Review of “Can riparian vegetation shade mitigate the expected rise in stream temperatures due to climate change during heat waves in a pre-alpine river?”

Dear Prof. Ghadouani,

there were 5 major issues addressed by referee 3+4:

1) The question was risen whether a previously performed **sensitivity study might have been sufficient to answer the questions** asked in this manuscript. Unfortunately no. The sensitivity study done on single parameters is not able to predict the behaviour of a multiparameter model if a composition of parameters are changed. Each future episode varies not only in air temperature but also in global radiation, wind speed and air humidity. The consequence of different vegetation scenarios during future episodes was not predictable especially not in a quantitative way by using a simple sensitivity analysis. As we had the chance to revise the manuscript we could include some new results regarding diurnal variations and trends caused by vegetation during higher temperature level episodes.

2) The question was raised **whether climate change would cause changes in vegetation and feedback to water temperature which are not covered in the study yet**. As the river Pinka is only 4% fully natural there is only a very limited natural vegetation dynamic. Even if the species distribution is changed, this will have no foreseeable effect on the vegetation height and density. Nonetheless it is possible therefore two additional vegetation densities and one additional vegetation height were considered and shown in the revised version to be able to discuss this aspect. The outcome of this study is that even if a very high shading is assumed, which can be achieved by choosing species which are adapted to the current climate and dense plantation, the effects of riparian shade can not fully mitigate the effects of climate change.

3) There was mentioned that **discharge changes are not taken into account**. The discharge chosen is already a low flow scenario, which is the average of the daily discharges below the 5% percentile of the climate period 1981 – 2010. If the mean low flow is reduced by 15% this is a reduction of only 5% of the MQ, therefore we consider it more important whether there is low flow or not. Heat waves must not always coincide with low flow and it is difficult to predict the discharge level within a certain episode. To be able to discuss this aspect of discharge reduction on water temperatures we included a scenario of -15% of MLF discharge for the 20a 2085 climate episode. We did not include discharge issues originally, because the aim was to compare the effect of atmospheric influences on the energy balance at the river surface and its influence on water temperature to the present situation and not to compare the wide range of possible discharge situations, which would be a different topic.

4) The **distribution of percent shade, bankfull width** was asked to be described and was included together with the anthropogenic influence along the river in a new Figure. As the bankfull width only varies between 4 and 10 m this aspect was not considered so important by the authors previously.

5) It was surprising for Referee No3 to read that **a 100% removal of vegetation would have less of an effect on stream temperatures than an increase in air temperature.** This misunderstanding arises we think from the formulation we used. If we speak of removal of vegetation this is referenced to the STQ vegetation, which is not full vegetation. In many areas it is rather sparse. If we compare full (V100) and no vegetation (V0) the change is clearly greater than the change due to increase of temperature.

We addressed all general and specific comments below and the manuscript was proofread by a native speaker to improve the language.

Kind regards, the Authors

Summary of relevant changes made in the Manuscript:

Andreas Melcher from the Instiute of Hydrology of our University was included as coauthor to our team.

Section 1 was shortened, and parts moved to the Discussion. The aims where reformulated including aspects of changing vegetation and interactions of vegetation and discharge.

Section 2 was extended including all formulas of the energy fluxes used in the manuscript. Section 2.4 strongly integrated in 2.2 and 4.3, as well as strongly reduced. The description of the present and future vegetation in the region (2.1), vegetation sampling and vegetation scenarios (2.3.2) was extended.

Section 3 was extended regarding diurnal variations and trends caused by vegetation during higher temperature level episodes. 5 additional vegetation scenarios and 1 additional discharge scenario were included.

Section 4.3 was extended including a discussion about vegetation and discharge feedback.

A list of abbreviations was included as in the Annex.

We are happy that finally we have been able to include the doi of the data underlying this study which has been published on the freshwater biodiversity data portal.

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Response to Referee#3

Dear Referee#3, thank you very much for your valuable and precise comments!

General comments:

No.	Comment	Response
1	The authors appear to have responded to earlier reviewer suggestions. I find the paper fairly cohesive and understandable. The main message is that careful predictions made using the model Heat Source indicate that the river Pinka will likely warm as a consequence of global warming, and by the end of the century even full shading will be insufficient to prevent temperature increases during 20-year return events of even 2 °C.	We agree.
2+3	The two aspects that I struggled with most in the paper were understanding individual sentences (suggested edits included) and coming to grips with results that suggested a 100% removal of vegetation would have less of an effect on stream temperatures	The value 1.8°C refers to the removal of existing vegetation (STQ) of a river which is not densely vegetated in all parts. The average change from full shade (V100) to no vegetation (V0) amounts to 5.8°. (see also response to

	than an increase in air temperature due to climate change. This point would be clarified if there were some other variable (e.g., vegetation density, percent shade, etc.) that readers could use to better understand the available shade for the STQ runs. Additionally, more information on the distribution of the bankfull width would be useful; if most of the river had 4m bankfull widths, I would expect that vegetation could feasibly grow to an extent that the entire stream could be shaded. If the majority of the stream had bankfull widths of 30 m, I would expect additions/removals of shade to have far less of an impact on stream temperatures.	comment 41 below). Regarding bankfull width: The river is anthropogenically influenced most of the course. The maximum bankfull width reached is 10m. Maximum vegetation as defined in the V100 scenario shades the whole river. Additional graphs including the changes in shading percentage (as a resultant of vegetation height, density, width and topography) and bankfull width (Figure 2) as requested. The VTS is moved to this Figure as well. Energy fluxes of different shading (Figure 7) and discharge (Figure 6) are included in the revised version.

<u>Specific comments:</u>

No.	Comment	Response
4	Page 1 Line 12: You use a passive voice in the first sentence. Start with “We simulated the influence…”	Changed accordingly in the manuscript
5	Page 1 Line 28: change to “the occurrence of many species”	Changed accordingly in the manuscript
6	Page 1 Line 30: provide a citation to support the “river continuum disruption” sentence	Citations added: Bloisa, J. L., Williams, J. W., Fitzpatrick M. C., Jackson, S.T., and Ferrierd, S., Space can substitute for time in predicting climate-change effects on biodiversity. Proceedings of the National Academy of Sciences, 110, Nr. 23, p.9374-9379, 2013. Matulla, C., Schmutz A., Melcher, A., Gerersdorfer, T., and Haas, P.: Assessing the impact of a downscaled climate change simulation on the fish fauna in an Inner-Alpine River, Int. J. Biometeorology., 52, 127-137, 2007.
7	Page 1 Line 31: Zoonoses are diseases that can be transmitted from animals to people. Is the statement here indicating that major fish kills	We apologize for this spelling mistake. We intended to write “zoocenosis”. But as this in not a well-used term we exchanged

	could result in disease transmission to people? Please clarify.	it to: “a disruption of animal communities”
8	Page 1 Line 33-34: This sentence is unclear. I cannot tell what it means.	As this sentence was also unclear for a previous reviewer we omit it.
9	Page 2 Line 9: change “temperatures” to “temperature”	Changed accordingly in the manuscript
10	Page 3 Line 9: change “neither groundwater” to “neither change in groundwater”	Changed accordingly in the manuscript
11	Page 3 Line 10: deleted “change”	Changed accordingly in the manuscript
12	Page 4 Line 7: change “these” to “this”	Changed accordingly in the manuscript, but the sentence moved to the section 4.3.
13	Page 5 Line 2: It is not clear on what preliminary work has been done.	Line 2 - 8 describing preliminary work is removed because the necessary aspects are described in the corresponding sections below and the focus should be on the present manuscript and not the previous work done.
14	Page 5 first paragraph: This paragraph needs to be revised. Try changing the sentences to an active voice. “Holzapfel et al. (2015) continuously recorded vegetation cover…”	See specific comment 13
15	Page 5 Line 2: What is meant by “during a different article by Trimmell”?	See specific comment 13
16	Page 5 Line 5: change to “these data were”	See specific comment 13
17	Page 5 Line 7: change to “Heat Source was further used”	See specific comment 13
18	Page 5 Line 8: What is meant by “uniform reach”? What aspects of it were uniform? In other portions of the manuscript the substrate is described as not being uniform, and the vegetation cover varies as well. Also, identify in this sentence that the Pinka is the target river.	The section was uniform terms of slope, bankfull width and discharge. Due to comments made by another reviewer the parts describing previous studies are shortened where not necessary and this part was removed.
19	Page 5 Line 27: What is the HISTALP?	HISTAP is the name of a project, which defined different regions in Austria which have distinct climate trends. As this

		additional information is not necessary for the statement and can be derived from the citation the sentence is shortened to: “Precipitation was reduced in our study region by 10-15%,.. “
20	Page 6 Line 22: change “good” to “met” and after “fit” add “were appropriate” if that statement is still true.	Changed to ”...we concluded that all assumptions were met and the model was appropriate to be used for predictions.”
21	Page 7 Line 3: This sentence is awkward. I suggest changing it to: “… conditions at the reference station data were extracted from the regional…”, add a comma after “Remo”, and delete text after the closing parenthesis. Provide a citation for ECHAM 5, as it is not introduced before this point.	Citations for the global climate models were included in the manuscript.
22	Page 7 Line 5: change “, therefore” to “; therefore,”	Changed accordingly in the manuscript
23	Page 7 Line 8: rephrase the statement “area encompassing the area under investigation”.	“In a second step the data were spatially localized to a 1 km x 1 km grid encompassing the area under investigation using the Austrian INCA data set (Haiden et al. 2011)”
24	Page 7 Line 29: change “situation was taken” to “data were obtained”.	Changed accordingly in the manuscript
25	Page 8 Line 9: change “which is corresponding” to “which corresponds”	Changed accordingly in the manuscript
26	Page 8 Line 16: change “were prevailing” to “prevailed”	Changed accordingly in the manuscript
27	Page 8 Line 19: What is meant by a “change” in discharge? Positive or negative change? The sentence indicates that any change of 0.1 m3/s will lead to an increase in stream temperature. Is this what is meant? Also, I am not convinced that the model is sensitive: a 0.1 m3/s change in discharge is a 55% increase or decrease for the upstream model boundary and still a sizable change for the downstream boundary (13%). Also, where did temperatures increase by	A decrease in discharge was meant and changed accordingly in the manuscript. A change of 0.01m3/s at the upstream model boundary was simulated with resulted in a 0.04°C increase on the average stream temperature during heat wave 2 – 8 August 2013 from DFS 26 to 48. 0.01m3/s was chosen because this was the acuracy of the gauge station. On Page 8 Line 19 the value was simply multiplied to indicate what a 4 fold

	0.4 C? Was this at the upstream boundary, downstream boundary, or at the station in the middle?	increase of stream temperature means for a higher change in discharge. The referee is correct that “very sensitive” is not correct in this context. Also it is misleading to compare m3/s with °C. Percentage values were added and admitted, that the model is not sensitive to discharge rates. In Figure 6 the effect of a discharge reduction of 15% is shown.
28	Page 8 Line 22: Please clarify what is meant by MLF. The statement “average discharge of all discharges below the 5% discharge” is not helpful. What are the time periods in question that are being used to make these assessments? Is this annual or on a daily basis? The word “were” on line 29 suggests that there are multiple MLF values that are being used.	MLF was defined as the average of all daily discharges below the 5% percentile discharge within the climate period 1981 - 2010. On line 24 there was a spelling mistake. There is only one MLF. This and the definition was changed accordingly in the manuscript.
29	Page 9 Line 1: I am not clear on how the moving average was calculated. Over what timeframe?	The moving average is an average over 30 years which is moving. We changed it to “the moving average over a 30 year climate period “ and hope it is clearer now.
30	Page 9 Line 5: Who measured the discharge and temperature during the 2013 episode? Was it the current set of authors?	The sentences was completed with: “... were measured during the 2013 episode in the field by the authors and by two permanent gauging stations.”
31	Page 9 Line 6: Please clarify “boundary. adding" The sentence starting with “adding” is incomplete.	The “boundary. adding” was replaced by “with the addition of “, because this sentences were meant to belong together.
32	Page 9 Line 10: Change beginning of sentence to “As mentioned,”	As reference to previous studies was removed were not necessary, the sensitivity analysis is treated here the first time so the sentence was changed accordingly in the manuscript.
33	Page 9 Line 13: “changes in water temperature”: where along the river were these changes found?	“ ... which caused changes in the average water temperature between DFS 26 and 48 during 2 – 8 August 2013 of … ”
34	Page 9 Line 15: What is meant by “mere”? Does it mean that topographic shade contributes little to the temperature, or that it contributes more than might have been anticipated?	“mere” was meant to emphasise that this refers to the topographic shade only and not taking into account bank shade or vegetation shade. The word was omitted.

35	Page 10 Line 7: I believe this paragraph contains errors and can be cleaner. Should Fig. 2a actually be Fig 2b? Is “conduction” referring to 2f? On line 13 (should this be appended to the end of line 12?) should 2f be 2d? Finally, what is this paragraph referring to? STQ? Please clarify and check.	Thank you very much. Indeed there were some errors regarding the reference to the Figures as indicated. The paragraph has been checked and clarified.
36	Page 11 Line 33: Change “supposed” to “supposing” Make the same change in the next paragraph as well.	Thank you. The first paragraph was changed accordingly in the manuscript. For the second we used “Under conditions of maximum riverine vegetation “, to prevent repitition and hope this is ok for you.
37	Page 12 Line 5: add “for” between “fully the”	Changed accordingly in the manuscript
38	Page 12 Line 30: Why did the addition and removal of trees become roughly the same between distances 53 – 60? Why do we see the pattern mentioned? Is this due to a lack of trees along the Pinka between distances 25-53?	Yes, between 25-53 there are very few trees, therefore addition of trees has more effect than removal. Between 53 and 60 the STQ vegetation cover is balanced, so that both addition and removal have the same effect. The aspect is mentioned to show, that not in all sections removal or addition of vegetation has the same effect.
39	Page 13 Line 6: change “temperature difference” to “temperature the difference”	Changed accordingly in the manuscript
40	Page 13 Line 12: This sentence contains many qualifiers. It is difficult to understand. Can it be simplified?	We tried to improve readability by splitting the information (that was requested by previous reviewers). “The modelled 20 year return period heat wave (20a) in the climate period 2071–2100 showed a +3.8 °C increase in air temperature with respect to the observed period. Increases in maximum, mean and minimum stream temperatures of close to +3 °C with respect to the observed period were simulated for this episode.“
41	Page 14 Line 11: This sentence relates to my general comments statement: why are these streams only warming by 1.8 C when all shade is removed?	1) The value 1.8°C is averaged twice: First it is the average daily max of the 5 day period. Here the max increase of maximum stream temperatures is 3.7°

	Yes, some studies (examining much shorter reaches) only see increases of this amount following complete canopy removal, but others see increases of even 10 C (Brown 1969 and Brown and Kryegier 1970). Again, this relates to understanding what the current shade levels are over the river.	(2085-1a, Table 4). These values are further averaged over all episodes 2) The value 1.8°C refers to the removal of vegetation of a river which is not densely vegetated in all parts. The average change from full shade to no vegetation amounts to 5.8°. 3) Brown and Krygier analysed streams of summer flow below 0.028 to 0.057m3/s, while here a river of 0.18 to 0.76m3/s analysed. Small rivers react much stronger to atmospheric influences. Also the reduction of the absolute maxima and not the average daily maxima is over 10 °C. The changes in average daily summer maxima are one dimension smaller (0.4 – 2.8°F). The reach of Berry Creek described by Brown 1969 is comparable to the upper boundary of this study but the change is given between the beginning of the reach and the end of the 600m long reach. When I understand the study correctly the 11°F change are not only to be accounted to the fact, that the reach is not shaded but also the the rise in temperature caused by the daily amplitude.
42	Page 14 Line 34: Change “good” to “well”	Changed accordingly in the manuscript
43	Page 15 Line 20: change “showed to aggravate” to “aggravated” or “was shown to aggravate”	This sentence was removed during the revision process to shorten the conclusion.

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Response to Referee#4

Dear Referee#4, thank you very much that you draw the attention closely to very important aspects which have not been addressed sufficiently. The aims were reformulated including aspects of changing vegetation, discharge and feedback mechanisms.

<u>General Comments</u>

No.	Comment	Response

1	This study evaluates the role of vegetation shading in mitigating the rise in stream temperature under climate change. The authors have evaluated 3 vegetation scenarios with varying degree of shading (zero, normal and maximum vegetation) using 1D energy balance and hydraulic model Heat Source (Boyd and Kasper 2003) for the river Pinka located in the eastern Austrian Alps. The Heat Source model was calibrated and validated by the lead author and results have already been published in the journal of Meteorologische Zeitschrift (Trimmel et al. 2016). Surprisingly, Trimmel et al. (2016) also evaluated the influence of shading using identical vegetation scenarios [no vegetation (V0), maximum vegetation (V100) and current condition (STQ)] along with few additional topographic shading scenarios [No topography (T0), no river bank (B0)]. The findings related to sensitivity of stream temperature to shading from the earlier paper have been summarized in section 2.4.	You are correct that too much emphasis was given on preliminary work. At many locations it is not necessary, because the manuscipt can stand on its own. We included 5 additional vegetation scenarios, analysis of amplitudes and trends. We integrated section 2.4 into the description of the model in section 2.2.
2	The authors argue and I quote "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." While this is true and this paper does bring additional analysis in terms of future climate change scenarios, one may have to wonder on the novelty and scientific contribution of this paper. Can't we use the sensitivity results reported by Trimmel et al. (2016), also summarized in this paper on page 9 section 2.4, to infer the role of shading in mitigating future warming?	Unfortunately we cannot. The sensitivity analysis was performed only by changing a single value along and comparing it to a base case. This cannot be used to predict the behavior of a multiparameter problem of future episodes, which consist of the interplay of global radiation, air humidity, air temperature, wind speed and type of shade.
3	As for as mitigating the effects of future warming by shading is concern what is the mechanism of increased shading under warmer climate? How can we have maximum vegetation height and density, when air temperature increases under the climate change scenario used in this study and a constant value of discharge? What about the effects of increased riparian vegetation and air temperature on discharge? Even if you ignore the significant (10-15% as reported on page 5	The issue of change in vegetation height and density under changing climate are adressed in chapter 2.1, 2.3.2. and 4.3. Two additional result subsections to look at the influence of different vegetation height and densities in terms of diurnal variations and trends. The reviewer is correct that both discharge and reduced shade is an important issue, so we included a scenario of a 15%

	section 2.1) changes in precipitation, vegetation and air temperature alone can modulate discharge and create a feedback with stream temperature. Even when considering the vegetation shading as end-member scenarios these feedback processes must be accounted and discussed.	discharge reduction in Figure 6 to be able to discuss this aspect. Discharge changes were not included originally in the study, because our emphasis was on finding out more about the influence of shade itself. It is clear to us that discharge has a major effect on stream water temperature, but we intentionally left it out to reduce the variability in the episodes.
4	Introduction is poorly re-written and can be condensed. Too much emphasis on discussing trends should be avoided. In the methodology section, the authors rely too much on readers' knowledge and reference to the earlier work. This paper should stand on its own.	Thank you very much for your feedback regarding the Introduction and Methodology. Some parts grew in length during the previous revision round, but we tried to move parts to the Discussion and shorten it without loosing too much content.
5	The model used in this study should be clearly explained and well justified.	The Methods was extended to cover all energy balance components briefly. Honestly we were not sure how much information about the model is desired by the readers. Using this feedback we revised the sections.
6	Information related to model calibration and validation should be reported as well.	The model was never calibrated by the authors. The information about validation was already included in the last version at Page 6, line 20-24.
7	It is unclear for readers that if the authors calibrated the model or they used the calibrated model.	This aspect was described at the beginning of the Methods and in the subsection in "Modelling energ y balance and stream temperature along the river". We tried to better clarify it .
8	How were the vegetation height and density sampled?	Section 2.3.2 Vegetation and morphology, where the sampling is described, was extended.
9	The language of the manuscript is VERY poor and not suitable for a publication. The paragraphs lack gradual transition and often end with one sentence.	Thank you for this feedback, we will consider this and try improve the language of the manuscript as we would like for all to follow it easily.
10	Stating how this manuscript is different from another is not a great way to start "Results" section.	To point out the distinction between preliminary work and this work was required during the last revision round, but as the sentence is placed wrong it is

		omitted now.
11	Both results and discussion are very hard to follow, sorry	Much additional and quantitative information, that makes these sections difficult to read was requested during the last revision, so we have difficulties to remove them.

Specific Comments

No.	Comment	Response
12	Pg1, line 27: This sentence needs a reference, "Stream temperature and assemblages of fish and benthic invertebrates …".	Citations added: Dossi, F., Leitner, P., Steindl, E. and Graf, W.: Der Einfluss der Wassertemperatur auf die benthische Evertebratenzönose in mittelgrossen Fliessgewässern am Beispiel der Flüsse Lafnitz und Pinka (Burgendland, Steiermark) in Österreich, Mitteilungsblatt für die Mitglieder des Vereins für Ingenieurbiologie, Ingenieurbiologie: Neue Entwicklungen an Fließgewässern, Hängen und Böschungen, 1/2015, 22–28, 2015. Melcher, A., Pletterbauer, F., Guldenschuh, M., Rauch, P., Schaufler K., Seebacher, M. and Schmutz S.: Einfluss der Wassertemperatur auf die Habitatpräferenz von Fischen in mittelgroßen Flüssen, Mitteilungsblatt für die Mitglieder des Vereins für Ingenieurbiologie, Ingenieurbiologie: Neue Entwicklungen an Fließgewässern, Hängen und Böschungen, 1/2015, 15–21, 2015.
13	Pg2, lines 25-27: this sentence is too long. Please break it into two sentences. "While net short wave radiation …"	The sentence was split in two.
14	Pg2, lines 26-27: Change "air humidity" and "wind" to vapor pressure and wind speed, respectively.	Changed accordingly in the manuscript
15	Pg2, lines 28-30: Please reword and revise.	This sentence doesn't fit at this position. The shortened version of the Introduction doesn't include this sentence
16	Pg2, line 34: Move "Since 1980" to the end of the sentence.	Changed accordingly in the manuscript
17	Pg3, line 23: one sentence cannot be a paragraph.	This sentence is misleading, because in the climate episodes also global radiation, air humidity and wind speed were included therefore the sentence is omitted.
18	Pg4, line 6: Revise and reword this sentence.	The sentence was reworded and moved to the discussion. "Apart from its influence on stream temperature vegetation can cast spatially differentiated shade, which results in areas of different sun exposure and energy balance."

19	Pg4, line 6: Again, one sentence cannot be a paragraph.	The sentence was moved down to the end of the chapter and included to the second to last paragraph.
20	Pg4, lines 18-20: adding discharge to a regression model may or may not increases the model performance.	“improves” was changed to “can improve”
21	Pg4, line 21-23: Again, this paragraph has only two sentences.	The sentence were included in the previous paragraph.
22	Pg5, line 27: “air temperature rose …” needs a reference.	Citation, which was already used at a different location added at this point: Auer et al. 2007.
23	Pg5, lines 31-33: This sentence is too long and vague.	The sentence was shortend to: “Using the deterministic model Heat Source version 9 (Boyd and Kasper, 2003; Garner 2007) the energy fluxes along the river, hydraulics and stream temperature were simulated along the River Pinka.” Additional information can be found in the following section below.
24	Pg5, line 33: What do you mean by this sentence “Existing data sets and parameters obtained from Austrian authorities and the literature were completed with field surveys and measurements”? Who are Austrian authorities? Are the data sets publicly available? If so you need to provide the link. How did you complete it?	Changed to: “The generation of the input data sets is described in the following section 2.3.” The responsible authorities were mentioned directly in the subsection treating with the kind of input data. Also the completion of the data is described there. We received the data directly from the authorities.
25	Pg8, line 17: What does DFS stand for?	Distance from source (DFS) was defined in section 2.1 (Page 5 line 23). There was a summary of the most frequent abbreviations included in the Annex.
26	Pg8, line 19: “A change in discharge of …” increase or decrease?	A decrease in discharge was meant and changed accordingly in the manuscript
27	Fig. 1: add geographic reference	Lat/Lon coordinates were added at the corners of the study region
28	Fig 2: very messy, legends on top of the lines	The figure was changed so no legends cover lines.
29	Fig. 3: Run statistical significance test and report results with the figure. Right now it is unclear whether STQ is significantly different from V0.	A two tailored paired students T test was run for the hourly values to determine whether the difference between STQ and V0 and STQ and V100 is significant. A p-value less than 0.0001 was received for each episode.

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. Global warming has already affected European rivers and their aquatic biota, and climate models predict an increase of temperature in Central Europe over all seasons. We simulated ~~T~~the influence of expected changes in heat wave intensity during the 21st century on water~~the~~ temperatures of a~~n~~ pre-alpine Austrian river~~are simulated~~ and analysed ~~the~~ future mitigating effects of riparian vegetation shade on ~~the~~ radiant and turbulent energy fluxes using the deterministic model *Heat Source*~~ analysed were~~. Modelled ~~S~~stream water temperature increased~~s of~~ less than 1.5 °C ~~were modelled~~ within the first half of the century. Until ~~For the period 2071–~~2100 a more significant increase of around 3 °C in minimum, maximum and~~,~~ mean ~~and minimum~~ stream temperature was predicted for a 20 year return period heat event. The result showed clearly that ~~Additional~~ riparian vegetation was not able to fully mitigate the predicted~~expected~~ temperature rise caused by climate change, but would be able to~~could~~ reduce ~~maximum, mean and minimum stream~~ water temperature~~s~~ by 1 to 2 °C. The ~~R~~removal of riparian~~existing~~ vegetation amplified~~–~~ stream temperature increases. Maximum stream temperatures could increase by more than 4 °C even in annual~~yearly~~ heat events. Such a dramatic water temperature shift of some degrees, especially in summer, would indicate a total shift of aquatic biodiversity. The results demonstrate that efficient river restoration and mitigation requires re-establishing riparian vegetation and emphasizes the importance of land-water interfaces and their ecological functioning in aquatic environments.

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 organisms (Davies-Colley and Quinn 1998~~,~~; Heino et al. 2009~~,~~; Magnuson et al. 1979). Heino et al. (2009) ~~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 is highly correlated ~~and~~ with the assemblages of fish and benthic invertebrates along the river course are highly correlated(Dossi et al. 2015;; Melcher et al. 2015). The duration and magnitude of especially the maximum summer stream temperatures in particular are limiting factors for the occurrence of fish many species. occurrence High temperatures may produce high physiological demands and stress while also reducing the oxygen saturation in the water column. The increased metabolic requirements together with the decreased oxygen availability can prove to be a limiting or even be lethal in combination; the average optimum temperature for cold water species is below 16 °C (Matulla et al. 2007; Pletterbauer et al. 2015, Melcher et al. 2014, Melcher et al. 2016).

Continuous warming of water temperatures induces changes from cold water to warm waterin fish species assemblages and slow altitudinal shifts of species, if the habitat is suitable and no migration barriers exist. River continuum disruption and river dimension reduces the fish zone extent significantly (Matulla et al. 2007; Bloisa et al. 2013). Extreme events where lethal thresholds of stream temperature are exceeded can cause a disruption of animal communities or even extinction of (cold water) species (Melcher et al. 2013;; Pletterbauer et al. 2015). The largest uncertainties in forecasts of total suitable habitat are climate uncertainty (Wenger et al. 2013). climate change in the 21st century (Capon et al. 2013). determining the vulnerability of natural and human systems to

Above that riparian ecosystems play a superior role in All 230 stations of the Austrian hydrographic central office, ofwith different elevations, distances from source and catchment areas have recorded an increases ofin stream temperature of 1.5 °C during summer (Jun - Aug) and 0.7 °C during winter (Dec – Feb) stream temperature of 1.5 °C between 1980 and 2011 (0.48 °C / decade)) (BMLFUW 2011). This change is not likely to be due to natural climatic cycles, but is part of a long term trend caused by anthropogenic changes in the atmosphere (APCC 2014).

Air temperatures have been rising and are expected to continue to rise globally within the next century (IPCC 2013). In eastern Austria mean air temperature has risen by 2 °C since 1880, 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 over the level of the reference period 1961-1990 by the end of the 21st century are expected in Ausria (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). SApart from this soil temperature is also 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).

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 precipitation trends (IPCC 2013). Northern Europe shows an increasing trend, while the Mediterranean has a decreasing trend (IPCC 2013, Böhm 2006). In southeastern Austria a precipitation decrease of about 10–15 % has been recorded over the last 150 years (APCC 2014;; Böhm 2012).summer (Apr – Sep) and winter (Oct – Mar) (Böhm et al. 2009, 2012). A continuation of this trend might aggravate the danger of summer drought.both The decrease has been observed in llIn eastern Austria Low flow discharge rates of rivers is are likely to decrease by 10 to 15 % for by 2021–2050 compared to 1976–2007 during all seasons (Nachtnebel et al. 2014From 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).

For the study region during summer heat waves neither change in groundwater nor snow melt contributions change are expected –changeto(APCC 2014). Heavy and extreme precipitation shows no clear increasing signal on average, but it is likely to increase from October to March (APCC 2014). -No clear trend of increasing wind speed (Matulla et al. 2008;; Beniston 2007) or increase in sunshine hours (Ahrens et al. 2014) washas been detected but changes in the climate system may also include changes in those parameters (APCC 2014). 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 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 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).

was calculated (APCC 2014, BMLFUW 2011). and 0.7 °C during winter (Dec - Feb) A mean trend of 1.5 °C during summer (Jun - Aug)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).230 stations of the Austrian hydrographic central office of different elevation, distance from source and catchment area recorded an increase of stream temperature.

Since 1980 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). . (Nachtnebel et al. 2014; Settele et al. 2014; van Vliet et al. 2016) 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(Hannah et al. 2008) is sensitive to air temperature changes ater temperatureW). Trimmel et al. 2016 ;, air temperature, wind and net radiation, play an important role (Caissie et al. 2007; Garner et al 2014; Hannah et al. 2008; Johnson 2004air humidityong wave radiation flux as well as the turbulent fluxes evaporation and convection, which are controlled by , let short wave radiation is the dominant energy input causing diurnal and seasonal water temperature variabilityWhile nStream temperature is controlled by advection of heat, dispersion and the net energy fluxes acting on the surface and river bed.

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). . Matulla et al. 2008)e.g. (Various studies indicate that from observations no long term increase of wind speed or storm activity can be detected in Europe

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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. are expected (APCC).change For the study region during summer heat waves neither groundwater nor snow melt contributions Precipitation changes which affect discharge volume 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). Stream temperature is controlled by advection of heat, dispersion and the net energy fluxes acting on the surface and river bed. Net short wave radiation is the dominant energy input causing diurnal and seasonal water temperature variability. Long wave radiation flux (Benyaha et al. 2012) as well as the turbulent fluxes evaporation and convection, which are controlled by air temperature, vapour pressure, wind speed and net radiation, play an important role (Caissie et al. 2007; Garner et al 2014; Hannah et al. 2008; Johnson 2004).

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). The sStreamside 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 (Holzapfel et al. 2013) and long wave radiation flux, evaporation and convection heat flux, who which are highly correlated to the openness of the sky.).

The main energy input during heat wave conditions is short wave radiation and the most significant output of stream energy occurs via evaporationTrimmel et al. 2016 ,, 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 Vegetation can reduce the incoming global radiation by up to 95% (Holzapfel et al. 2013). The reduction of short wave radiation can contribute significantly to reduce reducing the heating of rivers during warmer summers (Sinokrot and Stefan 1993; Parker and Krenkel 1969; Rutherford et al. 1997; Trimmel et al. 2016). Webb et al. 2008). Trimmel et al. 2016, 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. (Benyahya et al. 2012; Garner et al. 2014; Hannah et al. 2008;Vegetation can reduce the incoming global radiation by up to 95% (Holzapfel et al. 2013). 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.

Though the influence of vegetation on water temperature is evident, its ability to mitigate climate change is not yet sufficiently understood. heterogeneity provides ecological niches which are important for different development stages of river fauna(Clark et al. 1999). In particular, the maximum water temperatures during heat waves are reduced significantly by vegetation shade (Garner et al. 2014)ese. Thfluxes shade, which results in areas of different sun exposure and energy variablespatial highly produces stream temperature vegetation average

Apart from its influence on

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 can 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. Only tThese models are able to simulate energy flux changes caused by increased or decreased river shade. Though the influence of vegetation on water temperature is evident, its ability to mitigate climate change is not yet sufficiently understood. Latent and sensible heat flux as well as long wave radiation balance are non-linearly dependent on air temperature. It is not obvious whether the same level of shade will always lead to the same rate of heat reduction. Shading caused by tall but less dense trees may allow exchange of air, while lower riparian vegetation may cause the same level of shade but would reduce air movement. Vegetation can reduce warming but may also reduce nightly cooling by altering the energy fluxes on a local scale, which can only be modelled using deterministic methods.

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 withused different methods to make short-term forecasts ofpredict stream temperature and few tried to answer the question on how climate change might increase stream water temperature. One result or trend may however not be transferred from one river to another. Particular statements about the riparian vegetation's potential to mitigate the influence of climate change are only reliably valid for a given type of stream and for a given climate zone.Mainly Aair temperature was normally used as a surrogate for stream temperature and energy flux variations at in different river sections were not considered.influence of climate change are only reliably valid for a given type of stream and for a given climate zone.the the riparian vegetation's potential to mitigate about of tatements SParticular s One result or trend may however not be transferred from one river to other.

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 using a deterministic model.

The aims of the present studyarticle areis therefore (1) to estimate the magnitude of stream temperature rise during extreme heat events caused by the expected rise in air temperature until by 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 within the habitat optimum of the site specific aquatic fauna and (3) to analyse the possible variation of vegetation and potential interaction of vegetation and discharge with respect to climate change and their impact on water temperature.

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2 Methods

In the present article s reach (Trimmel at al. 2016).uniformHeat 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

Further . (Trimmel et al. 2016) to set up and validate the 1D energy balance and hydraulic model Heat Source (Boyd and Kasper 2003) for the river Pinka usedThis data was. Holzapfel and Rauch 2015, Holzapfel et al. 2015)(stream temperatures were recorded at 12 sites as well as main tributaries of the eastern Austrian river Pinka , along the riverwas recorded continuouslyegetation cover and river morphology

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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).

Stream temperature was simulated with the 1D energy balance and hydraulic model ***Heat Source*** (Boyd and Kasper 2003) for 51 km along a section of river including upstream forested regions and tributaries. Temperature was simulated for each 500m along section of the river, which amounts amounted 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 that 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 beenproduced within by the ENSEMBLE project (Hewitt et al. 2004) were further processed and the meteorological data extracted. The future upstream model water temperature was simulated according by the methodology of Caissie et al. -(2001).- ***Heat Source*** was used to simulate the stream temperature of the Rriver Pinka for 12 future episodes and three eight vegetation scenarios.

2.1 Study region

The R~~r~~iver Pinka originates at 1480 meters above sea level (m.a.s.l.) in the eastern Austrian Alps and discharges about 100 km downstream at 200 m.~~-~~a.~~-~~s.~~-~~l. into the R~~r~~iver Raab.~~-~~ The catchment ~~size~~ of the 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, the Pinka falls in the smallest of the ~~5~~ five 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 km ~~-~~(559 m.a.s.l) near its most upstream gauge in Pinggau~~(1~~ to DFS 62 km (240 m.a.s.l.) close to the gauge at Burg~~)~~ (Fig. 1).~~-~~ ~~In~~ For 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 (Fig. 2c). The maximum depth of the different river sections varied between 0.1 and 0.5 m and was 0.17 m on average. Only 4 % of the reaches presently fall into into the most natural or the second category according to Ledochowski (2014) (Fig. 2c). On the other hand, 60 % of reaches are classed as continuously influenced with no or very few natural sections (Fig. 2c).

Close to the source (DFS 0-12.5) the vegetation consists of commercial spruce forests (*Picea abies*) which undergo management. In the middle and downstream sections of the river, the near-natural deciduous riparian vegetation includes typical floodplain species of the region (willows (*Salix* sp.) and alders *Alnus glutinosa* and *incana*). In the downstream 80 % of the river (from DFS 34 to 61), riparian vegetation is reduced to one- or two-sided sparse tree plantations lining the river course for decorative purposes. These areas are mowed on a regular basis to prevent scrub growth. Other frequent trees like ash (*Fraxinus excelsior*), hazel (*Corylus avellana*), wild cherry (*Prunus avium*) and Elder (*Sambucus nigra*) can be found along the whole river course.

In this region air temperature ~~rose~~ has risen by 2 °C~~,~~ since 1880 (Auer et al. 2014). Precipitation has ~~reducedwas~~ declined by 10-15% in ~~region corresponding toHISTALPthe~~ our study region, ~~--which isby 10-15%,~~ the largest reduction in precipitation in Austria (Auer et al. 2007~~,~~; Böhm et al. 2009~~,~~; Böhm et al. 2012).

Potential changes in vegetation cover

Changes in vegetation height and density in floodplain forests in natural systems are mainly due to succession (Primack (2000); Garssen et al. (2014); Rivaes et al. (2014)). The present potential natural floodplain forest is in many areas reduced to narrow fringes accompanying the river, which are flooded at least annually. The river has been continuously straightened and regulated throughout the 20th century. Flood protection measures and land use pressure has further altered the river and riparian vegetation dynamics. The vegetation behind these fringes is in the transition zone between softwood and hardwood wetland and a further change towards upland or zonal vegetation is expected via terrestrialization processes, well known in the Danube region (Birkel and Mayer 1992, Egger et al. 2007. The dominant tree species present along the River Pinka, *Salix alba, Alnus glutinosa* and *Fraxinus excelsior* have a European-wide distribution (San-Miguel-Ayanz et al. 2016) so they are likely to defend their habitat. Some autochthonous species (*Populus alba, Prunus avium, Salix caprea, Fraxinus excelsior, Carpinus betulus*) which were present in 2013 are favoured by warmer climates (Kiermeyer 1995; Roloff and Bärtels 2006). Non-native species like *Robinia pseudoacacia* and *Acer negundo* are already present in the study region and might enlarge their habitat at the expense of native species (Kiermeyer 1995; Roloff and Bärtels 2006). Changes in tree species in favour of warmth-loving plants from downstream regions of the Raab/Danube catchment are possible (Lexer et al. 2014). Generally changes are likely to be not only driven by climatic but also anthropogenic factors as plantation of foreign species, which is not foreseeable.

2.2 Modelling vegetation influence on energy ~~balance~~fluxes 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 River Pinka ~~Pinka~~. The generation of the input ~~Existing~~ data sets ~~and parameters obtained from Austrian authorities and the literature were completed with field surveys and measurements~~is described in the following section 2.3 below. Vegetation affects water temperature directly by reducing short wave radiation input and reducing the view to sky which affects long wave radiation balance and the turbulent heat fluxes. Long wave radiation and the turbulent heat fluxes are non-linearly dependent on air temperature. Short and long wave energy flux, latent and sensible heat flux ~~as well as~~and conduction are taken into account:

$$\Phi_{Total}=\Phi_{Latent}-\Phi_{Sensible}-\Phi_{Longwave}-\Phi_{Solar}-\Phi_{Conduction}$$

(1)

where Φ_{Total} is the energy balance, Φ_{Latent} the latent heat flux, $\Phi_{Sensible}$ the sensible flux and ~~,~~ $\Phi_{Longwave}$ is the long wave radiation balance, all of which refer~~ring~~ to the stream surface. ~~;~~ Φ_{Solar} is the short wave energy which is absorbed by the water column and $\Phi_{Conduction}$ is the conduction flux to the stream bed.

~~**Latent heat flux was calculated using the Penman method, which included the radiation balance.**~~

Short wave radiation

The amount of radiation entering the stream $\Phi_{SolarEnter}$ is the radiation unobstructed by shading $\Phi_{AboveTopo}$ reduced by topographic shade $\Phi_{TopoShade}$, bank shade $\Phi_{BankShade}$, vegetation shade $\Phi_{VegShade}$ and reflected from river surface $\Phi_{SolarRef}$.

$$\Phi_{SolarEnter}=\Phi_{AboveTopo}-\Phi_{TopoShade}-\Phi_{BankShade}-\Phi_{VegShade}-\Phi_{SolarRef} \quad (2)$$

If topographic or bank shade is ~~occurring~~present, the direct radiation fraction is reduced by the radiation entering in the affected angles. If vegetation shade is ~~occurring~~present the direct radiation is reduced dependent on the vegetation density using a formulation of Beer's law by the term $\Phi_{SolarExtinct}$.

$$RE=-\log\left(\frac{1-VD}{10}\right) \quad (~~2~~3)$$

$$\Phi_{SolarExtinct}=1-\exp\left(-RE\left(\frac{LD}{\cos\left(\text{rad}\left(\theta_s\right)\right)}\right)\right) \quad (~~3~~4)$$

Where *RE* is the riparian extinction, *VD* is vegetation density, *LD* is the distance from the river cent~~er~~re and θ_s ~~I~~is the solar elevation angle. Φ_{Solar} which is finally absorbed by the water column is the amount of solar radiation entering the stream $\Phi_{SolarEnter}$ (2) minus the amount that is absorbed in the river bed $\Phi_{SolarAbsob}$ and reflected $\Phi_{SolarBedRef}$.

$$\Phi_{Solar}=\Phi_{SolarEnter}-\Phi_{SolarAbsorb}-\Phi_{SolarBedRefl} \quad (5)$$

VTS and long wave radiation balance

The view to sky VTS is calculated using modified vegetation density VD_{mod} and the vegetation angle θ_v. VTS is used to calculate the diffuse radiation below vegetation height, atmospheric longwave radiation $\Phi_{LongwaveAtm}$ (7), longwave radiation emitted from vegetation $\Phi_{LongwaveVeg}$ (6) and the reduction of wind speed at the river surface (11).

$$\mathrm{VTS}=1-\frac{max\,\theta_v * VD_{mod}}{7*90} \qquad (6)$$

Longwave radiation balance $\Phi_{Longwave}$ is the sum of all long wave components:

$$\Phi_{\mathrm{LongwaveAtm}}=0.96*\mathrm{VTS}*em*\sigma*(T_{\mathrm{airK}})^4 \qquad (7)$$

$$\Phi_{\mathrm{LongwaveVeg}}=0.96*(1\text{-VTS})*0.96*\sigma*(T_{\mathrm{airK}})^4 \qquad (8)$$

$$\Phi_{\mathrm{LongwaveStream}}=-0.96*\sigma*(T_{\mathrm{prevK}})^4 \qquad (9)$$

$$\Phi_{\mathrm{Longwave}}=\Phi_{\mathrm{LongwaveAtm}}+\Phi_{\mathrm{LongwaveVeg}}+\Phi_{\mathrm{LongwaveSream}} \qquad (10)$$

where *em* is the emissivity of the atmosphere, σ the Stefan Bolzmann constant and T_{airK} the air temperature and T_{prevK} the stream temperature of the advected water in degree Kelvin.

Latent and sensible heat flux

Latent heat flux Φ_{Latent} was calculated using the Penman method, which included the radiation balance:

$$E_{\mathrm{a}}=1.51\mathrm{E\text{-}9}+1.6\mathrm{E\text{-}9}*(w*\mathrm{VTS})*(e_{\mathrm{s}}-e_{\mathrm{a}}) \qquad (11)$$

$$E=\frac{\left(\left(\frac{\Phi_{\mathrm{Rad}}*\Delta}{(\rho*LHV)}\right)+E_a*\gamma\right)}{(\Delta+\gamma)} \qquad (12), \qquad \Phi_{\mathrm{Latent}}=-E*LHV*\rho \qquad (13)$$

where E_a is the aerodynamic evaporation, w the wind speed [ms^{-1}], E is the evaporation rate [ms^{-1}], Φ_{Rad} the sum of $\Phi_{Longwave}$ and Φ_{Solar_enter}, Δ the slope of the saturation vapour vs. air temperature curve, ρ is the density of water [kg m^{-3}], *LHV* the latent heat of vaporization [Jkg^{-1}]~~, E_a the aerodynamic evaporation~~ and γ is the psychrometric constant [mb°C^{-1}].

~~Convection~~ Sensible heat flux is calculated from evaporation via the Bowen ratio β:

$$\beta=\frac{\gamma*(T_{\mathrm{prev}}-T_{\mathrm{air}})}{(e_{\mathrm{s}}-e_{\mathrm{a}})} \qquad (14); \qquad \Phi_{\mathrm{Sensible}}=\Phi_{\mathrm{Latent}}*\beta \qquad (15)$$

where T_{prev} is the stream temperature, T_{air} is air temperature, e_s is the saturated vapor pressure and e_a the air vapor pressure.

Conduction heat flux

Conduction $\Phi_{Conduction}$ is dependent on the thermal conductivity of the sediment TC_{sed}, the sediment depth d_{sed} and sediment temperature T_{sed} and water temperature T_{prev} :

$$\Phi_{Conduction} = \frac{TC_{sed} * (T_{sed} - T_{prev})}{(d_{sed}/2)} \quad (16)$$

Water temperature

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} (1) was calculated using:

$$\Delta T = \frac{\Phi_{Total} * dt}{\left(\frac{A}{W_w}\right) * c_{H2O} * m} \quad (17)$$

where A is the cross sectional area ~~or~~ of 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.

Conclusively *Heat Source* includes all aspect of vegetation changes on stream temperature during future episodes and the main processes needed to answer the research questions can be modelled with *Heat Source*.

A first ~~The~~ model ~~adaptedhad been~~ set up and validat~~ed~~ion for usage at the River Pinka during heat wave conditions was done 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~~ 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 for the simulations used ~~in this article~~here. Tuning increased the coefficients of determination R^2 for water temperature stations of different vegetation height and density at DFS 31, 35, 37, 39 and 48 km ~~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 assumptions were met~~good~~ and the model ~~awaswerefit~~ was appropriate to be used for predictions. ~~The influence of bank shade on mean water temperature, excluding riparian vegetation, was calculated to be 0.31 °C, while the 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).~~

2.3 Preparation of input

2.3.1 Meteorological input

During the maximum heat wave event of 2013, field measurements were collected at the study site. Global radiation, air temperature, air humidity and wind speed ~~was~~ were 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 topological 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~~made. 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 an RMSE of 0.67°C and an 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 a proxy to represent the local meteorological conditions within the catchment.

To obtain future meteorological conditions at the reference station, data were extracted from the regional ~~conditions data from the regional~~climate models (RCM) Aladin (driven by the global climate model ARPEGE (Déqué et al., 1994)), Remo, and RegCM3 (both ECHAM 5 driven (Roeckner et al., 2003, ~~+~~ 2004)) ~~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~~ 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~~Table 1) 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 heat wave 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~~ 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 Holzapfel et al (2015) Kalny et al. (2015), Ledochowski (2014). and Holzapfel and Rauch (2015). First, aerial photographs were used to define the river centre line and a 50 m buffer on both sides, because the influence of riparian vegetation on the river is negligible beyond this point (Holzapfel and Rauch 2014). Within this zone, areas of homogeneous structure, land use and ecological function were mapped by hand. Additional information such as height, density and dominant vegetation typespecies were recorded as attributes of mapped features on. To verify and complete the attributes -field mapping was realizeddone using custom-built check-lists. The checklists included two tree levels, one shrub and one herb level. The recorded parameters for each level waswere height, density, overhang and dominant species. Vegetation height was estimated with a precision of +/- 5m, overhang with a precision of +/- 1m, and density with a precision of +/- 20%. Additionally the and morphology parameters river bankfull width (Fig. 2c), wetted width, average water depthiverThe r,measured.also slope were height o The inclination of the river slope as well as the roughness of the section (type of regulation, whether sinuous or straight) and type of substrate were noted..along the whole river stretch (Kalny et al. 2015; Trimmel et al. 2016)all recorded were and bed bank of the river morphology,. Vegetation overhanghe riverVegetation height and density was sampled in a 50 m buffer on both sides of t -From these data sources VTS (see formulaequation (4)) and percent shade waswere calculated (Fig 2a +, 2b). The river morphology parameters river bankfull width (Fig. 2c), wetted width, average water depth and height of river to slope top were also measured.

The riparian vegetation data situation was takenwere obtained after the phenological phase of leaf development was finished and leaves were already fully developed (Ellenberg 2012). The river investigated here is strongly influenced anthropogenically and highly regulated. The degree of anthropogenic influence was categorized by Ledochowski (2014) according to Mühlmann (2010) into 5five categories: entirely natural (1), slightly or not influenced. (2), strongly influenced but with remaining natural areas (3), continuously influencesd andwith few natural areas (4) -and completely regulated (5) (see Fig. 2c). This categorization includes mainly describes constraints toon bank and riverbed dynamics. The sStructure and substrate composition of stream bed and vegetation were additional parameters recorded by Ledochowski (2014). t, vegetation 30m heighThe entirely natural class is endowed with riparian vegetation of aboves densities of 76 to 100% and a riparian zone of above. Only 4 in widthm 49more thanpercent of the reaches presently fall into this On the other hand, or the second category. influenced classed as continuously are of reaches 60% continuously with no or hardly nvery fewocontinuously influenced areas coincide with reduced riparian vegetation The natural sections. area width and reduced vegetation height. stripsThe entirely natural class is endowed with riparian vegetation of above 30m height, vegetation densities of 76 to 100 % and a riparian zone of more than 49 m in width. The continuously influenced areas coincide with reduced riparian vegetation strips and reduced vegetation height.

(DFS 0-12.5)Close to the source Theists cons vegetation thecomposition ranges from commercial spruce of forests (Picea abies) close to the source which undergoes management. The middle and downstream In thethesection he t ,rivers of the and near natural deciduous riparian vegetation -sections floodplain species of the region (typical sinclude with and willows (Salix sp.*), alders Populus sppoplars (Alnus glutinosa* and *incana. .) and wild cherry (Prunus sp.)alder (Alnus glutinosa) ash (Fraxinus excelsior), , maples (Acer sp.),In the downstream (from DFS 34 to 61) 80% of the reach, riparian vegetation is reduced to (from DFS 34 to 61)riveronly with highly altered sections to decorative purposesfor lining the river course*

-sided sparse tree plantations or two- one the river coursee lining of e.g. maples (Acer sp.) or lime trees (Tilia sp.) growthhese areas are mowed on a regular basis to prevent scrub T.srees like a t.ACorylus avellanahazel (sh (Fraxinus excelsior),), and wild cherry (Prunus avium .ra) and Elder (Sambucus niger) can be found along the whole river course.

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Vegetation scenarios

Overall, tChanges in vegetation height and density in floodplain forests in natural systems are mainly due to succession. dynamical changes are expected. will be regulated for the foreseeable future, noiver Pinka Rdecline of water table. As the the inundation periods and intensity, days since rain and including the hydrological regime via changes in riparian vegetation cover onclimate change effect of Primack (2000), Garssen et al. (2014), Rivaes et al. (2014) studied the

fringes accompanying the river, which are flooded at least annually.narrow in many areas reduced to ispotential natural floodplain forest present The tweention zone behind thesis in the transi be. The vegetationsvegetation dynamicriparian The river has been continuously straightened and regulated throughout the 20st century. Flood protection measures and land use pressure has further altered the river and The dominant tree species present along the River Pinka, *Salix alba, Alnus glutinosa* and *Fraxinus excelsior* have a European-wide distribution (San-Miguel-Ayanz et al. 2016) so they are likely to defend their habitat. Some autochthonous species (*Populus alba, Prunus avium, Salix caprea, Fraxinus excelsior, Carpinus betulus*) which were present in 2013 are favoured by warmer climates (Kiermeyer 1995, Roloff and Bärtels 2006). Non-native species like *Robinia pseudoacacia* and *Acer negundo* are already present in the study region and might enlarge their habitat at the expense of native species (Kiermeyer 1995, Roloff and Bärtels 2006). Changes in tree species in favour of warmth-loving plants from downstream regions of the Raab/Danube catchment are possible (Lexer et al. 2014). Generally changes are likely to be not only driven by climatic but also anthropogenic factors as plantation of foreign species, which is not foreseeable.

the Danube region (Birkel and Mayer 1992, Egger et al. esses, well known ind via terrestrialization procetand hardwood wetland and a further change towards upland or zonal vegetation is expe

Taking into account all likely changes in tree species, no change in maximum vegetation height or density is predictable.

the maximum vegetation height of the riparian vegetation is not expected to change, ThereforePotential changes are most likely caused by different vegetation management strategies as intentional clearings, plantations or mowing. Four vegetation Mmanagement scenarios are chosen to estimate the impact of different levels of vegetation shade on future heat waves. This also makes it possible to quantify potential changes to warmth-loving species of reduced height and density. To estimate the influence of different shading elements the fThe fFollowing scenarios have been consideredwere used:

maximum vegetation cover (V100) andactual vegetation cover (STQ).intermediate vegetation (V0), no vegetation cover (V0), STQ used the best available status quo input data for vegetation, bank and topographic shade as described in Kalny et al. (2015)Ledochowski (2014) 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 (STQ)getation veriparianthe STQ of levelexisting positionat the which is representative for the natural dense riparian forest at the areas of existing riparian vegetation (STQ). This scenario ensured represented the maximum possible level of vegetation shade with no relief of -land use pressure. An intermediate height scenario (V50) was defined as 15 m vegetation height and 90 % vegetation density. A reduced density scenario (V70) was defined as 30m vegetation height and vegetation density of 70 %. Additionally scenarios of vegetation density 70 % (VD70), vegetation density 50 % (VD50) and of vegetation height reduced by 50 % (VH50) were considered. -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 correspondsing to the available geological information of the Rriver Pinka (Pahr 1984). 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 solar radiation 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 prevailedîng. The river flow volume increased from 0.18 -m^3s^{-1} close to the upstream model boundary at DFS 13 km to 0.76 m^3s^{-1} at the downstream model boundary (DFS 62 km). 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 was notvery sensitive to discharge rates. A decreasechange in discharge of the upstream boundary station of 0.01 m^3s^{-1} (6 %) lead to an4 times increase in average stream temperature from DFS 26 km to 48 km of (0.04 °C)(0.2%) (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 wasis defined as the average discharge of all daily discharges- below the 5% percentile discharge of the climate period 1981 – 2010. The mean low flow conditions (MLF) of the gauging station at Pinggau, DFS 13 km1981–2010 (MLF = 0.143 m^3s^{-1}), which is maintained by the Hydrographischer Dienst Österreich wasere used in the model. At the other end of the study region at DFS 62 km the corresponding flow volume was 0.795 -m^3s^{-1}. To take into account potential reductions of discharge a scenario of MLF discharge – 15 % (MLF -15) (MLF-15 = 0.122 m^3s^{-1}), which is a 5 % reduction of the mean annual discharge, was calculated .

2.3.5 Upstream boundary stream temperature

Stream temperature and discharge were used as upstream boundary conditions. For the 2013 episode these values rely on observations of the gauging station at Pinggau which is maintained by the Hydrographischer Dienst Österreich and a stream temperature measurement station maintained by the authors. To obtain equivalent data for future conditions, first the maximum water temperature was first modelled at DFS 11 km using the expected air temperature as input (Mohseni et al., 1998). The water temperature was split into two components: the ~~long-~~long-term seasonal component (or annual component) and the ~~short-~~short-term ~~non-~~non-seasonal component (or residuals series) (Caissie et al. 2001). The annual component was calculated according to the method of 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~~ N = 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 and~~,~~ the RMSE was 0.68 °C. For the summer half-year 2013 (Apr – Sept), the R^2 was 0.89~~,~~ and 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 over a 30 year~~moving average~~ climate period ~~of a 30 year climate period~~ and the reference period 1981–2010 was added to the annual component.

2.3.6 Input data of tributaries

The discharge levels and water temperature of the ~~river~~ River Pinka at the upstream model boundary and ~~the~~ its main 5 tributaries ~~of the 2013 episode~~ were measured during the 2013 episode in the field by the authors and by two permanent gauging stations. The remaining unmeasured tributaries added less than 5 % discharge each. Their future water temperatures were synthesized using the daily fluctuations of the water temperature at the upstream model boundary with the adding of a fixed offset depending on the distance of the inflow to the upstream model boundary. Missing discharge information was supplemented using proportions of the discharge levels of the gauge at Burg (DFS 62 km) as measured during 2013.

~~2.4 Uncertainties in predicted stream temperature~~

~~As mentioned before odel 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 the average water temperature between DFS 26 km and 48 km during 2 – 8 August 2013 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 consideringexcluding 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 beenwere 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 of 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 only 0.18 °C was calculatedestimated to result.

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3 Results

3.1 IThe iInfluence of vegetation shade and energy fluxes and vegetation shade on stream temperatures during the heat episode 2013 along the river

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 2 and 3in Fig. shown 2.

The mean view to sky (VTS) for the study region under current conditions (STQ) was 0.55. If all vegetation was were to be removed (V0) there was would still be some remaining shade caused by topography and the river bank, which reduces the maximumd VTS to a value of to 0.89. If maximum vegetation was assumed (V100), the value of VTS was is strongly reduced, but still amounted amounts to 0.16 on average because only a 90% vegetation density was assumed. Peaks in VTS were found at broader river sections or sections oriented East-West (Fig. 2a). The percentage shade is similar to the inverse of VTS but differs, as the south orientation is of importance (Fig. 2b).

During the STQ scenario Tthe most important energy inputs on the river surface during the study period and region were short wave radiation flux with an average of 101.6 W m^{-2} (Fig. 3a2a), sensible heat flux with an average of 39.9 W m^{-2} (Fig. 23de) and long wave radiation with an average of 17.2 W m^{-2} (Fig. 23be). Conduction only amounted to 1.3 W m^{-2} on average (Fig. 3e). 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. f23c).

DuringFor the V0 and V100 scenario the directioncharacteristic of the longitudinal 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 sensible 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. ~~2~~3a-~~f~~e).

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 leads to a rapid increase in the water temperature of the cool spring water, which is clearly seen in both measured and simulated data (Fig. ~~2~~3g~~h~~).

All energy fluxes were dependent on the degree of openness to the sky, and showed the same pattern along the river (Fig. ~~2~~3~~ab~~a - ~~f~~g). Short wave radiation and latent heat flux in particular were strongly influenced by the value of the VTS and showed distinct ~~cutbacks~~ reductions of up to 70% where shading occurred (Fig. ~~2~~3a~~b~~, ~~2~~3c~~d~~).

The energy balance was positive on average along the whole river ~~reach~~ (Fig. 3~~2~~f~~g~~). The V0 scenario showed the highest and the~~,~~ V100 scenario the lowest ~~aluest~~ net energy with ~~a~~ mean values of 55, 40 and 22 W m^{-2} for the V0, STQ and V100 scenarios respectively (Fig. 3~~2~~f~~g~~). 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. 3~~2~~f~~g~~), while during the V100 scenario ~~it~~ the corresponding figure 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. f2h. The continuous downstream warming is reversed ~~on~~ at about DFSs 16, 22, 26.5, 32, 43.5 and 53.5km ~~in the~~by about ~~range~~ of 0.5 °C for ~~1 km~~~~about~~ short distances~~3g (Fig. 2h)~~ caused by ~~the mixing with~~the addition of cooler water from tributaries (Fig. 3g).

3.2 Future climate and advective input

The selection criteria mean air temperature of modelled scenarios increased 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 modelled events were warmer than the 2013 heat wave. Air humidity during the selected events decreased slightly ~~until~~ by the end of the century~~, but had a value below average during the 2013 event~~ (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). The average global radiation received during each event per day was different for each event as well. For the 20 year return event in 2030, global radiation was ~~(~~ 28 MJ m^{-2} d^{-1}~~)~~ i.e. ~~global radiation was~~ higher than the same scenario in 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).

For the mean water temperature at the model boundary an increase of +4.1 °C for a 20 year return event of 2085 ~~in~~ with respect to 2013 levels 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~~2).

The extraction of ~~the~~ future climate data ~~were~~ was based on the location of the INCA grid. INCA data for the heat event in 2013 ~~could be~~was 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 in a 0.1 °C higher measured mean water temperature (Table 3). Maximum water temperature was affected also, with INCA showing a reduction of 0.3 °C below measured values. Minimum water temperature was 0.6 °C warmer when INCA data input were used.

~~To be able~~In order 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” hereafter.

3.3 Future stream temperatures

At DFS 39 km

To analyse future changes, ~~first the location of~~ the initial focus was upon 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 ~~3, Table 3) 4(Fig.~~ of the R~~r~~iver Pinka under ~~,~~ MLF conditions ~~and~~ with unchanged riparian vegetation (STQ) at DFS 39 km during the 20a heat wave event ~~of~~ for the periods 2016–2045, 2036–2065 and 2071–2100 ~~were~~ was predicted ~~with~~ to be 22.4 °C, 22.6 °C and 25.5 °C respectively (Fig. 4, Table 3). The corresponding predicted maximum water temperatures were 25.0 °C, 24.8 °C and 27.3 °C. These predictions represent~~ed~~ 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 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 in minimum temperatures of +3 °C was modelled. M~~Also m~~aximum water temperatures also showed increases. For the period 2016–2045, maximum temperatures increased more rapidly than mean temperatures with a change over baseline conditions of +0.6 °C. By 2071–2100 the increase in maximum temperatures was predicted to be 2.9 °C compared to the OBS period, which was similar to the predicted increase in mean and minimum water temperatures (Table 4).

~~edingSuppos~~Supposing~~If~~ the existing vegetation were removed (V0), the mean water temperature reached 26.7 °C during 20 year return period heat events at the end of the century, which was 4.2 °C above the level of the STQ scenario of the OBS period. Maximum temperatures ~~could even~~ reached 28.9 °C, which i~~i~~s 4.5 °C more than in the STQ scenario of the OBS period (Fig. 4~~3~~, Table 3, 4).~~eding~~

~~Suppos~~Under conditions of maximum riverine vegetation ~~was implemented~~ (V100), the expected mean water temperature was predicted to reach only 23.9 °C, which is 1.4 °C above the level of the STQ scenario during 2013 (Fig. 4~~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. 4~~3~~, Table 3, 4).

Vegetation was not able to compensate fully for the temperature increase expected by the end of the century. For the climate period 2036–2065 though, riverine vegetation had the potential to more than compensate for climate change during extreme events and could even cause a ~~reduced warming~~cooling of –1.2 °C on average and –1.4 °C ~~concerning~~ with respect to maximum temperatures (Table 4).

Longitudinal distribution

During the 2013 heat wave event for the STQ scenario, ~~The~~ the stream temperatures increased ~~from~~ between the upstream model boundary at DFS 11 km ~~to~~ and DFS 62 km ~~during the 2013 heat wave event for the STQ scenario including all available information about the present state of the river was~~by about 7° C (Fig. 3~~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. 5a-c).

The maximum values showed a similar pattern to 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. 5a).

V0 scenarios were always warmer than STQ scenarios and V100 scenarios were always cooler than the STQ scenarios. The mean differences along the river between V0 and STQ were 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. 5c).

Water temperature was especially sensitive to the removal of vegetation within the first 10 km (DFS 11 ~~-~~– 21 km) where there were dense forests which prevented the cool headwaters from warming (Fig. 5~~4~~d). In this region~~At DFS 11 - 21~~ temperatures increased by 1.4 °C under the no-~~when removal of~~ vegetation ~~is assumed~~scenario (V0-STQ). Additional tree cover (V100) caused a temperature reduction of ~~-~~0.9 °C ~~-~~compared to the STQ scenario (Fig. 5~~4~~d).

This can be explained by the slower flow velocities in the lower reaches (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~~ gives 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 5).

Diurnal ranges

For aquatic species the mean stream temperature is not the only relevant temperature parameter. The daily temperature range,~~-~~the absolute minima and maxima as well as the timing when extremes take place are also of importance. These vary along the river and change depending on the different vegetation shade intensities and discharge volumes (Fig. 6). In the contour plot shown as Figure 6~~-~~ the warming along the longitudinal gradient is clearly visible, but it is also obvious that the stream is warming to a higher peak each day until the end of the heat episode.

In Figure~~s~~ 6's lower panel ~~-~~ ~~t~~the daily water temperature amplitude is plotted, along with the energy balance components acting on the river surface for the two locations marked by the black bars in the contour plots~~Figure 6~~. Here the absolute values, amplitude and timing of extremes can be seen. While the energy balance shows the energy input taking place directly at the location, the water temperature includes the energy input of the whole water volume upstream. An upstream site (DFS 20 km) is compared to a downstream site (DSF 61 km). They are both open (VTS of V0 = 0.9, 1) but differ in average water depth (0.09 m, 0.31 m) and discharge levels (0.34 m^{3}~~/~~s^{-1}, 0.8 m^{3}~~/~~s^{-1}).

The daily amplitude of the water temperature is strongly damped by the larger flow volume which can be seen in the comparison of the upstream and downstream sites (Fig.~~s~~ ~~7~~6~~8 and~~). A decrease in discharge of -15% can also be seen to affect the daily minima and maxima of stream temperature in open sections (V0). During the V100 scenario the 15% discharge reduction has no visible effect (<<0.1 °C).

The daily amplitude of the energy fluxes is not affected by flow volume, but is reduced by vegetation shade. The hourly values of all energy fluxes are reduced synchronously. Decreased~~Increased~~ solar input and wind access close to the river surface caused by an in~~de~~crease in vegetation density lowers the energy fluxes. From V0 to V100 the maxima can increase more than 2 °C (Fig. 6 and 7). But changes in vegetation density of as little as 20 % can cause an increase of maximum water temperature of more than 0.5 °C (Fig. 7). A change from e.g. 100 % to 70 % raises the heat input by short wave radiation (+17 ~~W/m²~~Wm^{-2}) convection (+5.6 Wm^{-2}), and long wave radiation (+3.7 Wm^{-2}) but only~~also~~ increases heat loss by evaporation from the river surface (~~-~~-21 W~~/~~m^{-2})~~,~~ ~~),convection (+5.6) and long wave radiation (+3.7)~~ (Fig.~~ure~~ 7).~~ The difference between the two shading scenarios is less at the downstream site (hort wave: +7.5 , evaporation -10.4 , convection 0.2 , long wave 1.5)(Figure 8).~~ The shading affects the maximum as well as the minimum water temperature and leads to a reduction of the daily amplitude (Fig. 6 and 7). ~~-~~ An interesting aspect is that the peak of stream temperature occurs about 1h later when vegetation is included.~~-~~ With a vegetation density reduction of 50% (VD50) the diurnal range and especially the maximum temperatures are further increased (Fig. 7). It is interesting to note, that halving vegetation height has a similar or less significant effect as reducing vegetation density by 20% (Fig. 7).

Trends

The trend lines where calculated by minimizing the square error. An ANCOVA (analysis of covariance) showed significant interactions between vegetation and air temperature ($p < 0.001$). The equal slope assumption failed, the equal variance test was passed. Mean, maximum and minimum stream temperatures increase as air temperature increases (Fig. 8). Under the assumption of full vegetation, the intercept of the regression line is lowest for the mean and maxima, while under the assumption of no vegetation it is lowest for the minima. The difference between the vegetation scenarios is greatest for the maxima and smallest for the minima. The slope on the other hand is smallest for the maxima and greatest for the minima. All scenarios and values show a squared Spearman's rank correlation coefficient between 0.78 and 0.93. For mean and maximum temperatures the trend line of V0 is steeper than V100 (17 %), which means, that supposing no vegetation the maximum temperatures could lead to increase at a higher rate. For the daily minima the difference in slope is even greater (30 %). The regression lines of the halved vegetation height scenario (V50) and the reduced vegetation density scenario

(V70) cross for minima, mean and maxima values. The change in slope though is small (3.6 %, 1.4 % and 5.8 % for the mean, minima and maxima respectively) and statistically not significant.

4 Discussion

4.1 Energy fluxes during heat waves

In the present article evaporative heat flux was responsible for 100 % of heat loss from river water on average. Short wave radiation balance, long wave radiation balance and sensible heat flux were 64 %, 11 % and 25 % of the total energy input~~s~~ respectively.

During summer periods of high air temperature the difference between air and water temperature increases, which can trigger intensified evaporative flux that cools the river, but can also cause~~-~~ sensible heat flux to heat the water column (Benyahya et al. 2012). Benyahya et al. 2012 found that evaporative heat flux accounted for 100 % of energy outputs during 7-23 June 2008 while short wave radiation balance, long wave radiation balance and sensible heat flux were 72.53 %, 24.05 % and 2.03 % of the energy input respectively.

4.2 Magnitude of stream temperature rise

~~orIn the present article f~~The modelled 20 year return period heat wave (20a) ~~-~~in the climate period 2071–2100 showed a ~~with~~ +3.8 °C increase in air temperature ~~in~~ with respect to the observed period. ~~and drge was assumed and values for DFS 39 extracteMLF discha.;~~Increases in maximum, mean and minimum stream temperatures of close to +3 °C ~~in~~ with respect to the observed period were simulated ~~fofor DFS 39~~for this episode. During the Max event, the modelled increases of maximum, mean and minimum ~~values~~ temperatures w~~h~~ere 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 equates to an increase of 0.33 °C/decade.

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. The relatively low modelled temperatures were ~~is was~~ most evident in maximum water temperatures. For the V0 scenario low water temperatures were also predicted, which was caused increased evaporation. The maximum vegetation scenario (V100) shows ~~comparably warm~~similar stream temperatures ~~in respect~~ to 2013.

Temperature increase in Austrian stream waters is well-documented and ubiquitous. All From 1980 to 2011 230 stations of the Austrian hydrographic central office, of with different elevations, distances from source and catchment areas recorded an increases of stream temperature of an average of 1.5 °C (0.48 °C / decade) from 1980 to 2011 (BMLFUW 2011). between 1980 and 2011 according to this study (BMLFUW 2011)1.5 ° C

For Austrian rivers summer stream temperature increased by (0.48 °C / decade). The data were elevation-corrected using External Drift Top Kringing (Skøien et al. 2006) and a mean trend was calculated using the Mann-Kendall -Test (Burn and Hag Elnur, 2002) by BMLFUW (2011). Melcher et al. (2013) analysed 60 stations and found a similar trend of 1 °C within the last 35 years regardingfor mean August temperatures, which was independent of the river type (0.29 °C / decade). The annual mean temperature of the Rriver Danube has been rising (Webb and Nobilis 1995) and is likely to continue to rise to reach a value between 11.1 and 12.2 °C by 2050 compared to around 9 °C at the beginning of the 20th century at the border towith Slovakia (Nachtnebel et al. 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 with 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 Rriver Danube, daily amplitudes and extremes are not comparable to the Pinka, but trends in mean water temperature values are comparable though.

The temperature values predicted in this articleby this study were clearly above greater than 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), a 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 modelled water temperature rises 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

How will riparian vegetation vegetation systems behave in the future, what are the feedback mechanisms of increased shading under a warmer heat wave scenario? Decrease in discharge caused by increased evaporation from the river surfaces caused by missing riparian vegetation (V0 compared to V100) was calculated to be -0.001 m^3s^{-1} at the lower boundary of the river (DFS 61). Also during an MLF reduced by 15 % the loss of water to evaporation was only -0.001 m^3s^{-1}. Therefore mass loss was not found to be a significant driver of temperature rise in a river of this size. Further

there might be a potential decrease of discharge caused by increased withdrawal of river water by the riparian vegetation under warmer climates. As species of the floodplain forest are "spender" type plants that do not economise their water use, this needs to be considered. In this study a simulation is included with a discharge decrease of 15 %, a level that is presently expected from past observations. This estimation includes precipitation losses as well as increased evapotranspiration by the soil-vegetation system of the catchment area and increased evapotranspiration by the riparian vegetation via rises in air temperature. Different discharge scenarios were not simulated for all episodes, because the fact that low flow situation was chosen was more dominant than the expected reduction by 15 %.

The increased air humidity and reduced air temperature caused by transpiration of riparian vegetation close to the river reduces air humidity and air temperature gradients. The effect on water temperature was calculated to be a maximum of around 0.2 °C. More directly ~~V~~vegetation affects water temperature ~~directly~~ by reducing short wave radiation input but also it ~~and~~ reduc~~inges~~ the view to sky which affects long wave radiation balance and the turbulent heat fluxes.

Community changes which might affect vegetation height and density are possible ~~due to climate change~~within the next century though~~.~~ changes in vegetation height and density in floodplain forests in natural systems are mainly due to succession. Primack (2000), Garssen et al. (2014), Rivaes et al. (2014) studied the effect of climate change on natural riparian vegetation cover via changes in the hydrological regime including inundation periods and intensity, days since rain and the decline of water table. As the River Pinka is anthropogenically influenced and will be regulated for the foreseeable future no dynamical changes and no natural succession dynamics are expected which could cause an extreme change in vegetation cover.

~~D~~Different v~~V~~egetation scenarios were simulated in this study to quantify the potential effects of shading and wind reduction caused by vegetation. Compared to the status quo (STQ) scenario, additional riparian vegetation (V100) could reduce maximum stream temperatures during extreme heat waves ~~on average during all episodes~~ by 2.2 °C, mean temperatures by 1.6 °C and minimum temperatures 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~~ of 1.8 °C, 1.3 °C and 1.0 °C respectively in comparison with the STQ ~~actual~~ vegetation scenario ~~(STQ)~~ (~~calculated from~~ Table 4).

Removal of vegetation (V0) magnified ~~the~~ stream temperatures 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 mitigated part of the rise in maximum temperatures, so there was only a 1.1 °C increase. Although t~~T~~he increase of mean temperatures was reduced to about 1.4 °C, ~~so~~ riparian vegetation management alone was not enough to compensate for the predicted warming caused by climate change. The water temperature reduction 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 maximum water temperatures during heat waves in particular could be reduced significantly by vegetation shade. The daily mean and daily maximum temperature tends to increase more strongly for higher air temperatures if less vegetation is present. Daily minimum temperatures increase at an even higher rate. These trends go line with findings about experimental data analysed by Kalny et al. (2017).

Vegetation height and density can alter the slope of the temperature trend line. For example with dense low vegetation, water temperature starts lower and ends higher for the same air temperature compared to the high and less dense vegetation scenario, which indicates that there is some impeding of cooling during the night by lower vegetation compared to higher vegetation. Water temperatures rise more rapidly for dense low vegetation than high vegetation of reduced density. High vegetation of lower density cannot compete with dense high vegetation in terms of reduction of stream water temperature though.

During heat wave situations the reduction in air exchange causes an important lag in temperature rise, so the time of maximum solar exposure does not coincide with the maximum heat stress caused by water temperature. This lag is known in the literature (Brown and Krygier 1970).

Apart from its influence on stream temperature, vegetation can cast spatially differentiated shade, which results in areas of different sun exposure and energy balance. This heterogeneity can provide ecological niches which are important for different development stages of river fauna (Clark et al. 1999).

~~The water temperature difference between full and no showed scenarios vegetation~~

~~Therefore the ability of the vegetation to alter the stream's microclimate and water temperature is likely to remain the same. 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).also is that is affected by riparian vegetation (Leach and Moore 2010, Li et al 2012) -,no clear trend for future conditions. This can be explained considering that global radiation - the main parameter~~

~~e.~~

4.4 Limitations

V~~Attention has to be given to the fact that v~~egetation mainly causes ~~reduction of~~lower 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~~ In cloud conditions this effect is less pronounced and during night time it is absent, but~~while this effect is less pronounced~~ outgoing long wave radiation is still~~-~~ impeded~~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 scenarios.~~-~~

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~~ not measured and no ground water influence was assumed in the model. Although the model performed ~~good~~well (RMSE 0.88 °C) there might be some ground water influence between DFS 45 km and 55 km where the measurements lie below the simulation results.~~other~~

~~Not tackled were~~ Other ~~aspects related to~~possible future alterations to the river via development ~~and~~ or climate change were not considered here. These include~~, such as~~ potential ~~but not predictable~~ anthropogenic heat sources or sinks ~~as~~ like discharges of tempered waste water, possible changes in stream velocity and shading, ~~as~~ sediment changes caused by impoundments, regulation and canalization, ~~as well as~~or ~~feasible~~ discharge changes such as withdrawal of water for irrigation. The climate input ~~was using~~used only one possible emission scenario simulated by one regional climate model. ~~in general and the indirect effects of climate change on stream temperature like t Precipitation changes which affect discharge volume~~ The percentage contributions of surface, subsurface, groundwater and/or snow melt still have to be analysed in more detail (Johnson and Wilby 2015). Apart from rising air temperatures and discharge changes, anthropogenic influences like discharges 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 possible 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).

5 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 Rriver Pinka were simulated and the mitigating effect of riparian vegetation shade on the radiant and turbulent energy fluxes was analysed.

By the end of the century (2071–2100) in the study region 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.

Stream water temperature increases of less than 1.5 °C were modelled for the first half of the century. For the period 2071–2100 a more significant increase of 3 °C in maximum, mean and minimum stream temperatures was predicted for a 20 year return period heat event.

Discharge changes caused by increased evaporation due reduced shade was not found to be significant. Discharge changes caused by precipitation and increased evapotranspiration in the catchment area as expected from past observations was found to be insignificant compared to the changes caused by vegetation shade.

Vegetation could reduce stream temperature during heat waves, when conditions ofre high solar radiation is predominateusual. 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, and mean temperatures 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 status quo vegetation scenario on average. showed to aggravate the situation. Assumingwas shown Removal of vegetation With complete vegetation removal, maximum stream temperatures in annual heat events at the end of the century could increase exceed aby more than 4 °C compared to the observed period in annual heat events at the end of the century.increase compared to the present time.

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

Full vegetation cover

Daily amplitudes were reduced by riparian vegetation and the timing of the peak temperature was delayed by about one hour. A reduction of vegetation density by 20 % had shown a similar effect as a 50 % reduction of vegetation height.

Vegetation can reduce maximum temperatures more effectively on an absolute scale but also reduced the trends significantly compared to the no vegetation scenario. Minimum temperatures increased most.

This study shows that it is very likely that during extreme events a~~n~~ temperature increase of 2 °C will be exceeded during this century. This~~which ,~~ is the magnitude of an average of 2 °C which is the temperature ~~temperature~~ differentiation of ~~the local~~ fish zones and in particular for the occurrence of native cold water and warm water preferring fish species (Logez et al. 2013; 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 begin to experience temperature-induced mortality ~~reach their lethal phas~~(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 (DFS 13 km), 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 likely to be exceeded for 72 of 120 h. At the lower boundary of the trout zone (DFS 20 km), the 20 °C mark was exceeded for 70 of the 120 h during heat waves ~~20°C already were exceeded for 70 of the 120 h~~ at the beginning of the century, but ~~by could be reduced~~ riparian vegetation shade could reduce this~~during annual heat events to only last~~ period to 9 h in total. The mitigation possibilities of vegetation were limited though, and could not fully compensate for the whole predicted temperatures rise. At the end of the century in heat waves of a 5 year or ~~less~~ shorter ~~frequent~~ return period, even if maximum vegetation was assumed, 20 °C was exceeded during the whole heat wave event.

Global warming has multiple impacts on changes in aquatic ecosystems, whereas in combination with loss of habitat and other human pressures, this is leading to a deadly anthropogenic induced cocktail (Schinegger et al., 2011). The study affirmed the importance of shading and riparian vegetation along river banks for aquatic biodiversity and indicates the added value of riparian vegetation to mitigate climate change effects on water temperature. In addition, the used method provides a model for weighting of interactions of environmental parameters especially during heat wave events. The findings and recommendations gained with this methodology can help key decision makers choosing the right restoration measures. The study in general emphasizes the importance of land-water interfaces and their ecological functioning in aquatic environments.

6 Appendix

6.1 Abbreviations

DFS — distance from source

INCA — integrated nowcasting through comprehensive analysis

VTS — view to sky

climate episodes:

1a, 5a, 20a — episodes of 1 year, 5 year, 20 year return period within a 30 year climate period

Max — maximum event of a 30 year climate period

OBS — observed period (1981 - 2010)

2030, 2050, 2085 — 30 year climate period centred on 2030 (2016 – 2045), 2050 (2036-2065), 2085 (2071 - 2100)

discharge scenarios:

MLF — mean low flow of the gauging station at DFS 13 km: 0.143 $m^3s^{-1,}$ DFS 62 km: 0.795 m^3s^{-1}

MLF-15 MLF minus 15 % discharge

vegetation scenarios:

STQ “status quo”, exisiting/actual vegetation

V100 “maximum vegetation” - vegetation height 30 m, vegetation density 90 %

V70 “reduced density” - vegetation height 30 m, vegetation density 70 %

V50 “intermediate vegetation height” - vegetation height 15 m, vegetation density 90 %

V0 “no vegetation”

VD50,VD70,VD90 vegetation density 50 %, 70 %, 90 %

VH50,VH100 vegetation height 50 % (15 m) and 100% (30 m)

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Code availability: The last official version of ~~*TTools* and used software the~~ ***Heat Source*** software used are available online at: http://www.deq.state.or.us/WQ/TMDLs/tools.htm

The changes included in~~to~~ ***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 published on the freshwater biodiversity data portal (https://doi.org/10.13148/BFFWM8). As they~~sets for the present and future heat wave episodes used in this article~~ are part of the research project BIO_~~io~~CL~~l~~IC~~ie~~ the metadata is ~~and will be~~published together with the other vegetation, morphological and biological data sets produced in the project in the Freshwater Metadata Journal (https://doi.org/10.15504/fmj.2017.22).~~and receive a doi.on the freshwater biodiversity data portal (http://data.freshwaterbiodiversity.eu/)~~

Authors contributions: Melcher A. was in charge of the hydrobiological aspects. 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 helped Valeria Ledochowski to built the basic vegetation and morphology data set. Trimmel H. organized and executed the water temperature measurements further processed the all input data for the use of ***Heat Source***, adapted and validated the model. She ~~run~~ ran the ***Heat Source*** simulations for all selected episodes and prepared the manuscript.

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

	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 3: Daily minimum, mean and maximum 5 day mean water temperatures of the 5 day episodes averaged over the R~~r~~iver 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~~ DFS 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_Max	27.2	25.7	23.5	24.8	23.4	21.6	21.9	20.8	19.5
2050_1a	24.3	22.6	20.0	21.6	20.4	18.9	19.0	18.2	17.3
2050_5a	26.5	24.8	22.2	23.7	22.3	20.5	20.4	19.5	18.4
2050_20a	26.6	24.8	23.0	23.7	22.6	21.3	20.2	19.9	18.9
2050_Max	27.5	25.9	23.7	25.1	23.9	22.2	22.5	21.5	20.4
2085_1a	28.6	24.9	23.1	26.2	22.5	21.7	22.3	18.8	18.8
2085_5a	29.0	27.3	25.0	26.5	25.3	23.7	24.1	23.0	21.7
2085_20a	28.9	27.3	25.5	26.7	25.5	23.9	23.6	22.9	21.7
2085_Max	29.3	27.8	25.7	27.1	26.0	24.6	25.0	24.1	23.0

Table 4: Differences ~~to~~ between 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 km 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_Max	2.8	1.3	-0.9	2.3	0.9	-0.9	1.8	0.7	-0.6
2050_1a	-0.1	-1.8	-4.4	-0.9	-2.1	-3.6	-1.1	-1.9	-2.8
2050_5a	2.1	0.4	-2.2	1.2	-0.2	-2	0.3	-0.6	-1.7
2050_20a	2.2	0.4	-1.4	1.2	0.1	-1.2	0.1	-0.2	-1.2
2050_Max	3.1	1.5	-0.7	2.6	1.4	-0.3	2.4	1.4	0.3
2085_1a	4.2	0.5	-1.3	3.7	0	-0.8	2.2	-1.3	-1.3
2085_5a	4.6	2.9	0.6	4	2.8	1.2	4	2.9	1.6
2085_20a	4.5	2.9	1.1	4.2	3	1.4	3.5	2.7	1.6
2085_Max	4.9	3.4	1.3	4.7	3.5	2.1	4.9	4	2.9

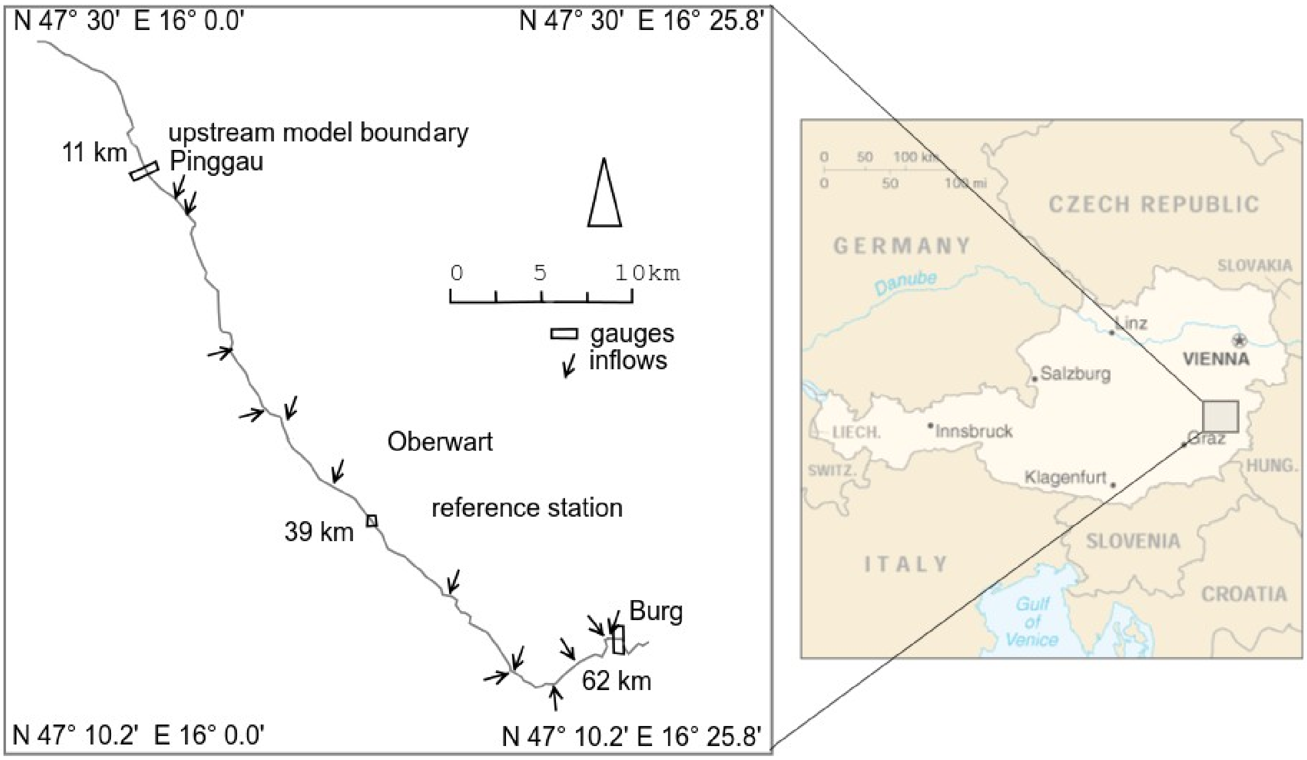


Figure 1: The study region in Pinka showing gauges, tributaries and the reference station (km markers shown as distance from source).

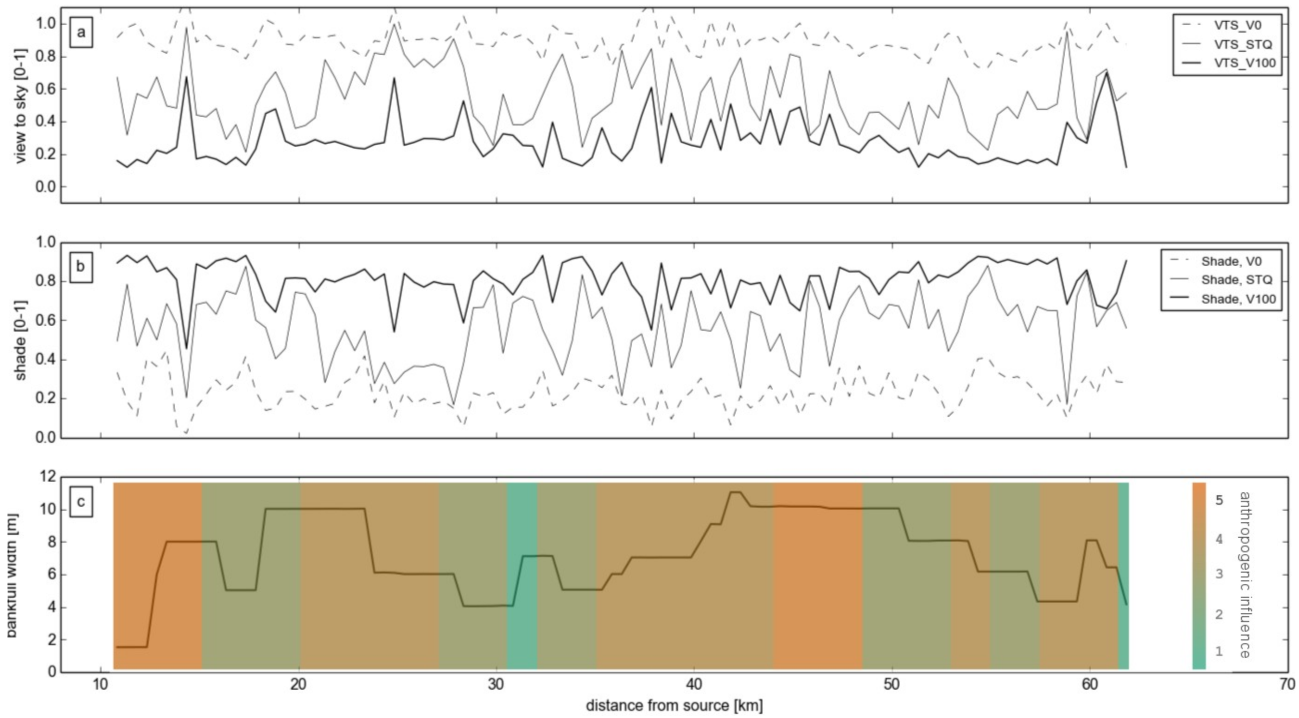


Figure 2: Characteristics of the River Pinka. (a) The longitudinal distribution of view to sky (VTS) and (b) shade at the river's surface, (c) the bankfull width and the level of anthropogenic influence on the river (legend on the right: entirely natural: (1)1, slightly or not influenced.: (2), strongly influenced but remainingwith natural areas: (3), continuously influenceds andwith few natural areas: (4) and completely regulated: (5))). at the river Pinka.

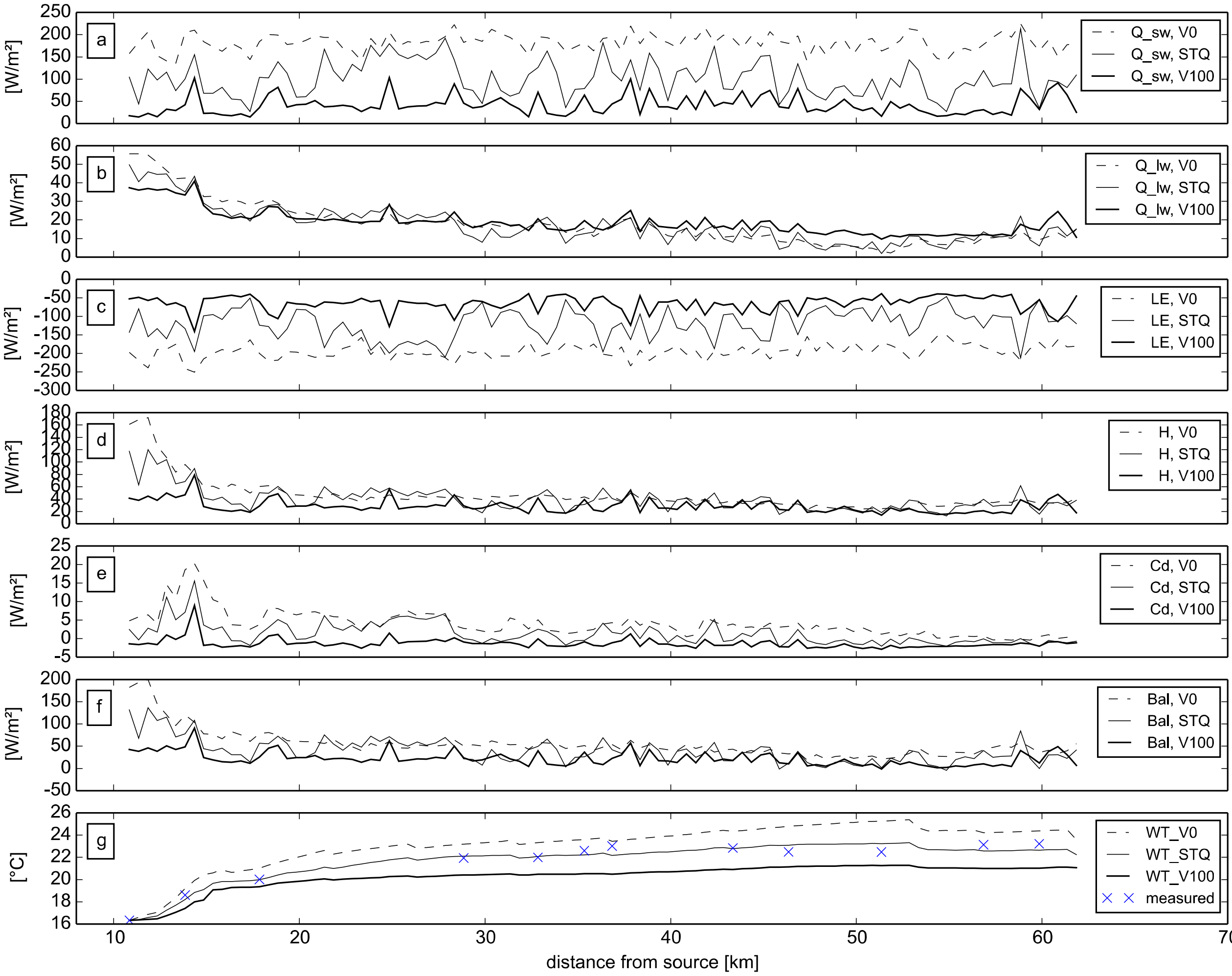


Figure 3~~2~~: Comparison of (a) the calculated ~~VTS levels,~~ short wave ~~(Q_sw)~~, (b) long wave ~~(Q_lw)~~ radiation balance, (c) latent ~~(LE)~~ and (d) sensible ~~(H)~~ heat flux, (e) conduction heat flux, (f) total energy balance ~~(Bal)~~ and (g) measured (measured) and simulated (WT) water temperature for the heat wave episode 4 – 8 August 2013 along the River Pinka for three vegeta~~tr~~ion sc~~e~~narios: no vegetation (V0), existing vegetation (STQ) and maximum vegetation (V100).

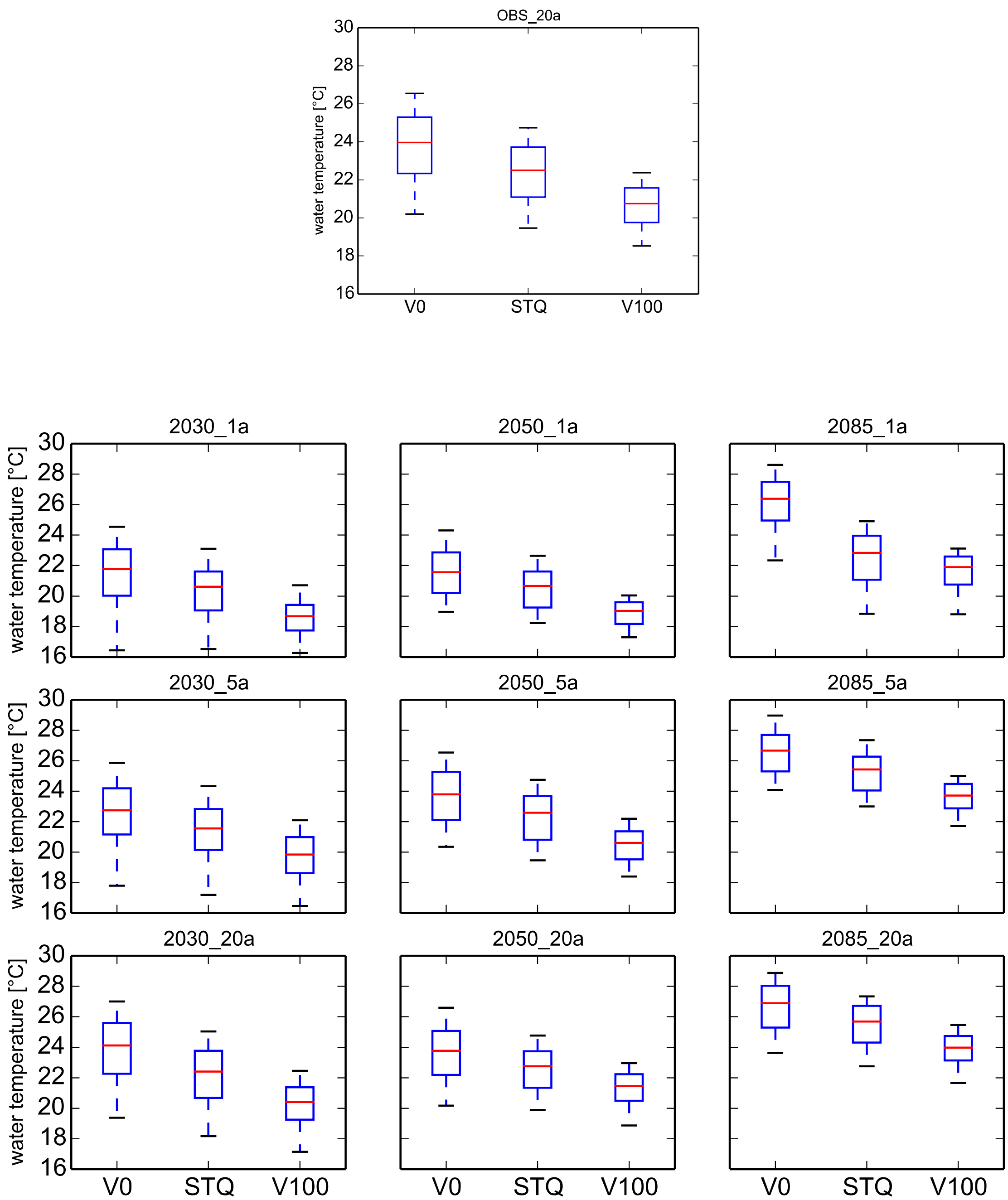


Figure 43: Box and whiskers charts showing the 5 day mean water temperature distribution during the 1a, 5a and 20a episodes for the climate periods centered on 2030, 2050, 2085 and with mean low flow discharge at DFM DFS 39 km. The hourly values of V0 (no vegetation) and V100 (full vegetation) are significantly different from STQ in all episodes (p<0.0001).

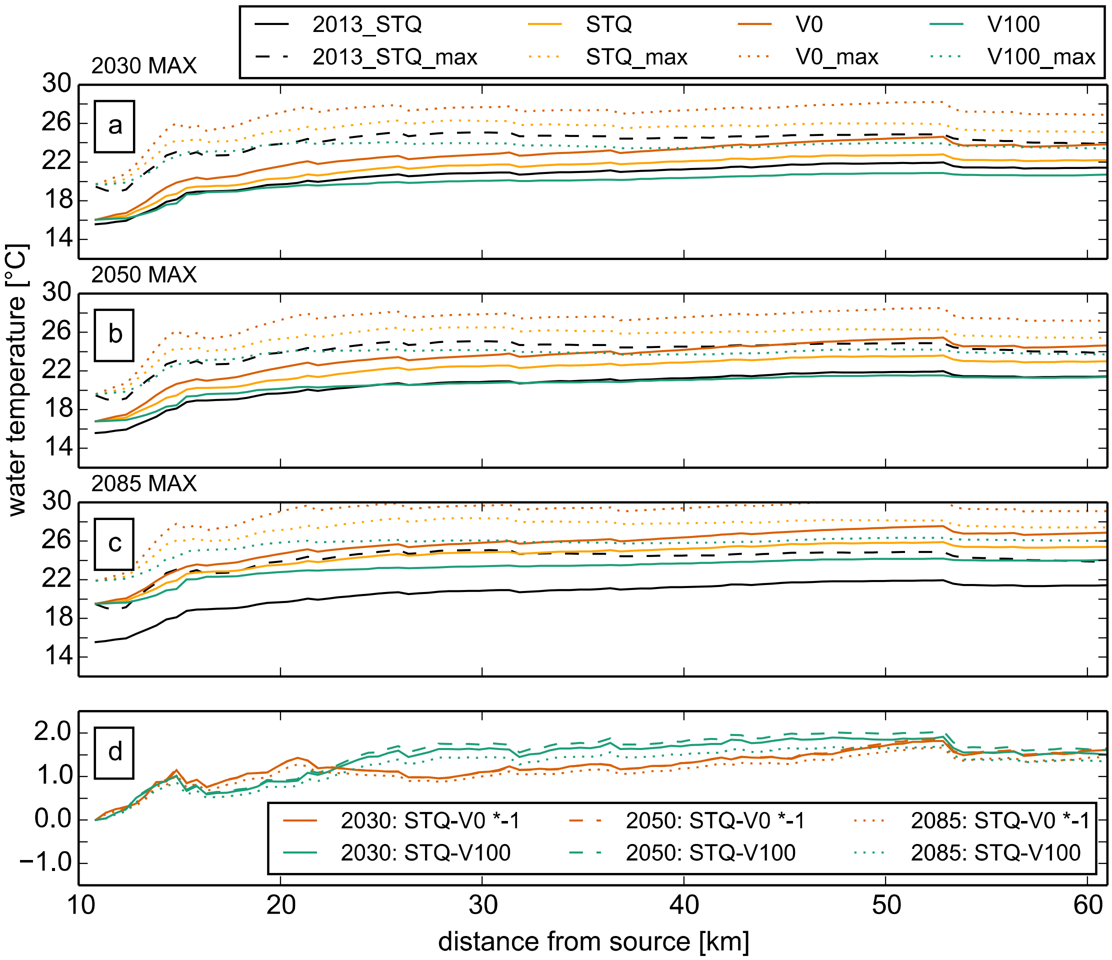
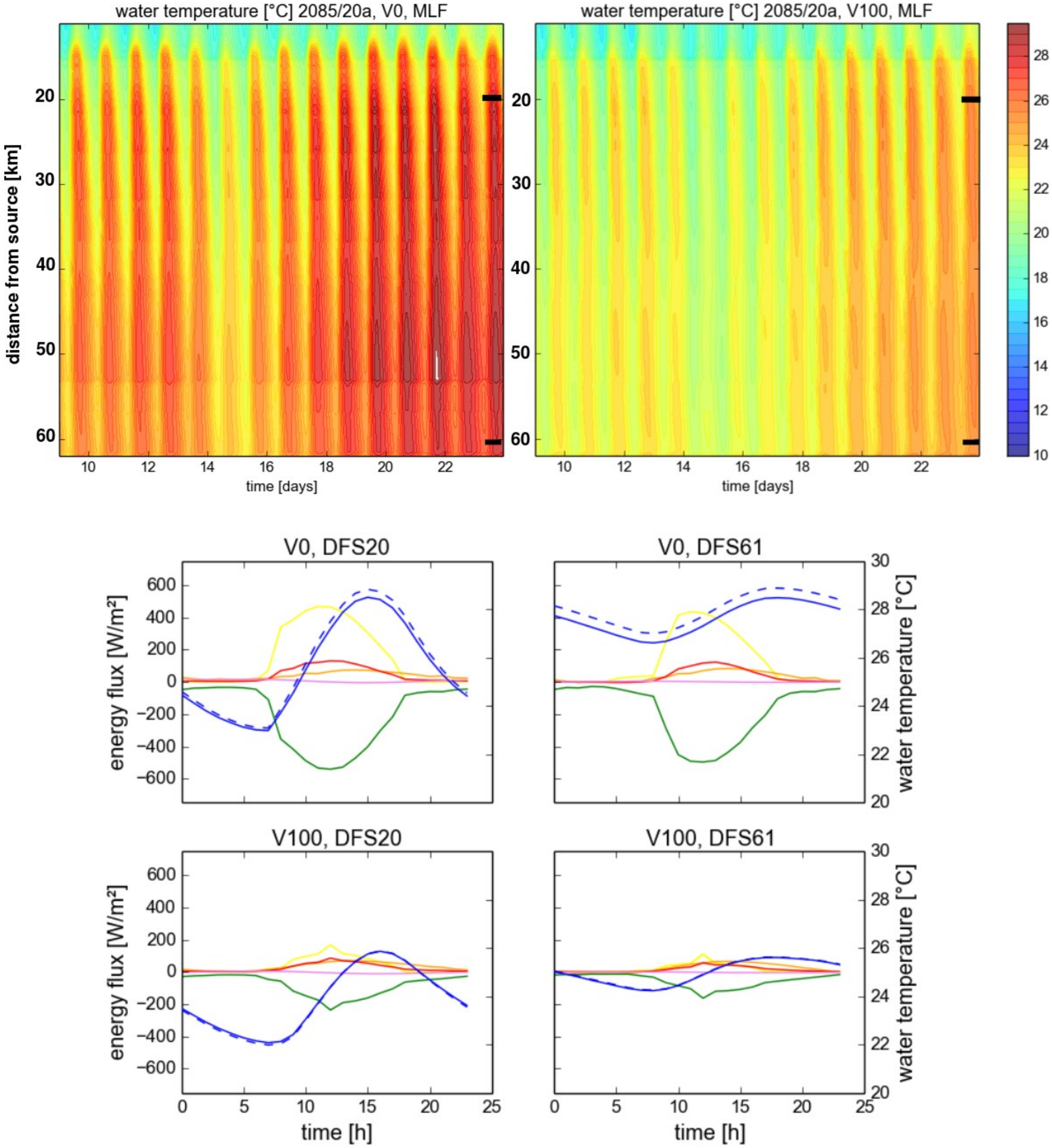


Figure 54: Mean and maximum water temperature averaged during the maximum events predicted for the climate periods centred on (a) 2030, (b) 2050 and (c) 2085 along the Rriver Pinka using vegetation scenarios V0 (no vegetatiooin), STQ and V100 (full vegetation) in comparison to the maximum event recorded in 2013. (d) The bottom panel shows tThe difference between STQ and V100 (green) and STQ and V0 (*-1) (red).



~~Figure~~ Figure 6: The effect of a 15% discharge reduction (MLF– 15%) of the mean low flow conditions (blue, dashed) on stream temperature compared to MLF (blue, solid) for an upstream (DFS 20 km) and downstream location (DFS 61 km) for the 20 year return period event centred on 2085 for no vegetation (V0) and maximum vegetation (V100). Diurnal amplitude of all energy fluxes (short wave radiation balance = yellow, latent heat flux = green, long wave radiation balance = red, s~~ensibltiv~~ensiblee heat flux = orange, conduction heat flux =v ~~v~~iolett) .

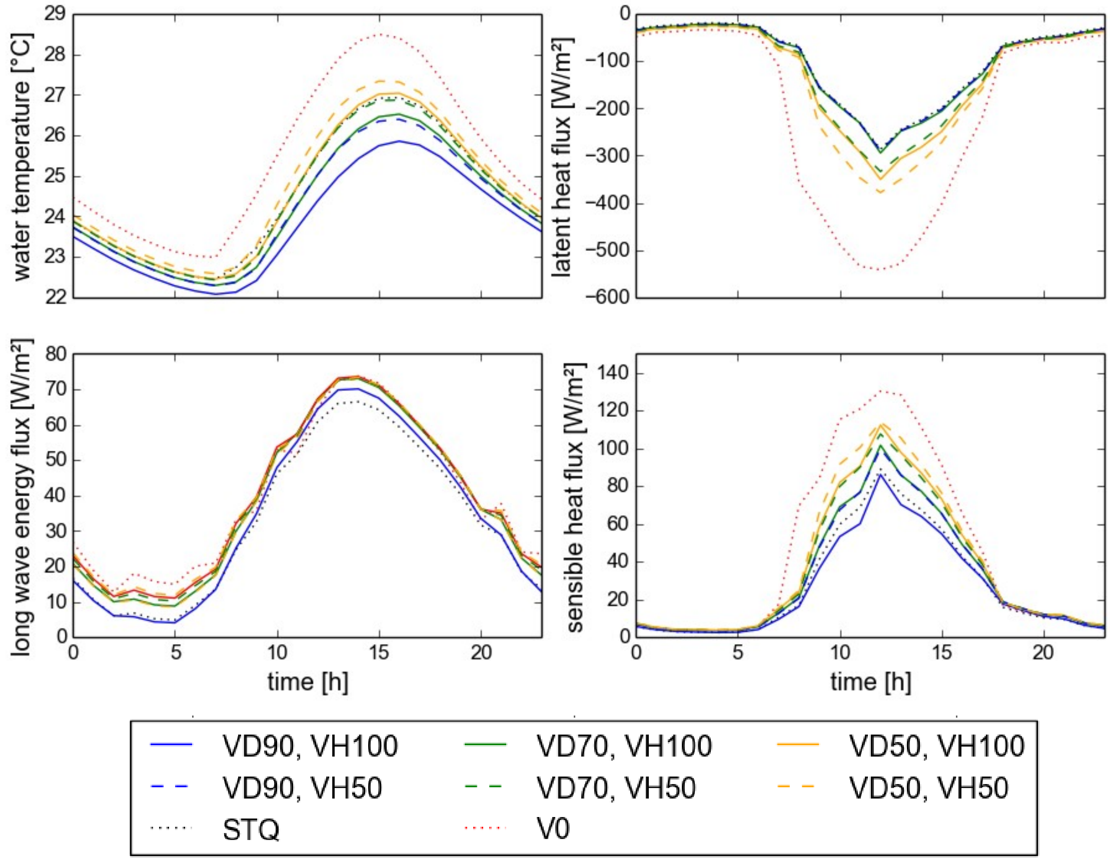


Figure 7: The effect of the vegetation scenarios of maximum vegetation height (VH100) and 50% vegetation height (VH50), natural dense vegetation (VD90), natural light vegetation (VD70), sparse vegeation (VD50), V0 (no vegetation), STQ (actual vegetation) on the diurnal amplitude of water temperature and the air temperature dependent energy fluxes longwave radiation, sensible and latent heat flux for the 20 year return period events of the final day of the climate periods centred on 2085, for mean low flow conditions (MLF) for an upstream location (DFS 20).

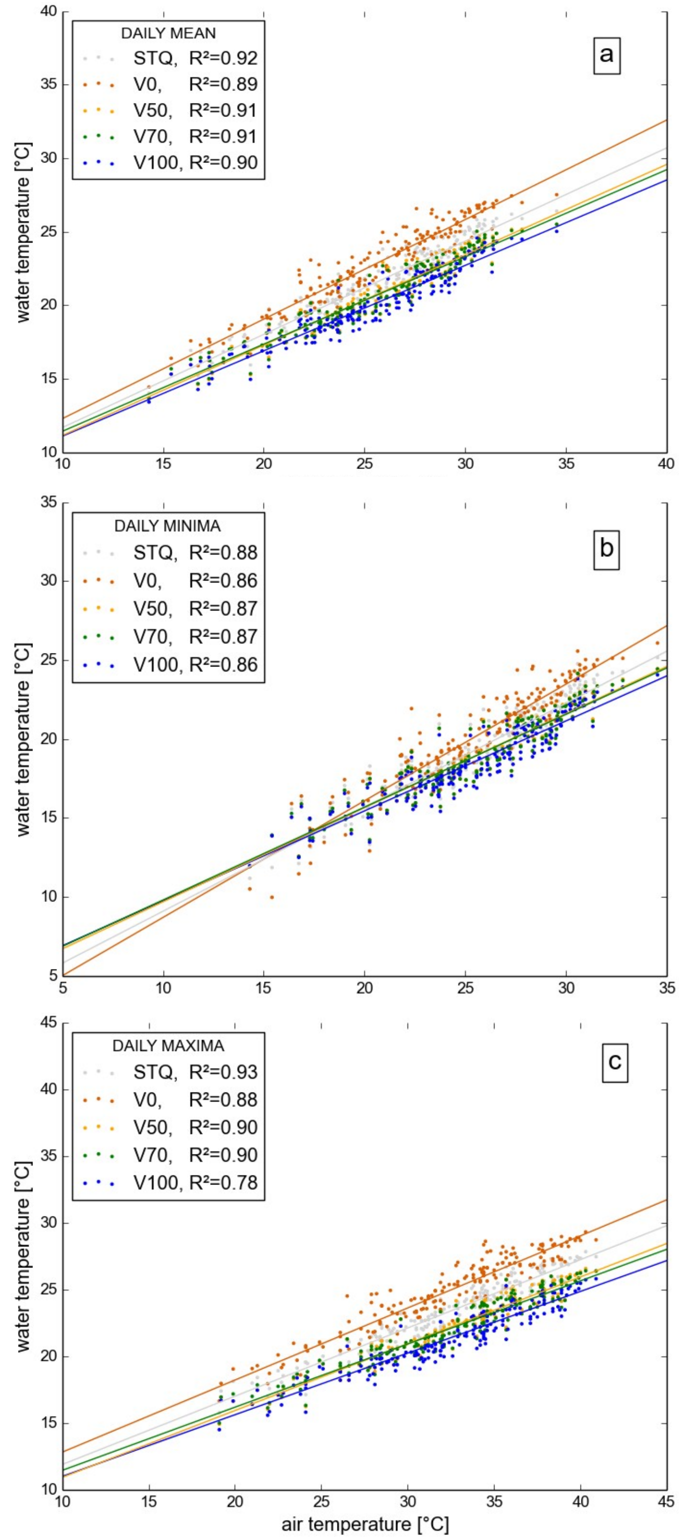

DAILY MEAN
STQ, R²=0.92
V0, R²=0.89
V50, R²=0.91
V70, R²=0.91
V100, R²=0.90
a
water temperature [°C]
DAILY MINIMA
STQ, R²=0.88
V0, R²=0.86
V50, R²=0.87
V70, R²=0.87
V100, R²=0.86
b
water temperature [°C]
DAILY MAXIMA
STQ, R²=0.93
V0, R²=0.88
V50, R²=0.90
V70, R²=0.90
V100, R²=0.78
c
water temperature [°C]
air temperature [°C]

Figure 8: Correlations between water temperature and ~~air temperature of~~ the daily (a) mean, (b) minima and (c) maxima air temperatures for the 1a, 5a, 20a and Max episodes of the climate periods centred at 2030, 2050 and 2085 for existing vegetation (STQ), no vegetation (V0), vegetation height 50% (V50), vegetation of 70% vegetation density (V70) and full vegetation (V100) reported with the squared Spearman's rank correlation coefficient. ANCOVA showed significant interactions between vegetation and air temperature ($p < 0.001$).