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Regional, multi-decadal analysis reveals that stream temperature increases faster than air temperature

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Abstract.

Stream temperature appears to be increasing globally, but its rate remains poorly constrained due to a paucity of long-term data and difficulty in parsing effects of hydroclimate and landscape variability. Here, we address these issues using the physically-based thermal model T-NET (Temperature-NETwork) coupled with the EROS semi-distributed hydrological model to reconstruct past daily stream temperature and streamflow at the scale of the entire Loire River basin in France ($10^5\,\mathrm{km}^2$ with 52278 reaches). Stream temperature increased for almost all reaches in all seasons (mean = +0.38 °C/decade) over the 1963–2019 period. Increases were greatest in spring and summer with a median increase of +0.38 °C (range=+0.11– +0.76 °C) and +0.44 °C (+0.08– +1.02 °C) per decade, respectively. Rates of stream temperature increases were greater than for air temperature across seasons for 50–86 % of reaches. Spring and summer increases were typically the greatest in the southern headwaters (up to +1 °C/decade) and in the largest rivers (Strahler order >5). Importantly, air temperature and streamflow exerted joint influence on stream temperature trends, where the greatest stream temperature increases were accompanied by similar trends in air temperature (up to +0.71 °C/decade) and the greatest decreases in streamflow (up to -16 %/decade). Indeed, for the majority of reaches, positive stream temperature anomalies exhibited synchrony with positive anomalies in air temperature and negative anomalies in streamflow, highlighting the dual control exerted by these hydroclimatic drivers. Moreover, spring and summer stream temperature, air temperature, and streamflow time series exhibited common change-points occurring in the late 1980s, suggesting a temporal coherence between changes in the hydroclimatic drivers and a rapid stream temperature response. Critically, riparian vegetation shading mitigated stream temperature increases by up to 16 % in smaller streams (i.e., <30 km from the source). Our results provide strong support for basin-wide increases in stream temperature due to joint effects of rising air temperature and reduced streamflow. We suggest that some of these climate change-induced effects can be mitigated through the restoration and maintenance of riparian forests, and call for continued high-resolution monitoring of stream temperature at large scales.

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1 Introduction

Stream temperature is a critical water quality parameter affecting the distribution of aquatic communities (Poole and Berman, 2001; Ducharne, 2008), but its future under global change remains uncertain. As air temperature (Ta) increases worldwide due to climate change, stream temperature (Tw) is expected to follow a similar trajectory (Mohseni et al., 1999; Kaushal et al., 2010; Van Vliet et al., 2011; Isaak et al., 2012; Arora et al., 2016). Indeed, there is growing evidence that stream warming is occurring around the world, affecting freshwater ecosystems through structural and functional changes in biological communities throughout the food web (Woodward et al., 2010; O'Gorman et al., 2012; Scheffers et al., 2016). Deleterious warming effects are documented from bottom-dwelling microorganisms (e.g Romaní et al., 2016; Majdi et al., 2020) up to macroinvertebrates (e.g Floury et al., 2013; Bruno et al., 2019) and fish communities (e.g Maire et al., 2019; Stefani et al., 2020). However, the paucity of long-term time series of Tw (Webb and Walling, 1996; Nelson and Palmer, 2007; Webb et al., 2008; Arora et al., 2016) has impaired the larger scale assessment of such trends, especially in light of confounding factors like hydrological changes and land use change. Hence, analyses of Tw trends, especially at large spatiotemporal scales, remain scarce (but see Kaushal et al., 2010; Orr et al., 2015; Arora et al., 2016; Michel et al., 2020; Wilby and Johnson, 2020).

To overcome the lack of Tw data, large-scale ecological studies typically use Ta as a proxy for Tw to assess the impact of climate change on the spatial distribution of aquatic organisms (e.g Buisson et al., 2008; Buisson and Grenouillet, 2009; Tisseuil et al., 2012; Domisch et al., 2013), but Ta can be an imprecise surrogate for Tw (Caissie, 2006). Indeed, many landscape and basin characteristics (e.g., stream discharge [Q], streambed morphology, karst resurgences, topography, and vegetation cover) contribute to the response of Tw to climate change over time and space (Stefan and Preud'homme, 1993; Webb and Walling, 1996; Webb et al., 2008; Hannah and Garner, 2015). For instance, riparian vegetation can obstruct solar radiation, which is the dominant heat flux at air-water surface (Caissie, 2006; Hannah et al., 2004), and therefore decrease Tw response to Ta (Loicq et al., 2018; Johnson, 2004). However, while riparian vegetation shading can greatly decrease the temperature of small rivers (Dan Moore et al., 2005; Loicq et al., 2018), it has limited effects on larger rivers since the width of such rivers is large enough that only a small part of it can be shaded. Rising groundwater temperature (Taylor and Stefan, 2009; Kurylyk et al., 2013, 2014) and reduced groundwater flows (Kurylyk et al., 2014) due to climate change may further contribute to Tw trends (Meisner, 1990; Arora et al., 2016), leading to asymmetric controls (vis-à-vis Ta) on Tw (Moatar and Gailhard, 2006), especially in headwaters (Caissie, 2006; Kelleher et al., 2012; Mayer, 2012). Finally, intensification of the water cycle (Huntington, 2006), with more frequent and severe droughts (Mantua et al., 2010; Giuntoli et al., 2013; Prudhomme et al., 2014), as well as more intense and sudden floods (Blöschl et al., 2019) may decouple Ta-Tw trends, exacerbating Tw increases that will most likely be evident during low summer flows when thermal capacity and flow velocity are at their minima (Webb, 1996; Webb et al., 2008).

There is thus a clear need to improve our estimates of Tw trends to assess how stream ecosystems will respond in the face of a changing climate. Unfortunately, extrapolating trend estimates derived from short time series may lead to paradoxical results, e.g., cooling streams in a warming world (Arismendi et al., 2012). This discrepancy in short- and long-term dynamics is likely due to confounding influences of Ta and hydrology, with implications for the persistence of specialized aquatic organisms (e.g.,

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for cold-water biota, Arismendi et al., 2013b) and the completion of their life cycle (e.g., for diadromous fish, Arevalo et al., 2020). Hence from an ecological perspective, it will be critical to understand and deconvolve the joint influences of changing Tw and Q regimes. In the absence of more robust data sources, modeling is thus an indispensable tool in meeting the these goals.

Tw models output data sets that can then be used to assess the magnitude of long-term trends, but model selection entails important considerations. For example, Tw can be estimated by developing a statistical, or stochastic, model based on multiple independent drivers (Benyahya et al., 2007), which is a common practice for large scale studies (e.g Mantua et al., 2010; Jackson et al., 2017, 2018). However, these statistical models lack mechanism; they cannot reveal the specific energy transfer mechanisms responsible for the spatiotemporal patterns of Tw (Dugdale et al., 2017). They are also unable to predict Tw for periods other than those used for their calibration due to, for instance, the non-stationary relationship between Ta and Tw over time (Arismendi et al., 2014). Alternatively, physically-based, or deterministic, models are entirely mechanistic; they predict Tw dynamics through a heat budget, accounting for energy exchanges and effects of landscape characteristics on energy transfer (Sinokrot et al., 1995; Webb and Walling, 1997; Yearsley, 2009; van Vliet et al., 2013). Critically, such process-based models can be used not only to reconstruct past time series, but they can be used in forecasting, or in predicting Tw response to projected climate or land-use changes (Dugdale et al., 2017; Caissie et al., 2007).

Here, we used a physical process-based thermal model coupled with a semi-distributed hydrological model to understand how Tw has responded to recent climate change at a large scale. To do so, we first assessed the performance of the models against field observations over the Loire basin, France, then reconstructed daily Q and Tw over the past 57 years over the whole hydrographic network. We then used model outputs to compute the magnitude of decadal trends in seasonal and annual Tw and Q. To understand the relative influences of Q and Ta on Tw, we compared their trends, anomaly behaviors, and temporal patterns. Finally, we sought to understand variation in Tw trends as a function of stream size, landscape attributes, and riparian shading.

2 Study area

The Loire River basin is one of the largest in Europe ($10^5\,\mathrm{km}^2$) encompassing an area with starkly contrasting HydroEco Regions ("HER"), land use/land cover, and climatic conditions (Moatar and Dupont, 2016), providing an ideal case study to disentangle the drivers of the spatial heterogeneity of trends in Tw. Mean annual precipitation (549–2130 mm), mean annual Ta (6.0–12.5 $^\circ\mathrm{C}$), and altitude (10–1850 m) provide spatially variable controls on stream thermal regimes. There are three main HER in this basin (Fig. 1, middle), which were categorized based on climate, lithology, and relief (Wasson et al., 2002). Granite and basalt dominate the southern headwaters of the basin (mostly in the Massif Central, HER A), whereas sedimentary rocks occupy the middle reaches with a potential for groundwater input (HER B), followed by granite and schist in the lower reaches (HER C) (see Fig. 1, top).

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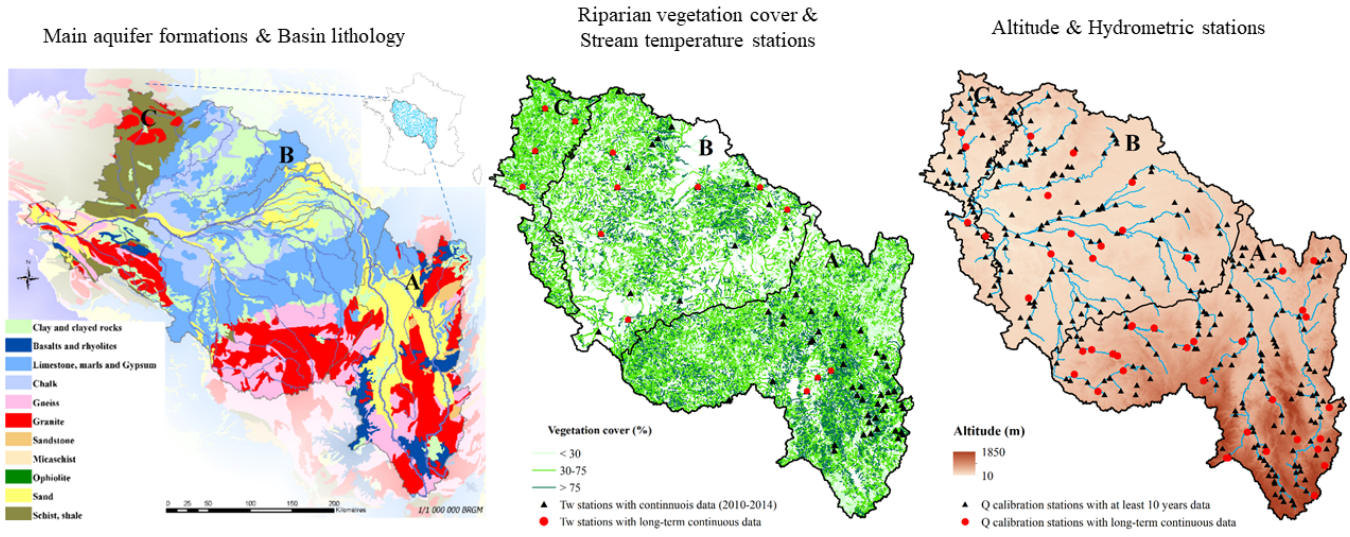

Figure 1. Maps of the Loire basin. (top) Main aquifer formations and lithology, (middle) riparian vegetation cover (Valette et al., 2012) and Tw stations, and (bottom) altitude (IGN, 2011) and hydrometric stations. The lithology map was adapted from Moatar and Gailhard (2006), based on original data from BRGM (French Geological Survey). All Tw stations were used to assess the performance of the T-NET thermal model, but only the ones with long-term data (in red) were used to assess the model accuracy for long-term trends. Complete information on Tw stations with long-term continuous data are provided in Table 1. All hydrometric stations were used for calibrating the EROS hydrological model, but only stations with long-term data (in red) were used to assess the model performance on long-term trends.

3 Method and data

We assessed how Tw responded to climate change over the past 57 years in the Loire River basin in four steps. First, we applied physically based Q and Tw models for the period 1963-2019. Second, we assessed model performance by comparing simulated daily Q and Tw to data from observation stations. Third, we assessed Q and Tw long-term trends. Fourth, we analyzed how hydro-climatic changes and landscape features could explain reconstructed trends in Tw. We performed all analyses on both seasonal and annual basis, where winter is December-February (DJF), spring is March-May (MAM), summer is June-August (JJA), and fall is September-November (SON).

3.1 Modeling daily Q and Tw

3.1.1 EROS hydrological model

The EROS hydrological model uses daily Ta (°C), solid and liquid precipitation (mm), and reference evapotranspiration (ET_0, mm) to produce mean daily Q and groundwater flows (Thiéry, 1988; Thiéry and Moutzopoulos, 1995; Thiéry, 2018). Meteorological inputs were provided by the 8 km gridded Safran atmospheric reanalysis data released by Meteo-France over

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the 1958–2019 period (Quintana-Segui et al., 2008; Vidal et al., 2010). ET_0 was computed from Safran variables with the Penman-Monteith equation (Allen et al., 1998). Observed Q data were extracted form the French national Banque Hydro database (http://www.hydro.eaufrance.fr/) for all available stations across the Loire basin (Fig. 1, bottom). Stations along the main Loire and Allier rivers were highly influenced by the management of large dams, notably through summer releases to sustain low-flows. Time series at these stations have been first naturalized by EDF (French Electricity) by taking into account recorded dam storages and releases. EROS was calibrated over the 1971-2018 period against daily Q at 352 sub-catchments (range=40-1600 km^2, mean=300 km^2) with at least 10 years of daily observations (Fig. 1). The calibration aimed at maximizing the Nash-Sutcliffe efficiency criteria (Nash and Sutcliffe, 1970) on the square root of streamflow and minimizing the overall bias, in order to simulate correctly the whole range of Q values (Thiéry, 1988; Thiéry and Moutzopoulos, 1995; Thiéry, 2018). A 3-year warm-up period (1971-1974) was discarded from the calibration period (1971-2018, which maximizes the amount of streamflow observations). The calibrated model was then used to simulate streamflow over 368 sub-catchments in the Loire basin over the whole 1963-2019 period. Streamflow was then distributed along the river network according to the drainage area for informing the T-NET model at the reach scale. Although meteorological variables were available from 1958, the first three years (1958-1962) was discarded for the sake of model convergence.

3.1.2 T-NET thermal model

The T-NET (Temperature-NETwork) thermal model computes Tw along the longitudinal dimension of the hydrographic network (a GIS polyline) of the Loire River basin. To simulate Tw, the equilibrium temperature (Te) is first computed, the temperature at which the net heat flux across the surfaces of the stream is null (Bustillo et al., 2014). The heat budget of each reach includes six fluxes (Wm^{-2}): net solar radiation, atmospheric longwave radiation, longwave radiation emitted from the water surface, evaporative heat flux, convective heat flux, and groundwater heat inflow. The hydrographic network of the model over the Loire basin consists of 52 278 reaches delimited either by confluences of two streams or a headwater source (i.e., first order reaches) (Beaufort et al., 2016; Loicq et al., 2018). The mean reach length is 1.7 km and 74 % of the reaches have a Strahler order lower than 3. To compute the six heat fluxes and the water travel time for each reach, the following input data were used:

- Meteorological variables: hourly Ta (°C), specific humidity (gkg^{-1}), wind velocity (ms^{-1}), shortwave radiation (Wm^{-2}) and longwave radiation (Wm^{-2}) were provided by the 8 km gridded Safran atmospheric reanalysis (Vidal et al., 2010). All reaches within a grid cell were assigned the values of the meteorological variables in that grid cell. For reaches flowing through more than one grid cell, meteorological variables were weighted by the relative length of the reach within each grid cell.

- Riparian vegetation shading: riparian vegetation is one of the major regulators of shortwave radiation. In the current study, patches of wooded area provided by the BD TOPO® (IGN, 2008) database were used as a proxy of vegetation. The vegetation species and length of each wooded patch in a buffer of 10 m were extracted for both right and left river banks (van Looy and Tormos, 2013). The vegetation density (vc) was then calculated as the ratio of patch length to reach length for both right and left river banks. In case of multiple wooded patches in any side of a river bank, the

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average vegetation density of the patches was considered. Then, the model proposed by Li et al. (2012) was used for the calculation of the dynamic shading factor (SF). The required average tree height for both right and left river banks was estimated based on vegetation species (see Table S1).

In the presence of different vegetation species, the average tree height (m) for each side of a river bank was calculated as follows:

$$H = \frac{1}{n}\Sigma_{i=1}^{n} H_i \frac{L_i}{L} \tag{1}$$

with H_i and L_i the height and length of the tree patch i, respectively, and L the reach length. Next we calculated the proportion of the river width that was shaded (W_{shaded}) and the dynamic shading factor (SF) as follows:

$$W_{\text{shaded}} = \frac{H_{\text{left/right}} \times \cot\Psi \times \sin\delta}{W} \tag{2}$$

$$SF_{\text{right}} = (W_{\text{shaded}})_{\text{right}} \times (vc)_{\text{right}} \tag{3}$$

$$SF_{\text{left}} = (W_{\text{shaded}})_{\text{left}} \times (vc)_{\text{left}} \tag{4}$$

$$SF = \begin{cases} SF_{\text{left}} & \text{if } SF_{\text{left}} > SF_{\text{right}} \\ SF_{\text{right}} & \text{otherwise} \end{cases} \tag{5}$$

where H is the average tree height (see Eq. 1), W the river width (see Eq. 7), Ψ the solar altitude angle, δ the angle between solar azimuth and the mean azimuth of T-NET reach, and vc the vegetation density. To take into account the phenology and stages of leaf growth, a coefficient corresponding to each season and transmissivity was applied to SF to calculate the final shading factor: $SF_{final} = SF \times (1 - \text{transmissivity})$. The transmissivity in leafless months (Jan, Feb, Nov and Dec), months of leaf growth (Mar and Apr), and full-leaf months (May-Sep) was fixed to 0.3, 0.2 and 0, respectively, following Hutchison and Matt (1977). The shortwave radiation was lastly regulated by a factor of $1 - SF_{final}$.

– River hydraulic geometry: stream width and depth were calculated using a hydraulic model assuming a rectangular river section being constant over 24 hours (Morel et al., 2020):

$$D(t) = D50 \times \left[\frac{Q(t)}{Q50}\right]^{f} \tag{6}$$

$$W(t) = W50 \times \left[\frac{Q(t)}{Q50}\right]^{b} \tag{7}$$

with f and b being at-a-reach exponents previously predicted by climate, hydrological, topographic and land use descriptors (see Morel et al., 2020, for more details). $Q(t)$ is the daily mean streamflow provided by the EROS hydrological model. The Q50, W50, D50 (the median of Q, width and height, respectively) and the exponents were available on the Theoretical Hydrographic Network for France (RHT, Pella et al., 2012). There was about 50 % correspondence between the reaches of the T-NET and RHT networks. For the rest of them, required hydraulic geometry variables for the T-NET

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reaches were extrapolated from the nearest RHT reach. These river hydraulic geometries allowed us to calculate the water velocity by the ratio of $Q(t)$ to rectangular wetted cross-section. The travel time was also defined by the ratio of water velocity to reach length.

3.2 Model assessment and validation

3.2.1 EROS hydrological model

Of the 352 calibration stations considered by EROS, 44 are part of the French Reference Hydrometric Network (RHN) described by Giuntoli et al. (2013) with long-term continuous high-quality data over the 1968-2019 period, especially for low-flows. These stations are shown with red points in Fig. 1. Seasonal and annual relative biases, together with Nash-Sutcliffe efficiency on Q, $ln(Q)$, and $\sqrt{Q}$ were computed over the 1968-2019 period on these RHN stations to provide an overview of the performance of the EROS model. Moreover, decadal trends (in % per decade) on seasonal and annual averages from the EROS simulation were compared to corresponding observed trends at each of the 44 reference stations.

3.2.2 T-NET thermal model

The T-NET model does not consider the influence of impoundments on thermal energy balance, and thus produces "natural" thermal regimes. Therefore, model performance was assessed on natural Tw stations, which are weakly influenced by impoundments. 72 near-natural stations with continuous daily data over the 2010–2014 period (see Fig. 1) were identified using the thermal signatures approach that allows distinguishing between natural and altered thermal regimes (see Seyedhashemi et al., 2020, for more details). Of these identified natural reaches, 58 were located on small/medium streams (with distance from the source $<100\,\mathrm{km}$), while the remaining are located on large rivers. The mean catchment area of natural stations was $153\,\mathrm{km}^2$ ($\pm 225\,\mathrm{km}^2$) for small/medium streams, and 16,804 km^2 ($\pm 18{,}833\,\mathrm{km}^2$) for large rivers. Seasonal and annual absolute biases were assessed at these 72 stations.

Long-term continuous data was available at 14 of the 72 near-natural stations, including 9 stations with 8-13 years data and 5 stations with 20-40 years data. These 14 stations are represented as red points in Fig. 1, middle), and listed in Table 1. The long-term evolution of annual mean Tw at these stations is shown in Fig. S1. These 14 near-natural stations with long-term continuous data comprise the validation dataset for the seasonal and annual trend assessment (see Table 1).

3.3 Time series reconstruction and assessment of long-term trends

Daily Q and Tw were reconstructed over the 57-yr period 1963–2019 using the EROS hydrological model and the T-NET thermal model. For each of the 52 278 river reaches, daily time series of Ta (from the Safran reanalysis), Q (from EROS), and Tw (from T-NET) were reconstructed. Seasonal and annual averages of these 3 variables were considered in the trend assessment.

We estimated the magnitude of trends in these time series with the non-parametric Theil–Sen estimator (Sen, 1968), and evaluated their significance with the Mann-Kendall test (Mann, 1945), commonly used in hydrological analyses (see e.g.

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Table 1. Characteristics of the 14 long-term Tw stations. See Fig. S1 for the evolution of observed annual Tw at these stations.

River (Location)	Catchment area (km^2)	Record period	Total years
Loire (Chinon)	57043	1977–2019	43
Loire (St-Laurent)	38088	1977-2019	43
Loire (Dampierre)	36212	1977–2019	43
Loire (Bellevile)	35172	1979–2019	41
Vienne (Civaux)	5795	1997–2017	21
Artière (Clermont-Ferrand)	48	2005–2017	13
Oudon (Segré)	1342	2004–2014	11
Mayenne (Ambrières-les-Vallées)	825	2004–2014	11
Bedat (Saint-Laure)	419	2008–2017	10
Credogne (Puy-Guillaume)	84	2008–2017	10
Loir (Flée)	6215	2010–2017	8
Huisne (Montfort-le-Gesnois)	1931	2010–2017	8
Jouanne (Forcé)	413	2010–2017	8
Merdereau (Saint-Paul-le-Gaultier)	123	2010-2017	8

Giuntoli et al., 2013) but also thermal analyses (e.g. Kaushal et al., 2010; Arismendi et al., 2013a; Arevalo et al., 2020). This test is robust to non-normal data, non-linear trends, and series with outliers and missing values. Trend magnitudes are reported in °C/decade for Ta and Tw, and in %/decade for Q (percentage of changes over whole period), to help for comparisons across the basin.

3.4 Hydroclimatic drivers of Tw trends

Distributions of trends in Tw and Ta were first compared for the whole basin at the seasonal and annual scales using the non-parametric Wilcoxon signed rank test (Bauer, 1972) to determine whether Tw trends were greater than Ta trends. To assess how Ta and Q influenced Tw, we first identified which reaches exhibited 1) jointly increasing trends in Tw and Ta, and 2) jointly increasing trends in Tw and Ta and decreasing trends in Q. Then, for each identified reach, we evaluated the strength and direction of these joint trends using Pearson correlation between 1) Tw and Ta, and 2) Tw and log(Q).

Ta, Tw, and Q seasonal and annual anomalies – with respect to the 1963-2019 interannual mean – were then used to synchronicity of extreme years. Change-points in time series of anomalies at each reach were computed with the non-parametric Pettitt test that considers no change in the central tendency as a null hypothesis (Pettitt, 1979). Change points were reported at the 95 % confidence level.

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3.5 Landscape drivers of Tw trends

Stream size and HER (see Fig. 1) were selected as the major potential landscape drivers. The Strahler order of each reach was used as a proxy for stream size. Reaches with Strahler order 5–8 were combined into a single group termed "large rivers". The Spearman correlation was computed between median decadal trends in Tw (i.e., median across all reaches) and Strahler order. Such correlations were computed across HERs and at seasonal and annual scales to evaluate the spatial heterogeneity and seasonality.

Lastly, the influence of riparian vegetation shading on trends in Tw was assessed using the daily average of the riparian vegetation shading (SF) simulated by T-NET. Seasonal shading was computed as the average of the daily SF over each season. For this analysis, only low-order reaches – distance from the source $< 30\,\mathrm{km}$ – were considered, based on previous observations that riparian shading primarily influences Tw at this scale (Dan Moore et al., 2005; Loicq et al., 2018). Then, as for the previous analysis for the influence of stream size, the correlation between median decadal Tw trends and five levels of riparian shading (<15 %; 15-25 %; 25-40 %; 40-60 %; >60 %) was computed across HERs and seasons.

4 Results

4.1 Performance of models against observations

The EROS model performed well at the annual scale with a median relative bias of 0.37% (see Fig. S2). It slightly underestimated winter Q (median bias=-7.26%) and spring Q (-6.79%), and overestimated summer Q (+37.7%) and fall Q (+24.7%). The mean NSE criteria for low, mean and high flows were 0.82, 0.85 and 0.79, respectively. No systematic bias was observed for modeled Tw at the stations located on small and medium rivers (see Fig. S2). Median Tw bias ranged from -0.26 °C (in fall) to 0.8 °C (in winter). Large rivers exhibited a small Tw underestimation, with a median bias ranging from -0.29 °C (in fall) to +0.15 °C (in winter), and the overall biases were still quite small across seasons (IQR=0.4–0.7 °C).

Trends in observed and modeled Q were well correlated for all seasons (Fig. S3), with the highest correlation across stations found in spring ($r = 0.69$, $p < 0.05$) and the lowest correlation found in summer ($r = 0.17$, $p = 0.26$). Both modeled and observed Q were slightly decreasing (up to -11 %/decade) for the majority of stations across all seasons, but the trend was significant for a very few of them (and mostly at the annual scale), all located in the southern headwaters in HER A (red points of Fig. S3). Moreover, there were only a few discrepancies between estimates of trend significance in modeled and observed Q across seasons (11-18 % of stations).

Modeled and observed Tw trends correlated well (see Fig. S4) across seasons, with the highest correlation in summer ($r = 0.94$, $p < 0.05$) and the lowest correlation in fall ($r = 0.29$, $p = 0.32$). Contrasting with trends in Q, trends for Tw increased for most stations across seasons, but the short period of record led to mostly non-significant (p=0.05) trends. However, stations with long-term data showed significant increasing trends for all seasons, with the exception of winter (Fig. S4). A visual comparison of observed and modeled Tw time series at stations with long-term data indeed suggested a strong coherence and agreement between observations and simulations for all seasons (Fig. 2). For the four stations along the main stem of the Loire

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river (Fig 2), the greatest increase occurred in spring – +0.61 (resp. +0.71) °C/decade in observations (resp. simulations) – and summer – +0.62 (resp. +0.58) °C/decade in observations (resp. simulations).

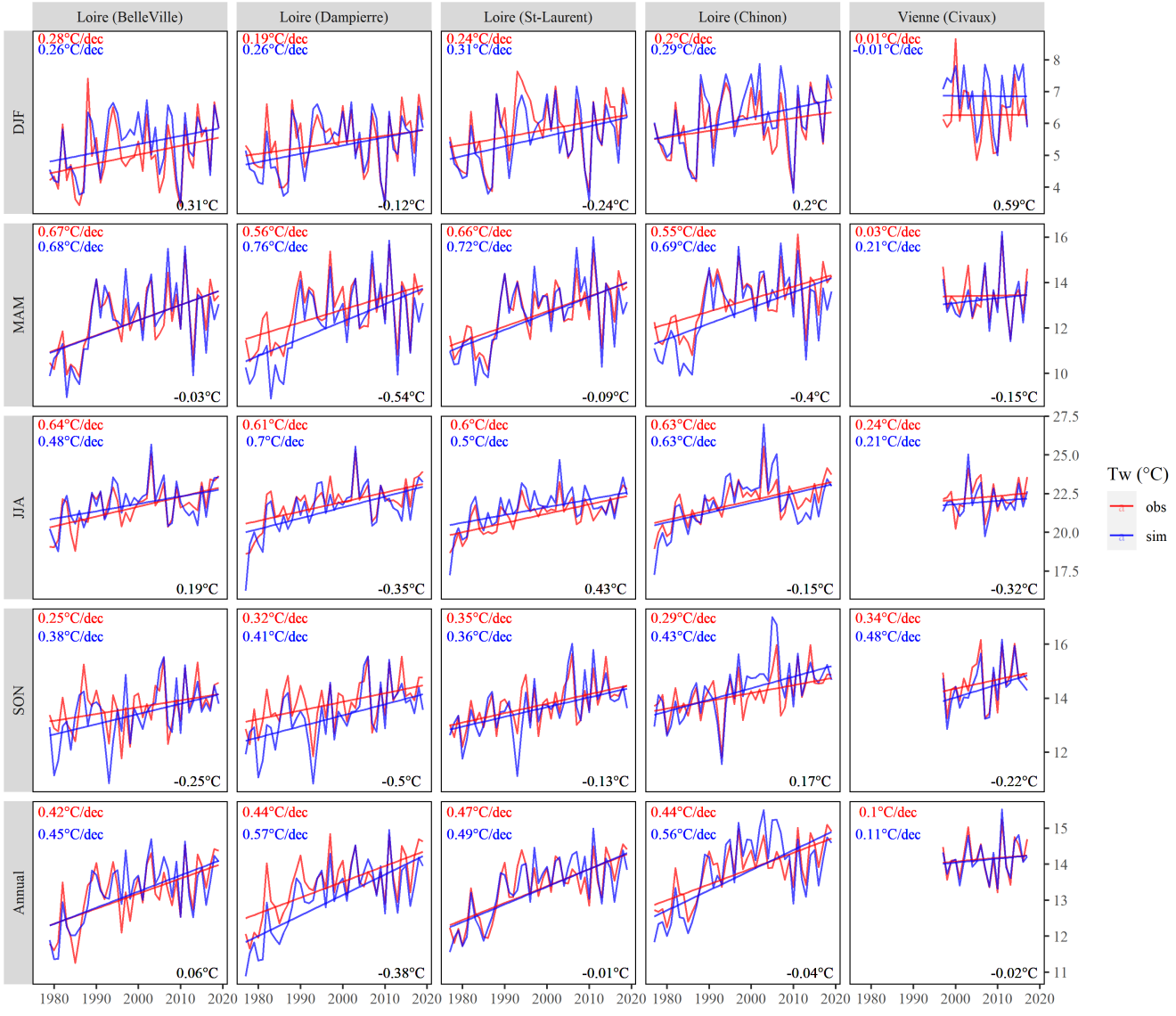

Figure 2. Seasonal and annual time series of observed and simulated Tw at stations with long-term continuous data (see Table 1 for more information) between 1977 and 2019. Numbers in red and blue in the top left corner of each graph show trend values (Sen's slope) in observed and simulated Tw. Numbers in black in the bottom right corner of each graph show the mean bias of the reconstruction.

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4.2 Spatial reconstruction of long-term trends

Tw increased in almost all modeled reaches for all seasons (Fig. 3, left; Fig. S5). Depending on the season considered, 62 % to 80 % of reaches showed trends in the range of +0.2- +0.4 °C/decade (i.e 1.14-2.28 °C over the whole 1963-2019 period). Summer Tw trends were more spatially variable than in other seasons, with more than 50 % of reaches showing values higher than +0.4 °C/decade (see Fig. S6). Such reaches were mainly located in the southern part of the basin, in HER A (see Fig. 3, left). Spring Tw trends showed a similar spatial pattern, but with lower trend values.

Likewise, Ta exhibited increasing trends for 99 % of all reaches across spring, summer, and the whole year (Fig. 3, middle). Values were mainly in the range of +0.2- +0.4 °C/decade (see Fig. S6). The highest Ta trend values were found in summer (resp. spring), when 67 % (resp. 22 %) of reaches showed values higher than +0.4 °C/decade. Such reaches were mainly located in HER A, especially in summer. Non-significant trends were found over the whole basin in winter, and in the southern part of the basin in fall.

In contrast to Ta and Tw, trends in Q were highly variable in magnitude and direction across the basin and across seasons (Fig. 3, right), and most were not significant at p=0.05 (Fig. S5). However, significant decreasing trends were found in the southern headwaters (HER A) in spring, summer, fall, and annual scale (Fig. S5). Decreasing trends were observed for the majority of reaches across seasons (66-83% of reaches), with the exception of winter (37%). Decreasing trends could have magnitudes greater than -5 % per decade, implying a -28 % loss in Q over the whole 1963-2019 period.

4.3 Hydroclimatic drivers of Tw trends

Relationships between trend estimates

The median of Tw trends were higher than that of Ta trends for every season ($p<0.001$ according to the Wilcoxon signed rank test), except for summer when the median trend values for Tw and Ta were very similar, but more variable for Tw (+0.08- +1.02 °C/decade) (Fig. 4). The greatest increase in Tw was found in summer (+0.44 °C/decade). Overall, Tw trends were more spatially variable than Ta trends, suggesting the conditional influence of Q trends (Fig. 4). Indeed, where Tw trends exceeded Ta trends, decreasing Q trends occurred coincidentally at the majority of reaches for all seasons – with the exception of winter – (43-72 %, depending on season; Fig. 5. Of these specific reaches where all factors converged (trend in Tw higher than trend in Ta, and decreasing trend in Q), most were located in HER A, especially in spring (52 % of such reaches) and summer (79 % of such reaches).

Synchrony of annual anomalies

We observed strong positive correlations between seasonal and annual averages of Tw and Ta across seasons (see Table 2). We further observed strong negative correlation between summer Tw and Q time series. The strong positive correlation observed between winter Ta and Q results from the particular hydroclimate of winters in the Loire basin, where they are either either warm and wet or cold and dry.

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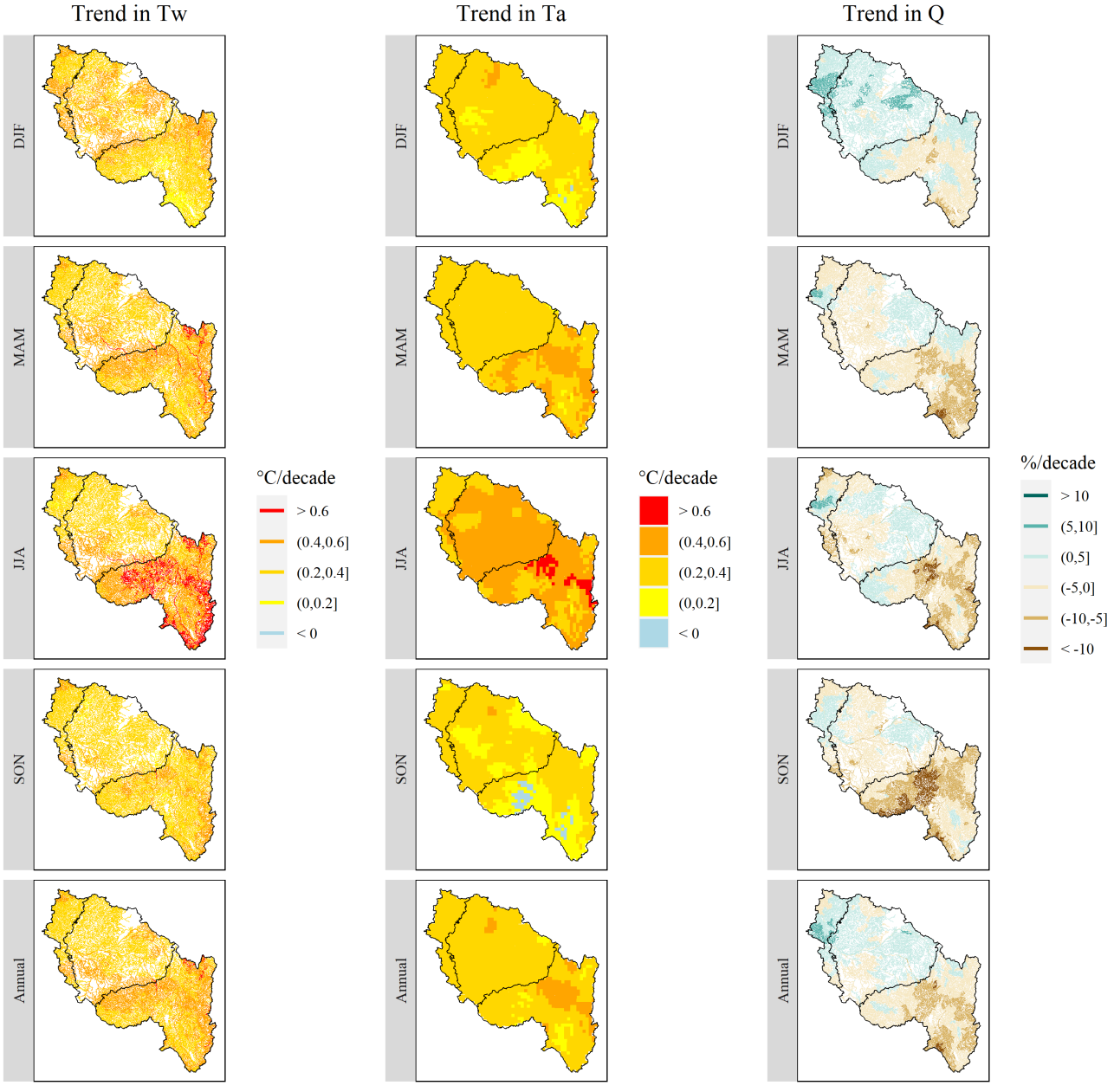

Figure 3. Spatial variability of trends in seasonal and annual Tw, Ta and Q over the 1963-2019 period, based on the Sen's Slope estimator. Solid black lines show the Hydro-Ecoregion (HER) delineation (see Fig. 1). The statistical significance of these trends is given in Fig. S5.

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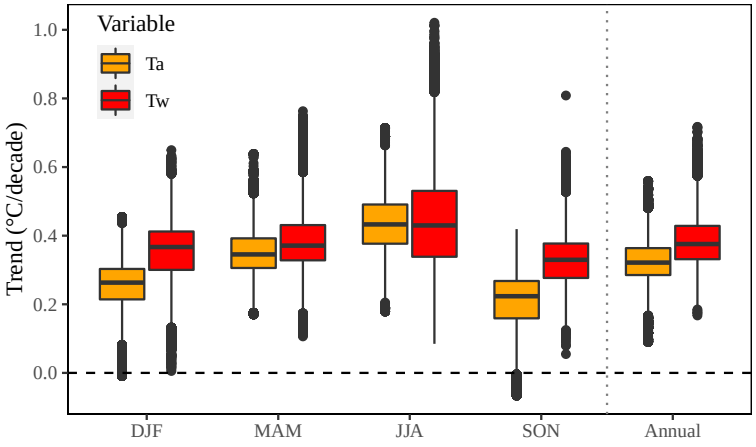

Figure 4. Distributions of seasonal and annual trends in Tw and Ta for all 52 278 reaches over the 1963-2019 period. Sen's slope is used as trend value estimate (see text).

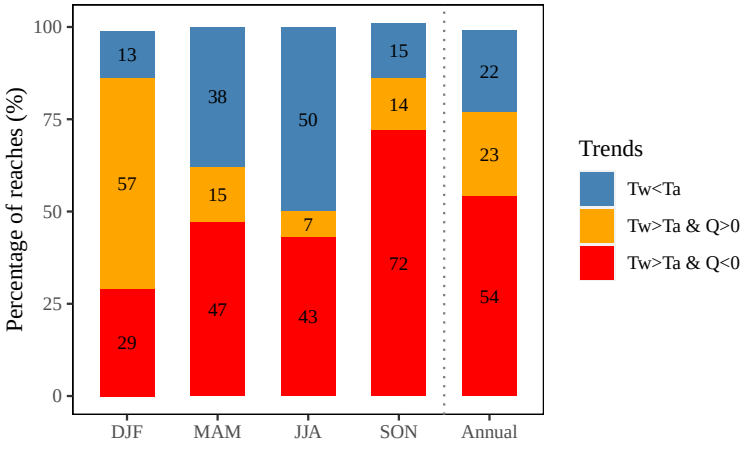

Figure 5. Percentage of reaches with consistent 1963-2019 trends in Tw, Ta, and Q, categorised with respect to two criteria: (1) Tw trend > Ta trend, and (2) sign of Q trend. Sen's slope is used as trend value estimate.

Annual anomalies of Tw, Ta, and Q exhibited variable patterns, with Tw and Ta generally increasing and Q remaining relatively stationary (Fig. 6). Tw anomalies were generally more variable than Ta, especially in summer, but both time series appeared to exhibit synchronous behavior. Change-point analysis supported this visual observation, where change-points in seasonal and annual averages were largely coincident across these time series (Fig. 7). Tw and Ta anomalies exhibited clear negative-to-positive change-points in the late 1980s at nearly all reaches, with median values shifting by approximately +2 °C. These change points were observed in all seasons, but were most pronounced and synchronous around 1988 in spring and summer. The change-points detected in winter Tw and Ta time series were less concomitant, occurring mostly in the early

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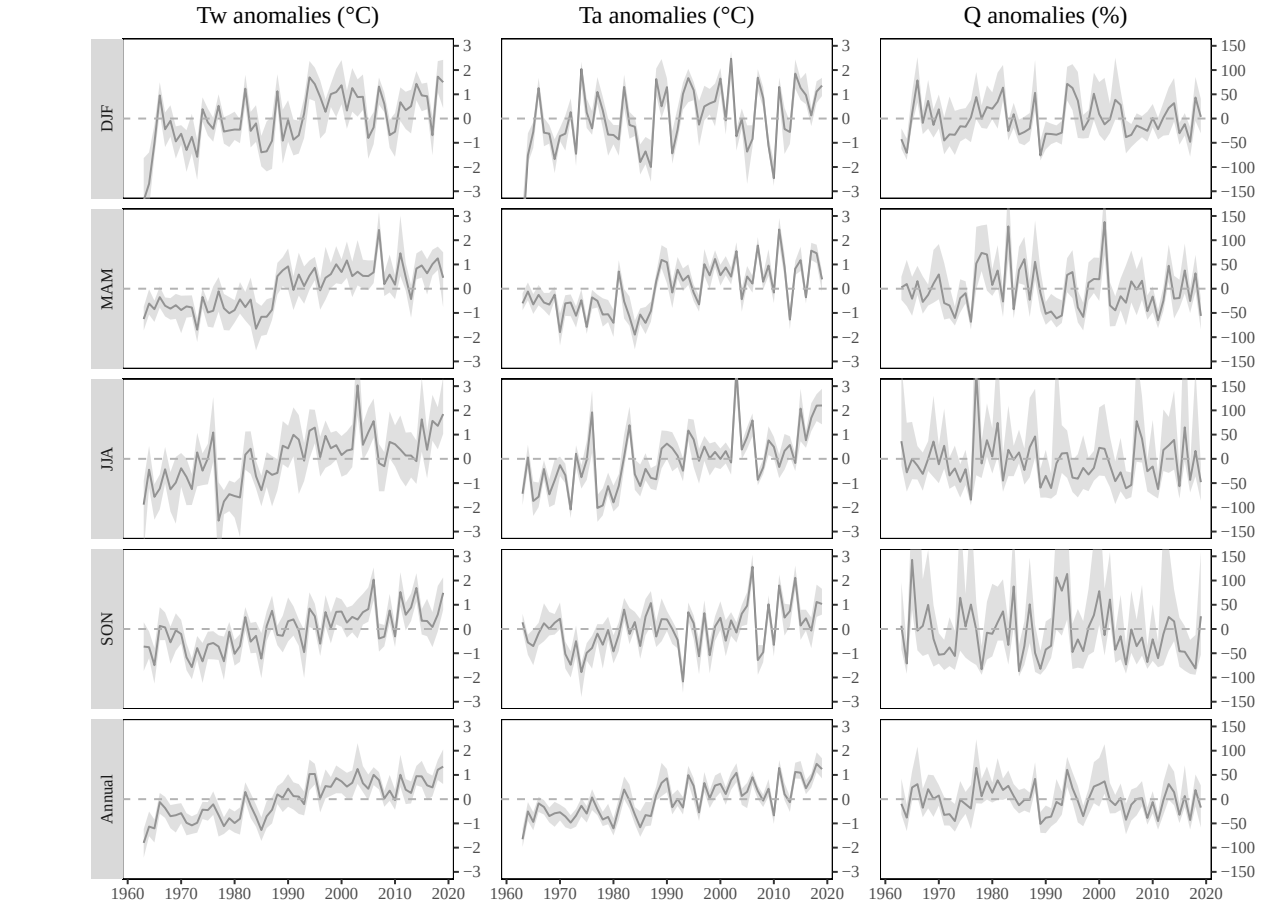

Figure 6. Seasonal and annual times series of anomalies in Tw (°C), Ta (°C) and relative Q (%) with respect to 1963–2019 averages. Grey intervals show the 5th and 95th percentiles across reaches, and the solid grey line depicts the median value. Note that Ta and Tw have the same scale.

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Table 2. Pearson correlation over the 1963–2019 period between seasonal and annual Tw and Ta and/or log-transformed Q time series, averaged over all reaches. Percentages in brackets show the proportion of reaches with a significant correlation at the 95 % confidence level.

Season	Tw and Ta	Tw and log(Q)
DJF	+0.73 (100%)	+0.52 (94%)
MAM	+0.78 (100%)	-0.02 (25%)
JJA	+0.82 (100%)	-0.40 (79%)
SON	+0.72 (99,6%)	-0.01 (19%)
Annual	+0.83 (100%)	-0.01 (22%)

1990s (1992 and 1993) for Tw and in the late 1980s (1986-1989) for Ta. The fall change-points were distributed between 1980 and 1994 for both Tw and Ta. The significant change-points in seasonal Q time series were detected for a substantially smaller proportion of reaches, e.g. less than 40 % of reaches for spring and summer. The majority of these reaches were located in HER A across seasons (66-86 % of such reaches), with the exception of winter (49 %) (see Fig. S8). In spring and summer, they occurred in the late 1980s, similarly to Tw and Ta. Conversely, the significant change-points detected in other seasons were much more scattered in time, probably due to the high interannual variability of Q.

Critically, the largest summer Tw and Ta positive anomalies over the study period were observed in 1976, 2003, 2006, 2015, 2017, and 2019, which corresponded to years with the largest negative anomalies in summer Q (Fig. 8). Note that this signal was much less clear for the other seasons (see Fig. S9).

4.4 Landscape drivers of Tw trends

4.4.1 Stream size and HER

Strahler order was strongly and positively correlated with Tw trends in spring and summer, but this effect was modulated by HER ,with HER A exhibiting the strongest correlations (Fig. 9). In other words, larger rivers tended to exhibit the largest increases in spring and summer Tw, especially for reaches located in the HER A. There, median trends in spring (resp. summer) ranged from +0.37 (resp. +0.49) °C/decade for small streams (Strahler order 1) to +0.55 (resp. +0.64) °C/decade for large streams (Strahler order ≥ 5).

4.4.2 Riparian shading

For small streams, i.e. reaches located closer than 30 km from the source, the shading factor SF and median trends in Tw were significantly and negatively correlated for all three HERs in spring, as well as for HER A in summer and at annual scale (Fig. 10). The highest correlation was found in summer in HER A. Unsurprisingly, the influence of riparian vegetation shading on trends in Tw was more important in spring and summer. The mitigating effect of shading on trends in Tw for small streams was observed for all HERs in spring, and only for HER A in summer and, to a lesser extent, in fall. The median spring Tw trend

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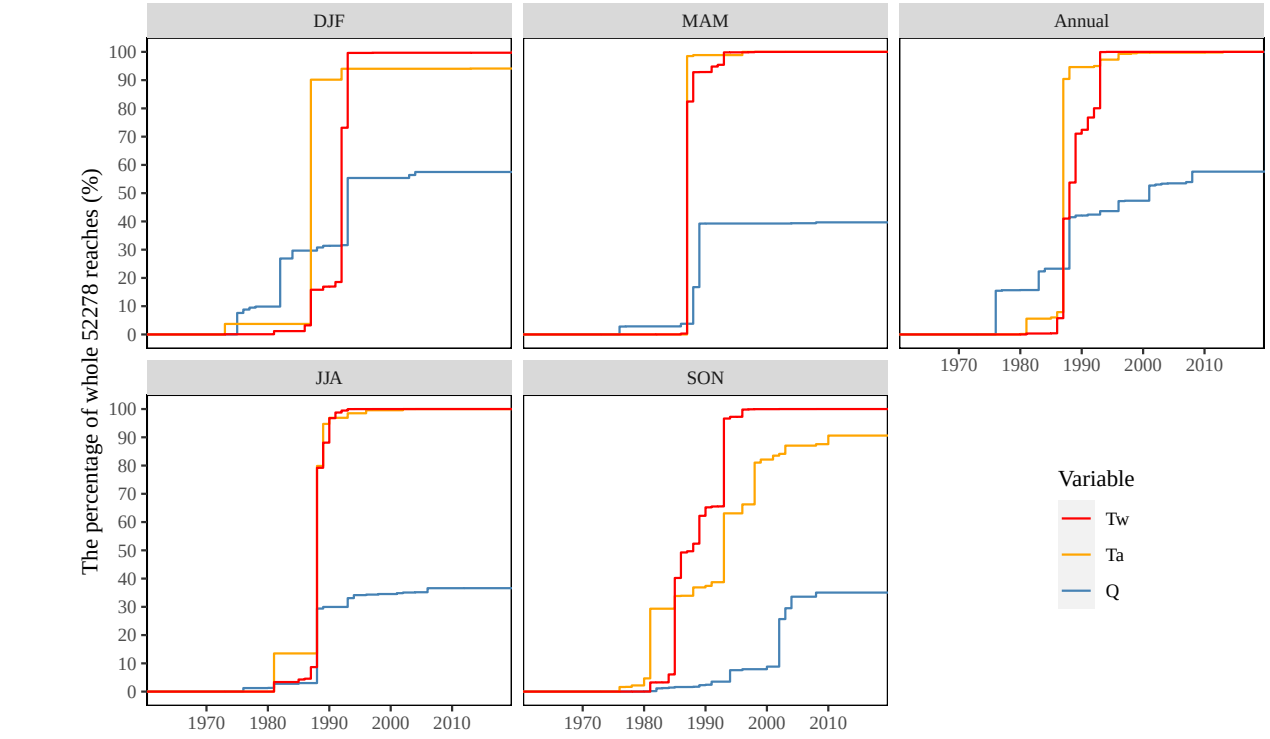

Figure 7. Change-point in Tw, Ta, and Q time series at the seasonal and annual scales, plotted as a proportion of reaches experiencing a shift in a given year. Only the first change-point detected at the 95% confidence level is considered, and non-significant change-points were removed, leading to curves not reaching 100 %.

in the HER A, B and C decreased by 12 %, 5 % and 4 %, respectively, from sparsely shaded reaches ($SF < 15\%$) to highly shaded reaches ($SF > 40\%$). For summer Tw in HER A, the median trends were 16 % lower between the lowest and highest shaded reaches.

5 Discussion

5.1 Quality and suitability of simulated Tw and Q

Although some biases were observed for both Q and Tw (Fig. S2), we found high correlations between modeled and observed trends in seasonal and annual Q, with the exception of summer (Fig. S3), and Tw, with the exception of fall (Fig. S4), demonstrating the adequacy of the modelling approach for temporal trend analyses. For Q, although largely non-significant (Fig. S5), decreasing trends were observed for the majority of the reaches across seasons (66-83% of reaches, with the exception of winter, Fig. S7) strongly suggested an effect on Tw. Moreover, the spatial pattern in simulated Q trends, with significant decreases

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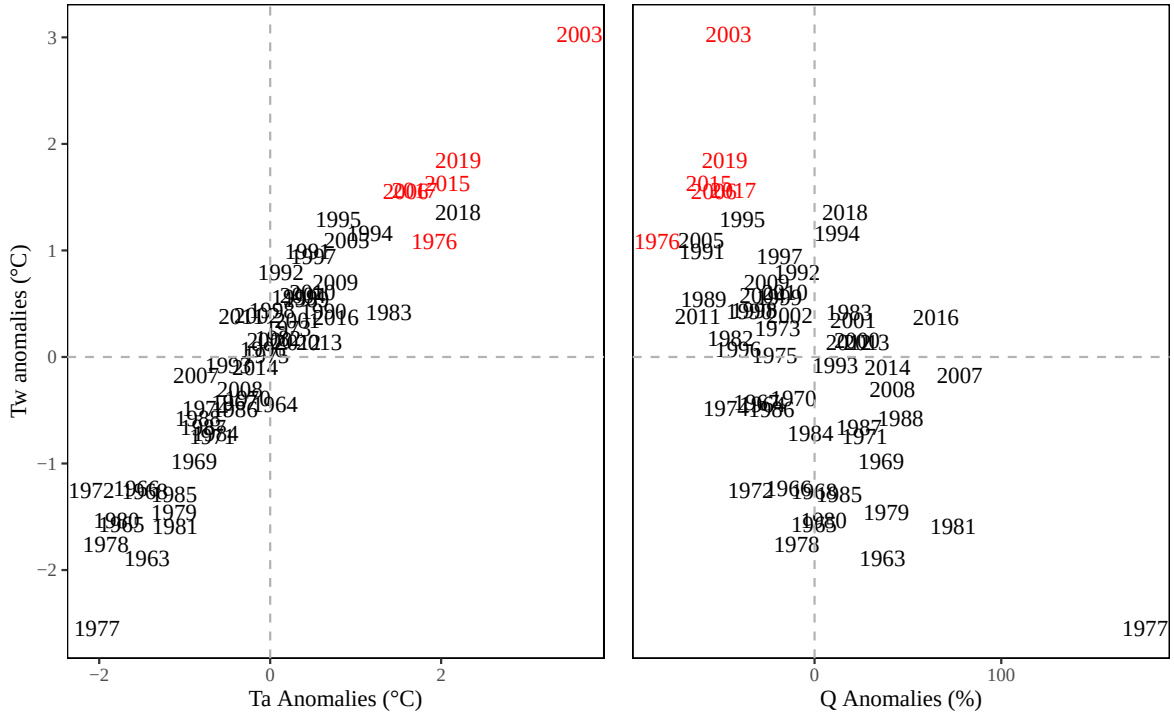

Figure 8. Relationship between summer anomalies in Tw on one side and summer Ta and Q anomalies on the other side. Individual years are identified from their median values across all reaches. Years with the highest anomalies in Tw, Ta, and Q are identified in red.

in the southern headwaters, was consistent with observations at the high-quality reference hydrometric stations (Giuntoli et al., 2013).

5.2 Agreement between trends in observed and simulated Tw

T-NET simulations over the 1963–2019 period showed significantly increasing trends in Tw for almost all reaches over the Loire basin across seasons, with an increase of +0.38°C/decade increase on average at the annual scale. To the best of authors' knowledge, the present study was one of the very few studies used modeled Tw to investigate past trend at a large scale (but see Isaak et al., 2017, 2012; Van Vliet et al., 2011). Table 3, summarizing recently published findings based on observations, demonstrate that the present results are consistent with trends observed in other European basin with clear increases in Tw over the recent decades. It also shows that the much larger scale and finer spatial resolution of the current study clearly stands out as unique. Although start year, end year and length of the study period can have can have a significant influence on trend estimates and trend detection (Arora et al., 2016), comparing trends with other studies conducted over different periods give us a comprehensive view upon the overall magnitude of changes in Tw and possible related drivers.

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Table 3. Recent studies on Tw trends in Europe. A comprehensive review of the relevant literature published prior to 2016 can be found in Arora et al. (2016). Magnitudes with unspecified season are related to annual scale. Notice that except present study, the others used observed Tw.

Country	Sites	Period	Rate of change (°C/decade)	Reference
France	**52278 reaches in the Loire basin**	**1963–2019**	**+0.17– +0.72 (Mean=+0.38)** **+0.01– +0.65 (+0.35) in winter** **+0.11– +0.76 (+0.38) in spring** **+0.08– +1.02 (+0.44) in summer** **+0.05– +0.81 (+0.33) in fall**	**Present study**
Austria	18 rivers	2010-2017	+1.9– +3.2 in summer	Niedrist and Füreder (2021)
England	6148 sites	2000-2018	-0.4	Wilby and Johnson (2020)
Switzerland	31 rivers	1979-2018	+0.33 (±0.03) +0.6– +1.1 in summer	Michel et al. (2020)
Poland	5 Carpathian rivers	1984–2018	+0.33– +0.92 +0.82– +0.95 in spring +0.75– +1.17 in summer +0.51– +1.08 in fall +0.25– +0.29 in winter	Kędra (2020)
France	11 stations on Loire, Vienne, Rhône, Seine, Meuse	1980-2015	+0.79 in spring	Maire et al. (2019)
Poland	6 stations on Warta River	1960-2009	+0.096– +0.28	Ptak et al. (2019a)
Croatia	6 stations on Kupa River	1990-2017	+0.23– +0.796	Zhu et al. (2019)
Switzerland	Rhine, Rhône, Aar, and Thur rivers	1983-2013	+0.27 (± 0.03)	Zobrist et al. (2018)
Northern Germany	132 sites	1985-2010 1985-1995	+0.3 (±0.03) +0.69 (±0.10) in spring +0.78 (±0.06) in summer +0.75 (±0.09) in fall +0.39 (±0.23) in winter +0.81 (±0.2)	Arora et al. (2016)
	475 sites	2000-2010	+0.9 (±0.07)	
England and Wales	2773 sites	1990–2006	+0.3 (±0.02)	Orr et al. (2015)
Poland	Coastal rivers (Rega, Parsęta, Słupia, Łupawa, Łeba)	1971-2015	+0.26– +0.31 +0.46 in April (The month with the highest trend)	Ptak et al. (2016)
France	4 stations on Loire River	1976–2003	+0.61– +0.71 +0.86– +1.07 in spring and summer	Moatar and Gailhard (2006)

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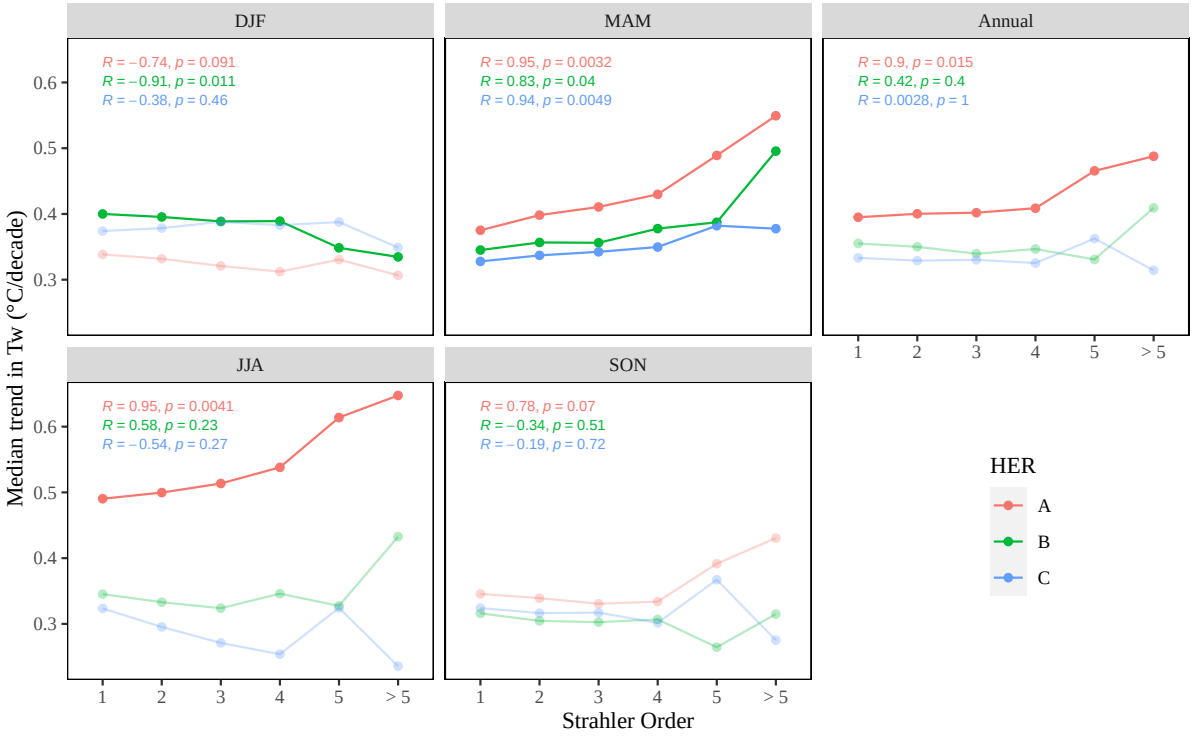

Figure 9. Relationships between reach size and median trends in Tw across reaches over 1963-2019, by HER and by season. Correlations and associated p-values are shown in the top-left corner of each graph, and significant relationships at the 95 % confidence level are identified by full solid lines.

Global-scale stream temperature modelling suggests trends in annual averages ranging from +0.2 to +0.5°C/decade over France (Wanders et al., 2019), which is consistent with our findings (mostly in the range of +0.2- +0.4°C/decade, Fig. S6). We found more pronounced trends in spring and summer, which was also found in other parts of Europe (e.g Kędra, 2020; Arora et al., 2016; Michel et al., 2020). Considerable discrepancies were also found between Tw and Ta trends across seasons for the majority of the reaches (see Fig. 3, and 5), which is a common finding for other sites around the world (Arora et al., 2016; Wanders et al., 2019). This highlights that changes in Ta may not be the only driver of changes in natural Tw.

5.3 Drivers and spatial patterns of trends in Tw

The greatest increases in Tw (up to +1 °C/decade) were predominately located in the southern headwaters of the basin, in HER A (Massif Central) where a greater increase in Ta (up to +0.71 °C/decade) and a greater decrease in Q (up to -16 %/decade) occurred jointly. The decrease in Q could be due to a significant increase in potential evapotranspiration (PET) (up to +10 %) over the whole of basin and a decrease in total precipitation (P) (up to -5 %/decade) (Figs. S10 and S11). Such trends, computed here based on variables from the Safran surface meteorological reanalysis (Vidal et al., 2010), are consistent with larger-scale

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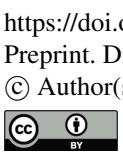

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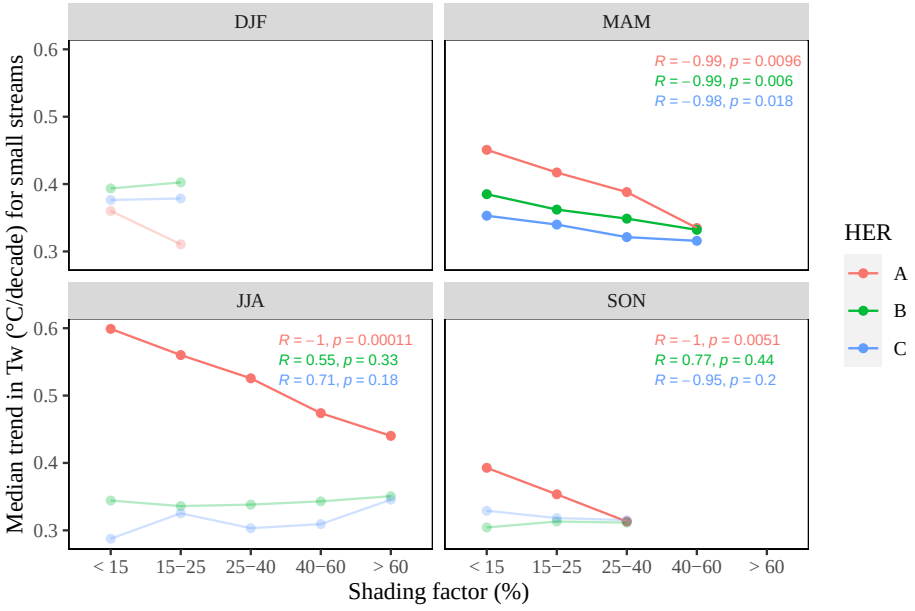

Figure 10. Relationships between shading factor and median trends in Tw over the 1963-2019 period for small streams, by HER and by season. Note that some shading factor classes are not observed in fall and winter. Correlations and associated p-values are shown on the top-right corner of each graph, and significant relationships at the 95 % confidence level are identified by full solid lines.

studies (see e.g. Spinoni et al., 2017; Tramblay et al., 2020; Hobeichi et al., 2021). Moreover, Vicente-Serrano et al. (2019) attributed annual streamflow trends in southern France mostly to trends in precipitation and potential evapotranspiration, as opposed to irrigation and land-use changes that have additional strong effects e.g. in the Iberian peninsula. In Switzerland, Michel et al. (2020) described an increase of $+0.33 \pm 0.03$°C/decade in Tw, resulting from the joint effects of increasing in Ta ($+0.39 \pm 0.14$°C/decade) and decreasing in Q (-10.1 ± 4.6%/decade) over the 1979–2018 period. In contrast with our results, they found Tw trends lower than Ta trends due to influence of snow melt and glacier melt. Trends in Tw might also be explained by trends in additional drivers, like shortwave radiation (Wanders et al., 2019), which is the dominant flux at air-water surface, and is notably increasing over Europe (Sanchez-Lorenzo et al., 2015). This might explain discrepancies between Tw and Ta trends in spring and summer, when no decreasing trend in Q are found (see Fig. 3).

Strong synchronicity between Ta and Tw anomalies was observed in the present study in the warmest years, and these years were also among those with the largest negative Q anomalies (see Fig. 8). Indeed, increase in summer Tw could be due to co-occurrence with the increase in summer Ta (average correlation: +0.82), and with decrease in summer Q (average correlation: -0.40). These findings are consistent with those of Michel et al. (2020): average Tw-Ta correlation: +0.61, and average Tw-Q correlation: -0.66. For the middle Loire river, Moatar and Gailhard (2006) found that the increase in Ta (resp. decrease in Q) explain 60 % (resp. 40 %) of the increase in Tw. Moreover, the significant change-point in Tw, Ta and Q time series in the late 1980s has also been found in other studies in Europe (Moatar and Gailhard, 2006; Arora et al., 2016; Zobrist et al., 2018; Ptak

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et al., 2019b; Michel et al., 2020). Long-term observational time series like that of the Loire at Dampierre also display a similar change-point.

5.4 Natural trends and anthropogenic influence on Tw

Natural Tw time series were used in the current study for detecting trends, as both EROS and T-NET models are used in a non-influenced set-up (see Sect. 3.1). However, anthropogenic impoundments (e.g. large dams, small reservoirs, and ponds) influence downstream Tw regimes in a diversity of ways that depend on their structure and position along the river continuum (Seyedhashemi et al., 2020). In this regard, on the one hand, large dams, by releasing cold hypolimnetic water in summer, can lower downstream Tw (Olden and Naiman, 2010), and mitigate increasing trend in Tw (Cheng et al., 2020). Nevertheless, it is anticipated that a considerable proportion of streams regulated by large reservoirs may still experience high temperatures and low flows under future climate change (Cheng et al., 2020). The mitigating influence of dams could be of importance for streams in the southern headwaters of the Loire basin since this area both experienced the greatest Tw trends and gathers most of existing large dams. On the other hand, ponds and shallow reservoirs, by releasing warm water can increase downstream Tw (Seyedhashemi et al., 2020; Zaidel et al., 2020; Chandesris et al., 2019) and exacerbate increasing trends in Tw (Wanders et al., 2019; Michel et al., 2020). Nevertheless, the warming effect can be local, and unregulated streams being located closer to such regulated streams may show limited to no warming (Wanders et al., 2019). The warming effect of such surface waters in the current study seem more significant for streams located in lowlands in the middle and north of the Loire River basin where most of the shallow reservoirs are located. In these streams, anthropogenically-induced trends in Tw may be greater than natural ones, and the warming process can get worse through the increasing demand for storing water in small reservoirs for irrigation.

5.5 Implications for river management and aquatic biota

The removal of riparian vegetation can increase Tw (Caissie, 2006), and changes in Tw can be even more sensitive to changes in riparian vegetation than to changes in Ta or Q (Wondzell et al., 2019). We showed that in small streams, an increase of $>$ 25 % of riparian shading could decrease the median trend in spring and summer Tw by 5-16 % (Fig. 10). Spring and summer Tw trends were more pronounced in large rivers, especially in the south of the basin, with a difference in median Tw trends of up to +0.18 °C/decade (Fig. 9), probably due to decrease in Q (up to -2 %/decade, see Fig. S12), greater thermal sensitivity, and the absence of mitigating factors like riparian vegetation shading or groundwater inputs (Kelleher et al., 2012; Beaufort et al., 2020).

Restoring riparian vegetation and shading can therefore substantially mitigate future increases in Tw. In addition, riparian restoration may lessen the impacts of climate change on flood damage to human infrastructure, on riparian biodiversity, on ecosystem vulnerability and on changes in Q (Palmer et al., 2009; Seavy et al., 2009; Perry et al., 2015). However, riparian restoration is not an easy task since the survival, persistence, growth rate of planted species as well as required time for thermal regime recovery under possibly severe future conditions should be studied beforehand (Perry et al., 2015). For instance, it may take between 5 and 15 years for rivers to recover their thermal regime following vegetation growth (Caissie, 2006; Edmonds

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et al., 2000). Moreover, the efficacy of riparian planting is also highly dependent upon the type and structure of forest stands (Dugdale et al., 2018), and this should also be considered in long-term projects.

Stream warming affects cold-water fish populations negatively at the warmer boundaries of their habitat (Hari et al., 2006). Furthermore, changes in spawning and migration timing (McCann et al., 2018; Arevalo et al., 2020), decreases in habitat availability and freshwater quality for organisms (Lennox et al., 2019), and shifts in species distribution (Comte et al., 2013) are already observed consequences of the long-term increase in Tw. Some major changes in fish density and community structure has already been reported in large rivers over France (Maire et al., 2019) for which we also found greater trends in Tw compared to small ones. Therefore, physical process-based thermal models like T-NET can also be used to assess the various stresses on freshwater habitat sustainability due to changes in Q and Tw (Morales-Marín et al., 2019).

6 Conclusions

Regional trends in Tw at the reach resolution were detected and assessed by using the T-NET physical process-based model coupled with the EROS hydrological model over the Loire basin. Using model outputs across 52 278 reaches over the Loire basin, for 3 variables (Ta, Q, and Tw), and 5 time scales (seasons plus annual), we found consistent increasing Tw trends at the scale of the entire Loire River basin, regardless of the season. Critically, the rate of warming for stream temperature was in the majority of cases higher than the rate of atmospheric warming, suggesting a decoupling of thermal trajectories linked to decreasing Q, especially in the southern headwaters. Moreover, Tw trends in all seasons except winter were greater in rivers with Strahler order > 5, which we attributed to the mitigation effect of riparian shading for large rivers.

The synchronicity of extreme events of low flows and high air temperature in the southern headwaters will likely generate a double penalty for existing cold-water aquatic communities. However, riparian shading in small mountainous streams may mitigate such warming. These findings underscore that Ta alone is likely not an adequate proxy to explain stresses and shifts experienced by aquatic communities over time and space, especially in regions with more pronounced stream warming, and thus there is a need to grow and maintain Tw sensor networks. This knowledge can help develop appropriate management strategies to conserve thermal refugia and mitigate extreme thermal events induced by climate change.

Author contributions. HS: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft preparation JPV: Conceptualization, Methodology, Writing - review and editing; JD: Methodology; Writing - review and editing; DT: Resources, Writing - review; CM: Resources; FH: Resources; AM: Writing - review and editing; FM: Conceptualization, Methodology, Writing - review and editing, Supervision

Competing interests. The authors declare that they have no conflict of interest.

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