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Determinants of thermal regime influence of small dams
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Cover letter

Dear Editor and Referees,

Thank you for the quality of your proofreading and comments; they have greatly improved the manuscript. We also appreciate your interest in the subject matter, which we think is of critical importance to managers across France and the world who are dealing with issues of small dam removal and ecological integrity. We believe we have substantially addressed all of the outstanding comments and issues, and we look forward to your second review of the work.

All of the referees remarked on the issue of data representativeness, so we will briefly discuss this issue here. Data scarcity (i.e., lack of data across years within sites) is a primary challenge for understanding thermal effects of small dams, and it is one of the primary reasons that we used a compiled dataset with data from field operators, which we bolstered with our own sampling. We acknowledge that using these two data sources may make reading and understanding a little more difficult, but we believe it enriches the analysis by increasing the number of time series and across-year examples, (though we agree this dataset is probably still insufficient to draw broad conclusions). Hence, we are aware of the issues with the dataset, and we have added text throughout to underscore this issue. However, we feel that the analysis and general results are valid and useful, regardless of data scarcity issues, which every study must deal with.

Throughout the manuscript, we have made major revisions based on the referees comments and suggestions. The major changes are:

- use of new statistical analysis methods to strengthen the robustness of the results,
- improved consistency between points raised in the comments and proposed figures,
- grammatical quality review: a final revision of English was done by a native speaker.

point-by-point response to the reviews

Below we respond to *comments*, which *are in italics*, in blue, show old text in red, and replacement text in green.

Referee #1

General comments :

" the presentation of the results to be mainly using individual sites as examples that are difficult to judge if they are representative."

Response: An improvement in the presentation and choice of sites selected as examples has been modified in the final text.

Specific comments :

"1. Figure 2 – why present years in reverse chronological order? Also, why this stream and these years? If possible, it would be preferable to compare 2014 (cold wet year) with 2015 (warmest, dry year in data set)."

Response: The aim was to highlight that the same site presented the same "patterns" of summer time-series for different years, regardless of the climatic characteristics of the year.
Taking into account the observation, we propose another example (new Figure 2) comparing a cold and humid year (2014) with a normal and dry year (2016) at another site (Veyle stream, Fretaz site): the structure of the thermal patterns between upstream and downstream is preserved.

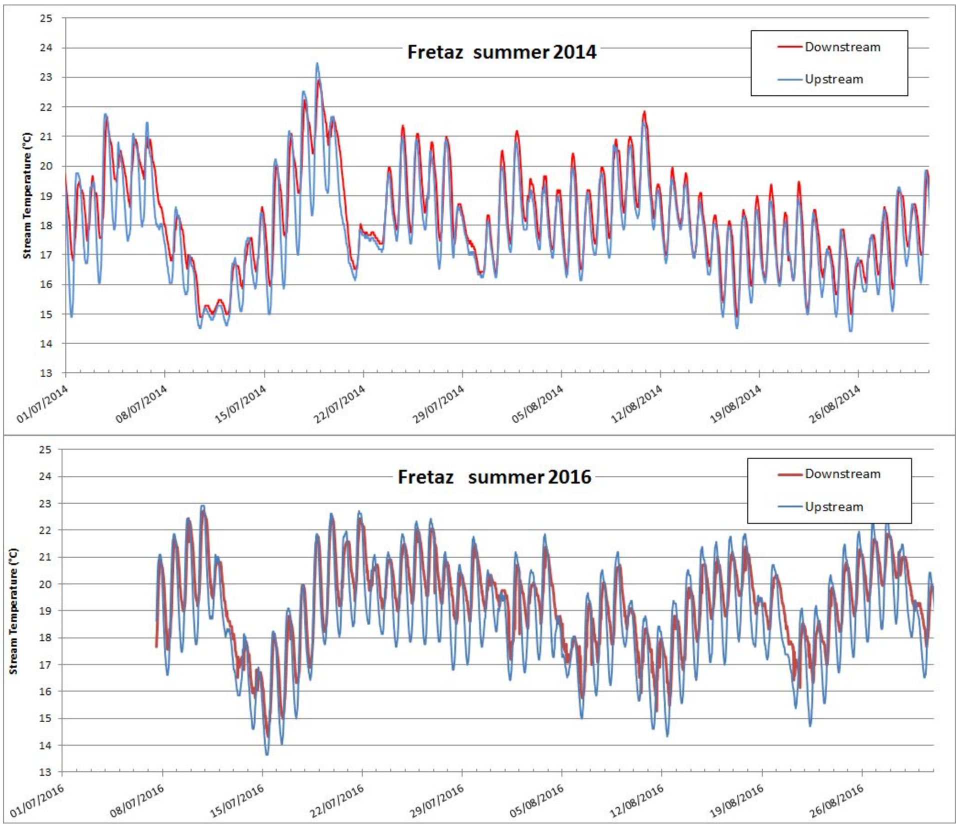


Figure 2. Time-series of water temperature (°C) upstream (blue) and downstream (red) of the dam Fretaz, Veyle stream, respectively in years 2014 and 2016.

The new text L180 to 189 is modified as

Previous text: L180 to 189

These periods vary from one year to another, likewise the intensity of the increases, but the general pattern remains the same, as demonstrated by the case of the dam Champagne (Renon stream), monitored in 2009 and 2015 (Fig. 2).

Furthermore, the average temperature downstream of the structure was systematically higher or equivalent than that measured upstream.

Different types of time-series were observed regarding the difference between upstream and downstream temperatures:

The most frequent (7/13) is the type observed on the dam of Champagne (Renon stream) in 2009 and 2015; the minimum 185 daily temperatures (T min) are, most usually, higher downstream of the structure, but the maximum daily temperatures (T max) remain within the same magnitudes (Fig. 2, only one example is presented here).

In the other cases (6/13), both the minimum and maximum daily temperatures are higher downstream of the structure, which results in a homothetic lag between the two temperature time-series (Fig. 3).

Replaced by

New text: L199 to 207

The periods of progressively increasing temperature vary in length, magnitude, and timing from one year to another, but the general pattern remains the same, as demonstrated by the case of the Fretaz dam , monitored in 2014 (a cold and humid year) and 2016 (a more normal year, Fig. 2; Table 2).

We observed two consistent patterns in upstream-downstream thermal regimes. In the first pattern, T_{min} is higher downstream, but T_{max} stays relatively constant (Fig. 2). We note that these upstream-downstream differences were muted in 2014, the cold and humid year (Fig. 2). This thermal pattern (i.e., where T_{min} increases downstream, but not T_{max}) is observed in 7 out of 13 cases (Table 3). In the other cases (6 out of 13; Table 3), we observed a second pattern, where both T_{min} and T_{max} are higher downstream of the structure, which results in a consistent shift between the two temperature time-series (Fig. 3, selected examples: Dompierre dam 2010 and Peroux dam 2015).

"2. General – figures don't do a very good job of illustrating points made in text in results. I question whether all the figures are needed (e.g., Figure 3).

Response: Fixed see above

Figure 5 – presenting time-series does not show correlation between two variables –one would need to plot air temp vs. water temp to show directly.

Response: We modify Figure 5 and the text as follows:

Previous text: L200 to 204

During the summer season, the differences in the daily mean temperatures upstream / downstream, are close or staggered during all the season. It is notable that the variability of the summer air temperature is much higher (range 17°C) than stream temperature (range 7.5°C) for these examples (Fig. 5), and that the daily water temperature is not well correlated to air temperature.

Replaced by

New text: L217 to 219

During the summer season, the upstream/downstream daily maximum water temperature differences are not well correlated with air temperature for the same periods. For example, a simple linear regression between daily maximum air temperature and daily maximum water temperature differences indicates that air temperature explains only 0.8% of the variability in upstream/downstream thermal regime shifts (Fig. 5).

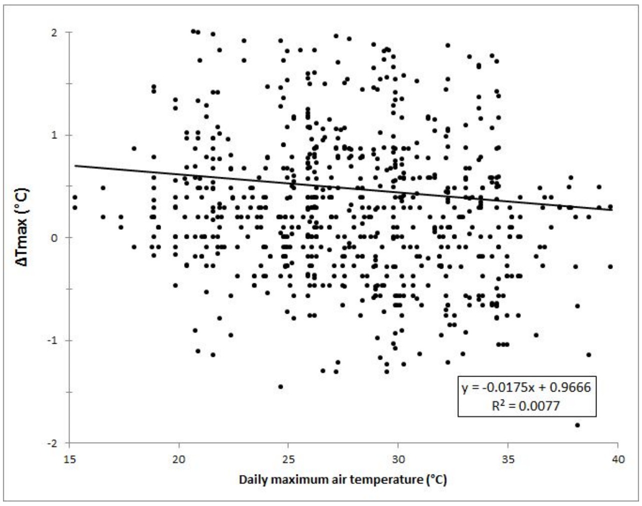


Figure 5. Relation between daily maximum air temperatures (°C), daily upstream/downstream temperature differences for all the data available for the study.

"Figure 4 – never covered in results section."

Response: We previously covered figure 4 in section 3.2 but now we changed the text to better explain the observed pattern. We also changed the site "Neuf" to "Fretaz 2014".

Previous text: L 191 to 194

The two dominant patterns can be illustrated by plotting the minimum and maximum temperature values at the site "Dompierre 2010" with a difference of order of + 1.5°C between the upstream and downstream of the site, comparing to "Neuf 2016", where these values are the same for minimum daily temperatures, or even slightly negative for the maximum temperatures (Fig. 4).

Replaced by

New text: L209 to 212

The two dominant patterns of temperature differences are further illustrated by plotting downstream versus upstream T_{min} and T_{max} values at the site. For example, at Dompierre in 2010, we observed a consistent shift of approximately +1.5°C (both T_{min} and T_{max}) between the upstream and downstream of the dam (Fig. 4A). In contrast, at Fretaz in 2014, this shift is dampened, and temperature values between upstream and downstream more closely follow a 1:1 relationship (Fig. 4B).

New figure 4

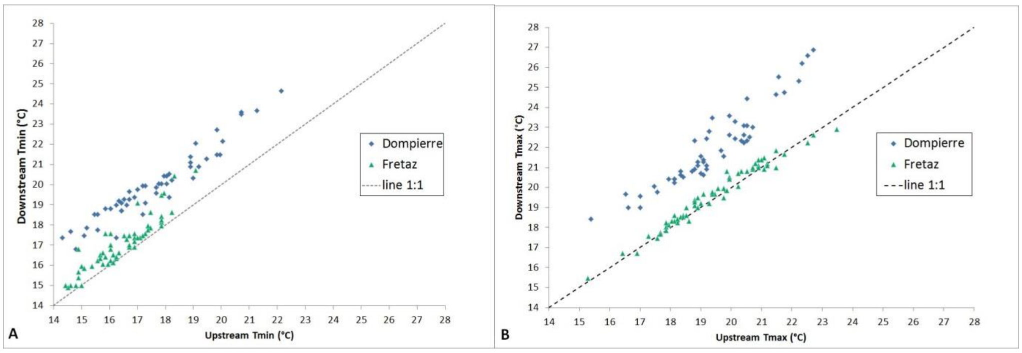


Figure 4. Minimum (A) and maximum (B) daily temperatures upstream and downstream of the dams-of-the river (Dompierre site, Veyle stream in 2010; Fretaz site, Veyle stream in 2014). Dashed line is 1:1 line.

"3. The authors mention differences in mean temperature, but never provide this information in a table. Further, they report median differences without justifying why this metric instead of means. I feel medians can be a useful indicator of central tendency, but the mean is also useful, and needs to be presented if it is discussed."

Response: To avoid any confusion, we eliminate any reference to daily mean temperature. We also have modified the section 2.4 Data analysis to remove any confusion about using mean temperature (L 156 to 159)

Previous text: L156 to 159

To determine if the dams alter the temperature regime, the minimum, average and maximum temperatures and amplitudes were calculated for each full day recorded, and the median values were recorded for the period. The calculations of daily differences of maximum and minimum water temperatures were performed for each pair of upstream/downstream records, and the median of these differences over the recording period was calculated.

Replaced by

New text: L165 to 170

To characterize the influence of dams on stream thermal regimes we first calculated three variables: daily difference between upstream and downstream temperature 1) maximums (ΔT_{max}), 2) minimums (ΔT_{min}), and 3) amplitudes (ΔT_{amp}) for each site and year. With these data, we then conducted the following analyses:

1. Median summer differences in ΔT_{max}, ΔT_{min}, and ΔT_{amp} (median is used instead of mean to limit the influence of extreme values),

2.…

"Section 3.4 – authors state that air and water temperatures do not correlate, but did not perform a correlation analysis".

Response: Fixed with a new figure 5

"5. Section 3.5 – how were these groups distinguished (meaning, what formal method was used). My impression is that the investigators did this "by eye", which is not acceptable in my view. A formal cluster analysis would be much more appropriate. Moreover, I think it is hard to defend splitting out groups with such a small number of sites."

Response: The requested additional statistical analysis has been completed and we propose the following changes

We add description of the statistical method used

Previous text: L 164 to 165

Finally, we propose a classification of the observed thermal behavior in 3 groups, based on differences between upstream and downstream dam daily maximum temperature, daily minimum temperature and daily amplitudes.

Replaced by

New text: L177 to 183

2.5 Site typology analysis

We observed different thermal regimes in our data and wanted to classify them. To do so, we carried out a hierarchical cluster analysis using Euclidian dissimilarities matrix according to the Ward's method (1963) using the daily dataset (n=807) of ΔT_{max} and ΔT_{min} obtained over all time-series. We forced the classification to integrate the different time-series effect by adding a complete disjunctive table differentiating each time-series to the data set. This procedure makes it possible to group the data first by time-series, then in a second step to differentiate them from each other (i.e., to differentiate site thermal regimes).

Previous text: L 204 to 217

3.5 Site typology based on summer thermal regime

The median values of the daily temperature variables calculated over summer (from 01/07 to 01/09) permit distinguishing two major types of response to the presence of a small dam (Table 3).

A first group (A) is characterised by:

- a median of the differences upstream/downstream of the maximum daily temperatures lower than 0.5°C;
- a median of the differences upstream/downstream of the minimum daily temperatures between + 0.4 and 1.3°C;
- a median of the differences in daily amplitudes lower than - 0.2°C.

A second group (B) is characterised by:

- a median of the differences upstream/downstream of the maximum daily temperatures higher than 0.5°C;
- medians of the differences upstream/downstream of the maximum and minimum daily temperatures in the same order of amplitude.

In addition two subgroups can be distinguished: subgroup (B2) with medians of upstream/downstream differences of daily maximum and minimum temperatures higher than 1°C, i.e. net warming between upstream and downstream, and subgroup (B1) with values ranging from 0.3 – 0.8°C.

Replaced by

New text: L221 to 231

3.5 Site typology

The hierarchical cluster analysis applied to the daily summer temperature anomalies distinguished three groups:

- a first group (A) characterized by :
    - median of ΔT_{max} less than 0.5°C;
    - median of ΔT_{min} between + 0.4–1.3°C;
    - median of ΔT_{amp} less than -0.2°C.
- a second group (B1) characterized by:
    - median of ΔT_{max} ranging from +0.6–1.2 °C;
    - median of ΔT_{min} between +0.3–1.1°C.
- a third group (B2) characterized by:
    - median of ΔT_{max} greater than 1.2 °C;
    - median of ΔT_{min} greater than 1.2 °C

Figure 6 changed.

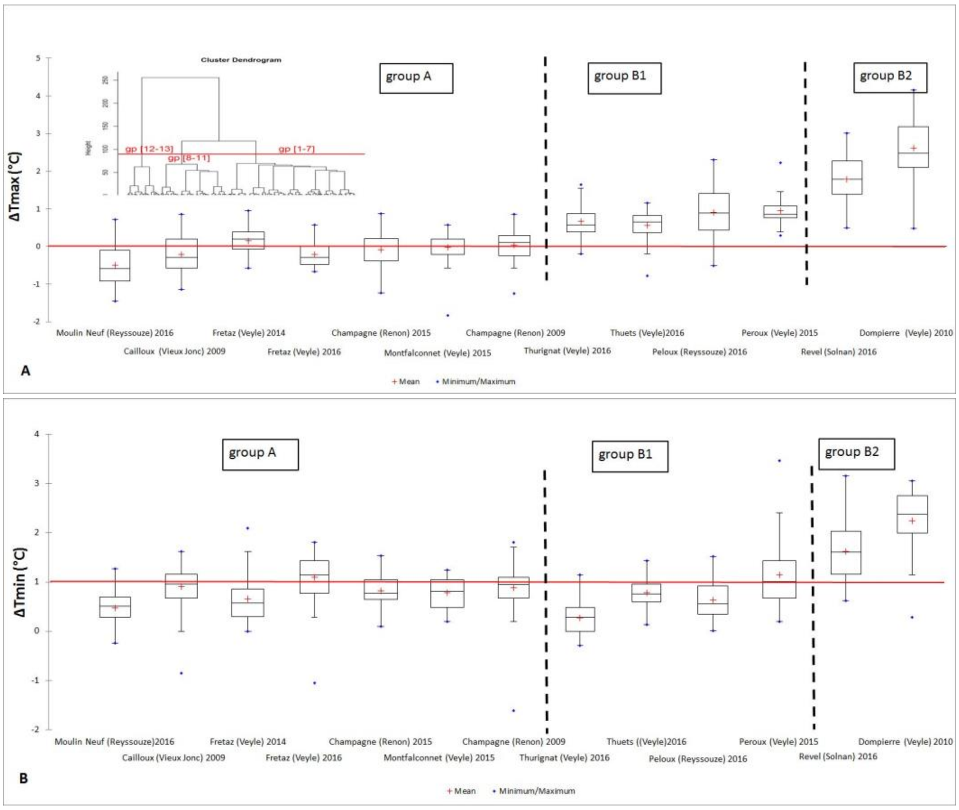


Figure 6. Box-plot distribution (25% - 75 %) of upstream/downstream differences of daily maximum and minimum temperatures for all the time-series studied. (Red lines: 0°C for daily maximum temperature and 1°C for daily minimum temperature are drawn to help reading). The vertical lines drawn in bold are the limits to the three classes of results of the hierarchical cluster analysis. Dendrogram CAH's result is shown at the top left of the figure.

"6. Section 3.6 – in the methods, the authors state that they used mean temperatures in the PCA analysis, but this doesn't show up in the results. Further, the reporting of the PCA results is very incomplete. Loadings of the various variables is needed, as is some criterion for determining what are the significant correlations. I can't say I understand fully how to interpret the circle correlation plot."

Fixed

Previous text: L 166 to 170 2.5 PCA analysis

In order to identify the characterization of the impacts of the different dams, a principal component analysis (PCA) was carried out using the software XLStat (ADDINSOFT™) on the water temperature variables: downstream / upstream difference of the maximum, average and minimum daily temperature and daily temperature amplitude. The physical characteristics of the structures (Table 1) were used as illustrative variables to evaluate the correlations with the temperature variables

Replaced by

New text: L184 to 191

2.6 Ordination analysis

To characterize the impacts of the different dams, a principal component analysis (PCA) was carried out using the software XLStat (ADDINSOFT™) on the three water temperature variables: ΔTmax, ΔTmin, and ΔTamp. We used the median values for variables on each time-series in order to build an input matrix (13 occurrences for three variables).

Then a complementary redundancy analysis (RDA) with automatic stepwise variable selection procedure was used to identify the physical dam characteristics (Table 1) that significantly explain the PCA results (ter Braak 1986).

After the RDA identified the relevant physical dam characteristics, we conducted multiple linear regression between these characteristics and temperature variables to determine specific effect sizes of these characteristics on thermal regime.

New text: L570 to 571 (References)

Ter Braak, C. J. F.: Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis, Ecology, 67, 1167-1179, 1986.

Previous text: L 220 232

3.6 PCA results

The first axis of the PCA analysis (78.3 %) is correlated to all temperature daily variables (calculated as differences between downstream versus upstream), in particular to the maximum daily temperature difference (Tmax_diff). The second axis discriminates the daily amplitude difference (Range_diff) with the minimum temperature (Tmin_diff) difference (Fig. 7).

For the determinants, the water residence time is the most correlated variable to the first axis F1, the size of the reservoir (surface, volume, length) correlates to both the first and second axis. The other physical-geographical characteristics related to the size of the watercourse (watershed, distance to the source), are correlated with the daily maximum temperature and associated with the second axis F2 (20.7 %); dam height has a very weak correlation with the axis F1.

The projection of the site series on these axes shows a strong spreading along the first axis. The dams measured two different years stay within the same range on this axis (Fretaz and Champagne) (Fig. 8). Groups B1 and B2 are distinguished by respectively the first and second axis association. This can be linked to the determinants of strong residence time influence for group B2, whereas group B1 is mainly characterized by the size of the impoundment (large impoundments, yet with relatively smaller residence time and thus less exacerbated thermal regime effects).

Replaced by

New text: L234 to 243

3.6 Ordination results

The first axis of the PCA analysis (74.1% of total inertia) is correlated to all daily temperature daily anomalies, in particular to the ΔT_{max}. The second axis (25.3%) discriminates the ΔT_{amp} with ΔT_{min} (Fig. 7). Results of the RDA show that the water residence time and the impoundment surface explain 95.2% of the PCA structure. The projection of the sites on these axes shows a strong spreading along the first axis (Fig. 8). Additionally, the dams that had two different measurement years stay within the same range on this first axis (i.e., Fretaz and Champagne) (Fig. 8).

Multiple regression analyses between the temperature variables (median values of ΔT_{min} and ΔT_{max}) and the physical characteristics obtained by the RDA (residence time and impoundment surface) resulted in high explanatory power ($R2 \approx 0.7$). These regressions identified the significant contribution of residence time for ΔT_{min} and ΔT_{max}, whereas only surface area had a significant contribution for ΔT_{max} (Table 4).

Figure 7 deleted

The new Figure 7 replaces Figure 8

Figure 8. PCA analysis. Correlation circle with temperature as active variables

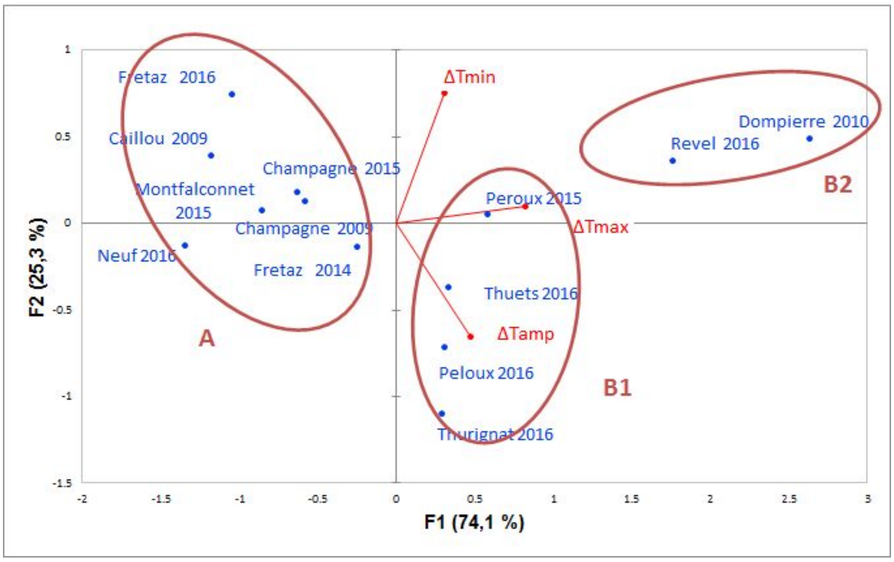


Figure 7. PCA analysis. Scatterplot of time series. Ellipses are drawn to visualize the groups obtained with the hierarchical cluster analysis

A new table is added

New text: L602 to 604

Table 4. Results of multiple linear regressions performed on the 2 indicators ΔTmin, ΔTmax using the dam physical characteristics surface area and residence time. Significant p-value are in bold.

Dependent variable	Independent variable physical characteristics	standardized coefficient	p-value	R2
ΔTmax	surface area	0.39	0.041	0.72
	residence time	0.80	0.001	
ΔTmin	surface area	-0.13	0.48	0.68
	residence time	0.80	0.001	

"*7. Section 3.7 – this section does not provide a synthetic view of any of the data, and the intent of this section is unclear. Suggest removing it entirely.*"

New text section 3.7

Previous text: L 234 to 239

3.7 Focus on temperature pattern in short period of time

Looking more specifically on a short period of time (three consecutive days), differences in the diurnal variation of the temperature of the river upstream and downstream of the dam shows that for the first group A, the maximum water temperatures upstream and downstream are close, while the minimum temperature downstream does not return to that of upstream (Fig. 9A). In the second group B the water temperature difference between upstream and downstream are more important and remain persistent during all the day period (Fig. 9B).

Replaced by

New text: L244 to 265

3.7 Ecologically relevant intra-daily temperature variation

To further illustrate the different thermal regime effects from our typology analysis, we compare intra-daily temperature variations for a three-day time series in group A (small thermal effect) with group B (large thermal effect; Fig. 9):

- In the example of group A (Fig. 9A), the downstream temperature is generally warmer than the upstream temperature (observed difference of 1°C warmer) except for a few hours during the three day sample observation period. The biological benchmark of 22°C is exceeded both upstream and downstream during the day of August 20. The rest of the time, temperatures are below this threshold. From a biological point of view, the duration above the thermal threshold is short, preceded and followed by more favorable temperatures (i.e., the remission period).
- In the example of group B (Fig. 9B), the downstream temperature is systematically higher than that of the upstream, with a temperature difference varying between +0.8–2.4°C. The 22°C threshold is exceeded downstream for a cumulative 42 h over the three-day period. August 15 and 16 have downstream temperatures that rarely go below 22°C, leaving no time for thermal remission (return to a temperature that is better tolerated physiologically by fish). At the same time, the upstream part of the stream is maintained at daily temperatures not exceeding this threshold.
- Additionally; differences in the diurnal temperature variation upstream and downstream of the dam shows that for group A, the maximum water temperatures are similar, whereas the minimum temperature downstream does not return to that of upstream (Fig. 9A). In group B the water temperature difference between upstream and downstream are persistent throughout the diurnal cycle (Fig. 9B).

For all sites, by studying the average daily duration with a temperature exceeding 22°C continuously, we can see (Fig. 10):

- downstream durations are always greater than or equal to that of the upstream durations, regardless of site typology,
- the largest upstream/downstream differences occur in the group B2 group,
- group A is generally not affected by an upstream-downstream increase, except for two sites which exhibit a two hour increase.

Previous text: L 162

(iv) the dam thermal effect considering an arbitrary threshold of 22 °C, with a calculation of the number of days above this threshold.

Replaced by

New text: L173 to 176

To assess the potential biological importance of dam thermal effects, we also calculated 1) the number of days that water temperatures were greater than 22°C, and 2) the mean of the maximum daily duration (in hours) where water temperature was greater than 22°C. We chose 22°C as an illustrative threshold known to be a thermal stress benchmark value for salmonids (Elliott and Elliot, 2010; Ojanguren et al., 2001).

We added a sentence L346

New text: L375 to 376

In addition, this threshold is known to be important for the life cycle of aquatic invertebrates (Ward, 1976; Brittain and Salveit, 1989).

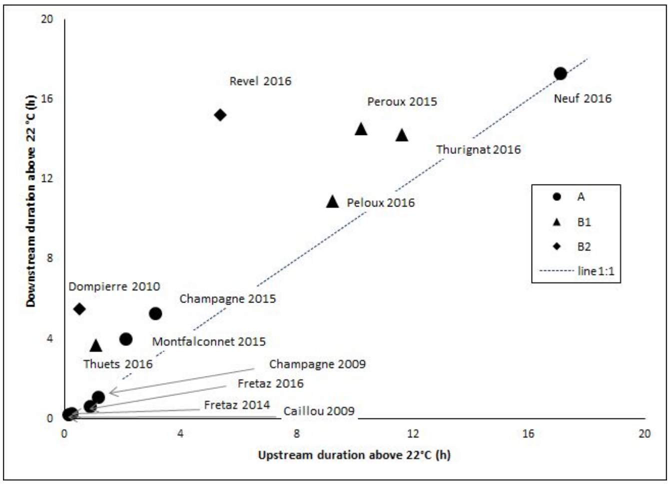


Figure 9. Mean of the daily maximum duration with T above 22 °C , upstream and downstream each site monitored in the study. A (circles), B1 (triangles), B2 (rhombus) are the groups of sites resulting from HCA.

"8. Section 3.8 – the arbitrary nature of this analysis provides little insight or direct ecological interpretation. In the discussion the authors correctly indicate that the choice of a 22 degree is actually not arbitrary, but has a basis in that temperatures above this point are generally deleterious to salmonids. Although I think this section could be a valuable contribution by the research, the fragmented presentation leads me to suggest removing it entirely."

Fixed above

"9. In the discussion, the authors talk about different years (hot vs. cool, or wet vs. dry), but none of the analysis really looks into this. I think it is an important point, so would like the authors to explore and quantify this in a reasonable way. "

Response: Fixed with new fig. 2 and fig. 5

"10. In the introduction and discussion, the authors talk about the importance of dam and reservoir size, but don't do any formal analysis. At a basic level, it would seem that correlation or regression of reservoir area, and another analysis with residence time, on the response variables of mean temperature difference, mean difference in maximum temperature, and mean difference in minimum temperature would be an important starting point."

Response: The statistical analyses (Redundancy analysis, multiple regressions) developed above answer this question.

"11. The discussion of biological effects was quite thorough."

Technical Comments:
"1. Many grammatical errors – far more than is appropriate for a scientific reviewer to make edits on, but these need to be addressed before publication."

Fixed

"2. The citation for Dunham et al. is incomplete, but I applaud investigators for addressing instrument calibration issues, which are often ignored!"

Fixed

Referee #2

General comments:

"In general, the paper discusses a relevant research issue, as is discussed based on the literature in the discussion. It is apparently based on an interesting dataset (though with some limitations, mentioned below), but the presentation and discussion of the results is relatively poor and not very clear, and calls for major revisions."

"the presentation and discussion of the results is relatively poor"

Response: We have significantly improved the version submitted, adding all the statistical analyses required to support the results. They reinforce, but do not change their meaning.

General comments:"It should be made more clear (in the introduction etc.), that the results are probably not easily transferrable to other areas, as the choses study sites are quite homogenous (focus on a certain region of France). "

Response: While we acknowledge the reviewer's comment that our study is based on a regional dataset, we believe that the results (i.e., that dam physical attributes influence downstream thermal regimes) is applicable to many other regions and systems. Additionally, we wanted to focus our results on the importance of these thermal regimes on ecophysiological processes, like effects to the brown trout. We have added a sentence in the discussion to clarify this point.

To remove any ambiguity, we delete the reference to regional stream temperature model in the abstract (L 12) and the introduction (L 114)

On the other hand, we propose in the discussion to complete the notion of the possibility of regionalization as follows

Previous text: L 323

One potential path for deepening research is regionalization as a function of thermal regimes and their governing factors (characteristics of aquifers/climate/bed material/conductivity).

Replaced by

New text: L346 to 349

One potential path forward is to create regionalized statistical models based on geographical data and dam databases, analogous to the way that ecological risk analyses are constructed (Allan et al. 2012; Van Looy et al., 2015). However, we realize that our dataset is provincial in temporal and regional extent, potentially limiting extrapolation of results to other areas with different groundwater and climatic influences.

General comments: "Furthermore, the study would greatly benefit from including more temperature data from the same site for several years – one would expect to also see quite some inter-annual differences. As this does not seem to be possible, the authors should at least discuss this shortcoming. Especially as the authors try to hint at a regionalization (e.g. at the end of section 4.1), this should be discussed better: What, for example, about the different groundwater regimes – are we talking about gaining or losing rivers? Etc."

Response: We have added a sentence to the discussion acknowledging these issues.

Line 348 to 349

However, we realize that our dataset is provincial in temporal and regional extent, potentially limiting extrapolation of results to other areas with different groundwater and climatic influences.

General comments: "The overall result – that the most important drivers of temperature regime changes in dams are residence time and surface area are not particularly surprising. Discuss this. (maybe one could even come up with some empirical linear relationship or empirical model, including those parameters, and water temperature, air temperature, solar radiation etc.?)"

Response: We agree that the results are not particularly surprising, but we note that these results are surprisingly absent from the literature. Hence, this work provides an important result that, to our knowledge, has not been previously presented. We have tried to quantify the heating due to the structures of small dams. The major determining parameters that emerge do not contradict physical knowledge. But it is important to point out that we were not seeking to highlight the physical determinants of the thermal regimes of rivers, but rather the factors responsible for heating due to a dam and its associated impoundment. We have thus provided knowledge on the orders of magnitude of heating for structures that have not yet been well documented.

But the statistical analysis we performed (see later) explain more efficiently relationships including this parameters.

Sentence added L307 (Previous text)

New text: L328 to 330 and L336 to 338
We found that residence time and surface area were the principal explanatory variables of upstream-downstream temperature differences. Indeed, redundancy analysis indicated the primary differences between our site typologies were explained by these variables.
(…)
Multiple regression (Table 4) clarified the direction and magnitude of these effects and indicated that ΔTmax is best explained by both residence time and surface area (group B effects), whereas ΔTmin is best explained only with residence time (group A effects).

"Specific comments:"
"Section 1: Please include some more general explanation on why the whole issue of dams changing the thermal regime is relevant (make your motivation more clear)"

Response: The motivation for the study is explained in the introduction to paragraph 1.5 (line 87 to 107), where we review the literature which shows that knowledge is scattered, and that some of the orders of magnitude characterized are significant for biological processes or organisms by being located in values at risk. Our goal is therefore to better document these orders of magnitude.

"Line 27: "These determinants are candidate to generalize results" – sentence a bit unclear, please reformulate"

Response: Sentence deleted.

"Line 47: "During summer, the factors leading to warming are: (i) the input of heat from upstream" – maybe you should be a bit more specific here. Mention why you focus on summers. What do you mean by the input of heat from upstream? Tributaries that are warmer than the main stream?"

Responses: Focus on summer:
We have mainly targeted the biological risk related to global warming.
Introduction § 1.1 line 35 – 37 "As ectotherms, aquatic organisms are very sensitive to ambient water temperature and to its alteration, especially in the vicinity of their upper thermal temperature tolerance (Brett, 1979; Coutant, 1987; McCullough et al., 2009 for Coldwater fish review; Souchon and Tissot, 2012 for European non salmonid fish review).".

Heat from upstream
We refer to the conceptual heat flow balance model of Kelleher et al., 2012: the heat flow from upstream depends on the inflow flow Qi and the temperature of the watercourse, which results from the addition of flows from the main river and its tributaries upstream of the studied section.
Kelleher, C., Wagener, T., Gooseff, M., Mcglynn, B., Mcguire, K. and Marshall, L. (2012). Investigating controls on the thermal sensitivity of Pennsylvania streams. Hydrological Processes. 26(5): 771-785.
To be precise we add "fluxes" in L 47

"Line 50: If you talk about different anthropogenic influences on stream temperature, you probably also should mention cooling water from power plants etc."

Response: The objective of the study is to quantify the effects small dams in stream; this does not concern cooling water from power plants affecting large rivers.

"Line 56: > 15 m of what?"

Fixed
15 m high

"Line 61 ff: These two "predictions" you are mentioning from 1983 and 1990 should be verified by now? Can you say something about this?"

The term prediction is inappropriate

Fixed

Previous text: L 61 to 63
In addition, Ward and Stanford (1983) predicted that dams in headwaters might not alter the natural temperature range, with the assumption that canopy and springs or groundwater influx can buffer annual temperature variations.

Replaced by
New text: L64 to 67
In addition, Ward and Stanford (1983) suggest that dams in headwaters might not alter the natural temperature range, with the assumption that canopy and springs or groundwater influx can buffer annual temperature variations. On the other hand, downstream warming may occur during summer releases from surface reservoirs (O'Keeffe et al., 1990).

"Line 84: With a height smaller than 5m?"

Fixed
New text: L85
In this work, we studied dams with a height less than 5 m , which we hereafter refer to as small dams.

"Line 88ff: Be more precise here. There are few articles even considering temperature effects? Those are the 43 sites or articles?"

These are "studies" in the manuscript of M'Baka et al (2015).
Fixed

"Line 106: "with closed riparian canopy or aquifers" – what do you want to say here?"

Previous text: L105 to 106
This variability is greater in headwaters due to the weak thermal inertia and great diversity of these waterbodies, and also to heterogeneous effects with closed riparian canopy or aquifers.

Replaced by

New text: L108 to 110
This variability is greater in headwaters due to the weak thermal inertia and great diversity of these waterbodies, especially with regard to local shading effects from riparian canopy cover and relative importance of spring or tributary discharges.

"Line 106ff: "This is the reason why it seems preferable in a first study to focus on the single effects of the impoundment immediately downstream the dam." – please reformulate/make your motivation more clear. How exactly is this resulting from the above?"

Fixed
Previous text L 106 to 107
This is the reason why it seems preferable in a first study to focus on the single effects of the impoundment immediately downstream the dam

Replaced by

New text: L110 to 111
Given this potential complexity with several possible confounding factors, this study focused only on the warming effect of small dams and their impoundment.

"Line 130: How is a "day of heat wave" defined?"

For scenario A1B (mean concentration of greenhouse gases), the estimation was more than ten additional days of heat waves by 2050.

Response: The definition is conform to International meteorological vocabulary WMO, 1996.

WMO, No. 182. TP. 91. Geneva (Secretariat of the World Meteorological Organization) 1966. Pp. xvi, 276. Sw. fr. 40

"Marked warming of the air, or the invasion of very warm air, over a large area; it usually lasts from a few days to a few weeks"

Fixed

Previous text: L129 to 130
For scenario A1B (mean concentration of greenhouse gases), the estimation was more than ten additional days of heat waves by 2050.

Replaced by

New text: L135 to 136
For scenario A1B (mean concentration of greenhouse gases), the estimation was more than ten additional days of heat waves (WMO, 1966) by 2050.

"Section 2.2: Mention right away in the text how many dams you study. And how did you chose those specific sites?"

Fixed

New text: L138
The 11 dams in the study area are overflow structures and …

The sites were chosen taking into account their distribution in the upstream downstream gradient and the size gradient of the reservoirs.

Line 145: Make it clear that the temperature sampling was performed for single summers (or two) per site, between 2009 and 2016

Fixed
We add sentence:
New text: L151 to 153
For two sites, we have data for two different summers (Champagne2009 and 2015, Fretaz 2014 and 2016) because the local water management organization was particularly interested in the thermal regimes of these rivers. (Table 1).

"Section 2.5: Please elaborate further on how you performed your PCA. Illustrative variables are explanatory variables? "In order to identify characterization of the impacts of the different dams" – reformulate, unclear!"

Fixed
Previous text: L 166 to 170
2.5 PCA analysis
In order to identify the characterization of the impacts of the different dams, a principal component analysis (PCA) was carried out using the software XLStat (ADDINSOFT™) on the water temperature variables: downstream / upstream difference of the maximum, average and minimum daily

temperature and daily temperature amplitude. The physical characteristics of the structures (Table 1) were used as illustrative variables to evaluate the correlations with the temperature variables

Replaced by

New text: L184 to 191

2.6 Ordination analysis

To characterize the impacts of the different dams, a principal component analysis (PCA) was carried out using the software XLStat (ADDINSOFT™) on the three water temperature variables: ΔTmax, ΔTmin, and ΔTamp. We used the median values for variables on each time-series in order to build an input matrix (13 occurrences for three variables).

Then a complementary redundancy analysis (RDA) with automatic stepwise variable selection procedure was used to identify the physical dam characteristics (Table 1) that significantly explain the PCA results (ter Braak 1986).

After the RDA identified the relevant physical dam characteristics, we conducted multiple linear regression between these characteristics and temperature variables to determine specific effect sizes of these characteristics on thermal regime.

New text: L566 to 567 (References)

Ter Braak, C. J. F.: Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis, Ecology, 67, 1167-1179, 1986.

Previous text : L 220 232

3.6 PCA results

The first axis of the PCA analysis (78.3 %) is correlated to all temperature daily variables (calculated as differences between downstream versus upstream), in particular to the maximum daily temperature difference (Tmax_diff). The second axis discriminates the daily amplitude difference (Range_diff) with the minimum temperature (Tmin_diff) difference (Fig. 7).

For the determinants, the water residence time is the most correlated variable to the first axis F1, the size of the reservoir (surface, volume, length) correlates to both the first and second axis. The other physical-geographical characteristics related to the size of the watercourse (watershed, distance to the source), are correlated with the daily maximum temperature and associated with the second axis F2 (20.7 %); dam height has a very weak correlation with the axis F1.

The projection of the site series on these axes shows a strong spreading along the first axis. The dams measured two different years stay within the same range on this axis (Fretaz and Champagne) (Fig. 8).

Groups B1 and B2 are distinguished by respectively the first and second axis association. This can be linked to the determinants of strong residence time influence for group B2, whereas group B1 is mainly characterized by the size of the impoundment (large impoundments, yet with relatively smaller residence time and thus less exacerbated thermal regime effects).

Replaced by

New text: L234 to 243

3.6 Ordination results

The first axis of the PCA analysis (74.1% of total inertia) is correlated to all daily temperature daily anomalies, in particular to the ΔT_{max}. The second axis (25.3%) discriminates the ΔT_{amp} with ΔT_{min} (Fig. 7). Results of the RDA show that the water residence time and the impoundment surface explain 95.2% of the PCA structure. The projection of the sites on these axes shows a strong spreading along the first axis (Fig. 8). Additionally, the dams that had two different measurement years stay within the same range on this first axis (i.e., Fretaz and Champagne) (Fig. 8).

Multiple regression analyses between the temperature variables (median values of ΔT_{min} and ΔT_{max}) and the physical characteristics obtained by the RDA (residence time and impoundment surface) resulted in high explanatory power (R2 ≈ 0.7). These regressions identified the significant contribution of residence time for ΔT_{min} and ΔT_{max}, whereas only surface area had a significant contribution for ΔT_{max} (Table 4).

Figure 7 deleted
The new Figure 7 replaces Figure 8

Figure 7. PCA analysis. Correlation circle with temperature as active variables

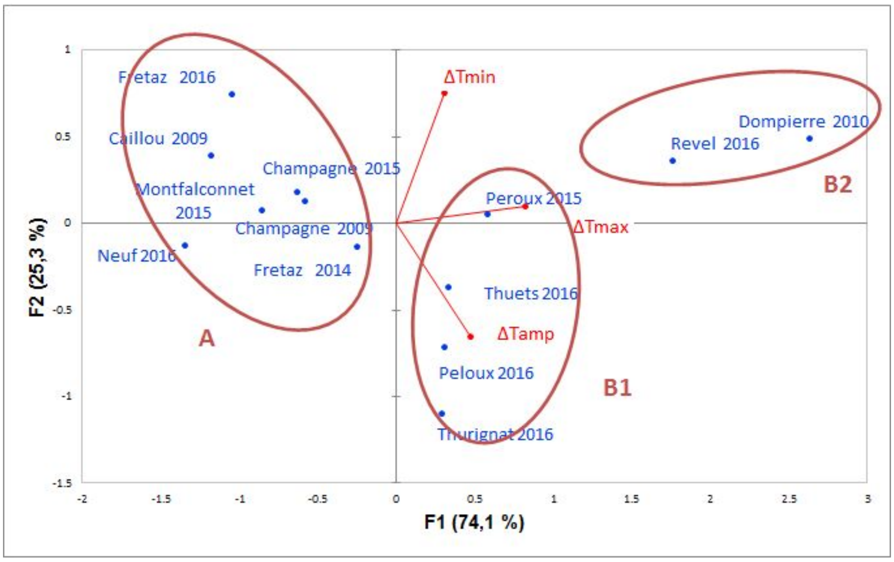


Figure 7. PCA analysis. Scatterplot of time series. Ellipses are drawn to visualize the groups obtained with the hierarchical cluster analysis

A new table is added
New text: L602 to 604

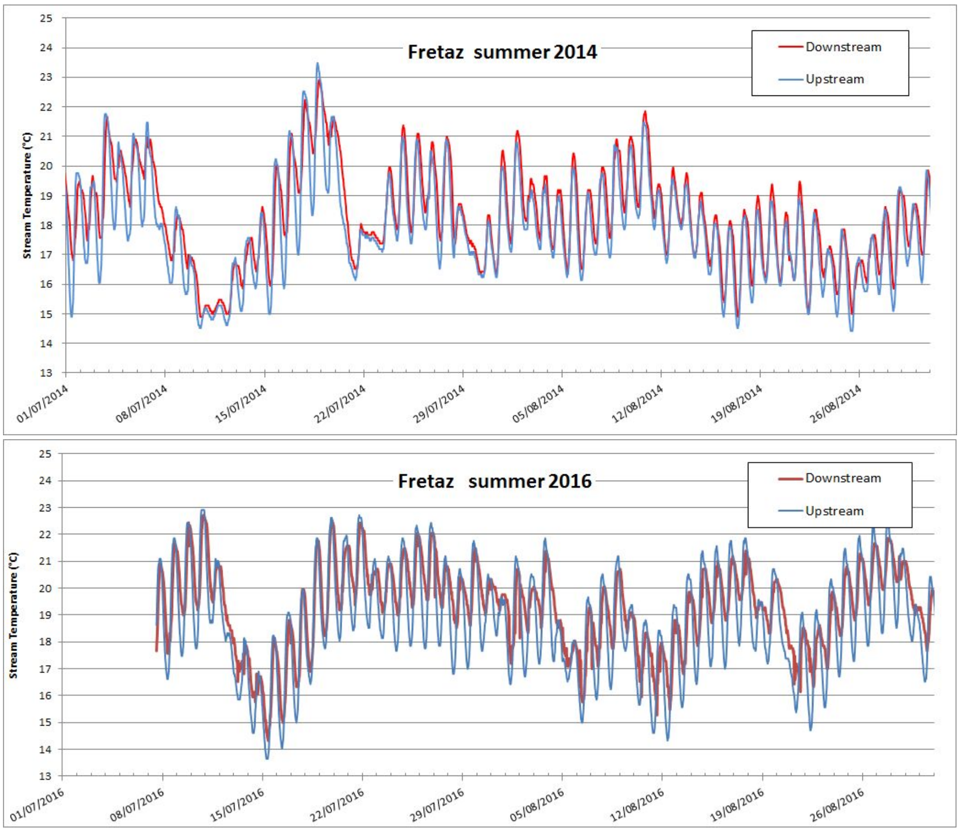
Table 4. Results of multiple linear regressions performed on the 2 indicators ΔTmin, ΔTmax using the dam physical characteristics surface area and residence time. Significant p-value are in bold.

Dependent variable	Independent variable physical characteristics	standardized coefficient	p-value	R2
ΔTmax	surface area	0.39	0.041	0.72
	residence time	0.80	0.001	
ΔTmin	surface area	-0.13	0.48	0.68
	residence time	0.80	0.001	

"Section 3.2/Fig. 4: I understand that the scatter plot for Dompierre shows “type 2”, so like in Figure 3. However, Neuf in Fig. 4 does not show “type 1”, like in Figure 2, because there is almost no difference between minimum temperatures up- and downstream. And, why don’t you simply show the same data in your timeseries plots (Fig.
2 and 3) and the scatterplot (Fig. 4) to illustrate the two types. Also, better to combine the figures and make the two types more clear by that."

Response: We follow the recommendation and propose a new set of figures

Fig. 2 Fretaz 2014 and 2016



and Fig. 4 Dompierre (type 2) and Fretaz (type 1)

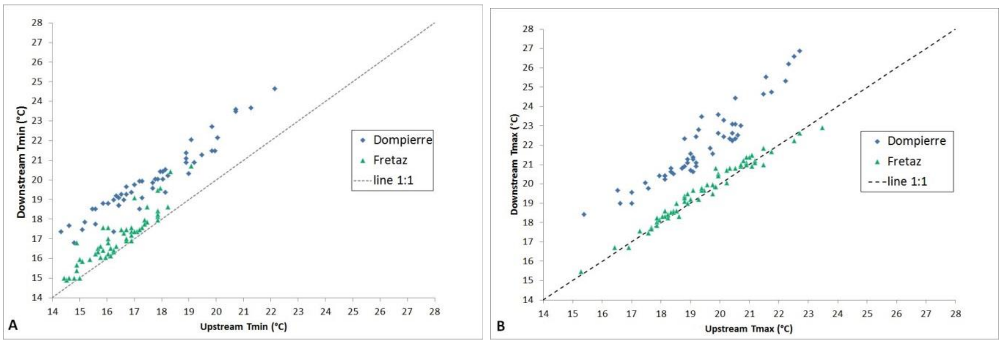


Figure 4. Minimum (A) and maximum (B) daily temperatures upstream and downstream of the dams-of-the river (Dompierre site, Veyle stream in 2010; Fretaz site, Veyle stream in 2014). Dashed line is 1:1 line.

Previous text: L 191 to 194

The two dominant patterns can be illustrated by plotting the minimum and maximum temperature values at the site "Dompierre 2010" with a difference of order of + 1.5°C between the upstream and downstream of the site, comparing to "Neuf 2016", where these values are the same for minimum daily temperatures, or even slightly negative for the maximum temperatures (Fig. 4).

Replaced by

New text: L209 to 212

The two dominant patterns of temperature differences are further illustrated by plotting the minimum and maximum temperature values at the site. For example, at Dompierre in 2010, we observed a consistent shift of approximately +1.5°C (both maximum and minimum daily temperature) between the upstream and downstream of the dam (Fig. 4A). In contrast, at Fretaz in 2014, this shift is dampened, and temperature values between upstream and downstream follow a 1:1 relationship (Fig. 4B).

New figure 4

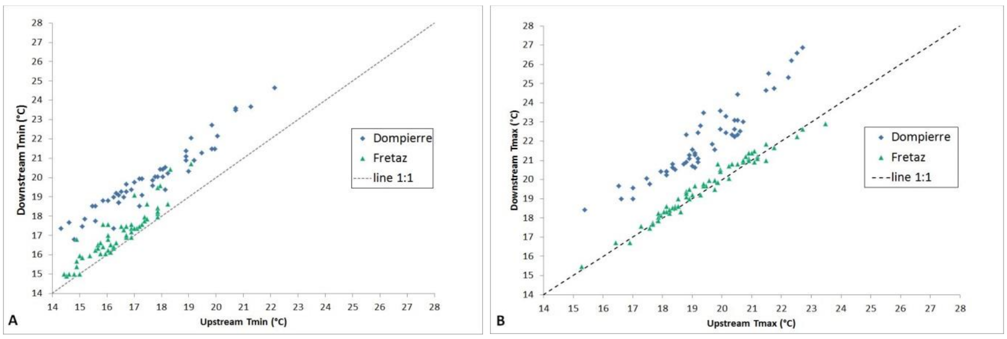


Figure 4. Minimum (A) and maximum (B) daily temperatures upstream and downstream of the dams-of-the river (Dompierre site, Veyle stream in 2010; Fretaz site, Veyle stream in 2014). Dashed line is 1:1 line.

"Section 3.3: 0.46% of what?"

L 197 This difference averages 0.46% for the 13 cases.

Response: This precision is deleted, as it is secondary

"Section 3.5: Specify how you calculate your differences (downstream – upstream?). And don't groups B1 and B2 both exhibit net warming? Be more precise."

Response: We propose to modify the section 2.4 Data analysis (l 156 à 159)

Previous text: L156 to 159
To determine if the dams alter the temperature regime, the minimum, average and maximum temperatures and amplitudes were calculated for each full day recorded, and the median values were recorded for the period. The calculations of daily differences of maximum and minimum water temperatures were performed for each pair of upstream/downstream records, and the median of these differences over the recording period was calculated.

Replaced by
New text: L165 to 170
To characterize the influence of dams on stream thermal regimes we first calculated three variables: daily difference between upstream and downstream temperature 1) maximums (ΔTmax), 2) minimums (ΔTmin), and 3) amplitudes (ΔTamp) for each site and year. With these data, we then conducted the following analyses:
1. Median summer differences in ΔTmax, ΔTmin, and ΔTamp (median is used instead of mean to limit the influence of extreme values),
2….

"Section 3.7: Confusing to speak of "short period of time" or "three consecutive days" – what you actually do is to look at shifts in intra-daily temperature variation."

Fixed

Previous text: L 234 to 239

3.7 Focus on temperature pattern in short period of time
Looking more specifically on a short period of time (three consecutive days), differences in the diurnal variation of the temperature of the river upstream and downstream of the dam shows that for the first group A, the maximum water temperatures upstream and downstream are close, while the minimum temperature downstream does not return to that of upstream (Fig. 9A). In the second group B the water temperature difference between upstream and downstream are more important and remain persistent during all the day period (Fig. 9B).

Replaced by

New text: L244 to 265
3.7 Ecologically relevant intra-daily temperature variation

To further illustrate the different thermal regime effects from our typology analysis, we compare intra-daily temperature variations for a three-day time series in group A (small thermal effect) with group B (large thermal effect; Fig. 9):

- In the example of group A (Fig. 9A), the downstream temperature is generally warmer than the upstream temperature (observed difference of 1°C warmer) except for a few hours during the three day sample observation period. The biological benchmark of 22°C is exceeded both upstream and downstream during the day of August 20. The rest of the time, temperatures are below this threshold. From a biological point of view, the duration above the thermal threshold is short, preceded and followed by more favorable temperatures (i.e., the remission period).
- In the example of group B (Fig. 9B), the downstream temperature is systematically higher than that of the upstream, with a temperature difference varying between +0.8–2.4°C. The 22°C threshold is exceeded downstream for a cumulative 42 h over the three-day period. August 15 and 16 have downstream temperatures that rarely go below 22°C, leaving no time for thermal remission (return to a temperature that is better tolerated physiologically by fish). At the same time, the upstream part of the stream is maintained at daily temperatures not exceeding this threshold.
- Additionally; differences in the diurnal temperature variation upstream and downstream of the dam shows that for group A, the maximum water temperatures are similar, whereas the minimum temperature downstream does not return to that of upstream (Fig. 9A). In group B the water temperature difference between upstream and downstream are persistent throughout the diurnal cycle (Fig. 9B).

For all sites, by studying the average daily duration with a temperature exceeding 22°C continuously, we can see (Fig. 10):

- downstream durations are always greater than or equal to that of the upstream durations, regardless of site typology,
- the largest upstream/downstream differences occur in the group B2 group,
- group A is generally not affected by an upstream/downstream increase, except for two sites which exhibit a two hour increase.

Previous text: L 162

(iv) the dam thermal effect considering an arbitrary threshold of 22 °C, with a calculation of the number of days above this threshold.

Replaced by

New text: L173 to 176

To assess the potential biological importance of dam thermal effects, we also calculated 1) the number of days that water temperatures were greater than 22°C, and 2) the mean of the maximum daily duration (in hours) where water temperature was greater than 22°C. We chose 22°C as an illustrative threshold known to be a thermal stress benchmark value for salmonids (Elliott and Elliot, 2010; Ojanguren et al., 2001).

And in discussion

Previous text: L 344 to 349

We have chosen temperature > 22°C as an illustrative threshold known to be a thermal stress benchmark value for salmonids especially for brown trout, Salmo trutta (Elliott and Elliot, 2010: upper critical incipient lethal temperature for alevins considered as a very sensitive stage; Ojanguren et al., 2001: general activity of brown trout juvenile). We also know that thermal regime and threshold values are important for the life cycle of aquatic invertebrates (Ward, 1976; Brittain and Salveit, 1989), and it is possible that changes in natural temperature regimes may be as important as altered stream flows to the ecological impacts of dam operations (Olden and Naiman, 2010).

Replaced by

New text: L372 to 376

In this study, we used a temperature of 22°C as an illustrative threshold known to be a thermal stress benchmark value for salmonids, especially for brown trout, Salmo trutta (Elliott and Elliot, 2010: upper critical incipient lethal temperature for juveniles, which is considered a very sensitive stage; Ojanguren et al., 2001: general activity of brown trout juvenile). In addition, this threshold is known to be important for the life cycle of aquatic invertebrates (Ward, 1976; Brittain and Salveit, 1989).

We add a new figure (Fig.9)

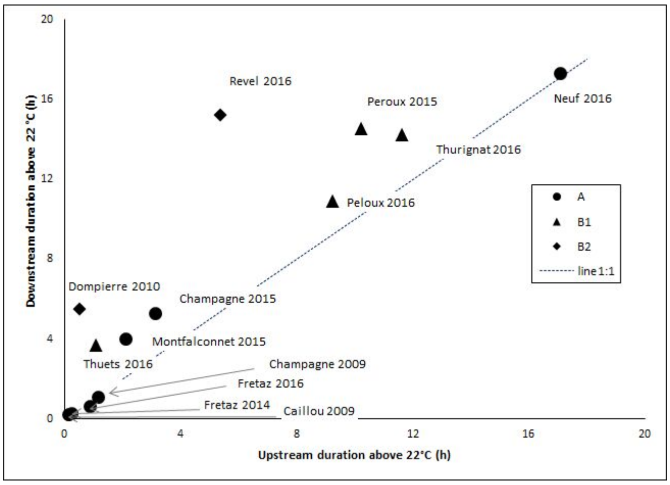


Figure 9. Mean of the daily maximum duration with T above 22 °C , upstream and downstream each site monitored in the study. A (circles), B1 (triangles), B2 (rhombus) are the groups of sites resulting from HCA.

"Section 4, first paragraph: Some of this would be better in the introduction. Same applies to first two paragraphs of section 4.1."

Response: That's right.

We think that the recall of the context in a few sentences make the discussion as an independently readable part.

"Line 317, 318: Again, specify the sign of your temperature differences."

Fixed

New text: L342

with overall median ΔT differences approximately +0.6–2.4°C.

"Line 344ff: Is Salmo trutta a common species in the rivers of your test sites?"

Response: Yes, Salmo trutta is endemic and emblematic and at the ecological limit of his distribution. This is why a warming effect added by dams to the natural thermal regime is likely to further limit its range.

"Line 378: "The thermal landscape is therefore potentially very fragmented due to this fact alone." What do you mean by this and the following sentences?"

Fixed
Previous text: L378
The thermal landscape is therefore potentially very fragmented due to this fact alone.

Replaced by
New text: L402 to 404
because of the high density of dams in the landscape (0.64 per km), the thermal landscape of this region is potentially fragmented. In other words, we expect that small dams in this region create a discontinuous distribution of stream thermal regimes throughout the river network..

"Line 385: Please specify which "spatial generalization elements" you mean."

Fixed
Previous text : L384 to 385
Our work provides spatial generalization elements to better document the present and future thermal landscape

Replaced by

New text: L409 to 410
Our work highlights physical dam characteristics that could be useful in a large-scale heat risk analysis, or in modeling scenarios aiming to account for changes in thermal regimes.

Technical comments:
"Be consistent with thousand separators (for example, you have 2 710000, 96 222, 59071)"

Fixed

"Be consistent on how to write "run-of-the-river dam"."

Fixed

"Line 38: Why do you cite Rader et al., 2007 as part of the review by Ellis and Jones?"

Fixed
Previous text:L38
(Rader et al., 2007 in Ellis and Jones, 2013)

Replaced by
New text: L40

(Rader et al., 2007)

"Line 42: "precipitation", not "precipitations", this comes up several times"

Fixed
Lines 44,130, 161

"Line 68: reformulate to "they are expected to increase downstream water temperature" or similar"
Fixed
Previous text: L68
they are expected to deliver downstream warmer water

Replaced by
New text: L74
they are expected to increase downstream water temperature

"Line 78: "(ROE, sept 2017)" why is this cited this way?"

Fixed
Suppressed

"Line 59: "water temperature patterns for tens of km"?"

Fixed
Previous text: L59
alter longitudinal downstream water temperature pattern tens of km

Replaced by
New text: L64
alter longitudinal downstream water temperature pattern for tens of km

*"Line 72ff: "very imprecise depending on national databases. For example, the Internation**al** Commission on Large Dams""*

Fixed
Previous text: L 72
nation databases.

Replaced by
New text: L77
national databases.

"Line 90ff: "Dripps et al. (2013): : :." – please reformulate, sentence unclear"

Fixed

Previous text : L90 to 92

Dripps et al. (2013) studying 3 residential artificial headwater lakes (17 to 45 ha) on stream (low flow discharge 0.0024 to 0.0109 m3/s) showed that they could increase summer downstream temperature by as much 8.4°C and decrease diurnal variability by as much 3.9°C.

Replaced by

New text: L91 to 93
Dripps et al. (2013) studied the influence of three residential artificial headwater lakes (17–45 ha) on stream (discharge = 0.0024–0.0109 m3 s-1) thermal regimes. They measured a summer downstream temperature increase by as much 8.4°C and a decrease of diurnal variability by as much 3.9°C.

"Line 95 ff: "Hayes et al. (2008) in the region of the Great Laurentian Lakes" – all this paragraph contains typos and grammar mistakes, please revise"

Fixed

Previous text: L95 to 97
Hayes et al. (2008) in the region of Great Laurentian Lakes measured a weak to null thermal effect of low-head barriers (<0.5 m in height) built to prevent the upstream migration of sea lamprey Petromyzon marinus, but a temperature elevation comprised between 0.0 to 5.6°C below small hydroelectric dams.

Replaced by

New text: L96 to 99
In the region of Great Laurentian Lakes, Hayes et al. (2008) studied two types of dams with different uses. They measured a weak to null thermal effect of low-head barriers (height <0.5 m) built to prevent upstream migration of sea lamprey (*Petromyzon marinus*, L.). On the other hand, they measured a greater effect for small hydroelectric dams (downstream temperature increases up to 5.6°C).

"Line 101: Maybe "explaining variables" is a better term"
Fixed
Previous text: L 101 to 102
and the difficulty to identify the master variables governing the thermal regime

Replace by

New text: L104
and the difficulty to identify the explaining variables

"Sector 2.1: Please revise language. Remove repetitive "on a basis of 230 000 km streams with permanent flow""

Fixed

Previous text: L 121 to 123

with a dam and weir density of 0.64 features per km greater than the French average of 0.42 features per km (Référentiel national des Obstacles à l'Ecoulement, ROE, September 2017) on a basis of 230 000 km for streams with permanent flow.

Replaced by

New text: L127 to 129
Dam and weir density is 0.64 features per km, which is 50% greater than the French average of 0.42 features per km for streams with permanent flow.

Referee #3
"General comments:
The purpose of this study was to quantify the downstream impacts of different types of small dams on summer water temperature in lowland streams. The topic of this manuscript is of high importance, and the research is critically needed since water temperature could impact the structure of aquatic communities and the functioning of the aquatic ecosystem as stated by the authors. The data set on water temperature the authors have collected seems to be robust, and with quite enough number of sites. I personally appreciated the calibration process made for the instruments to insure reliable data. The discussion is quite thorough and insightful, but more focus on literature review (others work) rather than focusing on the discussion of the current work. I found that data analysis severely lacking, and the presentation of the results to be using individual sites as examples that are difficult to judge if they are really representative. Therefore, without adequate data analysis I felt that the conclusions were not well supported. The language used is not sufficiently comprehensible and needs to be improved before publication. Many other specific and technical comments can be found below."

Response: We have taken all these comments into account and paid particular attention to the statistical analysis of the data to support our conclusions.

Specific comments
"1. P5, L159: Why authors calculate median differences and not mean? Please justifying why this metric instead of means."

Response: We prefer to work with seasonal variables that are not affected by exceptional one-time weather events.

To avoid any confusion, we eliminate any reference to daily mean temperature
And we propose to modify the section 2.4 Data analysis (l 156 à 159)

Previous text: L156 to 159
To determine if the dams alter the temperature regime, the minimum, average and maximum temperatures and amplitudes were calculated for each full day recorded, and the median values were recorded for the period. The calculations of daily differences of maximum and minimum water temperatures were performed for each pair of upstream/downstream records, and the median of these differences over the recording period was calculated.

Replaced by

New text: L165 to 170

To characterize the influence of dams on stream thermal regimes we first calculated three variables: daily difference between upstream and downstream temperature 1) maximums (ΔTmax), 2) minimums (ΔTmin), and 3) amplitudes (ΔTamp) for each site and year. With these data, we then conducted the following analyses:

1. Median summer differences in ΔTmax, ΔTmin, and ΔTamp (median is used instead of mean to limit the influence of extreme values),

2….

"2. Section 3.5: What is the scientific method used for group clustering?"

Fixed

We add description of the statistical method used

Previous text: L 164

Finally, we propose a classification of the observed thermal behavior in 3 groups, based on differences between upstream and downstream dam daily maximum temperature, daily minimum temperature and daily amplitudes.

Replaced by (new section)

New text: L177 to 183

2.5 Site typology analysis

We observed different thermal regimes in our data and wanted to classify them. To do so, we carried out a hierarchical cluster analysis using Euclidian dissimilarities matrix according to the Ward's method (1963) using the daily dataset (n=807) of ΔT_{max} and ΔT_{min} obtained over all time-series. We forced the classification to integrate the different time-series effect by adding a complete disjunctive table differentiating each time-series to the data set. This procedure makes it possible to group the data first by time-series, then in a second step to differentiate them from each other (i.e., to differentiate site thermal regimes).

Previous text: L 204 to 217

3.5 Site typology based on summer thermal regime

The median values of the daily temperature variables calculated over summer (from 01/07 to 01/09) permit distinguishing two major types of response to the presence of a small dam (Table 3).

A first group (A) is characterised by:

- a median of the differences upstream/downstream of the maximum daily temperatures lower than 0.5°C;
- a median of the differences upstream/downstream of the minimum daily temperatures between + 0.4 and 1.3°C;
- a median of the differences in daily amplitudes lower than - 0.2°C.

A second group (B) is characterised by:

- a median of the differences upstream/downstream of the maximum daily temperatures higher than 0.5°C;
- medians of the differences upstream/downstream of the maximum and minimum daily temperatures in the same order of amplitude.

In addition two subgroups can be distinguished: subgroup (B2) with medians of upstream/downstream differences of daily maximum and minimum temperatures higher than 1°C, i.e. net warming between upstream and downstream, and subgroup (B1) with values ranging from 0.3 – 0.8°C.

Replaced by

New text: L220 to 231

3.5 Site typology

The hierarchical cluster analysis applied to the daily summer temperature anomalies distinguished three groups:

- a first group (A) characterized by :
    - median of ΔT_{max} less than 0.5°C;
    - median of ΔT_{min} between + 0.4–1.3°C;
    - median of ΔT_{amp} less than -0.2°C.
- a second group (B1) characterized by:
    - median of ΔT_{max} ranging from +0.6–1.2 °C;
    - median of ΔT_{min} between +0.3–1.1°C.
- a third group (B2) characterized by:
    - median of ΔT_{max} greater than 1.2 °C;
    - median of ΔT_{min} greater than 1.2 °C

Figure 6 changed as :

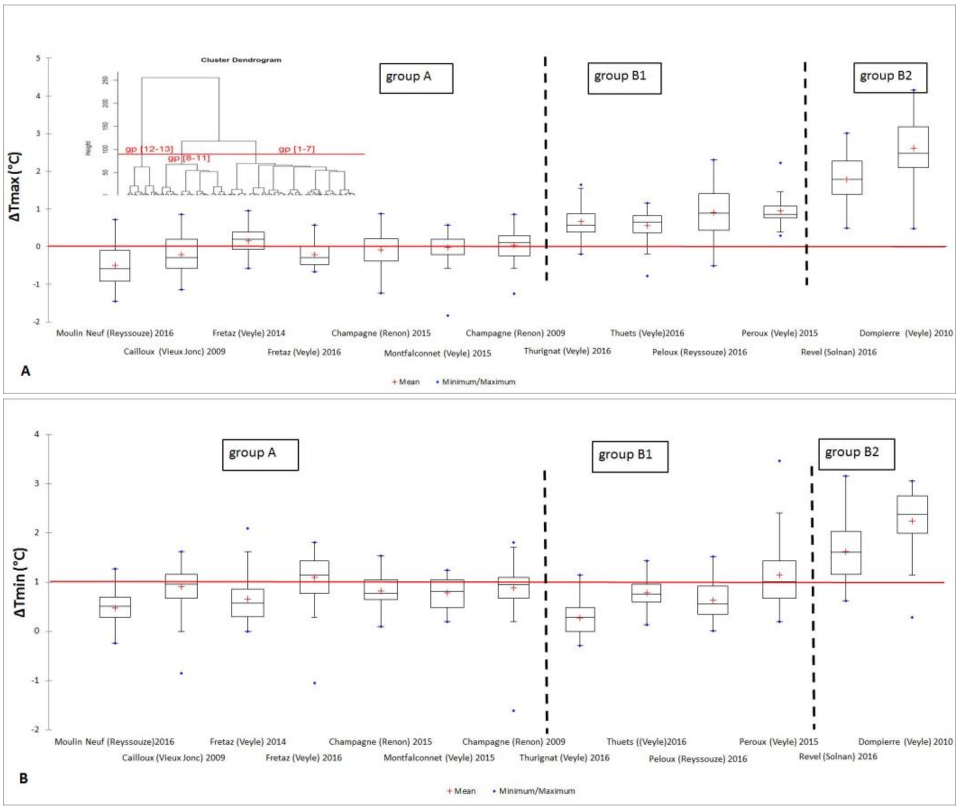


Figure 6. Box-plot distribution (25% - 75 %) of upstream/downstream differences of daily maximum and minimum temperatures for all the time-series studied. (Red lines: 0°C for daily maximum temperature and 1°C for daily minimum temperature are drawn to help reading). The vertical lines

drawn in bold are the limits to the three classes of results of the hierarchical cluster analysis. Dendrogram CAH's result is shown at the top left of the figure.

"3. Section 3.7: the results presented in this section are unclear and the purpose of presenting such results is unclear as well. I found it very hard to link this section with the discussion section. This would be easy for the reader if the results and discussion section were compiled in one section."

Fixed
Fully rewritten

L234 to 239
3.7 Focus on temperature pattern in short period of time
Looking more specifically on a short period of time (three consecutive days), differences in the diurnal variation of the 235 temperature of the river upstream and downstream of the dam shows that for the first group A, the maximum water temperatures upstream and downstream are close, while the minimum temperature downstream does not return to that of upstream (Fig. 9A). In the second group B the water temperature difference between upstream and downstream are more important and remain persistent during all the day period (Fig. 9B).

Replaced by

New text: L244 to 265
3.7 Ecologically relevant in intra-daily temperature variations
To further illustrate the different thermal regime effects from our typology analysis, we compare intra-daily temperature variations for a three-day time series in group A (small thermal effect) with group B (large thermal effect; Fig. 9):

- In the example of group A (Fig. 9A), the downstream temperature is generally warmer than the upstream temperature (observed difference of 1°C warmer) except for a few hours during the three day sample observation period. The biological benchmark of 22°C is exceeded both upstream and downstream during the day of August 20. The rest of the time, temperatures are below this threshold. From a biological point of view, the duration above the thermal threshold is short, preceded and followed by more favorable temperatures (i.e., the remission period).
- In the example of group B (Fig. 9B), the downstream temperature is systematically higher than that of the upstream, with a temperature difference varying between +0.8–2.4°C. The 22°C threshold is exceeded downstream for a cumulative 42 h over the three-day period. August 15 and 16 have downstream temperatures that rarely go below 22°C, leaving no time for thermal remission (return to a temperature that is better tolerated physiologically by fish). At the same time, the upstream part of the stream is maintained at daily temperatures not exceeding this threshold.
- Additionally; differences in the diurnal temperature variation upstream and downstream of the dam shows that for group A, the maximum water temperatures are similar, whereas the

minimum temperature downstream does not return to that of upstream (Fig. 9A). In group B the water temperature difference between upstream and downstream are persistent throughout the diurnal cycle (Fig. 9B).

For all sites, by studying the average daily duration with a temperature exceeding 22°C continuously, we can see (Fig. 10):

- downstream durations are always greater than or equal to that of the upstream durations, regardless of site typology,
- the largest upstream/downstream differences occur in the group B2 group,
- group A is generally not affected by an upstream/downstream increase, except for two sites which exhibit a two hour increase.

L 162 (section 2.4 Data analysis)

(iv) the dam thermal effect considering an arbitrary threshold of 22 °C, with a calculation of the number of days above this threshold.

Replaced by

New text: L173 to 176

To assess the potential biological importance of dam thermal effects, we also calculated 1) the number of days that water temperatures were greater than 22°C, and 2) the mean of the maximum daily duration (in hours) where water temperature was greater than 22°C. We chose 22°C as an illustrative threshold known to be a thermal stress benchmark value for salmonids (Elliott and Elliot, 2010; Ojanguren et al., 2001).

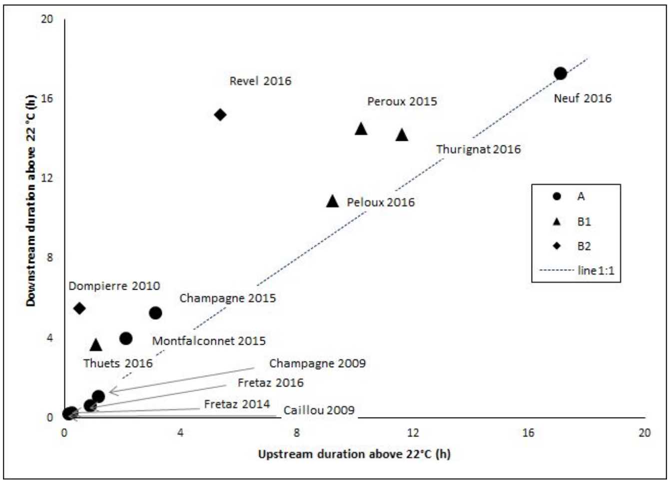


Figure 9. Mean of the daily maximum duration with T above 22 °C , upstream and downstream each site monitored in the study. A (circles), B1 (triangles), B2 (rhombus) are the groups of sites resulting from HCA.

Previous text: L 344 to 346

We have chosen temperature > 22°C as an illustrative threshold known to be a thermal stress benchmark value for salmonids especially for brown trout, *Salmo trutta* (Elliott and Elliot, 2010: upper critical incipient lethal temperature for alevins considered as a very sensitive stage; Ojanguren et al., 2001: general activity of brown trout juvenile).

Replaced by

New text: L372 to 376
In this study, we used a temperature of 22°C as an illustrative threshold known to be a thermal stress benchmark value for salmonids, especially for brown trout, Salmo trutta (Elliott and Elliot, 2010: upper critical incipient lethal temperature for juveniles, which is considered a very sensitive stage; Ojanguren et al., 2001: general activity of brown trout juvenile). In addition, this threshold is known to be important for the life cycle of aquatic invertebrates (Ward, 1976; Brittain and Salveit, 1989).

L 242
For example, for the maximum daily temperature threshold of 22°C (arbitrary value),

Supressed

"4. P7, section 3.8: Authors mention that the maximum daily temperature threshold of 22 °C is arbitrary value. While later in the discussion, the authors indicate that the choice of a 22°C is actually not arbitrary. I suggest that authors delete the word arbitrary and explain the basis of this threshold choice."

Fixed
Arbitrary is suppressed
See above

"5. P8, L255: the authors mention warmer, drier, colder and wetter years. Please discuss how these classifications are made?"

Fixed
Clarification by adding a sentence L 153

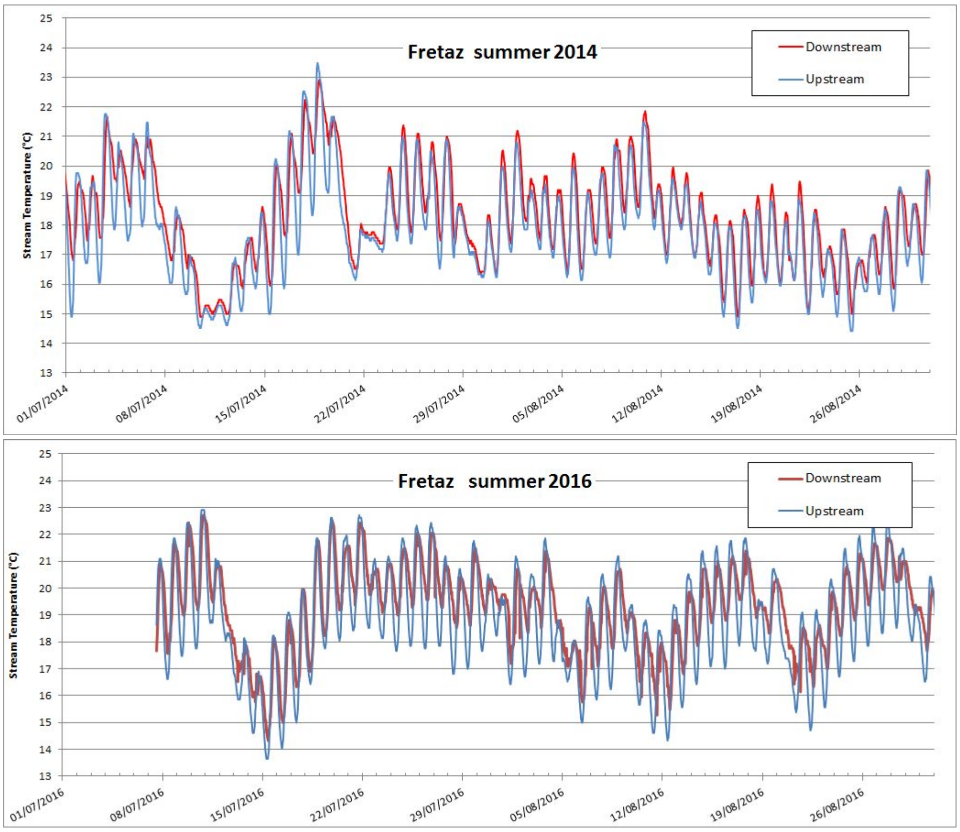
New text: L162 to 163
The summer climatic characteristics for our analysis period are compared with the normal values produced by Meteo France (1981–2010).

"6. P18: Fig.4: what is the reason for comparing temperature of different sites (Dompierre and Neuf) in different years (e.g. 2010 and 2016)."

Fixed

Response: Figure 4 has been modified. We now use the same sites as in Figures 2 and 3 to make it easier to read. The purpose of the comparison is to illustrate the distribution of the differences in diff_Tmin and diff_Tmax between the two main types of thermal response.
We follow the recommendation and propose a new set of figures (Fig.2 and Fig.4)

Fig. 2 Fretaz 2014 and 2016



and Fig. 4 Dompierre (type 2) and Fretaz (type 1)

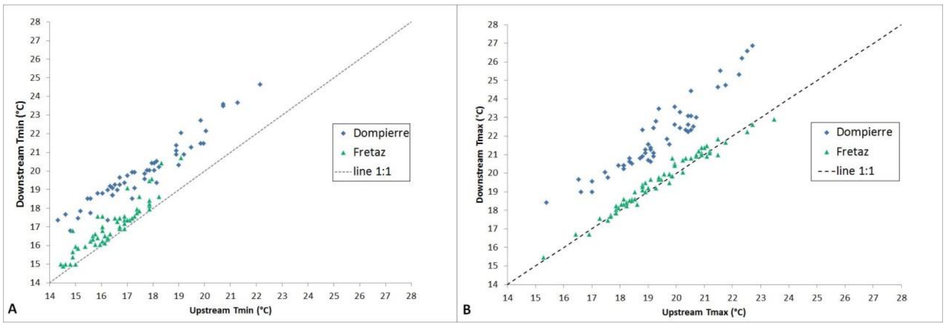


Figure 4. Minimum (A) and maximum (B) daily temperatures upstream and downstream of the dams-of-the river (Dompierre site, Veyle stream in 2010; Fretaz site, Veyle stream in 2014). Dashed line is 1:1 line.

Previous text: L 191 to 194

The two dominant patterns can be illustrated by plotting the minimum and maximum temperature values at the site "Dompierre 2010" with a difference of order of + 1.5°C between the upstream and downstream of the site, comparing to "Neuf 2016", where these values are the same for minimum daily temperatures, or even slightly negative for the maximum temperatures (Fig. 4).

Replaced by

New text: L209 to 212

The two dominant patterns of temperature differences can be further illustrated by plotting the minimum and maximum temperature values at the site. For example, at "Dompierre 2010", we observed a consistent shift of approximately + 1.5°C (both maximum and minimum daily temperature) between the upstream and downstream of the dam (Fig. 4A). In contrast, at "Fretaz 2014", this shift is dampened, and temperature values between upstream and downstream follow a 1:1 relationship (Fig. 4B).

"7. P19: Fig.3 caption: the authors state "time-series of water temperatures upstream (blue line) and downstream (red line) of the dams of Dompierre and Peroux, Veyle stream (2010 and 2015, two warm summer years, respectively + 1.1°C and 2°C, Table 2)", but when looking back in table 2, I have seen that air temperature difference from normal in 2010 is very small (+ 0.3) and NOT +1.1. The +1.1°C air temperature difference from normal is in the year 2009. Therefore, 2009 is almost four times warmer than 2010, hence one may expect the comparison between 2009 and 2015 instead of 2010 and 2015?"

Fixed

Corrected legend and site changed

Removal of "two warm summer years, respectively + 1.1°C and 2°C, Table 2" in Fig.3 caption.

"8. P19: Fig.3: Since air temperature difference from normal in 2010 is very small (+ 0.3), why the difference between upstream and downstream water temperature at Dompierre dam is very high? This cannot be due to long residence time and average surface are in absence of warm condition, so what could be the reason/s?"

Response: The low deviation from normal indicates a summer temperature close to this normal.

The figure shows that the amount of heat supplied to the stream during a "normal" summer is sufficient to vary the temperature between the upstream and downstream of the dam taking into account the long residence time (8.4 days) and the surface of the water body (10900 m²).

"9. It is insecurely to compare 2014 (cold and wet year) with 2015 (warm and dry year) for at least one site (e.g. Dompierre dam) to see the effect of air temperature."

The difference between the upstream and downstream of the dam does not appear to be solely related to air temperature, as shown in Figure 5.

Unfortunately, we have no data available for the same site for these two years.

We modify Figure 5 and the text as follows:

Previous text L 200 to 204

During the summer season, the differences in the daily mean temperatures upstream / downstream, are close or staggered during all the season. It is notable that the variability of the summer air temperature is much higher (range 17°C) than stream temperature (range 7.5°C) for these examples (Fig. 5), and that the daily water temperature is not well correlated to air temperature.

Replaced by

New text: L217 to 219

During the summer season, the upstream-downstream changes in thermal regime are not well correlated with air temperature for the same periods. For example, a simple linear regression between daily maximum air temperature and ΔTmax indicates that air temperature explains only 0.8% of the variability in upstream-downstream thermal regime shifts (Fig. 5).

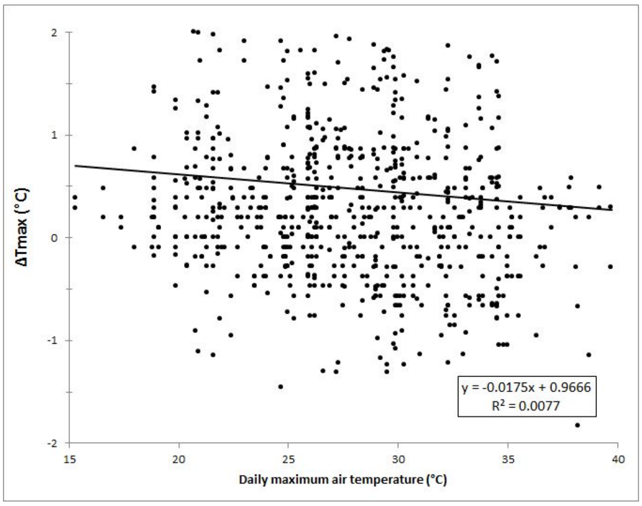


Figure 5. Relation between daily maximum air temperatures (°C), daily upstream/downstream temperature differences for all the data available for the study.

Technical corrections:

"1. P18: in Fig.2 caption, what is the word "respectively" refer to?"

Fixed

Response: New figure with site Fretaz 2014 – 2016 (Fig.2)

"respectively" is suppressed

2. P1, L18-19: "The mean increase of the minimum daily temperature was 1°C, with 85 % of the time-series showing an increase > 0.5 °C", this sentence is not clear or grammatically incorrect.

Fixed

Previous text: L18 to 19

The mean increase of the minimum daily temperature was 1°C, with 85 % of the time-series showing an increase > 0.5 °C.

Replaced by

New text: L18 to 19

Across all time series, the mean increase of T_{min} was 1°C. For 85% of time series, the increase in T_{min} was greater than 0.5°C.

"3. P2, L63-64: "surface release reservoirs", should read "surface reservoirs' release"."

Fixed

"4. P5, L148-149: "in the main flow of the channel" should read "in the main flow channel"."

Fixed

"5. P5, L151: "method Dunham et al. (2005)." should read "method introduced by Dunham et al. (2005)"."

Fixed

"6. P5, L157: the authors state that "and the median values were recorded for the period", how do you record the median? It should read "calculated" instead."
Fixed

"7. P6, L182: "Furthermore, the average temperature downstream of the structure was systematically higher or equivalent than that measured upstream" should read "Furthermore, the average temperature downstream of the structure was systematically equivalent or higher than that measured upstream"."
Fixed

"8. These are limited examples and the paper contains more. All grammatical errors should be fixed before publication."

A final revision of English was done by a native speaker

List of all relevant changes made in the manuscript,

The major changes we have made are:

- use of statistical analysis methods to strengthen the robustness of the results,
- improved consistency between points raised in the text and proposed figures,
- grammatical quality review.

Material and methods (section 2)

Temperature data analysis (Section 2.4)
This section has been completely rewritten to allow a more fluid reading, and to eliminate ambiguities: calculations of daily differences, choice of the seasonal median, and calculations of variables assessing the temperature exceeding 22° C.

Hierarchical cluster analysis (HCA) to classify the time series and results (new section 2.5)
Use of the HCA to classify time series thermal regime groups.

Ordination analysis (section 2.6 instead of PCA analysis)
Use of the ordination analysis, redundancy analysis and multiple linear regression to identify and to determine specific effect sizes of the relevant physical dam characteristics.

Results (section 3)

General temperature pattern (section 3.1) and magnitude of upstream/downstream differences (section 3.2)
We have chosen a more appropriate example (Fretaz site for summer 2014, summer 2016) to illustrate the main types of effects of weirs on water temperature (new Fig. 2 and Fig.3)

Correlation with air temperature (section 3.4)
A new linear regression between daily maximum air temperature and daily maximum water temperature differences show the weak correlation between these two variables.

Results of statistical analysis: (section 3.5 Site typology and section 3.6 Ordination results)
Comments on the result of statistical calculations that confirm the results presented in the initial manuscript by giving them numerical orders of magnitude.

Temperature pattern in intra daily variation (Section 3.7)
We have completed this section by adding the calculation result of the average daily duration exceeding 22°C upstream and downstream the dam. A new figure is added (Fig. 11) and belonging to groups A, B1 and B2 is indicated on the two figures.

Discussion (section 4)

The whole text has been improved to make it more fluent to read.

Marked-up manuscript version

All changes concerning vocabulary, grammar and typography are not marked in this document.

Only changes that have occured after the discussion phase and those that bring new elements to the manuscript are marked-up.

This concerns the main text, bibliography, tables and figures

Determinants of thermal regime influence of small dams

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Abstract.

The purpose of this study was to quantify the downstream impacts of different types of small dams on summer water temperature in lowland streams. We examined: 1) temperature regimes upstream and downstream of dams with different structural characteristics, 2) relationships between stream temperature anomalies and climatic variables, watershed area, dam height, impoundment length and surface area, and residence time, and 3) the most significant variables explaining the different thermal behaviours, and 4) the dam thermal effect considering a biological threshold of 22 °C, with a calculation of both the number of days with temperature above this threshold and the average hourly duration above this threshold.

Water temperature loggers were installed upstream and downstream of 11 dams in the Bresse Region (France) and monitored at 30 min intervals during summer (June to September) over the period 2009–2016, resulting in 13 paired water temperature time-series (two sites were monitored for two summers, allowing the opportunity to compare cold and hot summers).

At 23% of the dams, we observed increased downstream maximum daily temperatures by greater than 1°C; at the remaining dams we observed changes in maximum daily temperature between -1–1°C. Across sites, the mean downstream increase of the minimum daily temperature was 1°C, and for 85% of the sites this increase was higher than 0.5°C.

We grouped the sites into three typologies based on their responses to temperature anomaly variables (i.e., upstream-downstream differences in maximum daily temperature (ΔT_{max}), minimum daily temperature (ΔT_{min}), and daily temperature amplitude (ΔT_{amp})). From these typologies, we identified two main types of dam effects on thermal regime: 1) a downstream increase in T_{min} associated with T_{max} either unchanged or slightly reduced for impoundments of low volume (i.e., residence time shorter than 0.7 day and surface area less than 35,000 m^2), and 2) a downstream increase of both T_{min} and T_{max} on the same order of magnitude for impoundments of larger volume (i.e., residence time longer than 0.7 day and surface area greater than 35,000 m^2). These downstream temperature increases reached 2.4°C at certain structures with the potential to negatively influence the structure of aquatic communities and the functioning of the aquatic ecosystem.

Commentaire [CA1]: response comments referees #1; #2; #3 request to clarify section 3.7

precisions about thermal threshold 22 °C and potential biological effects.

Commentaire [CA2]: modified sentence (grammar and vocabulary)

Commentaire [CA3]: in response to comments from referee #3

"sentence not clear"

Commentaire [CA4]: modified sentences (grammar and vocabulary)

Overall, we show that small dams can meaningfully alter the thermal regimes of flowing waters, and that these effects can be accurately predicted with two simple measurements of dam physical attributes. This finding may have importance for modelers and managers who desire to understand and restore the fragmented thermalscapes of river networks.

Keywords: Stream, water temperature, summer thermal regime, small dam

Introduction

Temperature is a master physical variable in streams

Water temperature governs the geographical range, condition, and physiology of aquatic organisms (Allan and Castillo, 2007), with coincident influence on stream metabolism (Bernhardt et al., 2018; Brown et al., 2004). As ectotherms, aquatic organisms are very sensitive to ambient water temperature and to its alteration, especially in the vicinity of their upper thermal temperature tolerance (Brett, 1979; Coutant, 1987; McCullough et al., 2009 for Coldwater fish review; Souchon and Tissot, 2012 for European non salmonid fish review). Water temperature also governs the life history of invertebrates by affecting egg development, fecundity, dormancy, growth, maturation, voltinism, and emergence (Rader et al., 2007). Understanding the river thermal regime is therefore crucial to understanding ecological functioning (Hester et al., 2009), particularly in an era of global warming (IPCC, 2007 and 2013) and numerous ecological changes (Woodward et al., 2010).

Commentaire [CA5]: in response to comments from referee #2

reference revision

Drivers of water temperature

Major natural drivers of water temperature are 1) climate, i.e., solar radiation, air temperature, wind, precipitation, upstream water temperature, 2) topography, i.e., stream orientation, stream shading by surrounding vegetation, 3) stream bed characteristics, i.e., hyporheic exchanges, groundwater input, and 4) stream discharge (Caissie et al., 2006). These governing physical variables can be used to identify the primary environmental determinants on thermal regime for a given site (Caissie, 2006; Hannah et al., 2004 and 2008; Kelleher et al., 2012; Mohseni et al., 1998; Webb et al., 2008). During summer, which is a particularly sensitive time for aquatic organisms, the factors leading to stream warming are: 1) the input of heat fluxes from upstream (depending on discharge and water temperature), 2) direct and indirect solar radiation dominated by infrared radiation, 3) air-water conduction (convective heat flux or sensible heat), and 4) stream bed conduction. The factors leading to cooling are: 1) longwave radiation emitted by the water surface, 2) latent heat, and 3) the influx of groundwater. Importantly, the stream thermal regime may also be influenced by anthropogenic structures, with point-scale effects in the case of dams, or more spatially distributed effects in the case of riparian vegetation clearings. Hence, impacts can vary in spatial and temporal scope, depending on relative size effects of stream (headwater to river) versus human features (e.g., powerplant reservoir volume; extent of vegetation clearings). Specifically, dams can modify stream thermal regimes by storing volumes of water, and by increasing the contact surface of a stream with the atmosphere.

Commentaire [CA6]: in response to comments from referee #2

question about input of heat from upstream

Commentaire [CA7]: in response to comments from referee #2

"(…) mention (…) powerplant"

Large dam effects

The Hester and Doyle (2001) literature review reveals that the cooling effect of large dams (above 15 m high), where water is released downstream from cooler hypolimnetic layers during stratified periods, is the most described worldwide. The Serial Discontinuity Concept (SDC, Ward and Stanford, 1983) is largely based on this property of water cooling by large stratified impoundments. In the SDC framework, large dams can alter longitudinal downstream water temperature pattern for tens of km depending on dam characteristics, flow regime, river physical characteristics and downstream inputs of lakes, groundwater, and tributaries (Olden and Naiman, 2010; Ellis and Jones, 2013 for a review). In addition, Ward and Stanford (1983) suggest that dams in headwaters may not alter the natural temperature range, with the assumption that canopy shading, and springs or groundwater influx can buffer annual temperature variations. On the other hand, downstream warming may occur during summer releases from surface reservoirs (O'Keeffe et al., 1990).

Commentaire [CA8]: in response to comments from referee #2

clarification request

Commentaire [CA9]: in response to comments from referee #2

grammatical change

Commentaire [CA10]: in response to comments from referee #2

grammatical change

Small dam characteristics are not well established

Although much is known regarding thermal effects of large dams, less is known about the impacts of small dams, especially run-of-the river dams (RRD) with little or no thermal stratification and absence of surface releases (Cumming, 2004; Hayes et al., 2008). Due to the surface of the impoundment exposed to solar radiation and decreased flow velocity, RRD are expected to increase downstream water temperatures, contrary to large dams with cold hypolimnion release. These small dams have been built over many years for a variety of uses (e.g., mills, irrigation, livestock watering, storm water management, aesthetic lakes, hydroelectricity, stream stabilization). Moreover, in contrast to large dams, the number, spatial location, and characteristics of small dams are not well known or are often very imprecise depending on national databases. The International Commission of Large Dam (ICOLD, 2017) inventoried 59,071 large dams (i.e., height ≥ 15 m or height between 5–15 m impounding more than $3x10^6$ m^3) in 160 countries, but the number of smaller dams could be several million in the world. In France, the National Inventory of Dams and Weirs database maintained by the French Biodiversity Agency inventoried 96,222 hydraulics works crossing streams and rivers as of September 2017. This corresponds to a density of 0.42 obstacles per km on a basis of 230,000 km streams with permanent flow. However, the complete characteristics of these hydraulic works are not yet quantified, and it is important to note that height alone is not sufficient to discriminate their environmental effects (Poff and Hart, 2002). MBaka et al. (2015) proposed definitions for the different features, considering RRD as impoundments with height not exceeding river bank elevation, small weirs (SW) corresponding to heights around 5 m, and low-head dams (LHD) with heights between 5–15 m. In this work, we studied dams with a height less than 5 m, which we hereafter refer to as small dams.

Commentaire [CA11]: in response to comments from referee #2

reformulation request

Commentaire [CA12]: in response to comments from referee #2

vocabulary change

Commentaire [CA13]: in response to comments from referee #2

vocabulary change

Small dam thermal effects

In their review, Hester and Doyle (2011) concluded that most typical human impacts including small dams alter stream or river temperatures by 5°C or less. M'Baka et al. (2015), in their global review of downstream effect of small impoundments, found that out of 43 studies, 25% found a temperature increase effect, 2% a decrease effect and 73% no change. Dripps et al. (2013) studied the influence of three residential artificial headwater lakes (17–45 ha) on stream (discharge = 0.0024–0.0109 m^3 s^{-1}) thermal regimes. They measured a summer downstream temperature increase by as much 8.4°C and a decrease of diurnal variability by as much 3.9°C. Maxted et al.

Commentaire [CA14]: in response to comments from referee #2

reformulation request

(2005) found that impoundments (height <5 m and surface area <1 ha) in rural catchments increased downstream mean daily stream temperatures by 3.1–6.6°C during the critical summer period, and temperature differences were three times higher than those in woody catchments (0.8–2.0°C). In the region of Great Laurentian Lakes, Hayes et al. (2008) studied two types of dams with different uses. They measured a weak to null thermal effect of low-head barriers (height <0.5 m) built to prevent upstream migration of sea lamprey (*Petromyzon marinus*, L.). On the other hand, they measured a greater effect for small hydroelectric dams (downstream temperature increases up to 5.6°C). Analyzing the thermal effects of beaver dams, Weber et al. (2017) found a complex and diverse range of temperature responses. Similarly, some authors find little to no thermal influence of beaver dams (Sigourney et al., 2006), and others find extreme temperature increases up to 7°C in a headwater passing through large (5 ha) beaver dam complexes (Margolis et al., 2001).

Commentaire [CA15]: in response to comments from referee #2

grammatical and typo changes

These different studies show the extreme variability of the situations and the difficulty to identify the explaining variables governing the thermal regime, dam height alone appearing as a poor predictor. Nevertheless, several explanatory variables have been identified: stream size, stream order, watershed surface and vegetation cover, climate context, geology and alluvial aquifers, groundwater exchange, impoundment surface directly submitted to radiation, water residence time, and base flow discharge. This variability is greater in headwaters due to the weak thermal inertia and great diversity of these waterbodies, especially with regard to local shading effects from riparian canopy cover and relative importance of spring or tributary discharges. Given this potential complexity with several possible confounding factors, this study focused only on the warming effect of small dams and their impoundment.

Commentaire [CA16]: in response to comments from referee #2

vocabulary change

Commentaire [CA17]: in response to comments from referee #2

clarification request

Objective of the study

The purpose of this study was to quantify the downstream impacts of different types of small dams on summer water temperature in lowland streams. We chose to examine the summer period because this is when stream temperatures reach maximum annual values with the corresponding highest probability to reduce ecological functioning. We examined the following: 1) temperature regimes upstream and downstream of dams of different structural characteristics, 2) relationships between upstream-downstream stream temperature anomalies and climatic variables, watershed area, dam height, impoundment length and surface area, and water residence time, 3) the most significant variables explaining the different thermal behaviors, in order to account for dam diversity and functioning in future climate, and 4) the dam thermal effect considering a biological threshold of 22 °C, with a calculation of both the number of days with temperature above this threshold and the average hourly duration above this threshold.

Commentaire [CA18]: response comments referees #1; #2; #3
request to clarify section 3.7

precisions about thermal threshold 22 °C and potential biological effects.

Material and methods

Study area

Our study area is an alluvial lowland plain northeast of Lyon, France between the Jura and the north Massif Central (Fig. 1), at altitudes between 170–320 m. The main river in our study area is the Saone, which has a network of tributaries (Strahler order between 1–5) drained primarily by agricultural (67.4%; French average = 59.5 %) and urban land cover (7.2%; French average = 5.5 %) (UE-SOeS, CORINE Land Cover, 2012), characteristic of temperate European plain regions. Dam and weir density is 0.64 features per km, which is 50%

greater than the French average of 0.42 features per km for streams with permanent flow. The density of the stream network is comparable to that of the national average (0.4 km km^{-2}).

Climate in our study area is cold continental, characterized by hot, dry summers (average maximum temperature 25.8°C) and cold winters (average maximum temperature 5°C). Average annual precipitation for the region is 900 mm. This region is distinguished climatically by maximum median air temperatures in July (period 1960–1990) exceeding 25.5°C, equivalent to those of the Mediterranean region and of southwest France (Wasson et al., 2002). Regionalized climate projections on the scale of France (Peings et al., 2012) indicated that this region is susceptible to higher summer air temperatures, with increases of 2–3°C for maximum daily temperatures. For scenario A1B (mean concentration of greenhouse gases), the estimation was more than ten additional days of heat waves (as defined by WMO, 1966) by 2050.

Commentaire [CA19]: in response to comments from referee #2

language revision request

Commentaire [CA20]: in response to comments from referee #2

reference for "day of heat waves"

Sampling sites

The 11 dams in the study area are overflow structures that occupy sites of former water mills, some of which still produce energy. The study dams had heights between 1.0–2.4 m, with backwater flow lengths between 280–2,950 m, and impoundment volumes between 1,200–53,000 m^3. We calculated average residence time (in days) as the ratio of impoundment volume (m^3) to daily water flow volume (m^3 day^{-1}). The daily water flow volume is estimated from nearby hydrometric measurement sites (French database HYDRO) that are weighted by a correction coefficient during low flow periods. The correction coefficient is estimated from synoptic gauging performed by the regional hydrometric institute (Direction Regionale de l'Environnement, de l'Amenagement et du Logement, DREAL). Average residence times at our dams vary from 0.1–8.4 days (Table 1).

Commentaire [CA21]: in response to comments from referee #2

precision about the number of dams

The structures studied differ considerably in terms of the surface area of the impoundment upstream of the weir, the ratio between the volume of the impoundment to the discharge, expressed by residence time, and their position in the hydrographic network (Table 1). These variables govern: 1) the input of diurnal heat from solar radiation, 2) the loss of nocturnal heat linked to evaporation and emitted longwave radiation, and 3) the upstream permanent inflow of heat.

Temperature monitoring

The temperature sampling was performed in summer (from the end of June to the beginning of September) at different years between 2009–2016 by the local water management organization (Syndicat Mixte Veyle Vivante). For two sites, we have data for two different summers (Champagne 2009 and 2015, Fretaz 2014 and 2016) because the local water management organization was particularly interested in the thermal regimes of these rivers (Table 1).

Commentaire [CA22]: in response to comments from referee #2

clarification about single or double summers per site

We installed temperature sensors (Hobo® Pendant, Onset Computer Application; accuracy +/- 0.54°C) upstream and downstream of each dam. Upstream sensors were placed upstream of the backwater flow length of the dam, and downstream sensors were placed <100 m downstream of the dam in the main flow channel. Both upstream and downstream sensors were placed at depths between 20–50 cm.

The temperature was recorded at a time step of 30 minutes. The temperature sensors were calibrated each year using the simple "ice bucket" procedure method introduced by Dunham et al. (2005).

Commentaire [CA23]: in response to comments from referee #3

vocabulary change

The monitoring period had higher than normal air temperatures, except for 2014 (only one site), which was colder with significantly higher precipitation. Precipitation was close to the normal for most other years, except in 2009 and 2016, which were less than normal (Table 2). The summer climatic characteristics for our analysis period are compared with the normal values produced by Meteo France (1981–2010).

Commentaire [CA24]: in response to comments from referee #3

clarification requested about warmer, drier, colder and wetter years

Temperature data analysis

To characterize the influence of dams on stream thermal regimes we first calculated three variables: daily difference between upstream and downstream temperature 1) maximums (ΔT_{max}), 2) minimums (ΔT_{min}), and 3) amplitudes (ΔT_{amp}) for each site and year. With these data, we then conducted the following analyses:

1. Median summer differences in ΔT_{max}, ΔT_{min}, and ΔT_{amp} (median is used instead of mean to limit the influence of extreme values),
2. regression between daily upstream and downstream water temperature to directly assess dam thermal effects,
3. regression between daily air and water temperature over the whole recording period to assess the influence of air temperature on observed relationships

To assess the potential biological importance of dam thermal effects, we also calculated 1) the number of days that water temperatures were greater than 22°C, and 2) the mean of the maximum daily duration (in hours) where water temperature was greater than 22°C. We chose 22°C as an illustrative threshold known to be a thermal stress benchmark value for salmonids (Elliott and Elliot, 2010; Ojanguren et al., 2001).

Commentaire [CA25]: in response to comments from referee #2

clarification requested about calculation of the differences (downstream-upstream)

Commentaire [CA26]: response comments referees #1; #2; #3
request to clarify section 3.7

sentence added to explain calculations about thermal threshold 22 °C and potential biological effects.

Commentaire [CA27]: in response to comments from referee #1 and #3

clarification about mean vs. median

Site typology analysis

We observed different thermal regimes in our data and wanted to classify them. To do so, we carried out a hierarchical cluster analysis using Euclidian dissimilarities matrix according to the Ward's method (1963) using the daily dataset (n=807) of ΔT_{max} and ΔT_{min} obtained over all time-series. We forced the classification to integrate the different time-series effect by adding a complete disjunctive table differentiating each time-series to the data set. This procedure makes it possible to group the data first by time-series, then in a second step to differentiate them from each other (i.e., to differentiate site thermal regimes).

Commentaire [CA28]: in response to comments from referee #1 and #3

clarification about statistical method for group clustering : hierarchical cluster analysis (HCA)

Ordination **analysis**

To characterize the impacts of the different dams, a principal component analysis (PCA) was carried out using the software XLStat (ADDINSOFT™) on the three water temperature variables: ΔT_{max}, ΔT_{min}, and ΔT_{amp}. We used the median values for variables on each time-series in order to build an input matrix (13 occurrences for three variables).

Then a complementary redundancy analysis (RDA) with automatic stepwise variable selection procedure was used to identify the physical dam characteristics (Table 1) that significantly explain the PCA results (ter Braak 1986).

After the RDA identified the relevant physical dam characteristics, we conducted multiple linear regression between these characteristics and temperature variables to determine specific effect sizes of these characteristics on thermal regime.

Commentaire [CA29]: in response to comments from referee #1 and #2

clarification about the PCA analysis and explanatory variables

Results

General temperature patterns

Regardless of site or year, we observed consistent a pattern of summer temperature variations consisting of the following (Fig. 2):

- daily (diel) variation (minimum in early morning, maximum in late evening),
- periods of progressively increasing T_{min} and T_{max}, and
- rapid drops in temperature that interrupt these periods, and that are generally linked to precipitation events.

The periods of progressively increasing temperature vary in length, magnitude, and timing from one year to another, but the general pattern remains the same, as demonstrated by the case of the Fretaz dam , monitored in 2014 (a cold and humid year) and 2016 (a more normal year, Fig. 2; Table 2).

We observed two consistent patterns in upstream-downstream thermal regimes. In the first pattern, T_{min} is higher downstream, but T_{max} stays relatively constant (Fig. 2). We note that these upstream-downstream differences were muted in 2014, the cold and humid year (Fig. 2). This thermal pattern (i.e., where T_{min} increases downstream, but not T_{max}) is observed in 7 out of 13 cases (Table 3). In the other cases (6 out of 13; Table 3), we observed a second pattern, where both T_{min} and T_{max} are higher downstream of the structure, which results in a consistent shift between the two temperature time-series (Fig. 3, selected examples: Dompierre dam 2010 and Peroux dam 2015).

Magnitude of upstream-downstream differences

The two dominant patterns of temperature differences are further illustrated by plotting downstream versus upstream T_{min} and T_{max} values at the site. For example, at Dompierre in 2010, we observed a consistent shift of approximately +1.5°C (both T_{min} and T_{max}) between the upstream and downstream of the dam (Fig. 4A). In contrast, at Fretaz in 2014, this shift is dampened, and temperature values between upstream and downstream more closely follow a 1:1 relationship (Fig. 4B).

Reduction in the daily amplitude of downstream temperatures compared to upstream temperatures

We also observed that ΔT_{amp} was reduced for 61.5% of our time series (Table 3). This reduction in amplitude is primarily due to a truncated daily minimum downstream temperature that is on average 0.96°C higher than that of the upstream.

Dam thermal effects are not correlated with air temperature

During the summer season, the upstream-downstream changes in thermal regime are not well correlated with air temperature for the same periods. For example, a simple linear regression between daily maximum air temperature and ΔT_{max} indicates that air temperature explains only 0.8% of the variability in upstream-downstream thermal regime shifts (Fig. 5).

Site typology

The hierarchical cluster analysis applied to the daily summer temperature anomalies distinguished three groups:

Commentaire [CA30]: in response to comments from referee #1

clarification request the choice of the example showed in Figure 2
(site changed)

Commentaire [CA31]: in response to comments from referee #1

more explanation about uselfulness of Figure 3

Commentaire [CA32]: in response to comments from referee #1; #2 and #3

about section 3.2 and the link with the Figure 4
Site is changed according to the previous section 3.1 and figures 2 and 3

Commentaire [CA33]: in response to comments from referee #1 and #3

correlation with air temperature by plotting daily data across all sites

- a first group (A) characterized by:
    - median of ΔT_{max} less than 0.5°C;
    - median of ΔT_{min} between + 0.4–1.3°C;
    - median of ΔT_{amp} less than -0.2°C.
- a second group (B1) characterized by:
    - median of ΔT_{max} ranging from +0.6–1.2 °C;
    - median of ΔT_{min} between +0.3–1.1°C.
- a third group (B2) characterized by:
    - median of ΔT_{max} greater than 1.2 °C;
    - median of ΔT_{min} greater than 1.2 °C

The distribution of the differences between the minimum and maximum temperature values during summer (Fig. 6) confirms the difference between these three groups.

Ordination **analysis**

The first axis of the PCA analysis (74.1% of total inertia) is correlated to all daily temperature daily anomalies, in particular to the ΔT_{max}. The second axis (25.3%) discriminates the ΔT_{amp} with ΔT_{min} (Fig. 7). Results of the RDA show that the water residence time and the impoundment surface explain 95.2% of the PCA structure. The projection of the sites on these axes shows a strong spreading along the first axis (Fig. 7). Additionally, the dams that had two different measurement years stay within the same range on this first axis (i.e., Fretaz and Champagne) (Fig. 7).

Multiple regression analyses between the temperature variables (median values of ΔT_{min} and ΔT_{max}) and the physical characteristics obtained by the RDA (residence time and impoundment surface) resulted in high explanatory power ($R^2 \approx 0.7$). These regressions identified the significant contribution of residence time for ΔT_{min} and ΔT_{max}, whereas only surface area had a significant contribution for ΔT_{max} (Table 4).

Ecologically relevant intra-daily temperature variations

To further illustrate the different thermal regime effects from our typology analysis, we compare intra-daily temperature variations for a three-day time series in group A (small thermal effect) with group B (large thermal effect; Fig. 8):

- In the example of group A (Fig. 8A), the downstream temperature is generally warmer than the upstream temperature (observed difference of 1°C warmer) except for a few hours during the three day sample observation period. The biological benchmark of 22°C is exceeded both upstream and downstream during the day of August 20. The rest of the time, temperatures are below this threshold. From a biological point of view, the duration above the thermal threshold is short, preceded and followed by more favorable temperatures (i.e., the remission period).
- In the example of group B (Fig. 8B), the downstream temperature is systematically higher than that of the upstream, with a temperature difference varying between +0.8–2.4°C. The 22°C threshold is exceeded downstream for a cumulative 42 h over the three-day period. August 15 and 16 have downstream temperatures that rarely go below 22°C, leaving no time for thermal remission (return to a

Commentaire [CA34]: in response to comments from referee #1 and #3

results of statistical method for group clustering (HCA)

Commentaire [CA35]: in response to comments from referee #1 and #2 clarification requested about the PCA analysis

results of new Ordination analysis and the explanatory variables highlighted by the redundancy analysis temperature that is better tolerated physiologically by fish). At the same time, the upstream part of the stream is maintained at daily temperatures not exceeding this threshold.

- Additionally; differences in the diurnal temperature variation upstream and downstream of the dam shows that for group A, the maximum water temperatures are similar, whereas the minimum temperature downstream does not return to that of upstream (Fig. 8A). In group B the water temperature difference between upstream and downstream are persistent throughout the diurnal cycle (Fig. 8B).

For all sites, by studying the average daily duration with a temperature exceeding 22°C continuously, we can see (Fig. 9):

- downstream durations are always greater than or equal to that of the upstream durations, regardless of site typology,
- the largest upstream-downstream differences occur in the group B2 group,
- group A is generally not affected by an upstream-downstream increase, except for two sites which exhibit a two hour increase.

Commentaire [CA36]: response comments referees #1; #2; #3 request to clarify section 3.7

more accurate and complete results with calculation of average daily duration, with the perspective of the groups achieved by the HCA

Ecologically relevant seasonal temperature variations

We observed very similar results to our intra-daily duration analysis in our analogous study on the proportion of summer days where the maximum water temperature exceeded the threshold of 22°C. For example, group B was much more likely to exhibit downstream increases in daily threshold exceedances (Fig. 10). On the other hand, several of the group A sites had lower proportions of days where downstream daily exceedances were greater than upstream daily exceedances (i.e., Champagne 2015, Caillou 2009, Fretaz 2016).

Discussion

The number of small dams in streams is greater than the number of large dams (>15 m) by several orders of magnitude (Downing et al., 2006; Poff and Hart, 2002; Verpoorter et al., 2014). Despite this, small dam effects on thermal regimes are much less well known than those of large dams (Downing, 2010; Ecke et al., 2017; Smith et al., 2017). This therefore presents a challenge to identify and generalize the significant drivers of a realistic thermalscape (Isaak, 2017), which is essential to understanding the current ecological status of rivers and to predict with sufficient realism future changes under different climate change scenarios. In addition, summertime, with the highest temperatures, appears to be potentially the most critical period for aquatic organisms and as such requires special attention (Kemp, 2012; Zaidel, 2018).
The purpose of this study was to quantify the downstream impacts of different types of small dams on summer water temperature in lowland streams. We investigated these effects in 11 dams across five lowland streams in the Bresse region for different climate years (12 summer time series in warmer and drier years than normal and one series in a colder and wetter year 2014; Table 2). We observed clear influence of small dams on downstream thermal regime at all sites: 23% of the time series exhibited a >1°C elevation of T_{max}, and 77% of the time series exhibited T_{max} shifts between -1–1°C. Across all time series, the mean increase of T_{min} was 1°C. For 85% of time series, the increase in T_{min} was greater than 0.5°C. This increase reached 2.4°C at certain structures (Dompierre, Fig. 7).

Commentaire [CA37]: in response to comments from referee #3

sentence clarified

Our results corroborate the reviews and meta-analyses in the general trend for a small dam warming effect within a range of 0–3°C (Lessard and Hayes, 2003; Maxted et al., 2005; MBaka and Mwaniki, 2015; Ecke, 2017, 27 studies; Means, 2018, 24 sites; Zaidel, 2018, 18 sites). Occasionally, downstream warming effects reach as high as 7°C (Margolis et al., 2001; Carlisle et al., 2014), or 3–6 °C (Fraley, 1987; Lessard and Hayes, 2003, for a part of their sample; Dripps and Granger, 2013). One possible explanation is that such sites correspond to very large impoundments in comparison with low natural flows, with large areas exposed to solar radiation, which pleads for an analysis of the physical characteristics of their structures. There are also situations where the downstream temperature is lower than the upstream temperature, as we observed in one situation in our study (Moulin Neuf, Reyssouze, Fig. 7). We suggest that this phenomenon, as in the case of certain beaver dams (Majerova et al., 2015; Weber et al., 2017), occurs when the existence of a structure modifies the equilibrium conditions of the alluvial groundwater table, which under increased pressure can supply the downstream end of the structure with cooler water.

The morphology of the structures therefore appears to be of fundamental influence; impoundments with high-head dams and a small surface area would have cooler downstream temperatures, whereas impoundments with low-head dams and a large surface area would have warmer downstream temperatures (Fuller and Peckarsky, 2011, Rocky Mountains in Colorado; Means 2018, Upper Columbia River). We attempted to avoid possible temperature effects from alluvial groundwater by placing the downstream stations as close as possible to the dam (<100 m). Despite the operating precautions taken, it is possible that the site Moulin Neuf, Reyssouze, which had several secondary channels, was still influenced by groundwater inflows.

Dams in our study area also caused downstream dampening in diurnal thermal amplitudes. We observed that the daily amplitude of the downstream temperature compared to that of the upstream is reduced in 61.5% of studied cases, in the same proportion than the observations of Zaidel (2018) for 58% of the 30 structures in Massachusetts. Kemp et al. (2012) concluded also that the main influence of beaver ponds was a reduction in river temperature fluctuations. Amplitude reduction is primarily due to increased daily minimum downstream temperatures (by +0.96°C in our study). Studying 24 beaver ponds in Washington State, Means (2018) observed also that the minimum temperature downstream was 0.8°C higher compared to minimum temperature upstream.

What physical variables are important?

The effect of small dams on stream thermal regimes has yet received little attention, and there is still no consensus on which dam physical variables best predict downstream temperature patterns. Most research is focused on isolated case studies (i.e., one stream, Kornis et al., 2015; Majerova et al. 2015; Smith et al. 2017; Weber et al. 2017), and in cases where thermal measurements are secondary variables, there is often incomplete information about the physical dam characteristics (Kemp et al., 2012). Nevertheless, as early as the pioneering studies (Cook, 1940), certain dam characteristic emerged as candidate variables (e.g., exposed surface subjected to radiation and water residence time) to explain downstream shifts in thermal regime. At the same time, other commonly used dam characteristics, like dam water level and dam height, appear to be insufficient to predict a thermal effect downstream (Poff and Hart 2002). We have described precisely these different candidate metrics for the observed sites (Table 1). Our results show that the sites can be grouped based on different behaviors for ΔT_{min}, ΔT_{max}, and ΔT_{amp}.

We observed two distinct behaviors in upstream-downstream thermal regime shifts in the 13 time series (Fig. 7). The first behavior, which we call group A, is characterised by an impoundment effect that reduced the downstream amplitude of the daily temperature and increased the minimum temperature (the median of ΔT_{max} was limited to 0.3°C at most). The second behaviour, which we call group B (split into subgroups B1 and B2), is characterised by an increase of both daily minimum and maximum temperatures with a corresponding change in amplitude.

We found that residence time and surface area were the principal explanatory variables of upstream-downstream temperature differences. Indeed, redundancy analysis indicated the primary differences between our site typologies were explained by these variable. For example, Group A is characterised by a residence time less than 0.7 days and an impoundment surface area smaller than 35,500 m², whereas group B is characterised either by a long residence time (e.g., Dompierre dam with residence time = 8.4 days and surface area = 10,900 m²), or by a surface area larger than 35,000 m² with a shorter residence time (e.g., 0.2 days). These physical differences are directly linked to the observed differences in thermal regime shifts. In group A, we suggest that long residence times reduce cooling effects; the nocturnal input (i.e., the cooling effect) becomes negligible in the general heat exchange balance. Group B also exhibits this reduced cooling effect, but exhibits an additional heating effect linked to increased solar radiation from larger impoundment surface areas. Multiple regression (Table 4) clarified the direction and magnitude of these effects and indicated that ΔT_{max} is best explained by both residence time and surface area (group B effects), whereas ΔT_{min} is best explained only with residence time (group A effects).

Commentaire [CA38]: in response to comments from referee #2

discussion about most important drivers of temperature regime (surface and time residence) confirmed with multiple analysis regression

To summarize, we observed two primary thermal regime effects of small dams. The first group is characterised by a downstream impoundment effect that increases T_{min} and reduces T_{amp}, but does not significantly change ΔT_{max} (-0.6–0.3°C). The second group shows downstream increases in both T_{min} and T_{max}, with the little change to ΔT_{amp} (-0.3–0.4°C). For the second group, the change in thermal regime is much clearer, with overall median ΔT differences approximately +0.6–2.4°C. This clear break in the thermal regime between the upstream and downstream ecosystems was most notable during very hot periods. A larger sample of this second group type (group B) would permit a more quantitative characterisation of the dams (surface area, residence time, morphometry of the impoundment), and a possible indication of threshold values above which thermal regime shifts may emerge. One potential path forward is to create regionalized statistical models based on geographical data and dam databases, analogous to the way that ecological risk analyses are constructed (Allan et al. 2012; Van Looy et al., 2015). However, we realize that our dataset is provincial in temporal and regional extent, potentially limiting extrapolation of results to other areas with different groundwater and climatic influences.

Commentaire [CA39]: in response to comments from referee #2

complements about notion of the possibility of regionalization

In summary, although mean air temperature and dam height were poor predictors of daily summer temperature anomalies, residence time and surface area could clearly explain the differences in thermal regime induced by small RRDs. These variables are candidate to generalize results to other regions. However, this generalization necessitates more precise information than most dam descriptions in the vast majority of available public databases.

Analysis of the thermal regime from an ecological perspective

The influence of dams on downstream processes varies throughout time. For example, analyses of hydrological regimes shifts should simultaneously consider intensity, duration, frequency, seasonality, and rhythm of change

(Poff et al. 1997). Ecological stresses from thermal regime shifts should account for duration and amplitude of exposure to high temperatures and the recovery from stress during periods of lower temperature (Bevelhimer and Bennet 2000). In this work, we examined both seasonal and intra-daily thermal effects of dams using an ecological perspective.

Shifts in downstream ecological pattern and process are dependent on the magnitude of thermal change from upstream to downstream. For fish, the literature suggests that downstream increases of approximately 2°C (Hay et al. 2006) or 3°C (Verneaux 1977) can result in significant community shifts for many biotypologies. In this perspective, the majority of our sites belonging to groups A and B1 present a low risk with regard to the potential change in fish communities as they exhibited a moderate absolute downstream temperature increase between 0–1°C. However, the higher downstream increases of our group B2 (between 1.2–2.4 °C; Fig. 7) are likely to influence the composition of fish communities. This is especially true for certain species close to the threshold of their thermal comfort, which often are the same species already under conservation efforts. Such temperature increases can also amplify the general metabolism in the stream, possibly leading to the unwanted proliferation of algae, a less stable oxygen cycle, and stronger effects of toxic compounds (Heugens et al., 2001 in Souchon and Tissot, 2012).

On the scale of several days, it is important not to underestimate the influence of cumulative exposure to temperatures close to the maximum tolerable temperatures (Tissot & Souchon, 2010), for which the incidence of temperature variations has an impact on biological communities (Lessard and Hayes 2003; in 9 streams in Michigan, USA). In this study, we used a temperature of 22°C as an illustrative threshold known to be a thermal stress benchmark value for salmonids, especially for brown trout, *Salmo trutta* (Elliott and Elliot, 2010: upper critical incipient lethal temperature for juveniles, which is considered a very sensitive stage; Ojanguren et al., 2001: general activity of brown trout juvenile). In addition, this threshold is known to be important for the life cycle of aquatic invertebrates (Ward, 1976; Brittain and Salveit, 1989). By looking at the fraction of time that daily maximum temperatures exceeded this threshold, we found that the majority of sites in our study area, regardless of dam structure, are unfavorable in summer for species sensitive to this threshold. Importantly however, we found that for sites that are more favorable (e.g., Dompierre or Thuets, left side of figure), the presence of small dams induces a clear shift towards an elevated percentage of number of days above the temperature threshold, from less than 20% upstream to more than 40% downstream.

Commentaire [CA40]: response comments referees #2; #3
request to clarify section 3.7

sentence added in discussion justifying the choice of the threshold of 22°C

On the daily scale, it is necessary to not only consider the maximum tolerable temperature, but also its duration of influence, as the temperature of nocturnal remission and its duration must be sufficient for organisms to repair their heat stress proteins. For example, Schrank et al. (2003) and Johnstone and Rahel (2003) suggested that daily minima provide a respite from elevated daily maximum temperatures if there is sufficient time to repair protein damage (McCullough et al., 2009). We explored this issue by calculating the average hourly duration of temperatures above the 22°C threshold at each site. We found that small dams more than doubled this daily threshold exceedance duration on average (2.2±0.7, mean±se), and at one site (Dompierre) increased this duration by an order of magnitude (Fig. 9). To further illustrate this effect and the differences among site typology, we presented two examples of daily temperature regime during 3 days in August at sites Caillou (type A) and Revel (type B2) (Fig. 8). At Caillou upstream (Fig. 8A), the diel natural variation offers remission temperature for brown trout, with several hours at temperature <20°C each day. The situation is less favorable downstream with no sufficient time below this temperature. At Revel (Fig. 8B), the observed thermal daily pattern is similar, but the structure associated with group B2 exacerbated the warming of water, leading to fewer remission periods.

Without appropriate biological data, it is difficult to know how minimum and maximum water temperatures affect acclimation, performance, and stress (McCullough et al., 2009). Exploring this question may be especially relevant because small dams clearly alter stream thermal regimes. Moreover, future global warming could exacerbate these effects as it is expected to increase daily minimum temperatures more than daily maximum temperatures, with a corresponding decrease in the diurnal temperature range and an increase in mean daily temperature (Easterling et al., 1997; Vose et al., 2005).

Diversity of situations

We measured variable warming effects according to a diversity of situations present within a relatively modest geographical area (2,025 km²), subjected to the same climate. We suggest that based on the downstream warming effects we observed, and because of the high density of dams in the landscape (0.64 per km), the thermal landscape of this region is potentially fragmented. In other words, we expect that small dams in this region create a discontinuous distribution of stream thermal regimes throughout the river network. However, we acknowledge that to have a realistic thermal landscape, where ecological dynamics can be predicted in the long term, it is necessary to account for additional features than we have done here. For example, it is important to consider effects of unshaded versus shaded river reaches, which influence radiation warming effects, and the spatial distributions of groundwater inflows, which provide cooling effects. We note that regardless of application, using air temperature to predict water temperature at the daily scale should be used with caution (Fig. 5).

Commentaire [CA41]: response comments referees #2

clarification about "fragmented thermal lanscape "

Our work highlights physical dam characteristics that could be useful in a large-scale heat risk analysis, or in modeling scenarios aiming to account for changes in thermal regimes. For example, a simple model using only small dam residence time and surface area may be able to predict with sufficient accuracy thermal regime change at the regional scale. Moreover, the results presented here could also provide essential guidance to environmental protection authorities in their prioritization of rivers to be protected or restored, especially for those rivers that require greater thermal resilience.

Commentaire [CA42]: response comments referees #2

clarification about "spatial generalization elements"

Given the complexity and high variability of the river systems encountered in this study (Strahler orders spanning 3–5), it seems essential to us (and see Isaak et al. 2017, 2018; Steel et al. 2017; Dzara et al. 2018) to continue to conduct and expand well targeted stream temperature monitoring. This type of monitoring is requisite before being able to model stream temperature with sufficient spatial and temporal resolution. Modeling these systems accurately is a major challenge, because these aquatic spaces will undergo major thermal and hydrological alteration with climate change, where tipping points in biotic distributions are likely to occur.

Conclusion

We quantified the impact of small dams on the temperature of streams, and identified major drivers of these impacts, adding to a current paucity of information on this topic in the scientific literature. Our unique interannual, cross-site analysis of summer stream temperatures showed that contemporary dam impacts are already ecologically significant to downstream reaches, and these effects may be exacerbated by expected warming in the study area (see IPCC scenarios of global change for Val de Saone). We identified the primary drivers of the temperature regime responses as residence time and the impoundment surface area. The influence of these drivers in other landscapes needs to be confirmed by other data sets that are not yet well developed or accessible.

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Commentaire [CA45]: added reference for stiscal method used in the new version

Commentaire [CA46]: reference added in response to referee #2 comment about transferability of results

Commentaire [CA47]: reference added for "day of heat wave" definition

Table 1. Physical characteristics of dams of the river and impoundments.

Stream name	Dam name	Watershed (km^2)	Distance to the source (m)	Strahler order	Dam height (m)	Length (impoundment) (m)	Surface (m^2)	Volume (m^3)	Residence time (days)	Year of sampling
Veyle	Dompierre	32	11167	3	1.2	500	10900	10500	8.4	2010
Veyle	Fretaz	78	22859	4	1.5	535	3500	2600	0.1 0.1	2014 2016
Veyle	Montfalconnet	125	38146	4	2.4	1200	14400	20160	0.5	2015
Veyle	Peroux	500	50886	5	2.4	2150	39200	53000	0.6	2015
Veyle	Thuets	350	43912	5	1.9	2950	57000	51000	0.6	2016
Veyle	Thurignat	640	60537	5	1.4	1500	34600	31165	0.2	2016
Vieux Jonc	Cailloux	67	11680	3	1.0	280	2340	1200	0.7	2009
Renon	Champagne	122	42368	3	1.5	405	2840	2130	0.7 0.5	2009 2015
Reyssouze	Moulin Neuf	209	48217	3	1.0	1800	35520	12420	0.3	2016
Reyssouze	Peloux	145	34842	3	1.5	1700	49930	17340	0.5	2016
Solnan	Revel	88	15431	3	1.8	3200	31140	28370	2.6	2016

Table 2. Climatic characteristics during years of stream temperature monitoring (2009-2016).

Year (July–August)	Air temperature anomaly (°C)	Precipitation anomaly (%)
2009	+1.1	70
2010	+0.3	50
2014	**-1.8**	**165**
2015	+2	50
2016	+0.3	70

Source: https://www.infoclimat.fr station Lyon Bron normal 1991– 2015

Table 3. Median values of differences between daily maximum (ΔT_{max}) and minimum temperatures (ΔT_{min}) and the diurnal ranges (ΔT_{amp}) between upstream and downstream of the run-of-the-river dams. Daily maximum upstream temperature ($T_{max, up}$) is indicated to show the limited influence of the initial temperature on upstream/downstream differences.

Group	run-of-the river dam (stream)	ΔT_{max} (°C)	ΔT_{min} (°C)	ΔT_{amp} (°C)	$T_{max, up}$ (°C)
A	Moulin Neuf (Reyssouze) 2016	-0.6	0.5	-1.0	24.0
	Cailloux (Vieux Jonc) 2009	-0.4	0.9	-1.3	18.1
	Fretaz (Veyle) 2014	0.3	0.7	-0.3	19.4
	Fretaz (Veyle) 2016	-0.3	1.2	-1.4	21.2
	Champagne (Renon) 2015	0.1	0.9	-0.9	20.2
	Montfalconnet (Veyle) 2015	-0.1	1.0	-0.8	19.8
	Champagne (Renon) 2009	-0.1	0.7	-1.0	19.3
B1	Thurignat (Veyle) 2016	0.6	0.3	0.4	23.2
	Thuets (Veyle) 2016	0.7	0.8	0.0	21.0
	Peloux (Reyssouze) 2016	0.8	0.5	0.1	23.9
B2	Peroux (Veyle) 2015	1.1	1.1	-0.3	21.3
	Revel (Solnan) 2016	2.1	1.7	0.1	21.9
	Dompierre (Veyle) 2010	2.4	2.2	0.4	18.2

Table 4. Results of multiple linear regressions performed on the 2 indicators ΔT_{min}, ΔT_{max} using the dam physical characteristics surface area and residence time. Significant p-value are in bold.

Dependent variable	Independent variable physical characteristics	standardized coefficient	p-value	R^2
ΔT_{max}	surface area	0.39	**0.041**	0.72
	residence time	0.80	**0.001**	
ΔT_{min}	surface area	-0.13	0.48	0.68
	residence time	0.80	**0.001**	

Commentaire [CA48]: in response to comments from referee #1 and #2

clarification about the explanatory variables added results table

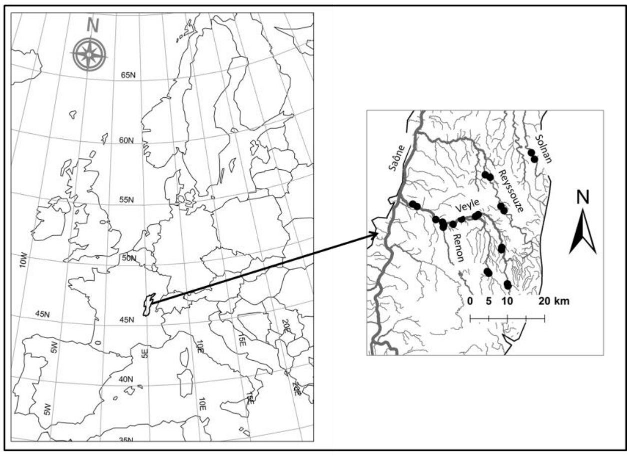


Figure 1. Location of the study area, the Bresse Region – The black points on the right map indicate temperature recording sites.

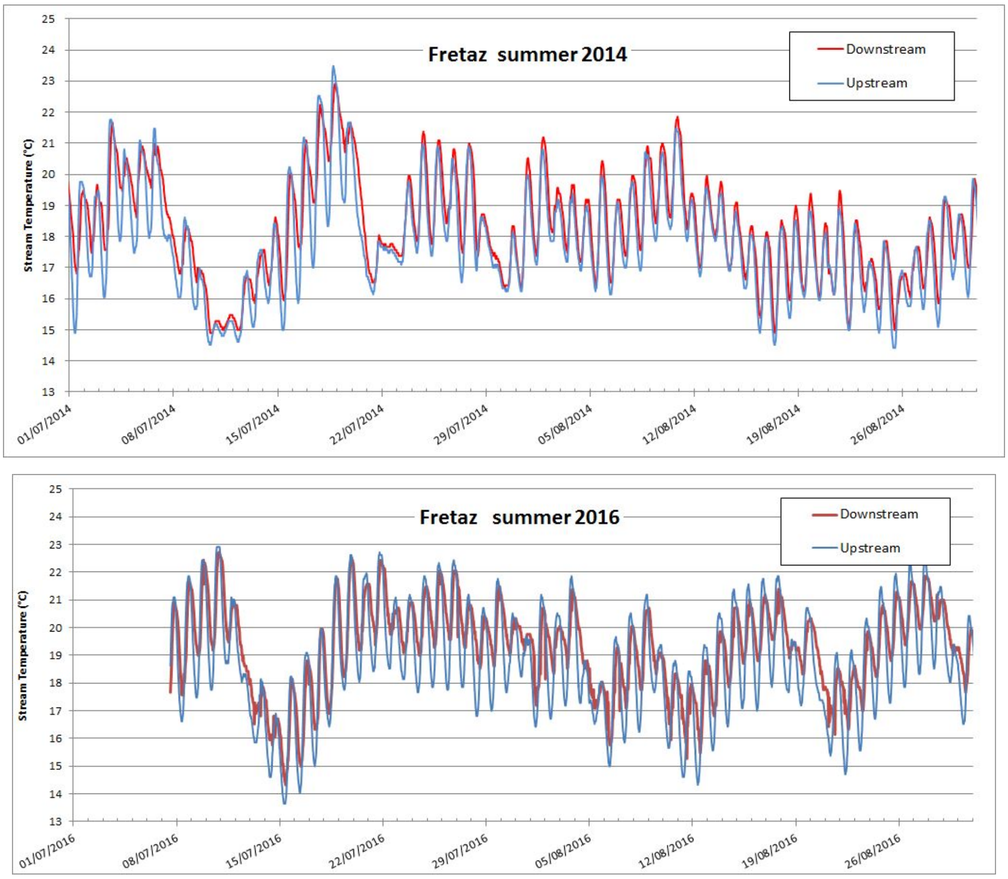


Figure 2. Time-series of water temperature (°C) upstream (blue) and downstream (red) of the dam Fretaz, Veyle stream, respectively in years 2014 and 2016.

Commentaire [CA49]: site changed to have non ambiguous demonstrative example with two different climate season see section 3.1

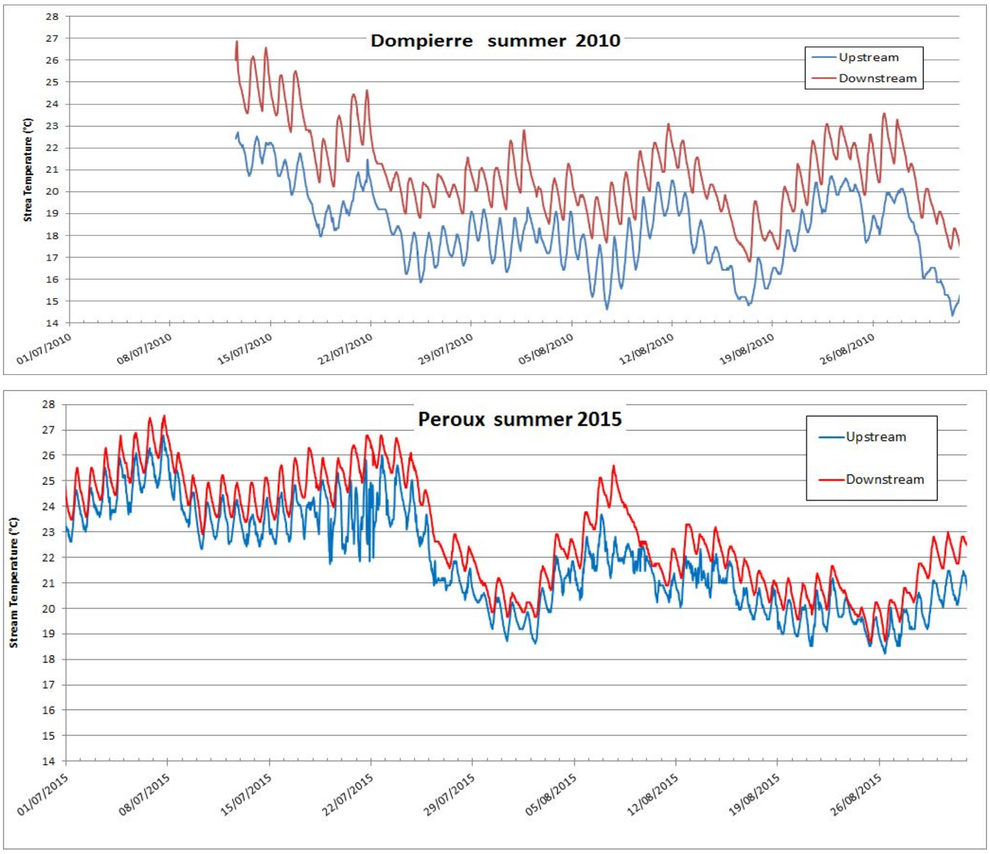


Figure 3. Time-series of water temperatures upstream (blue line) and downstream (red line) of the dams of Dompierre and Peroux, Veyle stream (2010 and 2015, two warm summer years, respectively + 1.1 °C and 2° C, Table 2).

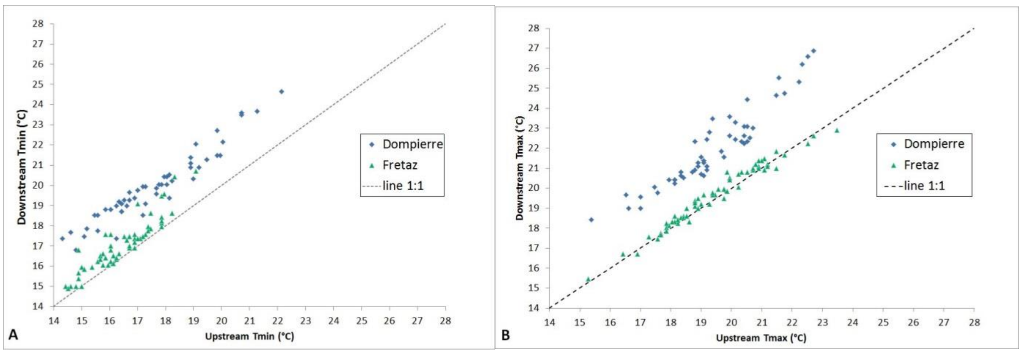


Figure 4. Minimum (A) and maximum (B) daily temperatures upstream and downstream of the dams-of-the river (Dompierre site, Veyle stream in 2010; Fretaz site, Veyle stream in 2014). Dashed line is 1:1 line.

Commentaire [CA50]: site changed according with the new figure 2

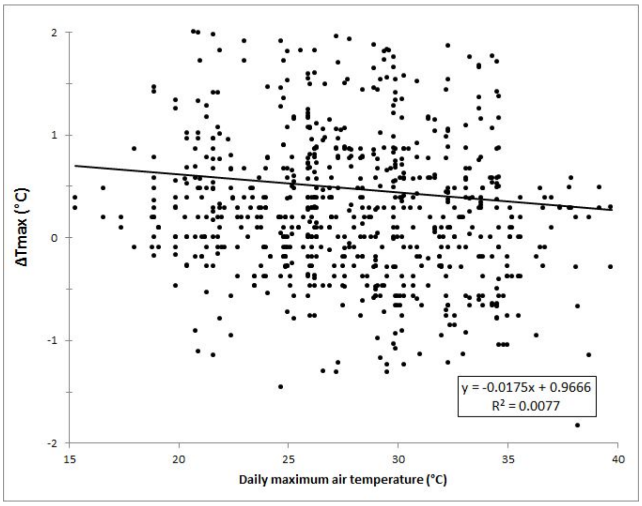


Figure 5. Relation between daily maximum air temperatures (°C), daily upstream/downstream temperature differences for all the data available for the study.

Commentaire [CA51]: figure changed according to in response to comments from referee #1 and #3

correlation with air temperature by plotting daily data across all sites

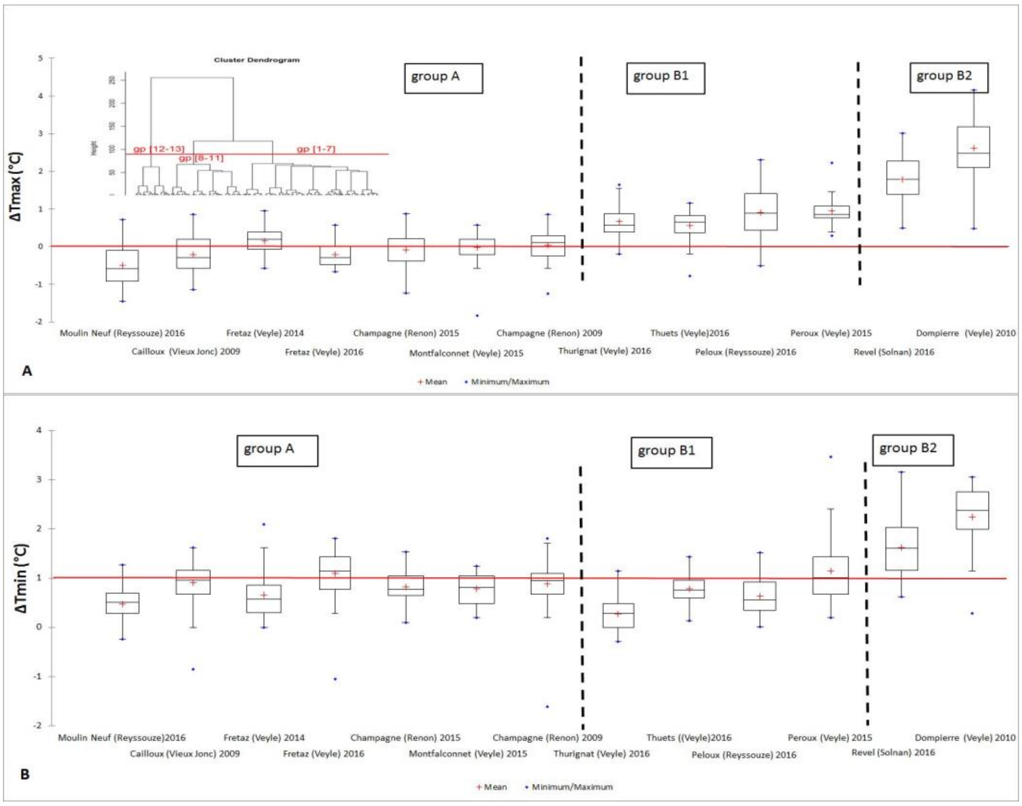


Figure 6. Box-plot distribution (25% - 75 %) of upstream/downstream differences of daily maximum and minimum temperatures for all the time series studied. (Red lines: 0°C for daily maximum temperature and 1°C for daily minimum temperature are drawn to help reading). The vertical lines drawn in bold are the limits to the three classes of results of the hierarchical cluster analysis. Dendrogram CAH's result is shown at the top left of the figure.

Commentaire [CA52]: change of the figure according to results of HCA (section 3.5)

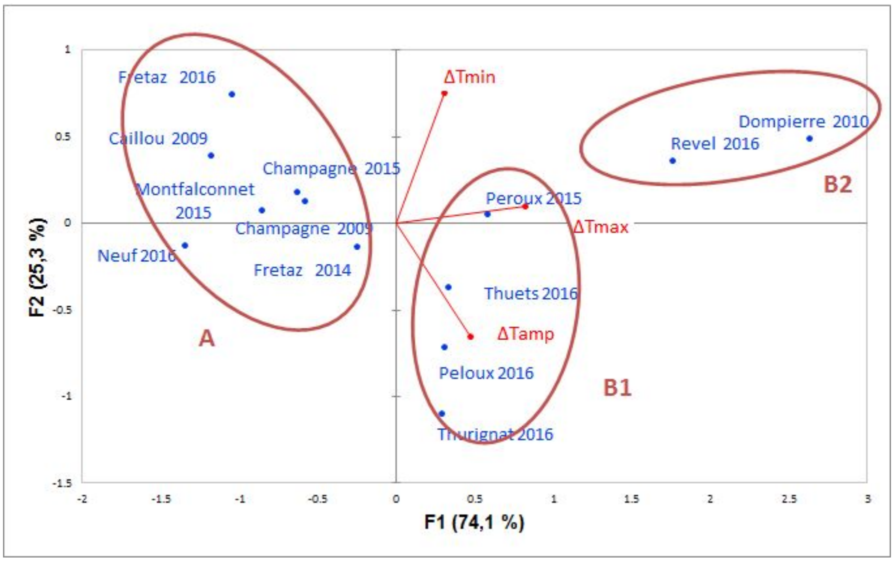
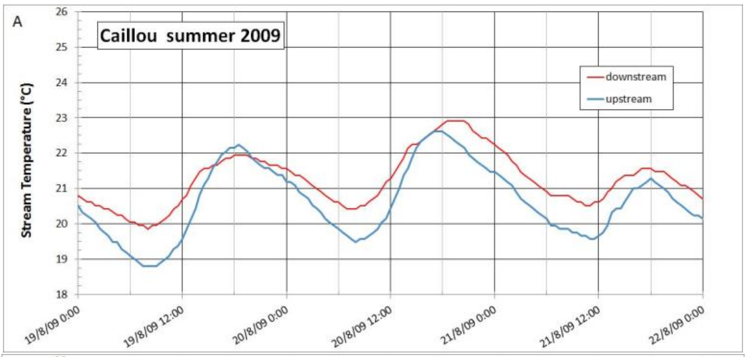


Figure 7. PCA analysis. Scatterplot of time-series. Ellipses are drawn to visualize the groups obtained with the hierarchical cluster analysis

Commentaire [CA53]: change according to new results of ordination analysis (section 3.6)



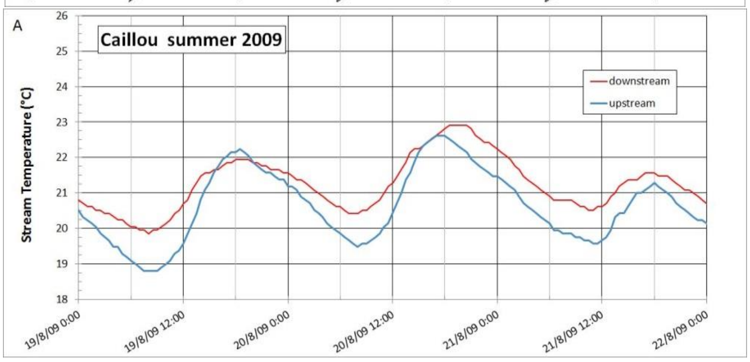


Figure 8. Time-series of water temperatures upstream (blue line) and downstream (red line) of the dams of A/ Caillou (Vieux Jonc stream) and B/ Revel (Solnan stream) focused on three days during August.

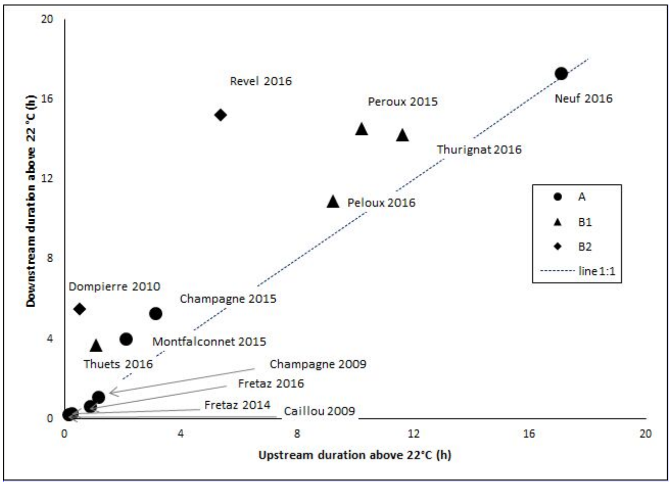


Figure 9 Mean of the daily maximum duration with T above 22 °C , upstream and downstream each site monitored in the study. A (circles), B1 (triangles), B2 (rhombus) are the groups of sites resulting from HCA.

Commentaire [CA54]: change according to results of HCA (site typology)

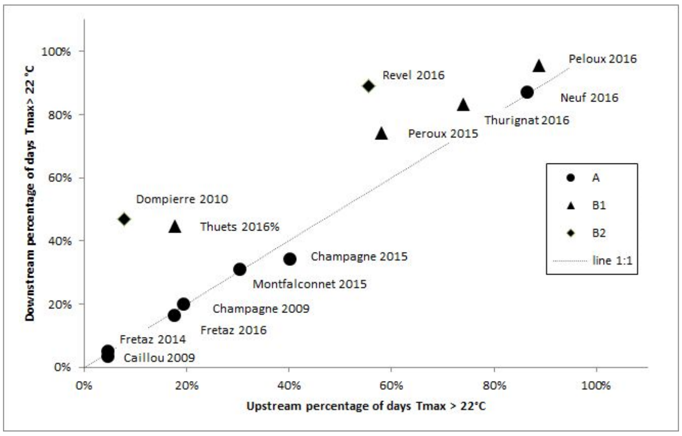


Figure 10. Percentage of number of summer days with a diurnal maximum temperature of water greater than 22 °C, upstream and downstream each site monitored in the study. A (circles), B1 (triangles), B2 (rhombus) are the groups of sites resulting from HCA.

Commentaire [CA55]: new figure added to highlight links between site typology and biological potential effects.