases are modelled within". Authors are presenting result in the present tense; it should be in the past tense. This applies throughout the document.	This will be corrected.
11	Pg. 1, line 14-15: "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". Sentence which is not saying anything, please be more specific.	Alternative formulation - joint with the subsequent sentence on Pg 1. line 15: "Stream water temperature increases of less than 1.5°C were modelled within the first half of the century. For the period 2071-2100 a more significant increase of around 3 °C in maximum, mean and minimum stream temperatures was predicted for a 20 year return period heat event."
12	Pg. 1, line 16: "to be in the region of 3 °C". In the range of 3 °C?	Yes.
13	Pg. 1, line 16: "Additional riparian vegetation". Not clear how this will be accomplished, regrowth, re-vegetation, etc., please clarify.	In the present study it was not relevant whether riparian vegetation regrows or is planted. The aim was to predict the effect of a potential vegetation cover, which is not present now, but can possibly be accomplished.
14	Pg. 2, line 4: "riparian ecosystems play a superior role in climate change". Riparian ecosystem plays a superior role in climate change to what?	We agree, that the statement is vague. Alternative formulation to "Above that riparian ecosystem play a superior role in climate change adaptation in the 21st century": "Above that riparian ecosystems play a superior role in **determining the vulnerability of natural and human systems to** climate change in the 21st century (Capon et al. 2013)."
15	Pg. 2, line 11: "21st century are nearly certain". Not sure about this level of	Alternative formulation: "... increases of 3.5°C by the end of the 21st century **are expected in Austria (APCC 2014,** Gobiet et

	certainty.	al. 2014).“ “is expected” is the formulation used by Gobiet et al. (2014) and APCC (2014, p.84 - Figure 1.10).
16	Pg. 2, line 19: “winter half-year”. Not sure about the meaning of this term winter half-year, please clarify.	“summer (Apr – Sept) and winter half-year (Oct – Mar)”
17	Pg. 2, line 23: “Long term increases of wind speeds or storm activity cannot be detected.” Not clear.	Alternative formulation: “Various studies indicate that from observations no long term increase of wind speed or storm activity can be detected in Europe (e.g. Matulla et al. 2008). For the alpine region also no clear signs of increasing wind speed or extremes are projected for the future (Beniston et al. 2007).” Beniston, M., Stephenson, D.B., Christensen, O.B., Ferro, C.A.T., Frei, C., Goyette, S., Halsnaes, K., Holt, T., Jylhä, K., Koffi, B., Palutikof, J., Schöll, R., Semmler, T., Woth, K., 2007. Future extreme events in European climate: an exploration of regional climate model projections. Climatic Change 81, 71-95. doi:10.1007/s10584-006-9226-z Matulla, C., Schöner, W., Alexandersson, H., Storch, H., Wang, X.L., 2008. European storminess: late nineteenth century to present. Climate Dynamics, 133-144. doi:10.1007/s00382-007-0333-y
18	Pg. 2, line 26: “dominant energy input causing diurnal fluctuations”. Energy inputs are contributing to both diel and seasonal water temperature variability.	We agree, this is a good complement of the sentence.
19	Pg. 3, line 1: “Since 1980 Austrian river temperatures have increased on average by 1.5 °C during”. Here I would be more specific, one, XX or all Austrian rivers.	Alternative formulation: “stations of the Austrian hydrographic central office of different elevation, distance from source and catchment area recorded an increase of stream temperature. The data were elevation corrected using External Drift Top-Kringing (Skøien et al. 2006) and a mean trend calculated using the Mann-Kendall-Test (Burn and Hag Elnur, 2002) by BMLFUW (2011). A mean trend of 1.5 °C during summer (Jun - Aug) and 0.7 °C during winter (Dec - Feb) was calculated APCC 2014 p. 417, BMLFUW 2011).” Skøien, J., Merz, R., and Blöschl, G., Top-Kriging – geostatistics on stream networks, Hydrolology and Earth System Sciences (HESS), 10, 277-287, 2006. Burn, D.H., and Hag Elnur, M.A, Detection of hydrologic trends and variability, Journal of Hydrology 255, p107-122, 2002.
20	Pg. 3, line 6: “affect discharge volume and velocity”. I would delete velocity, as it is implied.	We agree.

21	Pg. 3, line 10-12: The information related to changes in sediment transport and climate change is not important, unless authors are implying that is has an impact on water temperatures, and clearly this study is not addressing this.	We do imply, that sediment transport changes impact water temperature, because they might alter bed conduction flow and flow velocity. Both parameters affect stream water temperature. We consider it important to list all influencing factors, even if this study was not taking into account all aspect in our calculations, because they were not all relevant for our study region and period. Alternative formulation: "Sediment changes might alter the bed conduction flow as well as flow velocity, which can influence the magnitude and variability of stream temperature. Artificial changes which deteriorate the situation are presently illegal in Austria as well (WRG 1959). … This article focused on only on the increase in air temperature caused by climate change."
22	Pg. 3, line 33: "microthermal gradients in the river profile". Not clear.	Alternative formulation: "Apart from its influence on average stream temperature vegetation produces highly spatial variable shade, which results in areas of different sun exposure and energy fluxes. These heterogeneity provides ecological niches which are important for different development stages of river fauna (Clark et al. 1999)."
23	Pg. 4, line 16-24: Too many vague statements within this paragraph. Be more specific, how many sites within the Pinka River, which regional climate scenarios?	→ see response to general remarks, comment #1+2
24	Pg. 4, line 26-32: No need to describe the upcoming sections. Delete this whole section.	We thought this was requested by the journal within the "manuscript composition" guideline, but it was removed and integrated in the Methods.
25	Pg. 5, line 9-10: "In this region the highest temperature increases and the largest precipitation reductions in Austria have been observed (Böhm et al. 2009)." Be more specific, by how much?	Alternative formulation: "In this region air temperature **rose by 2°C since 1880. Precipitation was reduced in the HISTALP region corresponding to our study region** by 10-15%, which is the largest reduction in precipitation in Austria (Auer et al. 2007, Böhm et al. 2009, Böhm et al. 2012)." Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schöner, W., Ungersböck, M., Matulla, C., Briffa, K., Jones, P., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.-M., Begert, M., Müller-Westermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S., Szentimrey, T., Cegnar, T., Dolinar, M., Gajic-Capka, M., Zaninovic, K., Majstorovic, Z. and Nieplova, E.,. HISTALP—historical instrumental climatological surface time series of the Greater Alpine Region. International Journal of Climatology 27, 17–46. doi:10.1002/joc.1377, 2007. Böhm, R.: Changes of regional climate variability in central Europe during the past 250 years, The European Physical Journal Plus, 127, doi:10.1140/epjp/i2012-12054-6, 2012. Böhm, R., Auer, I., Schöner, W., Ganekind, M., Gruber, C., Jurkovic, A., Orlik, A. and Ungersböck, M.: Eine neue Webseite mit instrumentellen Qualitäts-Klimadaten für den Grossraum Alpen zurück bis 1760, Wiener Mitteilungen Band 216: Hochwässer: Bemessung, Risikoanalyse und Vorhersage, 2009.
26	Pg. 5, line 30-33: "The average	We agree. The sentence was omitted.

	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).”. Here the reviewer is confused, results from the present study are being reported or this analysis has been carried out before, not clear.	
27	Pg. 6, line 1-6: This information does not belong here. This information should have been presented in the introduction or in the discussion section.	We agree. This sentence was meant to describe the study region, but its position is misleading therefore the sentence was shortened and moved to the Methods.
28	Pg. 6, line 7-9: Is this what is new in the present study compared to Trimmel et al. (2016), i.e., studying a reach of 49 km rather 22.5 km?	We agree. This sentence was meant to describe the study region, but its position is misleading therefore this information is included in the paragraph about preliminary studies and scope of the present article at the beginning of the Methods.
29	Pg. 6, line 27-28: “These comparisons showed a high consistency, so the INCA data set was used”. Vague statement, please be more specific and quantitative.	Alternative formulation: “Since the local permanent meteorological stations of ZAMG were used to produce the gridded INCA data set, they are highly consistent. The comparison of the INCA data with the air temperature measured at our reference station close to the river showed a RMSE of 0.67°C and a R^2 of 0.99 for consecutive hourly measurements during summer half-year 2013 (1 Apr – 30 Sept). So the INCA data set was used as proxy to represent the local meteorological conditions within the catchment.”
30	Pg. 7, line 11: “Stream temperature and flow volume were used as upstream boundary condition.” Authors should use the term discharge or river discharge, rather than flow volume.	We agree. The term “discharge” will be used.
31	Pg. 7, line 17-20: It would be better if authors would have presented root mean square errors (RMSE) rather the R2, or presenting both, as the R2 is not very informative on a model’s performance. Also, not sure about the reported RMSE of 0.08 (◦ C? maybe). If it is an RMSE of 0.08 ◦ C, it does not fit with R2 values of 0.92 to 0.96.	We agree, that these two sentences are not very useful. We also have to admit, that there was a typing error regarding the RMSE and deeply apologize for this. Apart from this the periods are confusing. We suggest following alternative formulation including corrected values: “Observed hourly water temperatures (12 537 values) 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 this period was 0.96, the RMSE was 0.68 °C. For the summer half-year 2013 (1 Apr – 30 Sept), the R^2 was 0.89, the RMSE was 0.80 °C. “
32	Pg. 7, line 22: “The substrate temperature was initialized with the upstream model boundary temperature”. Not clear about the substrate temperatures, where and at which depth?	Alternative formulation: “Heat Source uses only one substrate temperature, which is representative for the whole sediment layer. The depth of the sediment layer is set to 1m, which is corresponding to the available geological information of the river Pinka. The substrate temperature used in the model is set equal to the stream temperature at the uppermost model point. For each consecutive model point the substrate temperature is calculated depending on the local thermal conductivity, thermal diffusivity, layer depth, hyporheic exchange, the river

		morphological profile and the received solar radiation at the river bed. "
33	Pg. 7, line 27: "Tributaries are defined by their water temperature and discharge values." Vague statement. Were they measured and then used in the model?	We hope the situation is clearer using this alternative formulation: "The discharge and water temperature of **the river Pinka at the upstream model boundary** and the main **5 tributaries** of the 2013 episode **were measured**. The remaining tributaries added less than 5 % discharge each. "
34	Pg. 7, line 28-29: Not exactly clear on what the boundary station means.	We hope the situation is clearer using this alternative formulation : "The water temperature data of the remaining tributaries and their future values were synthesised using the daily fluctuations of **the water temperature at the upstream model** boundary adding a fixed offset depending on the distance of the inflow to the **upstream model** boundary." → see comment #33
35	Pg. 8, line 9-10: Information presented within these two lines and related to the climate change aspect of this study should have been clearly stated in the introduction.	The reviewer is correct. This information is included in the aims at the end of the Introduction.
36	Pg. 8, line 26-27: "The most important influences of atmospheric energy fluxes and vegetation shade on stream temperatures are depicted in Fig. 2.". There is an issue with this figure, as three different vegetation scenarios were presented in Figure 2a and only one heat flux scenario is presented in Figure 2b. Also, all heat fluxes presented in Figure 2b are positive, which is not possible. Generally, some fluxes will be positive (incoming shortwave radiation); however, other will be negative (longwave radiation/evaporative flux), while sensible heat, for instance, will be both positive and negative.	We agree. Regarding Figure 2 all energy fluxes and all vegetation scenarios were included in the revised version. Latent heat flux is depicted in the negative direction (directed from the river column to the atmosphere). The information about the two different evaporation methods is omitted in, which is less important for the article than the comparison of the vegetation scenarios.
37	Pg. 9, line 1-11: All reported fluxes are positive within this paragraph (see comment above). How can authors have possibly fitted river temperatures,	We certainly agree that not all energy fluxes are positive. In this section we are distinguishing between "input" and "output". Outputs are always negative, while inputs are positive. There was a minus sign added to clarify this.

	with such fluxes?	
38	Pg. 9, line 13-14: “This leads to a rapid increase in the water temperature of the cool spring water.” Authors do not have the data to support such statement.	We do have measurement data, that fit the simulated data and show the same strong increase in water temperature close to the spring (Figure 2c - the measured data is plotted with an “x”). Alternative formulation: “This lead to a rapid increase in the water temperature of the cool spring water, **which is clearly seen in both measured an simulated data (Figure 2c)**.”
39	Pg. 9, line 32-33: “Future boundary water temperature increases by the end of the century by up to 4.1 °C (Table 2)”. Not clear.	Alternative formulation: “For the water temperature at the upstream model boundary an increases of 4.1°C for a 20 year return event of the 2085 in respect to 2013 was simulated (Table 2).
40	Pg. 10, line 9-10: “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).”. Was the water temperature increase due to tributary inflows (with different water temperatures) or due to the surrounding meteorological conditions (most likely tributary inflow)?	The increase was under the assumption of a realistic scenario, including all known parameters (tributaries, realistic vegetation, river gradient and morphology, meteorology,..). The sentence was completed and moved below to the description of the longitudinal distribution of water temperature: “The stream temperature increase from the upstream model boundary at DFS 11 to DFS 62 during the 2013 heat wave event for the STQ scenario including all available information about the present state of the river was about 7°C (Fig. 2).”
41	Pg. 10, line 14-15: Not sure why water temperature would drop from 25.0 °C to 24.8 °C (middle period) when the climate is warming from 22.4 °C to 22.6 °C.	On Pg. 10, line 14-15 the mean and maximum water temperature of a 20 year return event and all analyzed future climate periods are presented. The corresponding values are found in Table 3. Mean air temperature was rising from 27.2°C to 28.4°C (Table 2). The climate episodes used in this study were selected using air temperature thresholds. As they simulate realistic potential episodes they differ in global radiation, wind speed and humidity (see Table 2). Lesser amount of global radiation sums can lead to lower stream temperature despite higher air temperature. Higher wind speeds triggers increased evaporation which might lead to higher energy output and lower stream temperature despite higher air temperature. This is stated in the discussion already (Pg 12, line 21-24). While mean water temperatures don't react so strong, reduced global radiation and higher wind speeds have a stronger effect on i.e. the maximum stream temperature. The authors agree that the reaction of the maximum stream temperature should be pointed out in the discussion following Pg 12, line 24. i.e. “This was most evident in maximum water temperatures.”
42	Pg. 11, line 5: “additional vegetation becomes more distinct in the downstream sections”. Not clear about additional vegetation, please clarify.	Alternative formulation: “Looking at the longitudinal distribution of water temperature along the river it can be seen that for the Pinka the benefit of **additional tree cover maximizing riparian shade** became more distinct in the downstream sections.”
43	Pg. 11, line 12-32: This whole section on model uncertainties does not seem to belong in this paper. How can a reviewer assess a model uncertainties	We agree that the position of the chapter “Uncertainties” after the “Results” section was misleading. A subsection treating with uncertainties was included at the end of the Methods section. The model Heat Source is better described now in the Methods

	when no information was presented on the model?	section as well.
44	Pg. 11, line 30-32: “overhang caused changes in water temperature of +/– 0.40 ◦ C, +0.44 /–0.46 ◦ C and +0.01 /– 0.05 ◦ C respectively”. It is at times difficult for the reviewer to understand which data come from the present study or Trimmel et al. (2016). Authors should remember that this section is the results section and most of the information presented here seems to be discussion material.	This section was not intended to be a results section, it is a separate section treating the uncertainties. The uncertainties are moved as separate subsection to the Methods section now.
45	Pg. 12, line 12-13: “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.”. Not sure what authors mean, please clarify.	We agree that this formulation is confusing. We restructured the Discussion section to treat the magnitude of stream temperature rise and vegetation influences in separate subsections. We reformulate the former Pg. 12, line 12-15: “ The water temperature difference between full and no vegetation showed no clear trend for future conditions. This can be explained considering that global radiation - the main parameter, that is affected by riparian vegetation (Leach and Moore 2010, Li et al 2012) - is the main parameter that contributes to heating of the water column (Benyahya et al 2012, Hannah et al. 2008, Maheu et al. 2014) and is not expected to be affected by climate change (APCC 2014). Therefore the ability of the vegetation to alter the stream's microclimate and water temperature is likely to remain the same.”

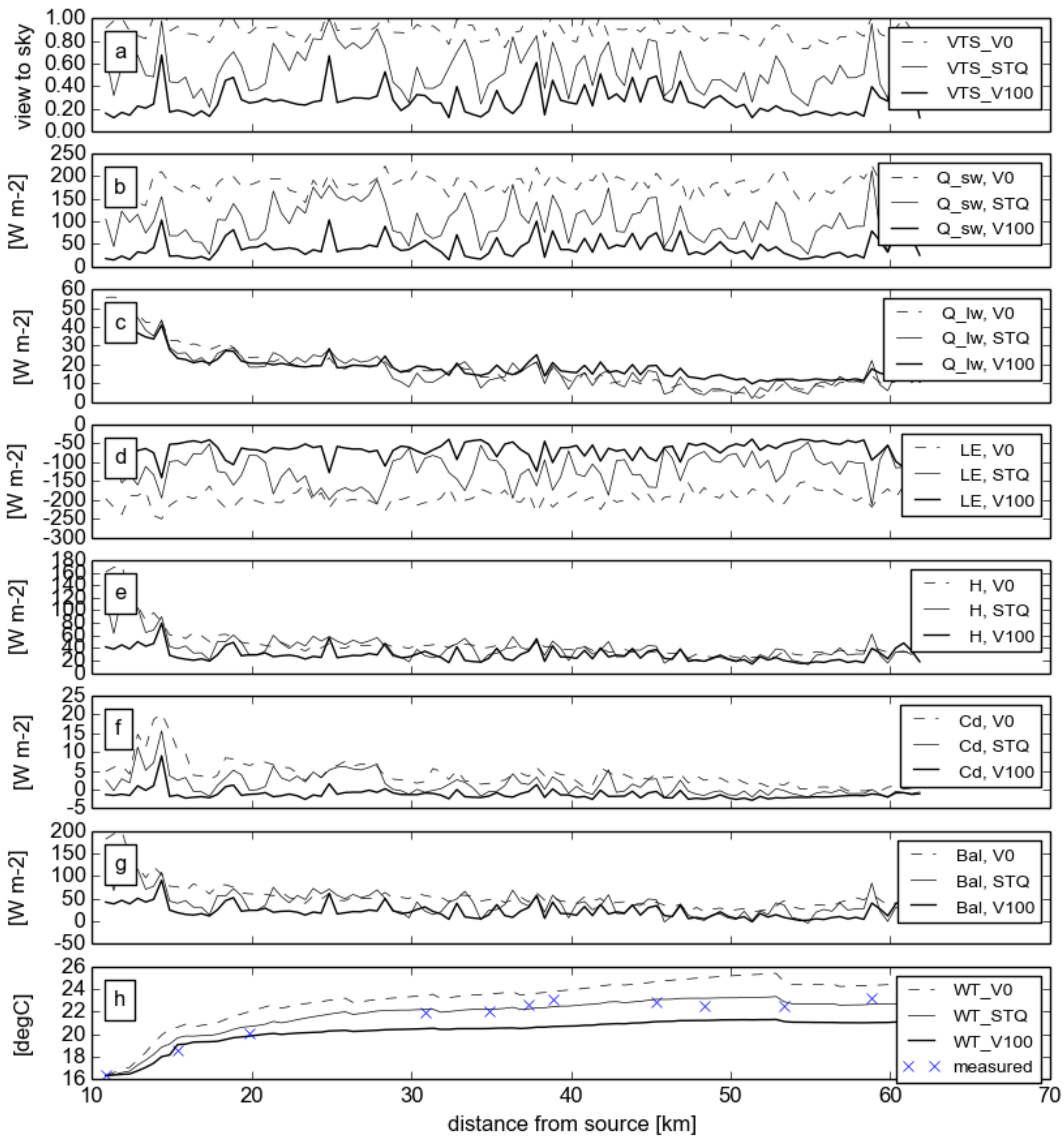

Figure 2: Comparison of the calculated VTS levels, short wave (Q_sw), long wave (Q_lw) radiation balance, latent (LE) and sensible (H) heat flux and measured (measured) and simulated (WT) water temperature for the heat wave episode 4 – 8 August 2013 along the river Pinka for three vegetation scnearios. no vegetation (V0), existing vegetation (STQ) and maximum vegetation (V100).

Response to Reviewer 2:

Dear Referee 2

The authors thank you for the constructive and useful comments and for your valuable time spent reviewing our manuscript “Can riparian vegetation shade mitigate the expected rise in stream temperatures during heat waves in a pre-alpine river?” by H. Trimmel, P. Weihs, H. Formayer, D. Leidinger and G. Kalny. You have been addressing many issues to clarify and improve readability of the manuscript. Below we address all your general and specific comments.

General comments

No.	Comment	Response
1	During reading the paper it is difficult to keep the focus/aims of the paper in memory. The overall objective is formulated in the title but in the text the reader will find other (sub)aims at several positions in different sections. The differentiation between objectives and methods is not appropriate. It is hard to follow the central theme of the paper since the structure of the paper is a little bit confusing.	We agree and worked on a clearer, more focused presentation of the aims. The authors agree that the Methods section is not well organized and difficult to follow. We included several subheadings and restructured this section to make it easier to read.
2	The paper includes 4 tables and 4 figures with a lot of information content but this is not represented adequate in the text, especially in the sections “Results“ and “Methods” more clear links between text and figures/tables would be helpful to understand the intention of the paper.	We agree. We tried to improve this in the revised version and added more links between text and figures/tables.

Specific comments:

No.	Comment	Response
3	P 1, title: the overall objective is formulated here. See also p 4, lines 22ff “The aim of this study. . .” and p 8, lines 9ff “ The focus of this study. . ..” are mentioned in different sections. The reader should find aims and focus of a paper at the beginning of the text to keep the central theme in mind.	We worked to clarify the overall structure but still kept the aims of the study at the end of the Introduction because they are derived from the state of the art. If wished they can be moved to the beginning of the Introduction as well.
4	P 1, line 13: “and turbulent energy fluxes were analysed”	This was corrected.
5	P 2, line 4: “ play a superior role. . .” please clarify	Alternative formulation: “Above that riparian ecosystems play a superior role in determining the vulnerability of natural and human systems to climate change in the 21st century (Capon et al. 2013).”
6	P 2 line 19: “summer and winter half-year” please clarify- which months/from-to?	Alternative formulation: “summer (Apr – Sep) and winter half-year (Oct to Mar)”

7	P 2, line 22: " autumn" please clarify- which months?	Alternative formulation: " .. increase from October to March ..."
8	P 3, line 1: " Austrian river temperatures. . ." which rivers were regarded – discharge values or other meaningful parameters were helpful. Is the Danube representative for the study area of this paper? Why?	Alternative formulation: "Since 1980 230 stations of the Austrian hydrographic central office of different elevation, distance from source and catchment area recorded an increase of stream temperature. The data were elevation corrected using External Drift Top-Kringing (Skøien et al. 2006) and a mean trend calculated using the Mann-Kendall-Test (Burn and Hag Elnur, 2002) by BMLFUW (2011). A mean trend of 1.5 °C during summer (Jun - Aug) and 0.7 °C during winter (Dec - Feb) was calculated (APCC 2014, BMLFUW 2011). Melcher et al. (2013) analysed 60 stations and found a similar trend of 1 °C within the last 35 years regarding mean August temperatures, which was independent of the river type. The annual mean temperature of the river Danube 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 at the border to Slovakia (Nachtnebel et al. 2014). Close to Vienna the increase will be up to 12.7 °C (Dokulil 2013). Due to the size of the river Danube amplitudes and extremes cannot be compared to smaller rivers like Pinka, but trends in mean water temperature values are comparable (BMLFUW, 2011)."
9	P 3, line 6: "indirect effects of climate change" – is it possible to quantify these uncertainties?	"For the study region during summer heat waves neither groundwater nor snow melt contributions change are expected (APCC). Apart from rising air temperatures and discharge changes, anthropogenic influences like discharge from waste water treatment plants and cooling water can influence stream temperatures in a negative way and are therefore presently illegal in Austria (WRG 1959). Other consequences of climate change are 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, which can influence the magnitude and variability of stream temperature. Artificial changes which deteriorate the situation are presently illegal in Austria as well (WRG 1959). Discharge reductions on the other hand have already been observed. From 1982 to 1990 the mean discharge of the river at the lower boundary of the study region decreased by 5.7 % (Mader et al. 1996) and has been further decreasing (APCC 2014). During the period 2008-2012 the mean discharge lay 20% below the values of 1982 (BMLFUW 2014). Van Vliet (2011) predicted a stream temperature rise of 0.3 °C and 0.8 °C on average for discharge reductions of 20 % and 40 % respectively. This article focused only on the increase in air temperature caused by climate change." BMLFUW Abteilung I/4 – Wasserhaushalt, Hydrographisches Jahrbuch von Österreich 2013, Wien, 2015. WRG – Wasserrechtsgesetz (water right law), BGBI. Nr. 215/1959, 1959.
10	P 3, line 30: "energy loss" – is it possible to assess/quantify?	Transpiration of the riparian vegetation causes additional energy loss of the system, which is small compared to the effects of shading and wind reduction. We calculated a reduction of 0.18°C if maximum vegetation cover is assumed. We suggest to include following explanation in the Introduction: "Transpiration of riparian vegetation only indirectly affects stream

		temperature. It increases air humidity and reduces air temperature close to the river, so air humidity and air temperature gradients are reduced. Benyahya et al. (2012) and Chen et al. (1993), recorded a difference in air humidity between open and forested stations of 5 % and 11 % and a difference of air temperature in 0.5 % and 0.61 °C respectively." This paragraph is now included in the "Methods" subsection "Uncertainties": "Microclimatic differences caused by vegetation shading, wind reduction and transpiration had been recorded during 5 July to 14 August 2015. Air temperature differences between forested and open stream reaches amounted to 1.5 °C on average. Differences in relative humidity was 11.8 % on average. Which is in accordance with Benyahya et al. (2012) and Chen et al. (1993), who recorded a difference in air humidity between open and forested stations of 5 % and 11 % and a difference of air temperature in 0.5 % and 0.61 °C respectively. Vegetation shading as well as the wind reduction caused by vegetation is included in the model. The micro scale changes in air temperature and air humidity of different river sections caused by transpiration are not included in the simulation, but Heat Source is not sensitive to these differences. Simulations were performed to estimate the error caused by this simplification and only a maximum error in water temperature of 0.18°C was calculated." Chen, J., Franklin, J.F., Spies, T.A., Contrasting microclimates among clearcut, edge, and interior of old-growth Douglas-fir forest. Agricultural and Forest Meteorology 63, 219-237, 1993.
11	P 4, line 26: "Sections". An outline of different sections would be helpful at the beginning of the paper maybe combined with clearly formulated objectives and aims of the paper.	We worked to clarify the overall structure but still kept the aims of the study at the end of the Introduction, because they are derived from the state of the art. If wished they can be moved to the beginning of the Introduction as well. The sections were integrated into the scope of the study which is described at the beginning of the Methods.
12	P 5, line 3: "river Pinka": which type of river represents Pinka compared to others in Austria?	We suggest to add: "According to Muhar et al (2004), who categorized all Austrian rivers with catchment areas > 500 km² corresponding to their annual discharge Pinka falls in the smallest of the 5 categories with 0 – 5 m³/s mean annual discharge." Muhar S, Poppe M, Egger G, et al (2004) Flusslandschaften Österreichs: Ausweisung von Flusslandschaftstypen anhand des Naturraums, der Fischfauna und der Auenvegetation. Bundesministerium für Bildung, Wissenschaft und Kultur, Wien
13	P 5, line 9: "highest temperature increases and . . ...reductions. . ." - how much? Please clarify.	Alternative formulation: "In this region air temperature rose by 2°C since 1880. Precipitation was reduced in the HISTALP region corresponding to our study region by 10-15%, which is the largest reduction in precipitation in Austria (Auer et al. 2007, Böhm et al. 2009, Böhm et al. 2012)." Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schöner, W., Ungersböck, M., Matulla, C., Briffa, K., Jones, P.,

		Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.-M., Begert, M., Müller-Westermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S.,Szentimrey, T., Cegnar, T., Dolinar, M., Gajic-Capka, M., Zaninovic, K., Majstorovic, Z. and Nieplova, E.,. HISTALP—historical instrumental climatological surface time series of the Greater Alpine Region. International Journal of Climatology 27, 17–46. doi:10.1002/joc.1377, 2007. Böhm, R.: Changes of regional climate variability in central Europe during the past 250 years, The European Physical Journal Plus, 127, doi:10.1140/epjp/i2012-12054-6, 2012. Böhm, R., Auer, I., Schöner, W., Ganekind, M., Gruber, C., Jurkovic, A., Orlik, A. and Ungersböck, M.: Eine neue Webseite mit instrumentellen Qualitäts-Klimadaten für den Grossraum Alpen zurück bis 1760, Wiener Mitteilungen Band 216: Hochwässer: Bemessung, Risikoanalyse und Vorhersage, 2009.
14	P 7, line 11: "flow volume" – discharge	We agree. The term "discharge" is used in the revised version.
15	P 7, line 26: "no deep groundwater influence" - means there is one? Significant/insignificant - please clarify	The groundwater influence of the Pinka in the study region is possible but unknown. During this article only simulations during low flow conditions were conducted. It it assumed, that during low flow conditions there is no influence of deep groundwater. We suggest to use a more direct formulation: "The sediment of this region is very inhomogeneous and the spatial distribution of the groundwater level is unknown (Pahr 1984). For low flow conditions it was assumed that there was no deep groundwater influence." In the end of the description of the model Heat Source we suggest to include: "The measurements fitted the simulation very well (average hourly was RMSE 0.88 °C for all measurement stations) so we conclude that all assumption were good and the model fit to be used for predictions." In the Discussion we suggest to add: "Ground water influence was unknown and no ground water influence was assumed in the model. Although the model performed good (RMSE 0.88) there might be some ground water influence between DFS 45 and 55 where the measurements lie below the simulation results."
16	P 7, lines 27ff: "Tributaries. . .partly estimated. . .adding a fixed offset. . ..was supplemented. . ." is this conform to the state of the art? Or part of model uncertainties?	Ideally the stream temperature and discharge of every single tributary should be measured. Practically this is very difficult for larger river sections. In our case the interpolated tributaries have less than 5 % of the discharge of the main river and are not influenced by tempered waste or cooling water. Thus we consider it part of the model uncertainties and state of the art at the same time.
17	P 8, line 9: "The focus. . ." see above	This sentence was integrated into the aims at the end of the Introduction.
18	P 8, line 18: "no significant changes in vegetation cover as it was the case in other studies performed earlier in the year" – what does significant mean in this context?	The authors admit that this sentence is confusing and suggest to omit it. To clarify the vegetation development stage we suggest to insert in the new Section 2.3.2 (Vegetation and morphology): "The riparian vegetation situation was taken after the phenological phase of leaf development was finished and leaves were already fully developed (Ellenberg 2012).

		Ellenberg, H. and Leuschner, H: Vegetation Mitteleuropas mit den Alpen, 6.Auflage, Verlag Eugen Ulmer, Stuttgart, XXIV+1134pp, 2012.
19	P 9, lines 15-25: Are these lines part of the results or taken from literature (which one?) - please clarify and quantify the mentioned effects if possible.	This part was complemented with quantitative information and discussion material moved to the Discussion.
20	P 9 line 33: ". . .up to 4.1 ◦ C (Table 2): Why is "max" lower than "20a" (Table 2, P 21)?	The future climate episodes used in this study were selected using 5 day mean air temperature thresholds. As they simulate realistic potential episodes they differ in global radiation, wind speed and humidity (see Table 2). Lesser amount of global radiation sums, as it is the case during the Max event of 2085 can lead to lower stream temperature and lower maximum air temperature despite higher mean air temperature. In the revised version this is described more in detail in section 3.2: "During the 20 year return event of 2085 on the other hand global radiation was higher than the Max event (20.9 MJ m^{-2} d^{-1}) of this climate period (Table 2). For the mean water temperature at the model boundary an increase of +4.1 °C for a 20 year return event of 2085 in respect to 2013 was simulated (Table 2). For the Max event of 2085, which had 2.2 MJ m^{-2} d^{-1} lower global radiation input a slightly lower temperature increase (+4.0 °C) was simulated (Table 3)."
21	P 11, line 8: "incoming solar radiation which"	This sentence is removed, because it is too imprecise.
22	P 11, line 10: A more detailed quantifiable description of figure 4 is desirable.	Alternative formulation: "Looking at the longitudinal distribution of water temperature along the river it can be seen that increases in mean stream temperature caused by increases of future air temperature affected all parts of the river (Fig. 4a-c). The maximum values showed a similar distribution as the mean values on a higher level. The average difference between mean and maximum values of the STQ scenario was 3.92 °C, 3.35 °C and 3.91 °C, the maximum difference between maximum values was 5.51 °C, 4.89 °C and 5.51 °C and the standard deviation of this difference was 0.71, 0.66 and 0.71 for 2030, 2050 and 2085 respectively (Fig. 4a-c). V0 scenarios were always warmer than STQ scenarios, V100 scenarios were always cooler than the STQ scenarios. The mean difference along the river between V0 and STQ was 1.25 °C, 1.26 °C and 1.13 °C, the maximum difference was 1.81 °C, 1.85 °C and 1.66 °C, the standard deviation was 0.35, 0.36 and 0.32 for 2030, 2050 and 2085 respectively. The mean difference between STQ and V100 was 1.42 °C, 1.52 °C, and 1.26 °C, the maximum difference was 1.92 °C, 2.05 °C and 1.72 °C, the standard deviation of this difference was 0.46, 0.49 and 0.41 for 2030, 2050 and 2085 respectively (Fig. 4a-c). Water temperature was especially sensitive to the removal of vegetation within the first 10 km (DFS 11 - 21) where there were dense forests which prevented the cool headwaters from warming (Fig. 4d). At DFS 11 - 21 temperatures increased by 1.4 °C when removal of vegetation is assumed (V0-STQ). Additional tree cover (V100) caused a reduction of -0.9 °C compared to the STQ scenario (Fig. 4d). This can be explained by the slower flow velocities (last 30 km - DFS 32-62: 0.003 m m^{-1}, 0.4 m s^{-1}) in comparison to the steeper upstream

		sections (first 10 km - DFS 11-21: 0.017 m m^{-1}, 0.6 m s^{-1}), which gave short wave radiation in unshaded sections more time to heat the water column. For the Pinka the benefit of additional tree cover maximizing riparian shade became more distinct in the downstream sections (DFS 25-55) where the additional tree cover caused a change of 1.75°C while removal only caused a change of around 1.25°C (Fig. 4d)."
23	P 11, line 11: "Uncertainties. . ." Model uncertainties should be a section following section 2.3. In the Results-section uncertainties should be discussed referring to the relevance to quantifiable results and the author's conclusions. Discussions about the model should be conducted before.	This part was shortened and integrated into the Discussion and Methods, where a new subsection was created as suggested. Uncertainties relevant for the direct evaluation of results are kept in the Results section.
24	P 12, line 12: "is not expected to increase. . ." – source? Please clarify.	We agree that this formulation is confusing. We suggest to restructure the Discussion section to treat the magnitude of stream temperature rise and vegetation influences in separate subsections. We suggest following explanation: "The water temperature difference between full and no vegetation showed no clear trend for future conditions. This can be explained considering that global radiation - the main parameter, that is affected by riparian vegetation (Leach and Moore 2010, Li et al 2012) - is the main parameter that contributes to heating of the water column (Benyahya et al 2012, Hannah et al. 2008, Maheu et al. 2014) and is not expected to be affected by climate change (APCC 2014). Therefore the ability of the vegetation to alter the stream's microclimate and water temperature is likely to remain the same." Leach JA, Moore RD (2010) Above-stream microclimate and stream surface energy exchanges in a wildfire-disturbed riparian zone. Hydrol Process n/a-n/a. doi: 10.1002/hyp.7639 Li G, Jackson CR, Kraseski KA (2012) Modeled riparian stream shading: Agreement with field measurements and sensitivity to riparian conditions. J Hydrol 428–429:142–151. doi: 10.1016/j.jhydrol.2012.01.032 Maheu A, Caissie D, St-Hilaire A, El-Jabi N (2014) River evaporation and corresponding heat fluxes in forested catchments, Hydrol Process 28:5725–5738. doi: 10.1002/hyp.10071
25	P 12, line 26: "by other studies." Which studies? Please specify.	The sentence is changed to "The values predicted in this article were clearly above the model uncertainty and lie in the upper region of the values published by other studies (BMLFUW 2001, Dokulil 2013, Melcher et al. 2013, 2014)." and moved to the end of the new section 4.2 (Magnitudes of stream temperature rise)
26	P 12, line 27: "For Austrian rivers. . ." which ones?	"From 1980 to 2011 230 stations of the Austrian hydrographic central office of different elevation, distance from source and catchment area recorded an increase of stream temperature (BMLFUW 2011)."
27	P 12, line 28: "An increase. . ."	"Dokulil (2013) extrapolated the quadratic regression of the period

	which scenarios were used? Is the Danube comparable with Pinka referring to the focus of this paper?	1900-2006 of the river Danube near Vienna and predicted an increase of up to 3.2 °C by 2050 in respect to 1900 (0.21 °C / decade). Using linear regression the increase was only 2.3 (0.15 °C / decade), but using the linear trend beginning from 1970 the increase was 3.4° C (0.23 °C / decade). Due to the size of the river Danube daily amplitudes and extremes are not comparable to the Pinka, but trends in mean water temperature values are comparable though."
28	technical corrections: P 2, line 18 and 20: 15 % P 5, line 14: 0.46 ms-1 P 7, line 7: 50 m	These have been corrected.

Summary of relevant changes made in the manuscript

Section 1 Introduction was extended including a paragraph about scientific novelty.

Section 2 Methods: The delimitation to other studies (especially the other article by Trimmel et al. 2016) and the aims and scope of this study was given here, integrating the paragraph "sections" as well. Subheadings were included and the subsections are rearranged. The description of the model Heat Source was extended. The begin of the study region was initially named "DFS 13" according to the location of the gauge Pinggau. Actually the model was initialized at DFS11, where water temperature was measured continuously during 2013. No tributaries entered the Pinka between DFS11 and DFS13, therefore the discharge was used from DFS 13. This is corrected in the text and in Figure 1.

Section 3 Results: Figure 2 was adapted to include all vegetation scenarios and heat fluxes. Generally figures and tables are described more quantitative and detailed. Figures and Tables are referenced more often.

Section 4 (Uncertainties in predicted stream temperature) was shortened, so redundant and not relevant sentences were deleted. We tried to include all aspects which were addressed during the article and moved this part to the Methods into a separate subsections, as recommended.

Section 5 Discussion: Subheadings were included to differentiate between change in stream temperature, influence of riparian vegetation cover on stream temperature and limitations. A discussion about energy fluxes was moved down from the results and included as subsection.

Can riparian vegetation shade mitigate the expected rise in stream temperatures due to climate change 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 were analysed. ~~Minor s~~Stream water temperature increases of less than 1.5°C ~~are~~were modelled within the first half of the century. ~~, but a more significant increase is predicted for~~For the period 2071–2100 a more significant increase of around 3 °C in ~~. The magnitude of~~ maximum, mean and minimum stream temperature was predicted ~~rises~~ for a 20 year return period heat event ~~was estimated to be in the region of 3 °C~~. Additional riparian vegetation was~~is~~ not able to fully mitigate the expected temperature rise caused by climate change, but could~~an~~ reduce maximum, mean and minimum stream temperatures by 1 to 2 °~~-~~C. Removal of existing vegetation amplified~~s~~ 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 determining the vulnerability of natural and human systems to 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 in Austria (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 expected~~nearly certain~~ in Austria (APCC 2014, 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, while ~~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 (Apr – Sep) and winter ~~half-year~~ (Oct – Mar) (Böhm et al. 2009, 2012). A continuation of this trend might aggravate the danger of summer drought. In eastern Austria low flow discharge rates 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 October to March~~autumn to spring~~ (APCC 2014). ~~Long term increases of wind speeds or storm activity cannot be detected.~~ Various studies indicate that from observations no long term increase of wind speed or storm activity can be detected in Europe (e.g. Matulla et al. 2008). For the alpine region also no clear signs of increasing wind speed or extremes are projected for the future (Beniston et al. 2007). 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 and seasonal water temperature variability~~fluctuations~~, long wave 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 on average by 2050 (BMLFUW 2011).

Since 1980 230 stations of the Austrian hydrographic central office of different elevation, distance from source and catchment area recorded an increase of stream temperature. The data were elevation corrected using External Drift Top-Kringing (Skøien et al. 2006) and a mean trend calculated using the Mann-Kendall-Test (Burn and Hag Elnur, 2002) by BMLFUW (2011). A mean trend of ~~Austrian river temperatures have increased on average by~~1.5 °C during summer (Jun - Aug) and 0.7 °C during winter (Dec - Feb) was calculated (APCC 2014, BMLFUW 2011).

Melcher et al. (2013) analysed 60 stations and found a similar trend of 1 °C within the last 35 years regarding mean August temperatures, which was independent of the river type. 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 at the border to Slovakia (~~Dokulil und Donabaum 2014; ~~Nachtnebel et al. 2014). Close to Vienna the increase will be up 12.7 °C (Dokulil 2013). Due to the size of the river Danube amplitudes and extremes cannot be compared to smaller rivers like Pinka, but trends in mean water temperature values are comparable (BMLFUW, 2011).

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). For the study region during summer heat waves neither groundwater nor snow melt contributions change are expected (APCC). 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~~can influence stream temperatures in a negative way and are therefore presently illegal in Austria (WRG 1959). ~~Ano~~Other consequences of climate change are~~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, which can influence the magnitude and variability of stream temperature. Artificial changes which deteriorate the situation are presently illegal in Austria as well (WRG 1959).

Discharge reductions on the other hand have already been observed. From 1982 to 1990 the mean discharge of the river at the lower boundary of the study region decreased by 5.7 % (Mader et al. 1996) and has been further decreasing (APCC 2014). During the period 2008-2012 the mean discharge lay 20% below the values of 1982 (BMLFUW 2014). Van Vliet (2011) predicted a stream temperature rise of 0.3 °C and 0.8 °C on average for discharge reductions of 20 % and 40 % respectively.

This article focused only on the increase in air temperature caused by climate change.

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 occurs~~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 by~~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). Transpiration of riparian vegetation only indirectly affects stream temperature. It increases air humidity and reduces air temperature close to the river, so air humidity and air temperature gradients are reduced. Benyahya et al. (2012) and Chen et al. (1993), recorded a difference in air humidity between open and forested stations of 5 % and 11 % and a difference of air temperature in 0.5 % and 0.61 °C respectively.

Apart from its influence on average stream temperature vegetation ~~shade can~~ produces ~~important~~ highly spatial variable shade, which results in areas of different sun exposure and energy fluxes. These heterogeneity provides ecological niches which are important for different development stages of river fauna~~*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.

The conclusion may be drawn that many studies have already addressed the influence of riparian vegetation on stream water temperature using field measurements. Other studies coped with different methods to predict stream temperature and few tried to answer the question on how climate change might increase stream water temperature. Mainly air temperature was used as a surrogate for stream temperature and energy flux variations at different river sections were not considered. One result or trend may however not be transferred from one river to other. Statements of the riparian vegetation's potential to mitigate influence of climate change are only reliably valid for a given type of stream and for a given climate zone. The novel aspect of the present study is to investigate the influence of climate change and of riparian vegetation on the same river and attempt to make a realistic forecast of the riparian vegetation's potential to mitigate climate change in a specific river.

The aim of the present article is therefore (1) to estimate the magnitude of stream temperature rise during extreme heat events caused by the expected rise in air temperature until the end of this century compared to the last observed period and (2) to investigate the ability of riparian vegetation to mitigate the expected water temperature rise.

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.

2 Methods

Preliminary work has been done and published by Holzapfel and Rauch (2015), Holzapfel et al. (2015) and during a different article by Trimmel et al. (2016). Vegetation cover and river morphology was recorded continuously along the river, stream temperatures were recorded at 12 sites as well as main tributaries of the eastern Austrian river Pinka (Holzapfel and Rauch 2015, Holzapfel et al. 2015). This data was used to set up and validate the 1D energy balance and hydraulic model Heat Source (Boyd and Kasper 2003) for the river Pinka (Trimmel et al. 2016).

Further Heat Source was used to analyse the mean influence of different meteorological, hydrological and shading parameters during heat wave conditions along a 22.5 km long uniform reach (Trimmel at al. 2016).

In the present article stream temperature was simulated with the 1D energy balance and hydraulic model Heat Source (Boyd and Kasper 2003) for 51 km along a section including upstream forested regions and tributaries for each 500m along the river, which amounts to a total of 103 sites. First the longitudinal changes of energy fluxes were analysed during the maximum heat wave, which took place in eastern Austria during summer 2013. Future heat wave episodes, which are likely to occur during the climate periods 2016-2045, 2036-1065 and 2071-2100 in the study region, were selected. Regional climate scenarios, which have been produced within the ENSEMBLE project (Hewitt et al. 2004) were further processed and the meteorological data extracted. The future upstream model water temperature was simulated according the methodology of Caissie et al. (2001). Heat Source was used to simulate the stream temperature of the river Pinka for 12 future episodes and three vegetation scenarios.

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 kmilometers downstream at 200 m. a.bove s.ea l.evel into the river Raab. The catchment size of Pinka is 664 km². According to Muhar et al (2004), who categorized all Austrian rivers with catchment areas > 500 km² corresponding to their annual discharge, Pinka falls in the smallest of the 5 categories with 0 – 5 m³ s^{-1} mean annual discharge. The study region covers a 51 km stretch of the river Pinka from distance from source (DFS) 11 (559 m.a.s.l) near its most upstream gauge close toin Pinggau at 13 km from the source (DFS 13) 1 and (559 m.a.s.l. to DFS 62 (240 m.a.s.l.) close 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 10km 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 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 meteorological reference station used is located at the centre of the study region at DFS 39.

In this region air temperature rose by 2 °C, since 1880. Precipitation was reduced in the HISTALP region corresponding to our study region by 10-15%, which is the largest reduction in precipitation in Austria (Auer et al. 2007, Böhm et al. 2009, Böhm et al. 2012)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^{3}s^{-1} at the upstream model boundary (DFS 13) to 0.76 m^{3}s^{-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.

scenarios

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.

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.

2.32 Predicting stream temperatureModelling energy balance and stream temperature along the river

Using the deterministic energy balance and hydraulic model Heat Source version 9 (Boyd and Kasper, 2003; Garner 2007) and topographic, vegetation, river morphology, hydrological and meteorological data sets, the energy fluxes along the river, hydraulics and stream temperature were simulated along the Pinka. Existing data sets and parameters obtained from Austrian authorities and the literature were completed with field surveys and measurements. Short and long wave energy flux, latent and sensible heat flux as well as conduction are taken into account:

$$\Phi_{Total} = \Phi_{Latent} + \Phi_{Sensible} + \Phi_{Longwave} + \Phi_{Solar} + \Phi_{Conduction} \qquad (1)$$

where Φ_{Total} is the energy balance, Φ_{Latent} the latent heat flux, $\Phi_{Sensubke}$ the sensible flux, $\Phi_{Longwave}$ 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 and $\Phi_{Conduction}$ the conduction flux to the stream bed. Latent heat flux was calculated using the Penman method, which included the radiation balance.

The effect of the energy balance of the water column on stream temperature was calculated by Heat Source taking into account flow velocity and river morphology. The stream temperature increase ΔT caused by Φ_{Total} was calculated using:

$$\Delta T = \frac{\Phi_{Total} * dt}{\left(\frac{A}{W_w}\right) * c_{H2O} * m} \qquad (2)$$

where A is the cross sectional area or the river, W_w is the wetted width, the c_{H20} is the specific heat capacity of water (4182 J kg^{-1} C^{-1}), m the mass of 1 m^3 water which is 998.2 kg.

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 Trimmel et al. (2016).

By fine tuning the morphological input (bottom width, roughness parameter Manning's n and sediment hyporheic thickness) and the wind parametrisation, the model's validity could be considerably improved for the simulations used in this article. Tuning increased the coefficients of determination R^2 for stations analysed in Trimmel at al. 2016 from 0.87–0.91 (daily minimum), 0.90–096 (daily mean) and 0.86–0.92 (daily maximum) to 0.96–0.98 (daily minimum), 0.96–0.99 (daily mean) and 0.94–0.98 (daily maximum). The measurements fitted the simulation very well (hourly RMSE was 0.88 °C averaged for all stream measurement stations) so we concluded that all assumption were good and the model fit to be used for predictions.

2.3 Preparation of input

2.3.1 Meteorological input

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~~at the study site. 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~~ Since the local permanent meteorological stations of ZAMG were used to produce the gridded INCA data set, they are highly consistent. The comparison of the INCA data with the air temperature measured at our reference station close to the river showed a RMSE of 0.67°C and a R^2 of 0.99 for consecutive hourly measurements during summer half-year 2013 (1 Apr – 30 Sept). So the INCA data set was used as proxy to represent the local meteorological conditions within the catchment.

To obtain future meteorological conditions data from the regional climate models (RCM) Aladin (driven by the global climate model ARPEGE), Remo and RegCM3 (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 selected. The RCMs were bias corrected using the quantile mapping technique (Déqué 2007) based on the E-OBS data set (Haylock et al., 2008) and scaled. 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 (Koutsoyiannis 2003, Goler & Formayer 2012). The temperature data were elevation corrected with a lapse rate of 0.65 °C per 100 m.

Selection of extreme heat events

The period chosen as past reference period ("OBS") was an extreme heat wave that ran from 4 – 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.

Future 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 spin up of the Heat Source model, so that all episodes have equal length of 14 days.

2.3.2 Vegetation and morphology

The riparian vegetation cover and river morphology of this region was investigated by Kalny et al. (2015), Holzapfel et al (2015) and Holzapfel and Rauch (2015). Vegetation height and density was sampled in a 50 m buffer on both sides of the river. Vegetation overhang, morphology of the river bank and bed were all recorded along the whole river stretch (Kalny et al. 2015; Trimmel et al. 2016). The riparian vegetation situation was taken after the phenological phase of leaf development was finished and leaves were already fully developed (Ellenberg 2012).The vegetation composition ranges from commercial spruce forests (Picea abies) 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.

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 occurred. V100 was defined as: 30 m height and 8 m overhang and 90 % vegetation density. This scenario ensured the maximum possible vegetation shade. The fact that the density was below 100 % still enabled some exchange with the atmosphere. River bank and topography were not changed in the vegetation scenarios.

2.3.3 Definition of sediment layer and conduction flux

Heat Source uses only one substrate temperature, which is representative for the whole sediment layer. The depth of the sediment layer is set to 1m, which is corresponding to the available geological information of the river Pinka. The substrate temperature used in the model is set equal to the stream temperature at the uppermost model point. For each consecutive model point the substrate temperature is calculated depending on the local thermal conductivity, thermal diffusivity, layer depth, hyporheic exchange, the river morphological profile and the received solar radiation at the river bed. The sediment of this region is very inhomogeneous and the spatial distribution of the groundwater level is unknown (Pahr 1984). For low flow conditions it was assumed that there was no deep groundwater influence. .

2.3.4 Definition of discharge

During the analysed period 4 – 8 August 2013 low flow conditions were prevailing. The river flow volume increased from 0.18 m^3s^{-1} close to the upstream model boundary at DFS 13 to 0.76 m^3s^{-1} at the downstream model boundary (DFS 62). The mean flow velocity was 0.46 ms^{-1} and it took the river water about 30 hours to traverse the studied length of the river.

The model ~~is~~was very sensitive to discharge rates. A change in discharge of 0.1 m^3s^{-1} lead~~s~~ 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 mean low flow conditions (MLF). MLF is defined as the average discharge of all discharges below the 5% percentile discharge. The mean low flow conditions (MLF) of the gauging station Pinggau DFS 13 1981–2010 (MLF = 0.143 m^3s^{-1}), which is 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~~was

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 m3s-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).~~

2.3.5 Upstream boundary stream temperature

Stream temperature and discharge~~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 11~~3~~ 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 hourly water temperatures (12 537 values) 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.~~ for this period was 0.96, the RMSE was 0.68 °C. For the summer half-year 2013 (Apr – Sept), the R^2 was 0.89, the RMSE was 0.80 °C. 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).~~

2.3.6 Input data of tributaries

~~Tributaries are defined by their water temperature and discharge values.~~ The discharge and water temperature of the river Pinka at the upstream model boundary and the main 5 tributaries~~inflows~~ of the 2013 episode ~~could be partly estimated using field measurements~~were measured. T~~he water temperature data of t~~he remaining tributaries added less than 5 % discharge each. ~~and t~~Their future water temperature values were synthesised using the daily fluctuations of the water temperature at the upstream model boundary.~~station~~ adding a fixed offset depending on the distance of the inflow to the upstream model 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 Uncertainties in predicted stream temperature

As we already mentioned before, the model uncertainties of the Heat Source model were already determined in a previous study by Trimmel et al. (2016). The results will be used in the analysis of the present paper. In the following we give a short summary of the main results: The model is most sensitive to changes in vegetation height (+/-5 m), density (+/-20 %) and overhang (+/-1 m), which 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). 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 estimated to be 0.44 °C. Existing vegetation on the other hand was found to be responsible for 4 times as much influence on temperatures as bank or topographic shade (1.68 °C) (Trimmel et al. 2016).

Microclimatic differences caused by vegetation shading, wind reduction and transpiration had been recorded during 5 July to 14 August 2015. Air temperature differences between forested and open stream reaches amounted to 1.5 °C on average. Differences in relative humidity were 11.8 % on average, which is in accordance with Benyahya et al. (2012) and Chen et al. (1993) , who recorded a difference in air humidity between open and forested stations of 5 % and 11 % and a difference of air temperature in 0.5 % and 0.61 °C respectively. Vegetation shading as well as the wind reduction caused by vegetation is included in the model. The micro scale changes in air temperature and air humidity of different river sections caused by transpiration are not included in the simulation, but Heat Source is not sensitive to these differences. Simulations were performed to estimate the error caused by this simplification and only a maximum error in water temperature of 0.18 °C was calculated.

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 during the heat episode 2013

In order to interpret the influence of vegetation shade on future water temperature it is important to understand the influence of vegetation shade on the present conditions first. While in the previous study of Trimmel et al. (2016) only the propagation of uncertainties of input parameters on the mean stream temperature of a 22.5 km long reach during the heat episode of 2013 was analysed, here the longitudinal distribution of a more diverse section including the headwaters of the river Pinka was shown and discussed.

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) was~~is~~ 0.55. If all vegetation was~~is~~ removed (V0) there was~~is~~ still some remaining shade caused by topography and the river bank which reduced~~s~~ VTS to a value of 0.89. If maximum vegetation was~~is~~ assumed (V100), the value of VTS was~~is~~ strongly reduced, but still amounted~~s~~ to 0.16 on average because only 90% density was assumed. Peak~~s can~~s in VTS were found~~be seen~~ at broader river sections or sections oriented East-West (Fig. 2a).

The most important energy inputs on the river surface during the study period and~~-~~ ~~For the study period and~~ region~~ the most important inputs on the river surface~~ were short wave radiation flux with an average of 101.6~~2~~ W m^{-2} (Fig. 2a), sensible heat flux with an average of 39.9~~40~~ W m^{-2} (Fig. 2e) and long wave radiation with an average of 17.2 W m^{-2} (Fig. 2c). Conduction only amounted to 1.3 W m^{-2} on average. The relative percentage of short wave radiation balance, long wave radiation balance and sensible heat flux were 64 %, 11 % and 25 % of the inputs respectively that heated the water column.

The main energy output was latent heat flux (Fig. 2f).

During the V0 and V100 scenario the direction of the energy fluxes remained the same. During the V0 scenario the relative percentage of short wave radiation balance increased (73 %), while long wave radiation balance (7 %) and conduction heat flux (18 %) decreased. During the V100 scenario the trend was opposite. Short wave radiation balance decreased (47 %) and long wave radiation balance (21 %) and sensible heat flux (32 %) increased (Fig. 2a-f). ~~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 as well as conduction showed their highest values close to the source during all vegetation scenarios. This lead~~s~~ to a rapid increase in the water temperature of the cool spring water, which is clearly seen in both measured and simulated data (Fig. 2h).

All energy fluxes were~~are~~ dependent on the degree of openness to the sky, and showed the same pattern along the river (Fig. 2a - g). Short wave radiation and latent heat flux in particular were~~are~~ strongly influenced by the value of the VTS and showed distinct cutbacks of up to 70% where shading occurred~~s~~ (Fig. 2b, 2d).

The energy balance was positive on average along the whole river reach (Fig. 2g). The V0 scenario showed the highest, V100 scenario the lowest values with a mean value of 55, 40 and 22 W m^{-2} for the V0, STQ and V100 scenario respectively (Fig. 2g). The greatest differences between the different vegetation scenarios were found close to the source, where during the V0 scenario up to 200 W m^{-2} net energy were available to heat the water column (Fig. 2g), while during the V100 scenario it was only 91 W m^{-2}. The positive energy balance can explain the gradual warming of the stream temperature along the river (Garner et al. 2014) which can be seen in Fig. 2h. The continuous downstream warming is reversed on DFS 16, 22, 26.5, 32, 43.5 and 53.5 in the range of 0.5 °C for about 1 km (Fig. 2h) caused by the mixing with tributaries.

~~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 and advective input

The selection criteria mean air temperature increased~~ds~~ 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 were~~are~~ warmer than the 2013 heat wave. Air humidity during the selected events decreased~~ds~~ slightly until the end of the century, but had~~ds~~ 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 speeds of 2013 also exceeded~~eds~~ the wind speeds of all future eveents (Table 2). In the 20 year return period event of 2050 wind speeds were higher (1.1 m s^{-1}) than in 2030 (0.9 m s^{-1}) and 2085 (0.8 m s^{-1}) (Table 2). ~~Table 2 also shows t~~The average global radiation received during each event per day was different for each event as well. For the 20 year return event 2030 (28 MJ m^{-2} d^{-1}) ie. global radiation was higher than 2050 (23.1 MJ m^{-2} d^{-1}) and 2085 (23.1 MJ m^{-2} d^{-1}). During the 20 year return event of 2085 on the other hand global radiation was higher than the Max event (20.9 MJ m^{-2} d^{-1}) of this climate period (Table 2).

~~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)~~For the mean water temperature at the model boundary an increase of +4.1 °C for a 20 year return event of 2085 in respect to 2013 was simulated (Table 2). For the Max event of 2085, which had 2.2 MJ m^{-2} d^{-1} lower global radiation input a slightly lower temperature increase (+4.0 °C) was simulated (Table 3).

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 resulted~~ds~~ in a 0.1 °C higher water temperature (Table 3). Maximum water temperature was~~is~~ affected also, showing a reduction of 0.3 °C. Minimum water temperature was~~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 stream ~~water~~ temperatures

At DFS 39

~~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~~first~~,~~ 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 conditions and STQ at DFS 39 during the 20a heat wave event of the periods 2016–2045, 2036–2065 and 2071–2100 were~~are~~ predicted with 22.4 °C, 22.6 °C and 25.5 °C respectively. The corresponding predicted maximum water temperatures were~~are~~ 25.0 °C, 24.8 °C and 27.3 °C. These predictions represented 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 was~~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 showed increases. For the period 2016–2045, maximum temperatures increased more than mean temperatures with a change over baseline conditions of +0.6 °C. By 2071–2100 the increase in maximum temperatures was~~is~~ predicted to be 2.9 °C comp~~aa~~ared to the OBS period, which was~~is~~ similar to the predicted increase in mean and minimum water temperatures (Table 4).

Supposed the existing vegetation were removed (V0), the mean water temperature ~~might~~ reached 26.7 °C during 20 year return period heat events at the end of the century, which was~~is~~ 4.2 °C above the level of the STQ scenario of the OBS period. Maximum temperatures could~~an~~ 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 (V100) the expected mean water temperature was~~is~~ predicted to reach only 23.9 °C, which is 1.4 °C above the level of the STQ scenario during 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 was~~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 had~~s~~ 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).

Longitudinal distribution

The stream temperatures increased from the upstream model boundary at DFS 11 to DFS 62 during the 2013 heat wave event for the STQ scenario including all available information about the present state of the river was about 7° C (Fig. 2). Looking at the longitudinal distribution of water temperature along the river it can be seen that increases in mean stream temperature caused by increases of future air temperature affected all parts of the river (Fig. 4a-c).

The maximum values showed a similar distribution as the mean values on a higher level. The average difference between mean and maximum values of the STQ scenario was 3.92 °C, 3.35 °C and 3.91 °C, the maximum difference between maximum values was 5.51 °C, 4.89 °C and 5.51 °C and the standard deviation of this difference was 0.71, 0.66 and 0.71 for 2030, 2050 and 2085 respectively (Fig. 4a-c).

V0 scenarios were always warmer than STQ scenarios, V100 scenarios were always cooler than the STQ scenarios. The mean difference along the river between V0 and STQ was 1.25 °C, 1.26 °C and 1.13 °C, the maximum difference was 1.81 °C, 1.85 °C and 1.66 °C, the standard deviation was 0.35, 0.36 and 0.32 for 2030, 2050 and 2085 respectively. The mean difference between STQ and V100 was 1.42 °C, 1.52 °C, and 1.26 °C, the maximum difference was 1.92 °C, 2.05 °C and 1.72 °C, the standard deviation of this difference was 0.46, 0.49 and 0.41 for 2030, 2050 and 2085 respectively (Fig. 4A-c).

~~for the Pinka the benefit of additional vegetation becomes more distinct in the downstream sections.~~ Water temperature was especially sensitive to the removal of vegetation within the first 10 km (DFS 11 - 21) where there were dense forests which prevented the cool headwaters from warming (Fig. 4d). At DFS 11 - 21 temperatures increased by 1.4 °C when removal of vegetation is assumed (V0-STQ). Additional tree cover (V100) caused a reduction of -0.9 °C compared to the STQ scenario (Fig. 4d).

This can be explained by the slower flow velocities (last 30 km - DFS 32-62: 0.003 m m^{-1}, 0.4 m s^{-1}) in comparison to the steeper upstream sections (first 10 km - DFS 11-21: 0.017 m m^{-1}, 0.6 m s^{-1}), which gaveive 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).

For the Pinka the benefit of additional tree cover maximizing riparian shade became more distinct in the downstream sections (DFS 25-55) where the additional tree cover caused a change of 1.75°C while removal only caused a change of around 1.25°C (Fig. 4d).

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~~4 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).~~

4.1 Energy fluxes during heat waves

In the present article evaporative heat flux was responsible for 100 % of the heat loss on average. Short wave radiation balance, long wave radiation balance and sensible heat flux were 64 %, 11 % and 25 % of the inputs respectively that heated the water column.

During summer periods of high air temperature difference between air and water temperature increases, which can trigger intensified evaporative flux that cools the river, but also can cause sensible heat flux to heat the water column (Benyahya et al. 2012). Benyahya et al. 2012 measured during 7-23 June 2008 evaporative heat flux to account for 100 % of energy outputs while short wave radiation balance, long wave radiation balance and sensible heat flux were 73 %, 25 % and 3 % of the inputs respectively that heated the water column.

4.2 Magnitude of stream temperature rise

In ~~this stud~~the present article~~y~~ 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 for DFS 39. During the Max event increases of maximum, mean and minimum values where 3.4 °C, 3.5 °C and 4 °C respectively. When looking at the whole river mean changes of 3.3 °C for the maximum and 3.9 °C mean temperatures were calculated. Melcher et al (2014) also found that average and maximum temperatures show similar warming trends. An increase of 3.9°C from the OBS period to 2085 corresponds to an increase of 0.43 °C/decade. An increase of 3°C to an increase of 0.33 °C/decade.

~~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. This was most evident in maximum water temperatures. 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.~~

From 1980 to 2011 230 stations of the Austrian hydrographic central office of different elevation, distance from source and catchment area recorded an increase of stream temperature (BMLFUW 2011).

For Austrian rivers~~, for example~~ summer stream temperature increased by 1.5 ° C between 1980 and 2011 ~~(~~according to this study (BMLFUW 2011) (0.48 °C / decade). ~~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).~~

Melcher et al (2013) found a trend of 1°C within the last 35 years regarding mean August temperatures independent of the river type (0.29 °C / decade).

Dokulil (2013) extrapolated the quadratic regression of the period 1900-2006 of the river Danube near Vienna and predicted an increase of up to 3.2 °C by 2050 in respect to 1900 (0.21 °C / decade). Using linear regression the increase was only 2.3 (0.15 °C / decade), but using the linear trend beginning from 1970 the increase was 3.4° C (0.23 °C / decade). Due to the size of the river Danube daily amplitudes and extremes are not comparable to the Pinka, but trends in mean water temperature values are comparable though.

The values predicted in this article were clearly above the model uncertainty and lie in the upper region of the values published by other studies (BMLFUW 2001, Dokulil 2013, Melcher et al. 2013, 2014) .

Considering a likely discharge decrease (Nachnebel et al. 2014) slightly higher temperature rise might be expected. 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. Discharge decreases of 20 % and 40 % increased the water temperature rise by 0.3 °C and 0.8 °C on average (Van Vliet et al. 2011).

4.3 Ability of riparian vegetation to mitigate the expected stream temperature rise

Vegetation scenarios were simulated. Compared to the STQ scenario, additional riparian vegetation (V100) could reduce maximum stream temperatures during all episodes on average by 2.2 °C, mean by 1.6 °C and minimum by 0.9 °C during extreme heat waves (calculated from Table 4). Removal of existing vegetation (V0) amplified stream temperature increases, and could cause an average increase of maximum, mean and minimum stream temperatures by 1.8 °C, 1.3 °C and 1.0 °C respectively in comparison with the actual vegetation scenario (STQ) (calculated from Table 4).

Removal of vegetation ~~would~~(V0) magnif~~y~~ied 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 (V100) on the other hand ~~could~~ mitigated part of the rise in maximum temperatures, so there w~~ould~~as only ~~be~~ a 1.1 °C increase. The increase of mean temperatures wasis -reduced to about 1.4 °C, so riparian vegetation management alone wasis 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. The These redureduction rates predicted in the present article lie within the range of observed changes of pre- and post harvest situations found in literature (Cole and Newton 2013; Moore et al. 2005).

The water temperature difference between full and no vegetation showed no clear trend for future conditions. This can be explained considering that global radiation - the main parameter, that is affected by riparian vegetation (Leach and Moore 2010, Li et al 2012) - is the main parameter that contributes to heating of the water column (Benyahya et al 2012, Hannah et al. 2008, Maheu et al. 2014) and is not expected to be affected by climate change (APCC 2014).

Therefore the ability of the vegetation to alter the stream's microclimate and water temperature is likely to remain the same.

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).

4.4 Limitations

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.

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). Ground water influence was unknown and no ground water influence was assumed in the model. Although the model performed good (RMSE 0.88) there might be some ground water influence between DFS 45 and 55 where the measurements lie below the simulation results.

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

65 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 wasis 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 was predicted during annual or less frequent extreme heat waves in comparison to the observed period of 1981–2010.

~~Minor s~~Stream water temperature increases of less than 1.5 °C were~~are~~ modelled for the first half of the century~~,~~. For the period 2071–2100 a more significant increase of 3 °C in ~~but a strong increase is predicted for the period 2071–2100. The magnitude of~~ maximum, mean and minimum stream temperatures was predicted ~~rises~~ for a 20 year return period heat event. ~~is estimated to be in the range of 3 °C~~.

Vegetation could reduce stream temperature during heat waves, where high solar radiation is usual. Additional riparian vegetation was not able to fully mitigate the expected temperature rise caused by climate change, but could reduce maximum stream temperatures by 2.2 °C, mean by 1.6 °C on average during extreme heat waves. Removal of existing vegetation amplified stream temperature increases, and could cause an increase of maximum and mean stream temperatures by 1.8°C and 1.3 °C respectively in comparison with the actual vegetation scenario on average.

Removal of vegetation showed to aggravate the situation. Assuming vegetation removal maximum stream temperatures could exceed a 4 °C increase compared to the observed period in annual heat events at the end of the century.

There might be counterproductive effects of full vegetation cover on stream water temperatures during periods of reduced solar radiation, which can increase stream temperature, but generally riparian vegetation can produce important thermal gradients in streams which are vital for many species (Clark et al. 1999).

~~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 was~~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 20°C already wi~~s~~ere exceeded for 70 of the 120 h at the beginning of the century, but could~~an~~ be reduced by riparian vegetation shade during annual heat events to only last 9 h in total. The mitigation possibilities of vegetation were~~are~~ limited though, and could not~~annot~~ 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 wasis assumed, 20 °C wasill 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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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.

	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.**~~

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 2m above the river (M.) and interpolated measurement data from the INCA (I.) data set are shown.

	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 2m above the river (M.) and interpolated measurement data from the INCA (I.) data set are shown.**~~

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.

	(a) max.			(b) mean			(c) min.		
	V0	STQ	V100	V0	STQ	V100	V0	STQ	V100
OBS Meas.	26.6	24.7	22.4	23.8	22.4	20.7	20.2	19.5	18.5
OBS 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_Mmax	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_Mmax	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_Mmax	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.

Table 4: Difference to the 20a event of the OBS period (2013) (with mean low flow discharge) of predicted maximum (a), mean (b) and minimum (c) water temperatures for the 1a, 5a, 20a and Max event at DFS 39 for the climate periods centered on 2030, 2050 and 2085 for vegetation scenario V0 (no vegetation), STQ (vegetation unchanged), V100 (maximum vegetation).

	(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_Mmax	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_Mmax	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_Mmax	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).

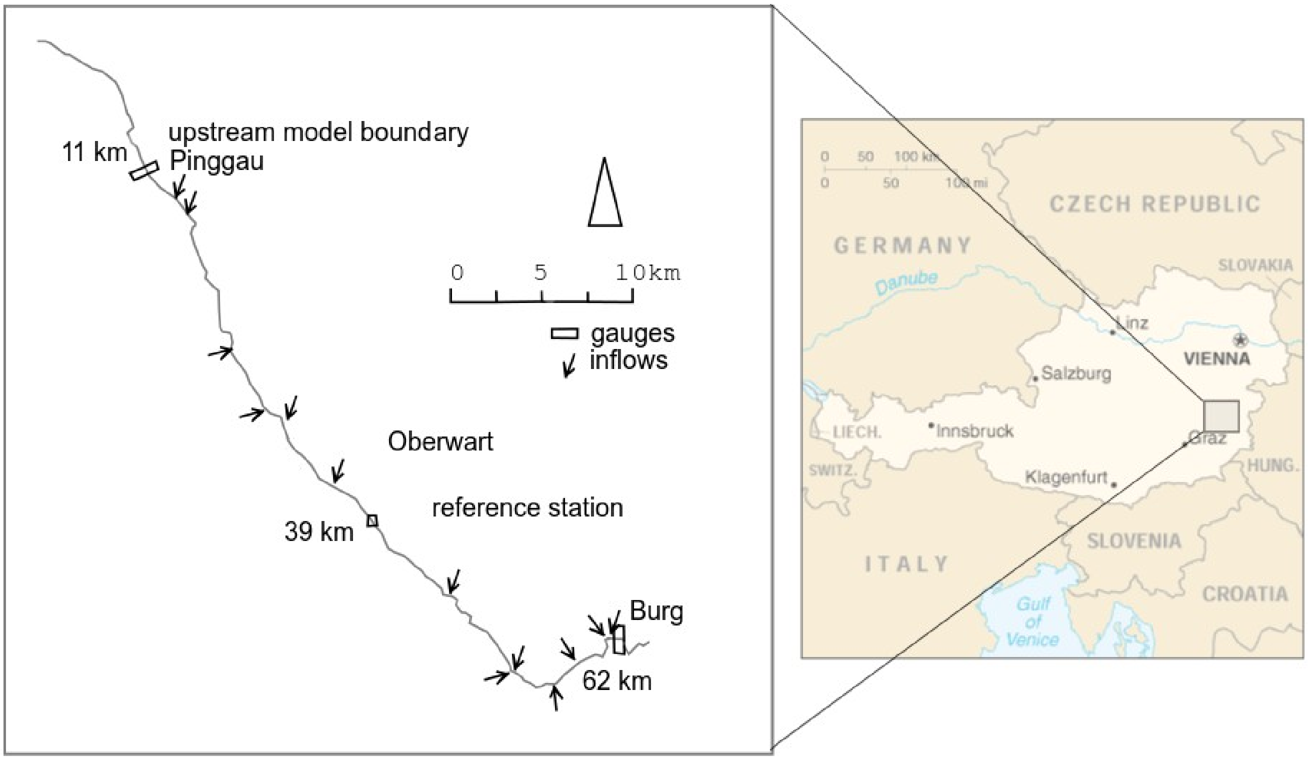

Figure 1: The study region in Pinka showing gauges, tributaries and the reference station (km markers shown as distance from source).

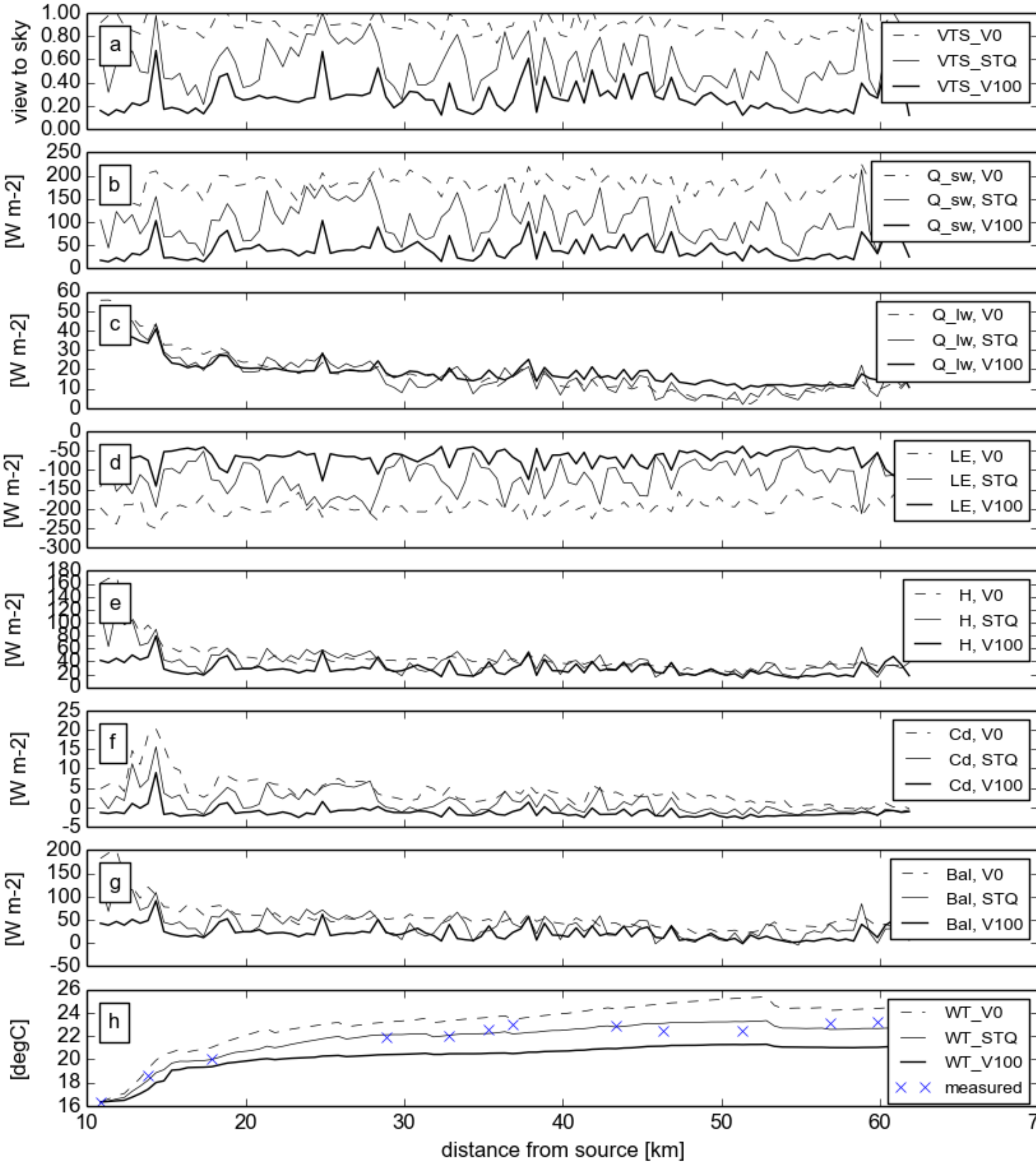

Figure 2: Comparison of the calculated **VTS levels**, short wave (Q_sw), long wave (Q_lw) radiation balance, latent (LE) and sensible (H) heat flux and measured (measured) and simulated (WT) water temperature for the heat wave episode 4 – 8 August 2013 along the river Pinka for three vegetation scnearios. ~~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.~~

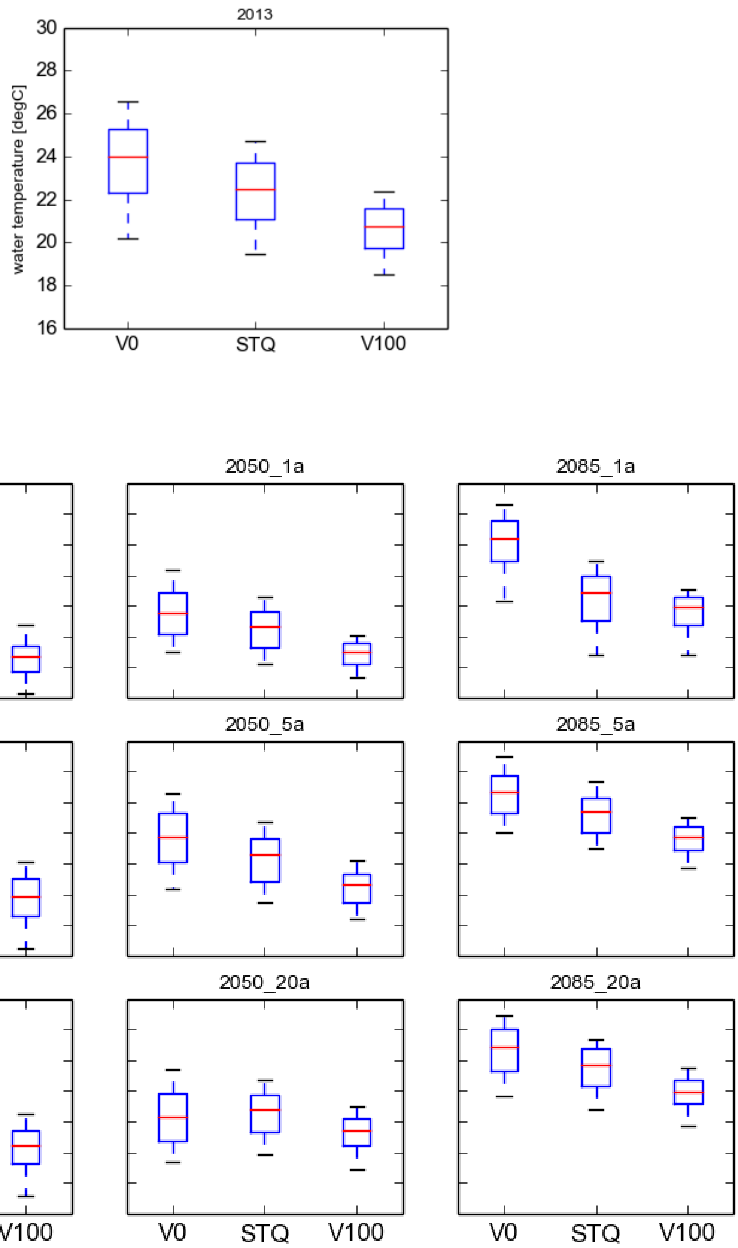

Figure 3: Box and whiskers chart showing the 5 day mean water temperature distribution during the 1a, 5a and 20a episodes for the climate periods centered on 2030, 2050, 2085 and mean low flow discharge at DFM 39.

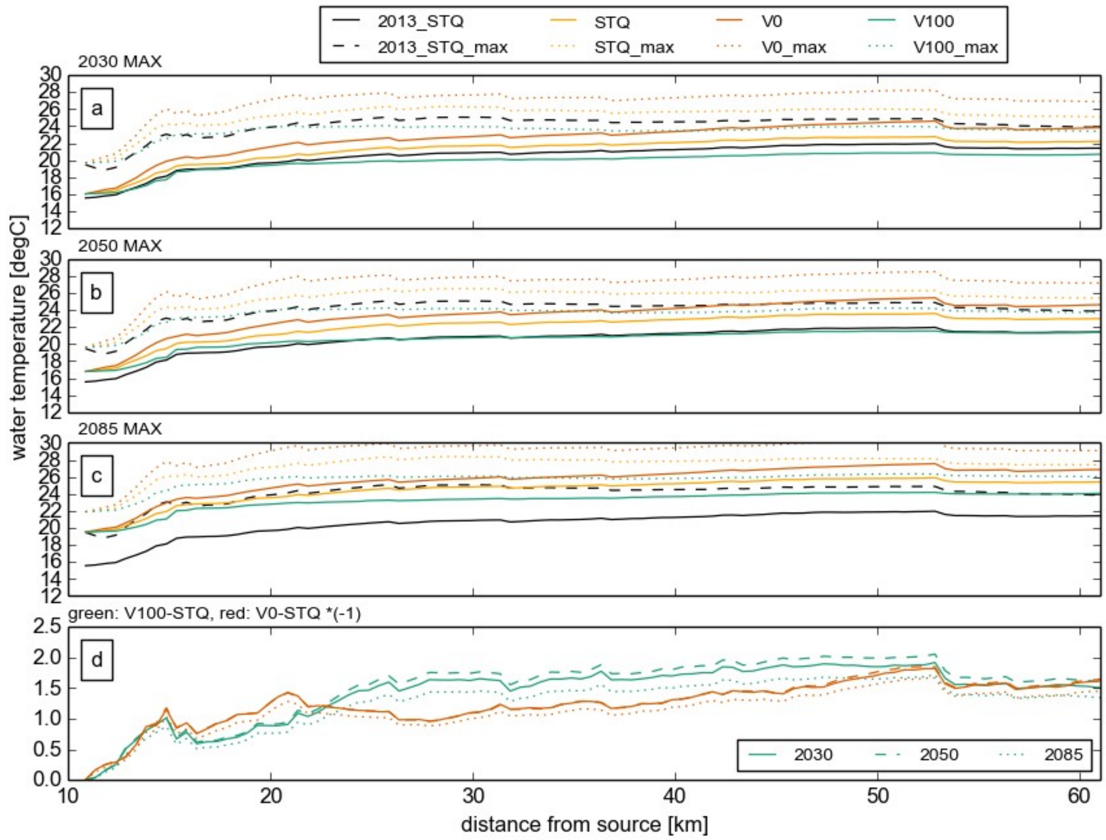

Figure 4: Mean and maximum water temperature averaged during the maximum events predicted for the climate periods centred on 2030, 2050 and 2085 along the river Pinka using vegetation scenarios V0, STQ and V100 in comparison to the maximum event recorded in 2013. The bottom panel shows the difference between STQ and V100 (green) and STQ and V0 (*-1) (red).