Small dams alter thermal regimes of downstream water

André Chandesris [1], Kris Van Looy [2], Jacob S. Diamond[1], Yves Souchon [1]

[1] River Hydro-Ecology Lab, National Research Institute of Science and Technology for Environment and Agriculture, UR Riverly, Lyon, France

[2] OVAM, Stationsstraat 110, 2800 Mechelen, Belgium

Correspondence to: A. Chandesris (andre.chandesris@irstea.fr)

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, 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 -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 hierarchically clustered the sites based on three temperature anomaly variables: upstream-downstream differences in 1) maximum daily temperature (ΔT_{max}), 2) minimum daily temperature (ΔT_{min}), and 3) daily temperature amplitude (ΔT_{amp}). The cluster analysis 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 impair the structure of aquatic communities and the functioning of the aquatic ecosystem.

Overall, we show that small dams can meaningfully alter the thermal regimes of flowing waters, and that these that these effects can be explained with sufficient accuracy (R2=0.7) with two simple measurements of small 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, impoundment, weir, run-of-river dam

1 Introduction

1.1 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). For example, as ectotherms, aquatic organisms are very sensitive to ambient water temperature and to its alteration, especially near 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).

1.2 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 altering heat storage volumes, and by increasing the contact surface of a stream with the atmosphere.

1.3 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. This view may be incomplete however, as downstream warming may occur during summer releases from small surface reservoirs (O'Keeffe et al., 1990).

1.4 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 because their spatial distribution and physical characteristics are not well established. This is especially true for 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 increased 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, and 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 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 alone, 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 5–15 m. In this work, we studied dams with a height less than 5 m, which we hereafter refer to as small dams.

1.5 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. (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).

These studies illustrate the large variability in the downstream responses to small dams, and the difficulty to identify the explaining variables governing these responses, with dam height alone a poor predictor. Nevertheless, several explanatory variables are clearly relevant, including 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. Variability in downstream responses appears to be 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.

1.6 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 characteristics, and dam hydraulic geometry, 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.

2 Methods

2.1 Study area

Our study area is an alluvial lowland plain northeast of Lyon, France between the Jura and the north Massif Central mountain ranges (Fig. 1), at altitudes 170–320 m. The main river in our study area is the Saone, which has a network of tributaries (Strahler order 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.

2.2 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 1.0–2.4 m, with backwater flow lengths 280–2,950 m, and impoundment volumes 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 d^{-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).

The structures studied differ considerably in impoundment surface area, 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.

2.3 Temperature monitoring

The temperature sampling was performed in summer (from the end of June to the beginning of September) at different years from 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).

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 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).

The monitoring period had higher than normal air temperatures, except for 2014 (only one site), which was colder with significantly higher precipitation. Precipitation was normal throughout the study period, 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).

2.4 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 maximum 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).

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).

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: 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.

3 Results

3.1 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).

3.2 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).

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.

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.

3.3 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} + 0.4–1.3°C;
  - median of ΔT_{amp} less than -0.2°C.
- a second group (B1) characterized by:
  - median of ΔT_{max} +0.6–1.2 °C;
  - median of ΔT_{min} +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 hierarchical cluster analysis differentiates the B2 group primarily from the B1 and A groups (Fig. 6). We propose to retain the major distinction between group A and group B, because it is based on a temperature increase between upstream and downstream, only for T_{min} (group A), but for T_{min} and T_{max} (group B), which is an important threshold for the physiology of aquatic organisms. The distribution of the differences between the minimum and maximum temperature values during summer (Fig. 5) confirms the difference among these three groups.

3.4 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. 6). 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. 6). Additionally, the dams that had two different measurement years stay within the same range on this first axis (i.e., Fretaz and Champagne) (Fig. 6).

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).

3.5 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. 7):

- In the example of group A (Fig. 7A), the downstream thermal warming effect is limited to the nighttime (T_{min}) period (observed difference of 1°C warmer). Additionally, although the biological benchmark of 22°C is exceeded both upstream and downstream during the day of August 20,the duration above the thermal threshold is short, preceded and followed by more favorable temperatures (i.e., the remission period).
- In contrast, in group B (Fig. 7B), the downstream temperature is systematically higher than that of the upstream, with a temperature difference varying +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.

These differences between the downstream responses in diurnal temperature variation hold throughout the time series. In other words, group A has a consistent response of no change in downstream maximum water temperatures, coupled to a consistent increase in downstream minimum temperature (e.g., Fig. 7A). Group B differs in that the downstream maximum temperatures are also increased (e.g., Fig. 7B).

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.

3.6 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. 9). 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).

4 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 -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. 6).

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. 6). 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.

4.1 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. 6). The first behaviour, 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 among our site typologies were explained by these variables. For example, Group A is characterised by a short residence time (less than 0.7 days) and a small impoundment surface area (less than 35,500 m²), whereas group B is characterised either by a large surface area (greater than 35,000 m²) with a short residence time (e.g., 0.2 days; group B1), or by long residence times (e.g., 8.4 days; group B2,). These physical differences are directly linked to the observed differences in thermal regime shifts. In group B2, 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. However, for group B1 dams with short residence time, but large surface areas, increased energy supply by solar radiation on the larger surface may overwhelm any potential cooling effects. 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).

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.

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.

4.2 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 0–1°C. However, the higher downstream increases of our group B2 (1.2–2.4 °C; Fig. 6) 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.

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. 7). At Caillou upstream (Fig. 7A), 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. 7B), 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).

4.3 Diversity of situations

We measured variable warming effects according to a diversity of situations present within a relatively modest geographical area (2,025 km^2), 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).

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 diagnose 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.

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.

5 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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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

[†]2014 is bold to highlight the relatively large climate anomaly in this year

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**	

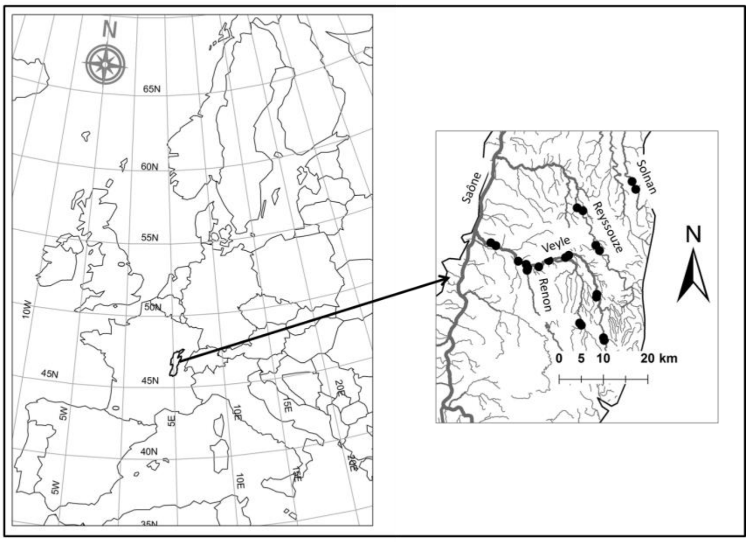


Figure 1. Location of the study area, the Bresse Region – The black points on the right map indicate temperature recording sites.

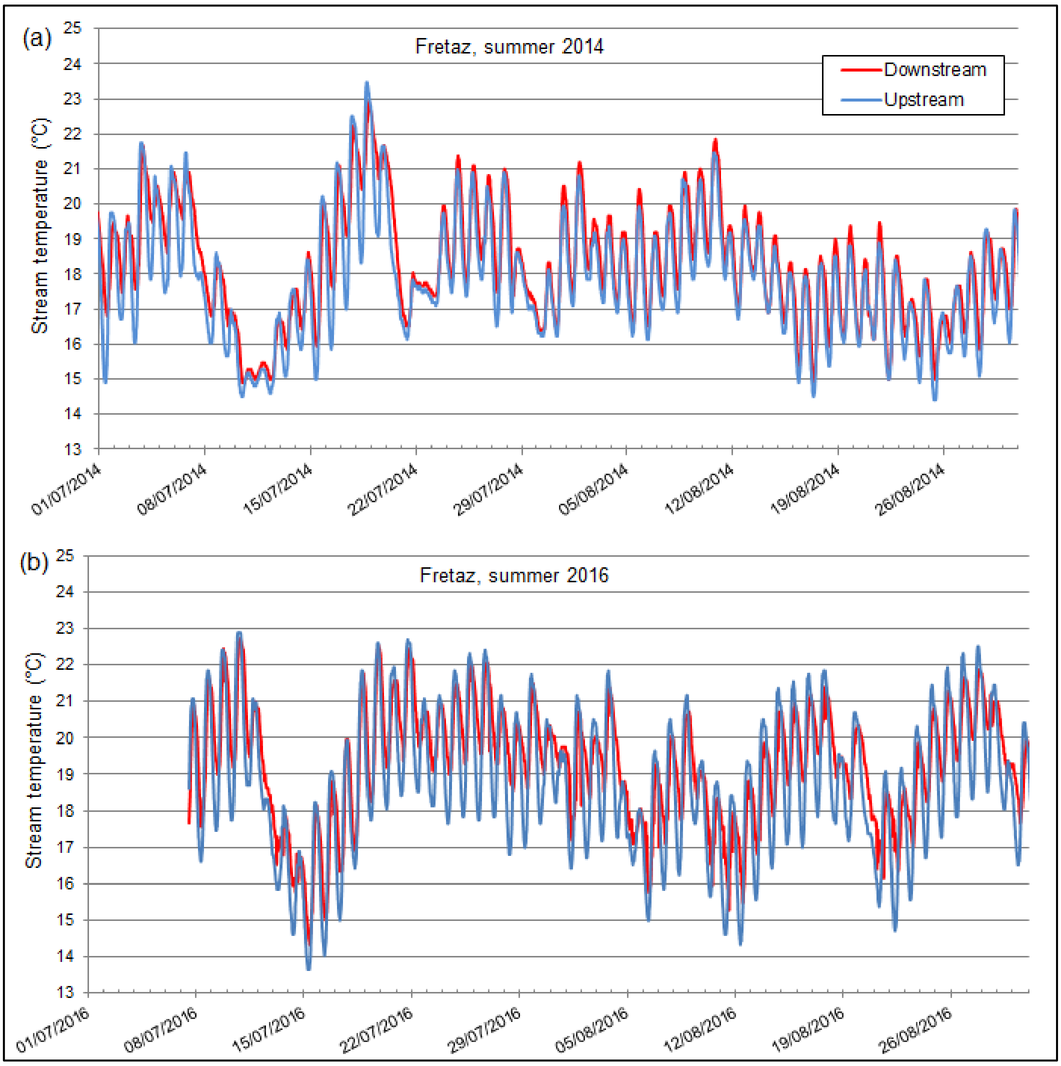


Figure 2. Time-series of water temperature (°C) upstream (blue) and downstream (red) of the dam Fretaz, Veyle stream, respectively in years 2014 (a) and 2016 (b). These example sites are illustrative of the group A typology, where T_{min} is increased downstream, but not T_{max}.

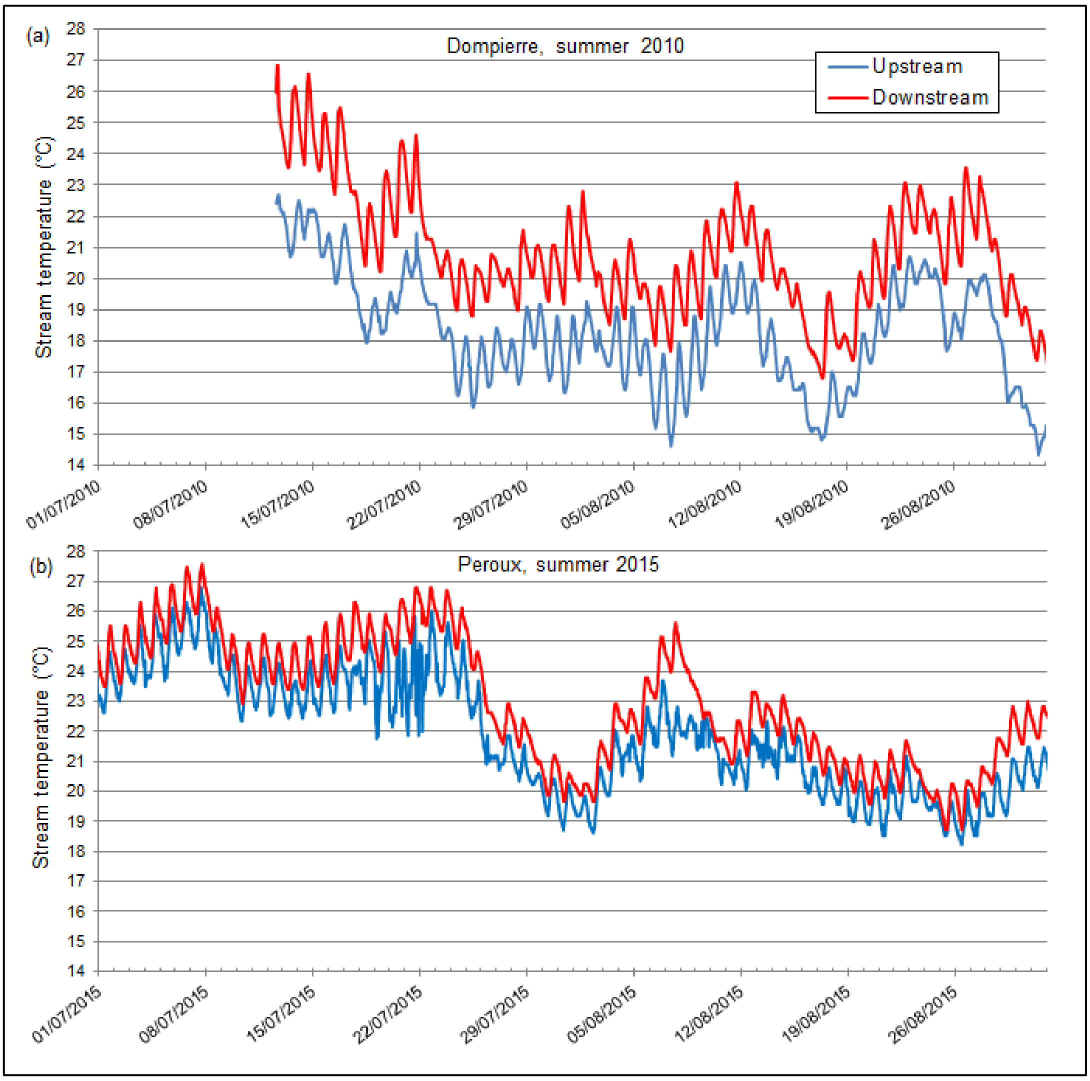


Figure 3. Time-series of water temperatures upstream (blue line) and downstream (red line) of the dams of Dompierre (a) and Peroux, Veyle stream (b) (2010 and 2015, two warm summer years, respectively + 1.1 °C and 2° C, Table 2). These example sites are illustrative of the group B typology, where both T_{min} and T_{max} are increased downstream.

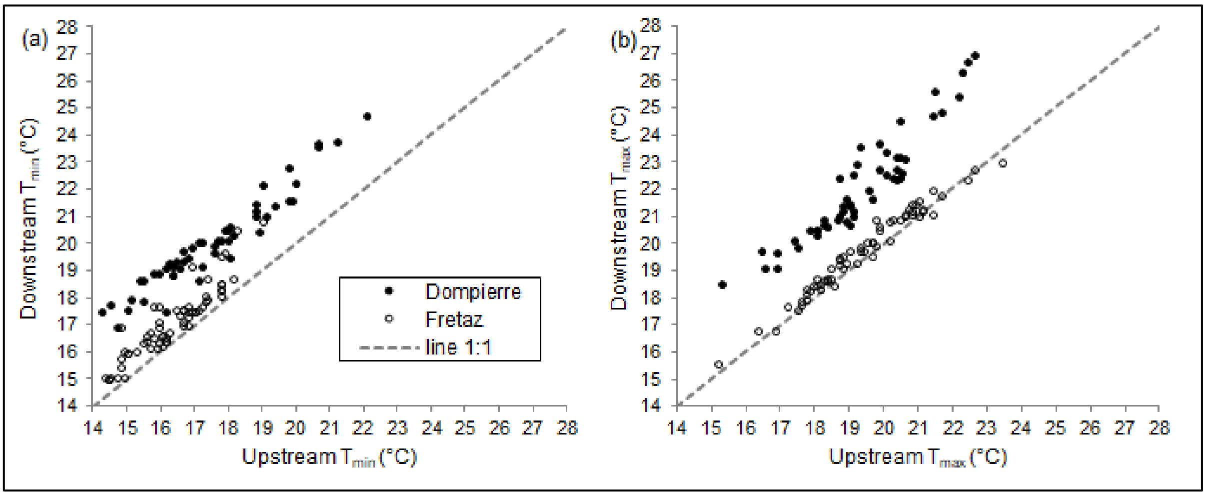


Figure 4. Minimum (a) and maximum (b) daily temperatures upstream and downstream of the dams-of-the river (Dompierre site, Veyle stream in 2010; Fretaz site, Veyle stream in 2014). Dashed line is 1:1 line.

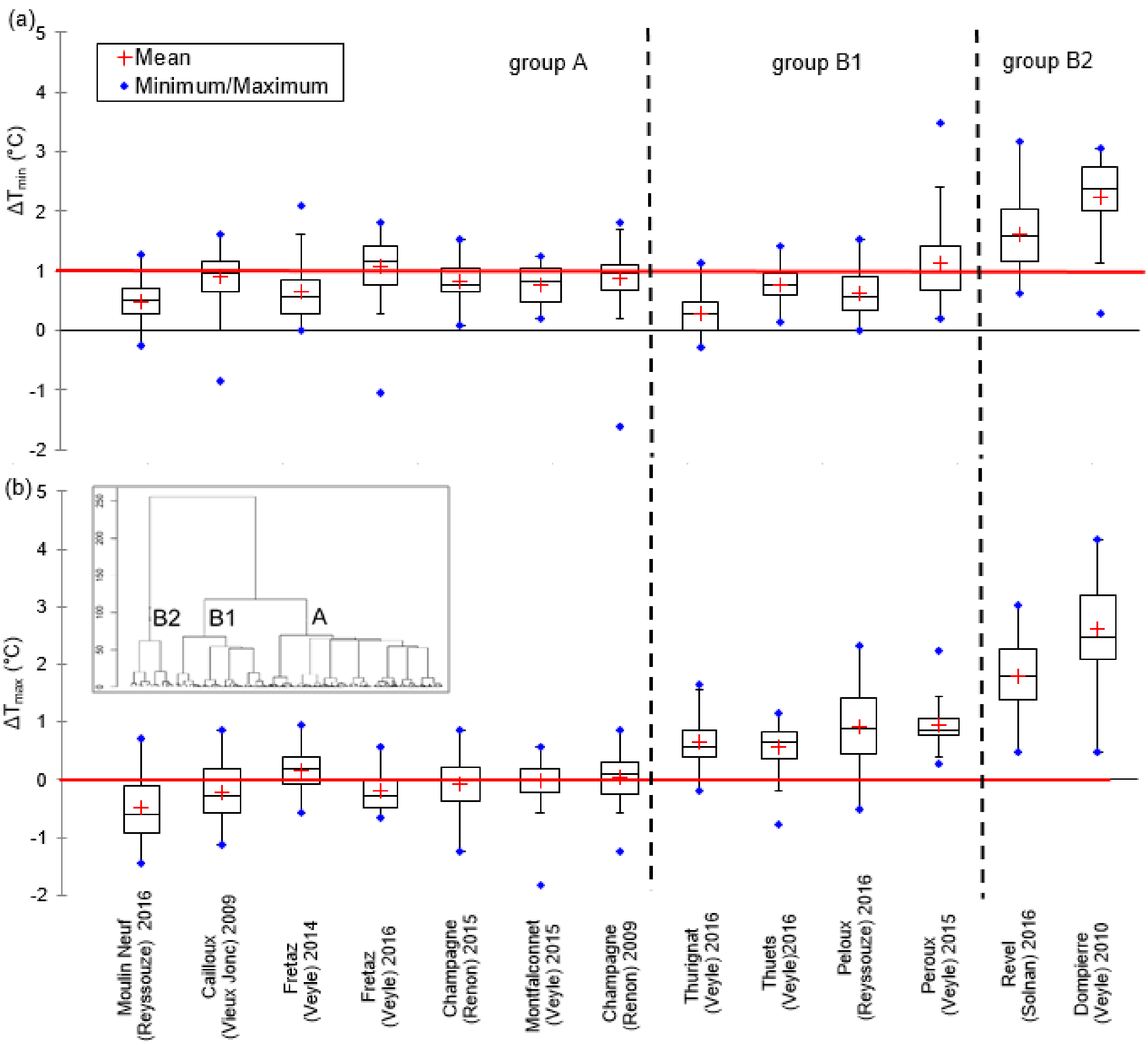


Figure 5. Box-plot distribution (25–75%) of upstream-downstream differences of daily minimum (a) and maximum (b) temperatures for all the time series studied. (Red lines: 0°C for ΔT_{max} and 1°C for ΔT_{min} are drawn to help distinguish typologies). The vertical dashed lines drawn in bold are the limits to the three typologies based on the hierarchical cluster analysis. Dendrogram hierarchical cluster analysis is shown as an inset.

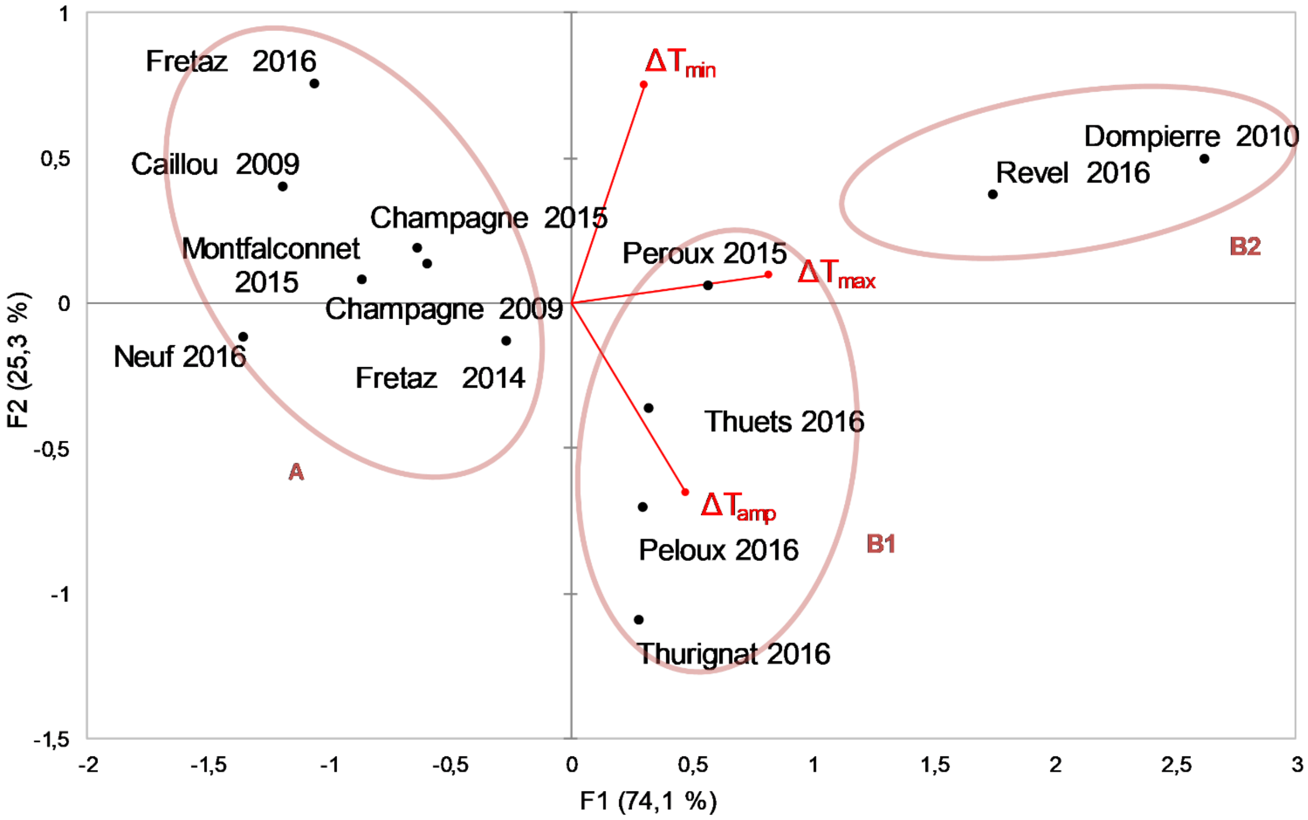
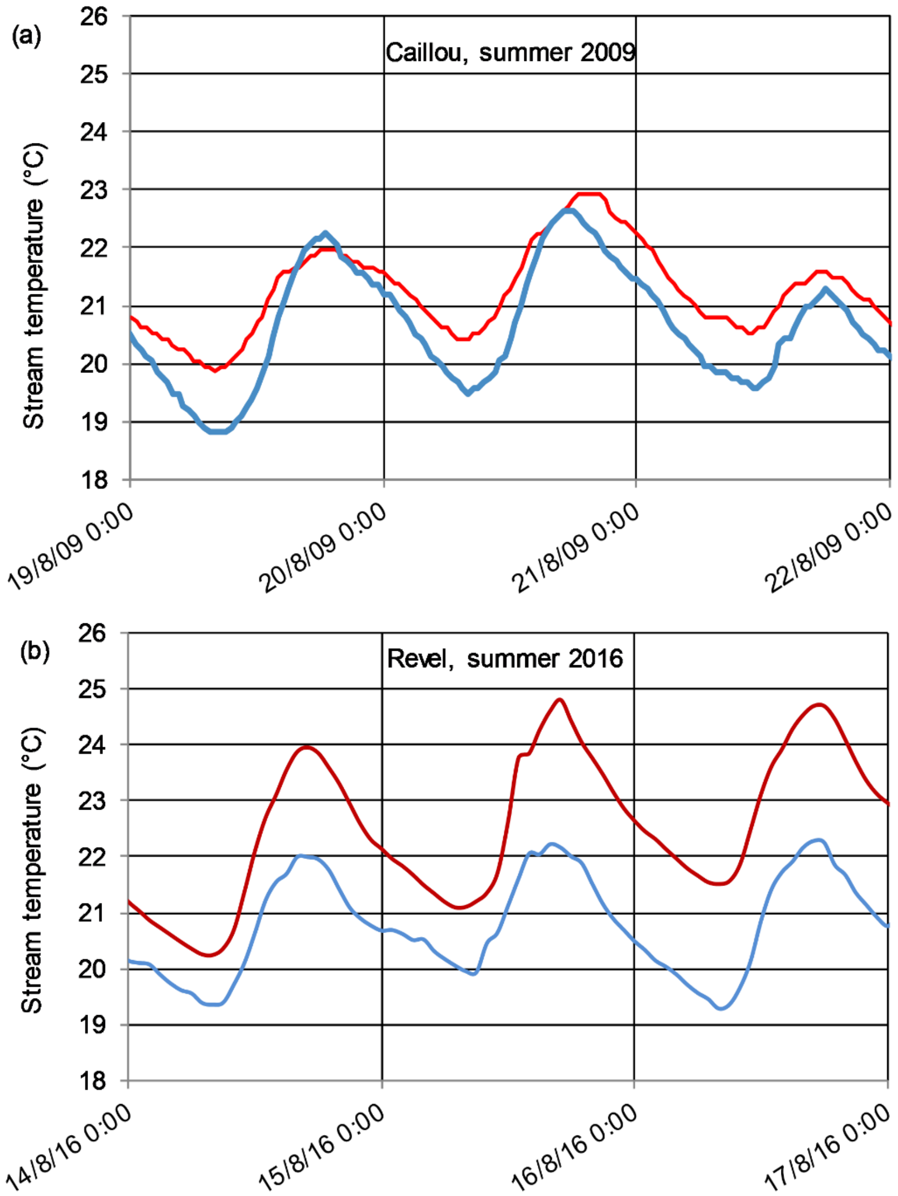


Figure 6. PCA analysis with sites plotted and temperature anomaly variables shown. Ellipses are drawn to visualize the groups obtained with the hierarchical cluster analysis.



620 **Figure 7. 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) for three days during August.**

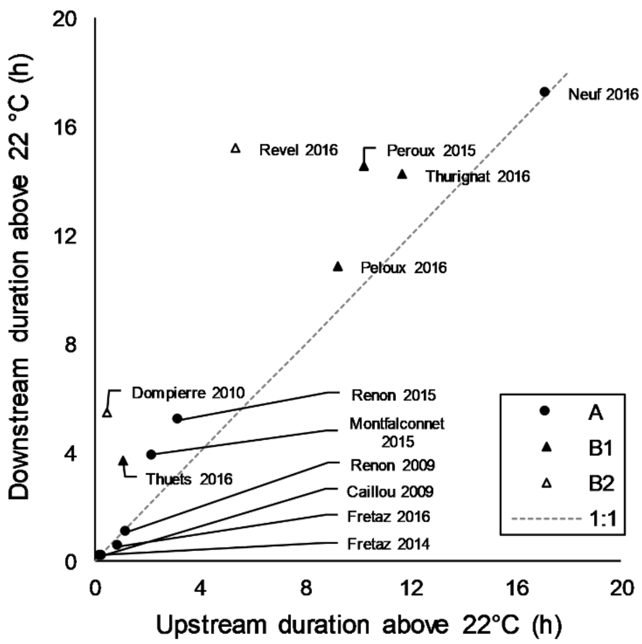


Figure 8. Mean of the daily maximum duration with stream temperature above 22 °C, upstream and downstream each site monitored in the study. A (circles), B1 (closed triangles), B2 (open triangles) are the groups of sites resulting from hierarchical cluster analysis.

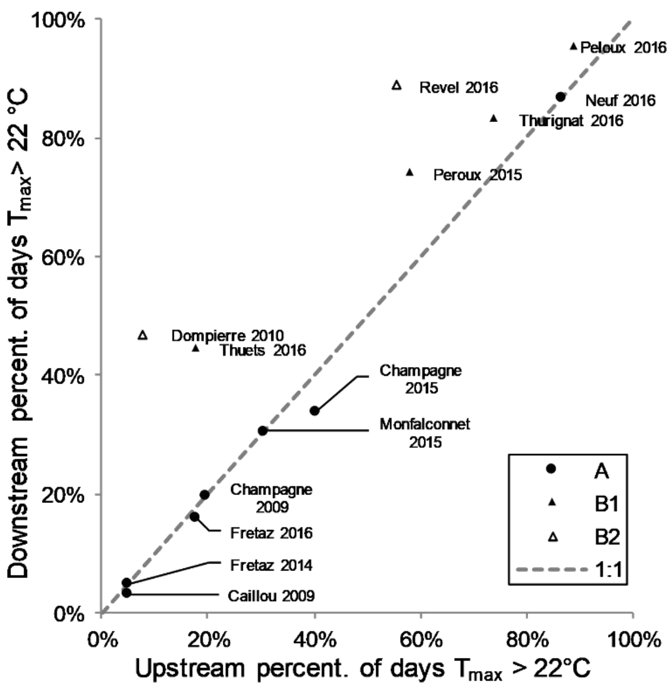


Figure 9. Percentage of number of summer days with a diurnal maximum temperature of water above 22 °C, upstream and downstream each site monitored in the study. A (circles), B1 (filled triangles), B2 (open triangles) are the groups of sites resulting from hierarchical cluster analysis.