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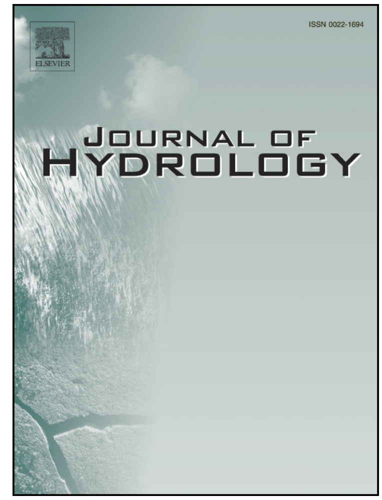

Research papers

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Evaluation of water temperature under changing climate and its effect on river habitat in a regulated Alpine catchment

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Abstract

Habitat quality of alpine river is largely affected by human activity. The exploitation for hydropower, combined with anthropogenic climate change, can alter mountain riverine ecosystems, leading to less suitable hydro-thermal regimes for the fish. Here, we present a new methodology to assess water temperature within a river featuring water exploitation for hydropower purposes, usable to assess future potential deterioration of riverine habit suitability in response to (increasing) water temperature. We then propose an application focusing upon the case study of the Serio River, in Northern Italy, largely exploited by hydropower productions and highly populated by a very sensitive species, brown trout (*Salmo trutta*). The methodology proposed involves a set of tools, i.e. i) the hydrological model *Poli-Hydro*, to evaluate natural hydrological regime, ii) a hydropower plants scheme to assess river water withdrawal, iii) fish density-environment curves to evaluate the hydraulic suitability in terms of trout potential density for adult, young, and fry as a function of hydraulic features, i.e. depth and velocity, and iv) a new, physically based model, *Poli-Wat.Temp*, to assess changes in river water temperature, and possible outbreaks of temperature dependant lethal conditions, such as proliferative kidney disease, and others. To provide an assessment of river suitability, possibly complementing (improving?) models based upon solely hydraulic indexes, we propose a new synthetic River Stress index, combining i) potential fish density as driven by hydraulic variables, and ii) thermal suitability. Given that utmost unsuitable conditions (thermally, and likely hydrologically) are expected under future climate conditions pending global warming, we then projected water temperature, and stream flows until the end of the century, in response to socio-economic scenarios of AR6 of the IPCC, to explore the potential for future decrease of river quality. Water temperature would be largely susceptible to climate change with increase up to +6.5 C° in the worst scenarios, while no clear trend is observed for fish density. Overall, potential density would decrease in winter for adults, and in summer for juvenile and fry in downstream sections. Therefore, by coupling hydraulic, and thermal suitability, one finds that i) Alpine rivers would likely face longer critical periods, with respect to those predicted based upon a solely hydraulic habitat based assessment, and ii) continuous temperature increase as projected until the end of the century would result into worse conditions in summer months, seriously endangering fish guilds.

Keywords

Water temperature modelling; Physical habitat modelling; River stress indicator; Climate change

1. Introduction

Global warming effects upon water ecosystems have now been evident for years. The impact of climate change on freshwater availability was assessed both at regional (Arnell, 1999; Lehner et al., 2006), and global scale (Doll and Zhang, 2010; Sperna et al., 2012; Vorosmarty et al., 2000). Among others, several studies were carried out that highlighted significant warming in the European Alps, decreasing of snow and ice cover, and stream flows modification thereby (Bocchiola and Diolaiuti, 2010; Bocchiola, 2014; Fuso et al., 2020). Few studies focused upon changes of water temperature, which is crucial for the distribution of biotic organisms in the rivers, featuring direct and indirect effects. Beside the direct influence upon dissolved oxygen (Webb et al., 2008; Van Vliet et al., 2013), increase in water temperature may provide emergence of diseases, such as proliferative kidney disease PKD in freshwater fish (Carraro et al., 2017). PKD is a major threat to wild and farmed salmonid populations because of its lethal effect at high water temperatures. The disease was recognized as a frequent cause of decline in fish populations over the last decades, even driving local extinctions of endemic and/or commercially important fish species (Borsuk et al., 2006).

When studying thermal regime of rivers, attention was cast hitherto upon the link between water, and air temperature. The latter can indeed be seen as a driver of the former, because it affects heat flows to/from water (Edinger et al., 1968; Zhu et al., 2018). Thus, projected air temperature increase under global warming will likely affect mountain streams temperature, and living conditions of river species (Isaak et al., 2010; Santiago et al., 2016; Borgwardt et al., 2020). Stochastic models exist that link water and air temperature, and are easy to implement, thanks to the large diffusion of air temperature data (Caissie et al., 2001, Caissie et al., 1998). Further meteorological data are needed to apply more sophisticated deterministic models based upon energy balance (Caissie et al., 2005, Bustillo et al., 2015). However, the latter are more appropriate to analyse anthropogenic activities directly impacting rivers, e.g., diversion channels, industrial flows, and presence of reservoirs (Benyahva et al., 2007). Dams and minor barriers disrupt the hydrological and fluvial ecosystem connectivity, affecting the river environment, and thermal regime (Kedra and Wiejackza, 2017). Particularly, diverted water is less susceptible to heating, given that often times diversion channels are buried in the ground. Then, return of such colder water in the main river (typically at some length downstream, and at a lower altitude) would cause a sudden drop in water temperature. On the other hand, water flow left in the river has less thermal inertia due to decreased discharge, leading to higher temperature in summer, and lower in winter (Meier et al., 2003). Thermal models depending upon air temperature only may not be always suitable, i.e. the effect of flow magnitude cannot be neglected (Toffolon and Piccolroaz, 2015), and more sophisticated heat exchange models are required, that make spatial dependence and effects of increasing flow downstream more explicit.

The EU Biodiversity strategy for 2030 (EC, 2020) states the need to re-establish freshwater ecosystems, and the natural functions of rivers. In this context, the assessment of river habitat quality is a key factor (Lamouroux et al., 1998, Canobbio et al., 2013), and one expects that fish distribution/abundance will reflect riverine conditions on a larger spatial scale (Lamouroux and Cattaneo, 2006, Van Compernolle et al., 2019). Physical habitat models have been widely used to describe the connection between instream flow and habitat availability for different target species (Fornaroli, 2016). However, in addition to hydrological flows, water temperature is determinant for river species occurrence (Nukazawa et al., 2011, Jonsson B. et Jonsson N., 2009). Thus, to simulate habitat suitability, it seems relevant to consider multiple habitat characteristics, and integrated frameworks that couple water temperature and hydraulic parameters may be considered (Morid et al., 2020).

The main goals of our study are 1) to propose a new physically based thermal model, called *Poli-Wat.Temp* to assess water temperature of a river characterized by complex geometry of withdrawal, and return to/from hydropower plants, and 2) to evaluate the combined effect of hydraulic, and thermal stress upon mountain river habitat, by elaborating a new index, which we call *River stress*.

We develop here the method and then we propose an application to a stretch of an Alpine river, the Serio catchment in northern Italy. We chose this catchment for two reasons, i.e. i) it nests several hydropower plants, displaying a complex geometry of diversion/return channels, affecting both hydrological and thermal regimes, and ii) it is populated by *Salmo trutta*, the presence of which is nowadays made possible by high dissolved oxygen and somewhat acceptable water temperature (Armour, 1994). The thermal model was calibrated using field data of air and water temperature, taken during surveys in several cross sections along the Serio River. River discharge at several chosen locations along the stream was assessed using the semi-distributed, physically based hydrological model *Poli-Hydro* (Soncini et al., 2017) at the basin scale. For habitat quality assessment, we then used the so modelled discharges as an input to density-environmental functions for *Salmo trutta* at different stages (young, adult, and fries), calibrated recently for the Serio River (Fornaroli et al., 2016), to then evaluate the limiting effects of hydro-morphological variables, such as water depth, current velocity, substrate size and composition, upon habitat conditions. We then propose a new index of river stress, by combining habitat suitability and water temperature, so obtaining more credible habitat assessment under given climate conditions.

We projected water temperatures, and stream flows to the end of the XXI century, in response to climate change as projected under the socio-economic scenarios (SSP) of the most recent assessment report (AR6) of the Intergovernmental panel on climate change (IPCC), to highlight areas of increased stress, usable for future planning of adaptation strategies. The paper is organized as follows. The case study and available data are reported in section 2, where also the methods are discussed. The results of model calibration, and subsequent of application are discussed in Section 3. Discussion, and conclusions are in sections 4, and 5, respectively.

2. Materials and methods

2.1. Case study

Serio River is 124 km long, nested in Lombardy region (northern Italy), flowing in the provinces of Bergamo (BG) and Cremona (CR), to the outflow of the Adda River (Figure 1). It has a watershed of 1256 km^2, and the source is located at 2500 m asl nearby Torena mount, in the Orobic Prealps. Serio is a mountain river, with mono-cursal bed, step-pools geometry, and coarse substrate. At ca. 600 m asl in Parre (BG), the river becomes more and more braiding, and gravel/sand bottomed. At ca. 100 m asl, it starts meandering with very gentle slope, and fine substrate. Here we consider the river stretch upstream of Parre, most relevant for water quality assessment, and for measurable presence of the target fish species.

The watershed is located within a temperate region, with a total precipitation of ca. 1300 mm per year, and mean temperature of +23.8 °C in July, and -1.5°C in January. The river receives large precipitation in autumn, and large snow melt in spring. No ice melt contribution is present here, due to the absence of permanent glaciers in the area. The hydrological regime displays low discharges in January and February, mild flow in spring, and main floods in fall.

The Serio River is largely exploited for hydropower production. Seven run of river power plants are located along the river that we know of, in Valbondione to Parre stretch (Figure 1). The water collecting and returning points form 7 stretches, where the hydrological and thermal regime is altered with respect to natural conditions.

The considered reach is classified as a "high regard" area for fishing by the province of Bergamo (2009), where the most valued fish species is Brown Trout (*Salmo trutta*), protected from overfishing by a limitation in time and amount (Lombardy region, 2003). Changes in precipitation and temperature may negatively affect the hydrological regime of the area (Armour, 1994, Viganò et al., 2016, Groppelli et al., 2011), leading to critical hydro-thermal conditions for the fish. It is therefore essential to study the impact of such present, and potential future changes upon river quality, to plan adaptation strategies for safeguarding of the species and their ecosystem.

Here, we assessed the effect of climate change upon river habitat within 8 stations of the Upper Serio (Figure 1), where hydro-morphological and topographic surveys, together with electro fishing samplings were carried out, as described e.g. in Viganò et. al (2016).

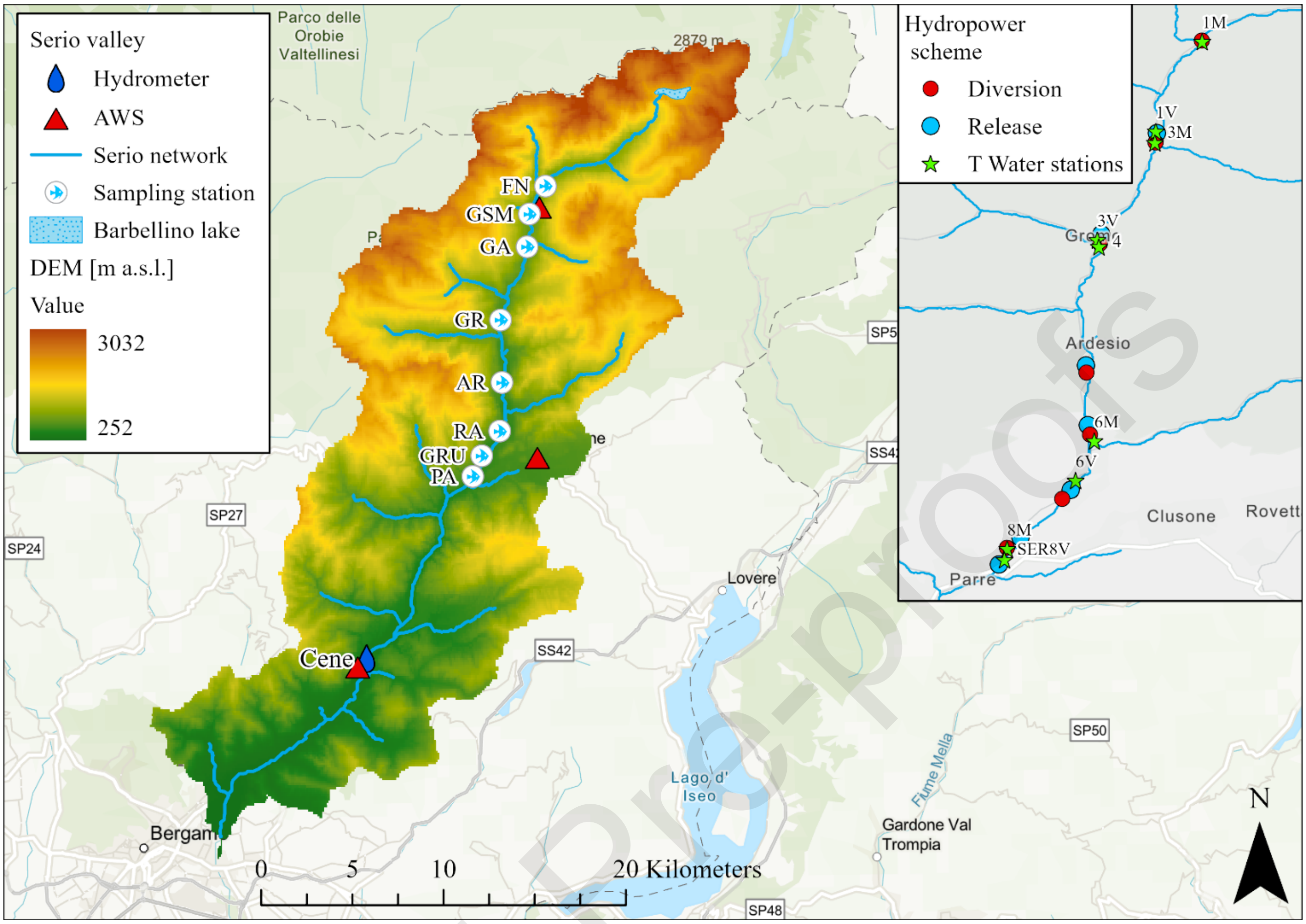

Figure 1. Catchment area of Serio River. We report the position of automatic weather stations (AWSs), hydrometric stations, sampling station for fish habitat assessment, and water temperature sampling stations, and as well a scheme of the hydropower diversion-restitution system. Geographic Reference System WGS 84.

2.2. Data available

Daily series of precipitation, and air temperature from 3 automatic weather station (AWS) of ARPA Lombardy Authority were used here as inputs to the hydrological model *Poli-Hydro* (e.g. 9). The model was implemented with a spatial resolution of 100x100 m^2, for a 10 year control run period (CR), 2012-2021. Other inputs were the GIS map, i.e. digital elevation model (DEM) of the catchment (Earth data Available online: https://earthdata.nasa.gov/), and the land use maps from CORINE land cover (CLC

2018 — Copernicus Land Monitoring Service Available online: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018). Daily discharges at Ponte Cene hydro station during the CR period were used for model calibration under natural regime conditions, while data of Minimum Instream Flow (MIF) and maximum operable discharge (Q_{HY}) for each hydropower station were used to switch from natural, to regulated hydrological regime (Table 1).

To setup the thermal model, water temperature data were gathered within the sites reported in Figure 1 (see Table 2), for three years (June 2018-October 2021), using *iButton* devices (range -5 to +26 °C, resolution: ±0.0625°C, measurement interval 10 min). Water temperature data were downloaded, and a linear interpolation between consecutive measurements was performed to obtain a continuous trend of water temperature (one value per minute), and eventually daily mean, maximum and minimum temperature. Finally, density-environmental relationships for *Salmo trutta* at different stages (fry, juvenile, adult) as derived after sampling in eight stations along the river (Fornaroli et al., 2016) were used for river habitat assessment (Table 1).

Station	ID	Longitude	Latitude	Altitude m a.s.l.	MIF [m^3s^{-1}]	Q_{HY} [m^3s^{-1}]
Fiumenero	FN	9.96°	46.02°	788	0.4	4.5
Gromo San Marino	GSM	9.95°	46.01°	750	0.4	4.5
Gandellino	GA	9.94°	45.99°	687	0.6	4.5
Gromo	GR	9.93°	45.95°	604	0.9	9.7
Ardesio	AR	9.93°	45.92°	542	1	8
Rasini	RA	9.92°	45.90°	537	1.1	12
Grumella	GRU	9.91°	45.89°	495	1.3	11
Parre	PA	9.90°	45.88°	487	1.5	10.3

Table 1. Fish sampling stations with acronym and location. For each station are reported the values of Minimum Instream Flow (MIF) and maximum operable discharge (Q_{HY}) of hydropower plant affecting the station.

ID	Longitude	Latitude	Altitude m a.s.l.
1M	9.959°	46.021°	789
1V	9946°	45.996°	691
3M	9.946°	45.993°	692
3V	9.930°	45.966°	635
4	9.930°	45.964°	626
6M	9.929°	45.910°	516
6V	9.924°	45.899°	503
8M	9.905°	45.880°	491
8V	9.904°	45.877°	486

Table 2 Water temperature stations (from upstream to downstream). Coordinates in WGS84.

2.3. River suitability assessment

To assess the river suitability of Serio River several methods/models were applied here in cascade. For clarity, we report in Figure 2 a flowchart displaying the data and methods adopted here.

Using precipitation and air temperature data (P, T), and watershed GIS maps we setup the hydrological model *Poli-Hydro*, to derive daily discharges Q. We used then the modelled discharges as input to a habitat suitability model that defines fish potential density, used to evaluate habitat suitability in the sample locations. With the thermal model, based upon known the geometry of the hydropower system, and of the return (tail-race) system, we then used T, and the modelled discharge Q, to assess pointwise daily water temperature T_w. Then, we defined habitat suitability classes and water temperature thresholds for PKD. Next, we provided an indicator of stress of the river *RS*, by matching hydraulic habitat suitability, with suitability based upon water temperature, which we call *TS*. For future projections, we downscaled values from GCM scenarios to get future precipitation, and temperature, P_{fut} and T_{fut}. These were fed to *Poli-Hydro* to assess future discharges Q_{fut}. Still using the thermal model, we then exploited T_{fut}, Q_{fut}, to evaluate future scenarios of water temperature $T_{w,fut}$, and suitability thereby. Here, we assumed for simplicity that the present hydropower scheme would remain unchanged in the future. Finally, with the same approach above, we provided projections of the future river stress RS_{fut}.

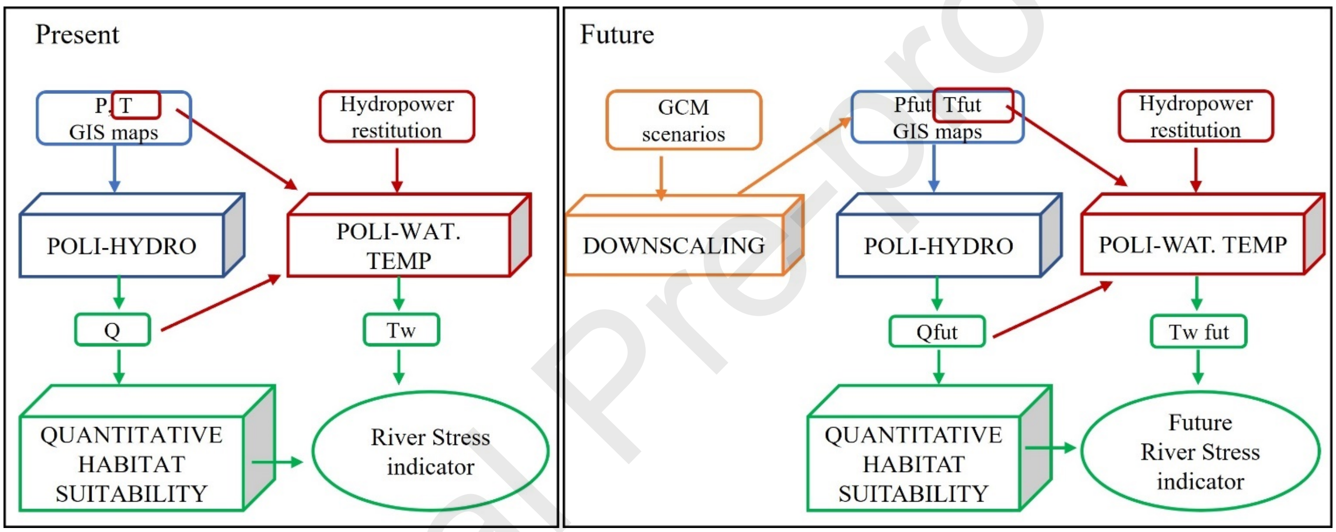

Figure 2. Flowchart of the methodology adopted for present and future river stress assessment.

2.4. Hydrological modelling

The *Poli-Hydro* hydrological model was already used, validated, and described in several studies hitherto (Soncini et al., 2017), where the reader is referred thereby for a detailed description. *Poli-Hydro* computes daily soil water balance for each cell within the catchment area (here defined with ARC-GIS software). The control variable is soil water content, inputs are given by liquid precipitation, air temperature, and snow/ice melt, and outputs are water fluxes in the river. Snow accumulation on the ground, in the form of Snow Water Equivalent (SWE) is assessed from precipitation, i.e. snowfall when temperature in one cell is below 0°. SWE melt is then evaluated with a mixed degree day formula (e.g. Pellicciotti et al., 2005). Temperature is distributed spatially using monthly vertical gradients as from observations. By doing so, the model can reconstruct for each cell rainfall, snow pack on the ground, snow/ice melt (however as reported, no ice surface is present in the catchment here), surface and subsurface flows. The latter are then routed (using a IUH function, i.e. Nash model) to the final outlet of each sub-basin, to obtain daily stream flow hydrographs. The model was calibrated here for natural discharge estimation, and then validated using goodness of fit statistics, i.e. *Bias*, and monthly *NSE* (Nash-Sutcliffe Efficiency) calculated against the observed discharges at Ponte Cene hydrometer, relatively undisturbed by flow regulation, and simulated discharges. To include water withdrawal from hydropower stations, for each location, we assumed that 90% of the discharge above minimum instream flow (i.e. ecological flow) MIF is diverted, until maximum operable flow (Equation 1).

$$
\begin{aligned}
Q &= Q_{nat} && if\ Q_{nat} < Q_{MIF} \\
Q &= (Q_{nat} - Q_{MIF}) \cdot 10\% + Q_{MIF} && if\ Q_{MIF} < Q_{nat} < Q_{HY} \\
Q &= Q_{nat} - Q_{HY} && if\ Q_{nat} > Q_{HY}
\end{aligned}
\qquad (1)
$$

Here Q is actual river discharge to be assessed, and Q_{nat} is natural discharge as evaluated by *Poli-Hydro*. Q_{MIF} is Minimum Instream Flow value, specific for each power plant, and Q_{HY} is maximum discharge conveyed to the power plants. As per regulation of Lombardy region, Q_{MIF} is provided for every plant (Table 1), and we used the proposed values accordingly, in the assumption that hydropower managers properly release Q_{MIF} downstream of intakes.

2.5. Hydraulic habitat assessment

To assess hydraulic based suitability, we used a habitat suitability model that defines potential density based upon a limiting factor approach, as recently proposed by Fornaroli et al. (2016). These functions use water velocity/depth, substrate characteristics, availability of refuges, and mesohabitat type. The latter is divided in four categories, namely i) Shallow pool, ii) Deep pool, iii) Riffle, iv) Run, as retrieved within the 8 sampling sites (Figure 1, Table 1). Using the functions as developed in our study area (Fornaroli et al., 2016) we assessed the potential density (PD) (ind/m^2) with respect to discharge for the young and adult trout, and for fries, obtaining a potential number of individuals per square meters in each site, for each discharge level. So, we calculated *PD* for the CR period in each sampling site, and for each life stage of *Salmo trutta*. We then defined two classes of quality, i.e. poor and good, corresponding to the intervals for PD 40-60%, 60-100%, of the maximum value of daily potential density PD_{max}, respectively. We chose 40% as a lower bound, because it was the lowest value resulting from our simulations. Thus, we added up the total number of days in each class, for the 4 seasons (winter, spring, summer, and fall) and we averaged over three different decades, i.e. CR (2012-2021) as a reference in the present conditions, a period one P1, half century (2046-2055), and a period two P2, end of century (2091-2100), to evaluate future river suitability.

2.6. Water temperature modelling

Here we developed a model for water temperature assessment, which we called *Poli-Wat.Temp*. This is a coupled model, interacting with *Poli-Hydro*, to take as an input estimated stream flows, and air temperature data. The *Poli-Wat.Temp* model uses a one-dimensional energy balance equation, suitable for shallow rivers where vertical gradient of temperature can be neglected (Caissie et al., 2005), as follows:

$$\frac{\partial T_w}{\partial t} + v \cdot \frac{\partial T_w}{\partial x} - \frac{1}{A} \cdot \frac{\partial}{\partial x}\left(A \cdot D_L \cdot \frac{\partial T_w}{\partial x}\right) = \frac{B}{\theta \rho A} \cdot H_{tot} \quad (2)$$

Therein, T_w is water temperature, v is mean water velocity, x is distance along river axis, A is cross section area, B is river width, D_L is a dispersion coefficient in the flow direction, θ is specific heat of water, ρ is water density, H_{tot} is total heat flux from the external environment to the river, including solar radiation, air temperature, evaporative heat fluxes, and net long-wave radiation. Here, we considered air temperature, and incident solar radiation as external sources of heat, that we modelled as linear functions of the air-water temperature gradient, and of incident, clear sky solar radiation, respectively

$$H_{tot} = \alpha \cdot (T_{air} - T_w) + \beta \cdot Rad \quad (3)$$

The dispersion term in Eq. 2 $\partial\left(A \cdot D_L \cdot \partial T_W / \partial x\right) / \partial x$ may be generally neglected in alpine rivers, characterized by medium/high flow velocity, so that heat transfer along the x axis basically occurs by advection (Deas and Lowney, 2000) $v \cdot \partial T_w / \partial T_w$.

We solved Eq. 2 recursively, to evaluate heat fluxes from an upstream station to a downstream one, with temperature T_{w1}, and T_{w2} respectively, using a finite differences scheme, where ∂x was approximated with the distance L between the considered stations, and ∂t is 1 day.

Using a first-order upwind scheme, and approximating river channel shape with a rectangular one, roughly valid for naturally shaped rivers, such as Serio River here in several traits, we moved from Equation 2 to Equation 4, and then isolated $T_{w2,i2}$ to explicity assess downstream temperature at day 2 (Eq. 5).

$$(T_{w1,i2} - T_{w1,i1})/\Delta t + v/L \cdot (T_{w2,i2} - T_{w1,i2}) = \frac{1}{\theta \rho h} \cdot (\alpha \cdot (T_{air} - T_{w1,i2}) + \beta \cdot Rad_{i2}) \tag{4}$$

$$T_{w2,i2} = T_{w1,i2} + \frac{L}{v \Delta t \theta \rho h}(\alpha \cdot (T_{air} - T_{w1,i2}) + \beta \cdot Rad_{i2}) - \frac{L}{v \Delta t}(T_{w1,i2} - T_{w1,i1}) \tag{5}$$

Therein $i1, i2$ indicate day 1, and 2, and h is water depth. The water depth, and the velocity v could be evaluated as (power) functions of discharge. In this space dependant formulation, one needs to fix an upstream initial condition for temperature. Therefore, we set the initial condition of the temperature at the largest lake upstream, i.e. Barbellino lake, where changes in temperature are more gradual and season dependant. The Barbellino reservoir is an artificial lake located at 1870 m a.s.l., 9.3 km upstream of the first thermal station, where outflow is regulated by a hydropower dam, 69 m tall. Serio River starts at the toe of the Serio waterfall (with a 315 m jump, i.e. the tallest waterfall of Italy) watered with the reservoir output. Generally, due to thermocline water temperature at a depth of 20+ m can be taken as constant, at +4° C (Dodds et Whiles, 2010). However, withdrawal from the bottom outlet has a mixing effect that has been shown to impact upon *hypolimnion* (lake bottom) temperature (Saber et al., 2019, Nurnberg). Therefore, here we modelled Barbellino hypolimnion temperature using a sinusoidal function, well representing lake bottom temperature in other regulated lakes (48). Therein, minimum water temperature can be fixed at +4 °, and phase, amplitude and mean values are related to seasonal air temperature as

$$T_{wBar} = \gamma \overline{T}_y + \omega(\overline{T}_{sum} - \overline{T}_y) \cdot \sin\left(2\pi \frac{day - lag}{365} - \pi\right) \tag{6}$$

Therein, $\overline{T}_y$ and $\overline{T}_{sum}$ are annual, and July mean temperature estimated at Barbellino lake, that we linked to average, and summer variation of water temperature, respectively. Also, γ, ω, lag are calibration parameters. For model tuning, we used data of water temperature at the station of Fiumenero.

As mentioned above, along the river stem several hydropower plants divert water, modifying stream flows, and temperature thereby. To account for this, the thermal balance as from Eq. 5 was further modified to consider stream flow changes between different sections, as due to i) hydrological flow increase (contributing catchment), ii) water diversion for hydropower, and iii) water return from hydropower (tail race channels). The water used for hydropower in Serio River is often collected in channels buried in the ground, i.e. largely insulated from the atmosphere, and restitution at lower altitude occurs quite rapidly with respect to stream flow dynamics (i.e. with a shorter delay than the time span required for the river flow to reach the same altitude). Accordingly, we made the hypothesis that diverted/returned water keeps the same temperature, i.e. the water temperature at the restitution point is the same as the (stream) temperature at the point of withdrawal. One can thereby assess water temperature downstream of a flow returning point (i.e. downstream of a tail race channel) as the weighted average of the upstream (in river) temperature, and the tail race temperature as

$$T_{w3} = \frac{T_{w1} \cdot Q_1 + T_{w2} \cdot Q_2}{Q_1 + Q_2} \tag{7}$$

Here, T_{w3} is water the temperature downstream tail race, and T_{w1}, T_{w2} are temperature of instream and diverted water, and Q_1,Q_2 are discharge values thereby.

2.7. Critical temperature for thermal suitability

In this case of study, where *Salmo Trutta* is abundant, and oxygen rate during our ten-year campaign was always found at saturation level due to the high water turbulence of many riffles/rapids, we chose as a target disease PKD, being particularly temperature dependant (Waldner et al., 2019), and a main threat for Alpine trouts (e.g. Wahli et al., 2007). To define the critical thresholds of water temperature for PKD we relied upon the most recent literature (Carraro et al., 2017, Santiago et al., 2016, Borgwardt et al., 2020), and we decided to use the criteria as set out by Borgwardt et al. (2020), considering water temperature T_w, and a corresponding consecutive duration d_{Tw}.

When the daily mean temperature is above $T_w \geq +15$ °C, a situation of i) *possible outbreak* of PKD occurs if the exceedance lasts for $d_{Tw} \geq 14$ consecutive days (Eq. 8), and a situation of ii) *low mortality* occurs when $d_{Tw} \geq 29$ consecutive days (Eq. 9). The most worrisome condition, i.e. iii) *high mortality*, takes place when the daily mean temperature exceeds $T_w \geq +18$ °C and $d_{Tw} \geq 26$ consecutive days (Eq. 10).

$$Possible\ Outbreak\!:\quad T_w \geq\ +15\,°\mathrm{C}\ \cap\ d_{Tw} \geq 14 \tag{8}$$

$$Low\ Mortality\!:\quad T_w \geq\ +15\,°\mathrm{C}\ \cap\ d_{Tw} \geq 29 \tag{9}$$

$$High\ Mortality\!:\quad T_w \geq\ +18\,°\mathrm{C}\ \cap\ d_{Tw} \geq 29 \tag{10}$$

2.8. River stress indicator

To provide a more comprehensive habitat assessment under present, and future climate, we constrained habitat suitability upon water temperature, by calculating a River Stress indicator RS, representing the number of days per year when the river is in stress conditions. RS is defined as the union of i) days of poorest river quality, e.g. number of days when PD is 40-60% of PD_{max}, and days when ii) water temperature is above the lowest threshold for PKD occurrence, e.g. possible outbreak, ideally more responsive to climate change.

$$RS = 0.4\, PD_{max} \leq PD \leq 0.6\, PD_{max} \quad \cup \quad (T_w \geq +15\,°\mathrm{C} \;\cap\; d_{Tw} \geq 14) \tag{11}$$

We calculated the total number of days when the river would be in a poor quality conditions at each sampling site, for the 4 seasons, and we averaged this number on the three reference decades, CR (2012-2021), P1(2046-2055), and P2 (2091-2100).

2.9. Hydrological projections

To evaluate future air temperature to constrain hydrological scenarios we performed a downscaling of the outputs from six Global Circulation Models (GCMs), from the last Assessment Report 6 (AR6) of the IPCC, namely European EC-Earth3.0 (EC-Earth), CESM2 (Danabasoglu et al., 2020), ECHAM6.3 (Mauritsen et al., 2019), HADGEM3 (Ridley et al., 2018), MIRCOC6 (Kataoka et al., 2020), and CMCC-CM2 (Cherchi et al., 2019). For each model, we considered the 4 shared socio-economic pathways (SSPs) that are being used as part of the experiment Coupled Model Intercomparison Project Phase 6, CMIP 6, of the AR6 (O'Neill et al., 2016). SSP 1 and SSP 5 project a positive development of society, but while the latter would be at the expense of an economy based on fossil fuel, the former foresees a sustainable economy. The SSP 2 scenario follows the historical trend, while the SSP 3 and SSP 4 foresee a negative development of the society dynamics worldwide. Four SSPs scenarios were used in this study, based on the Representative Concentration Pathways of the AR5, i.e., RCP 2.6, 4.5 and 8.5 scenarios, namely SSP 126, 245, 585 and an intermediate SSP370 scenario. Precipitation was spatially downscaled (i.e. from GCM cell to rain gauges), with a stochastic space random cascade model (Groppelli et al., 2011a), while for temperature we used a correction with a mean monthly ΔT approach (Groppelli et al., 2011b).

3. Results

3.1. Hydrological modelling and flow projections

Poli-Hydro model was calibrated to fix the necessary parameters of soil permeability, and snow melting for a calibration period 2015-2018, by matching Q values as measured at the Ponte Cene hydrometer (Figure 3). The bias between observed and modelled monthly stream flows was $Bias_{\%}$ = -7%, and NSE = 0.71. Similar statistics values were obtained for the validation period, 2019-2020 ($Bias_{\%}$ = -6%, NSE = 0.73). A table with the calibration parameter of *Poli-Hydro* model is given in the supplementary material.

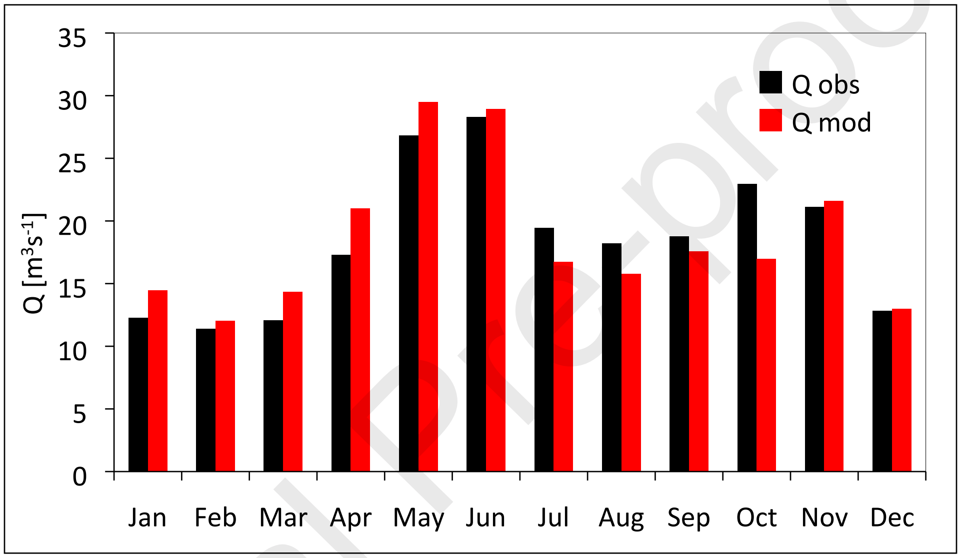

Figure 3. Mean monthly flows at Cene Ponte obs/mod during the period 2015-2018.

After model calibration, we used *Poli-Hydro* to assess projected flow discharges. We report in Figure 4 the projected mean monthly flow for each SSP, averaged over the 6 GCMs, at mid-century P1, and end of century P2, and comparison with discharges in CR period (2012-2021). The increase of liquid precipitation at the expense of solid precipitation in winter months would lead to an increase of stream flows therein. The decrease of discharge between May and October would be due to decrease of precipitation and to a lack of snowmelt and increase of evapotranspiration. Overall, the average annual discharge ($E[Q_y]$) of 21.26 m^3s^{-1} in the CR period, would decrease in the future to $E[Q_y]$ = 19.19 m^3s^{-1}, and $E[Q_y]$ = 17.83 m^3s^{-1} for SSP 585 at P1, and P2, respectively.

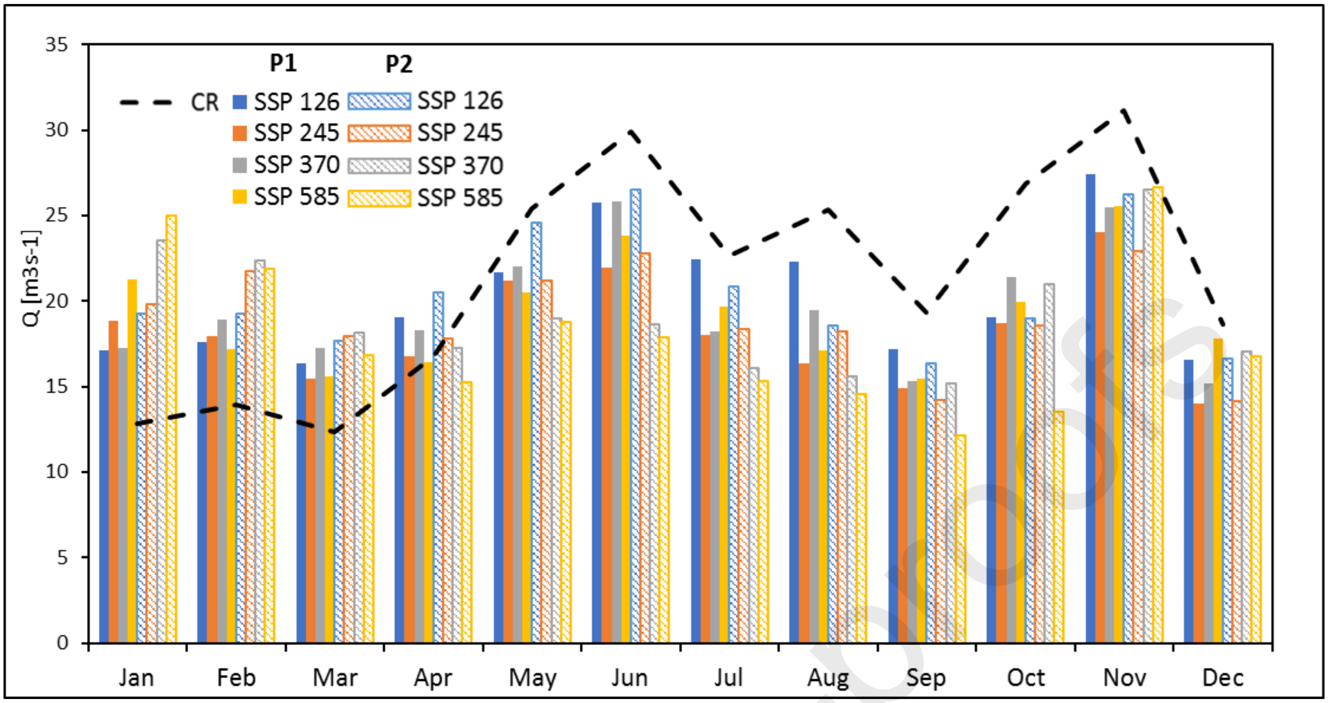

Figure 4. Projected mean monthly flows at Cene Ponte for each SSP at mid-century P1 (solid colour) and end-century P2 (striped colour). The black line represents the mean monthly discharge in the CR period.

3.2. Thermal modelling

Poli-Wat.Temp model calibration, namely for parameters α and β, was carried out by minimizing $Bias_{\%}$ and Random Mean Square Error*, RMSE***.** For calibration, starting from the measured water temperature at Fiumenero (1M), we applied the thermal model downstream, and then we corrected the parameters in order to fit the modelled water temperature to observed data in Parre (8V).

Then, we calibrated the parameters $\gamma, \omega, Lag,$ of Barbellino temperature model by applying *Poli-Wat.Temp* from Barbellino to the first station where we had measured data, i.e. Fiumenero. Here, we minimized *bias* and *RMSE* of the modelled temperature against the measured data at Fiumenero station (Figure 5). The calibration parameters for the *Poli-Wat.Temp* for Barbellino temperature are shown in the supplementary material (Table 5, Table 6).

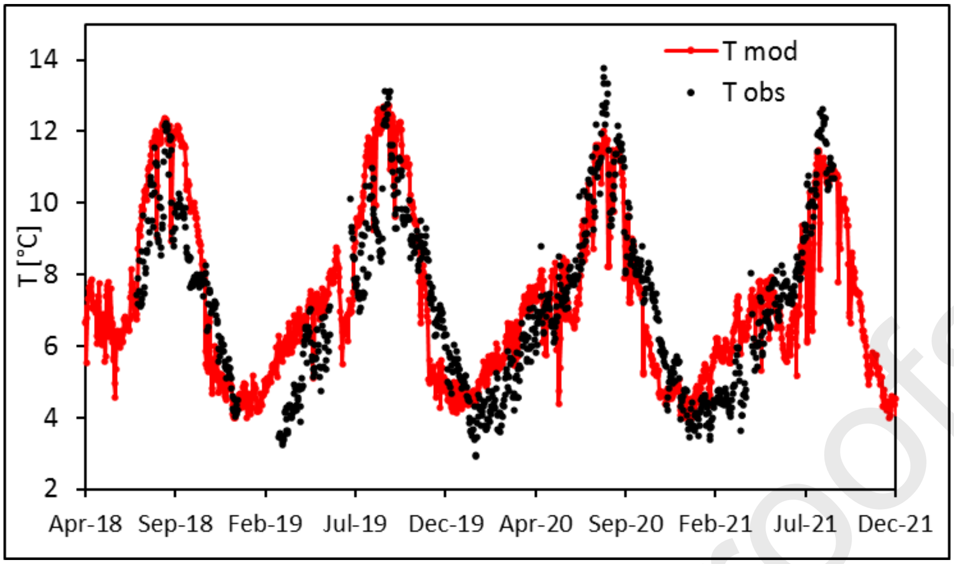

Figure 5 Time serie of estimated water temperature at Fiumenero station (red) vs observed ones (black).

Finally, we applied the thermal model from Barbellino to Parre, and we performed model validation, by matching for each station the computed values of water temperature with the measured ones, and evaluating *bias* and *RMSE* thereby (Table 3).

Station	Bias	Std
1M	-0.31	2.06
1V	0.89	2.32
3V	0.07	1.44
3V	0.70	1.74
4	0.33	1.18
6M	-0.15	1.49
6V	-0.06	2.11
8M	-0.16	1.60
8V	-0.12	1.39

Table 3. Values of bias and standard deviation [C°] of measured vs modelled temperature at each station of Serio River.

3.3. Thermal suitability

In Figure 6 we report the mean monthly temperature as simulated for the 8 river stations during the CR period (2012-2021) for the most critical month, i.e. August, when temperatures are the highest (and the flow the lowest). Although the average temperature is below the critical one for PKD, also in the most downstream stretch, sporadic exceeding of the threshold is found for the 3 most downstream stations, where PKD may burst, possibly with low impact.

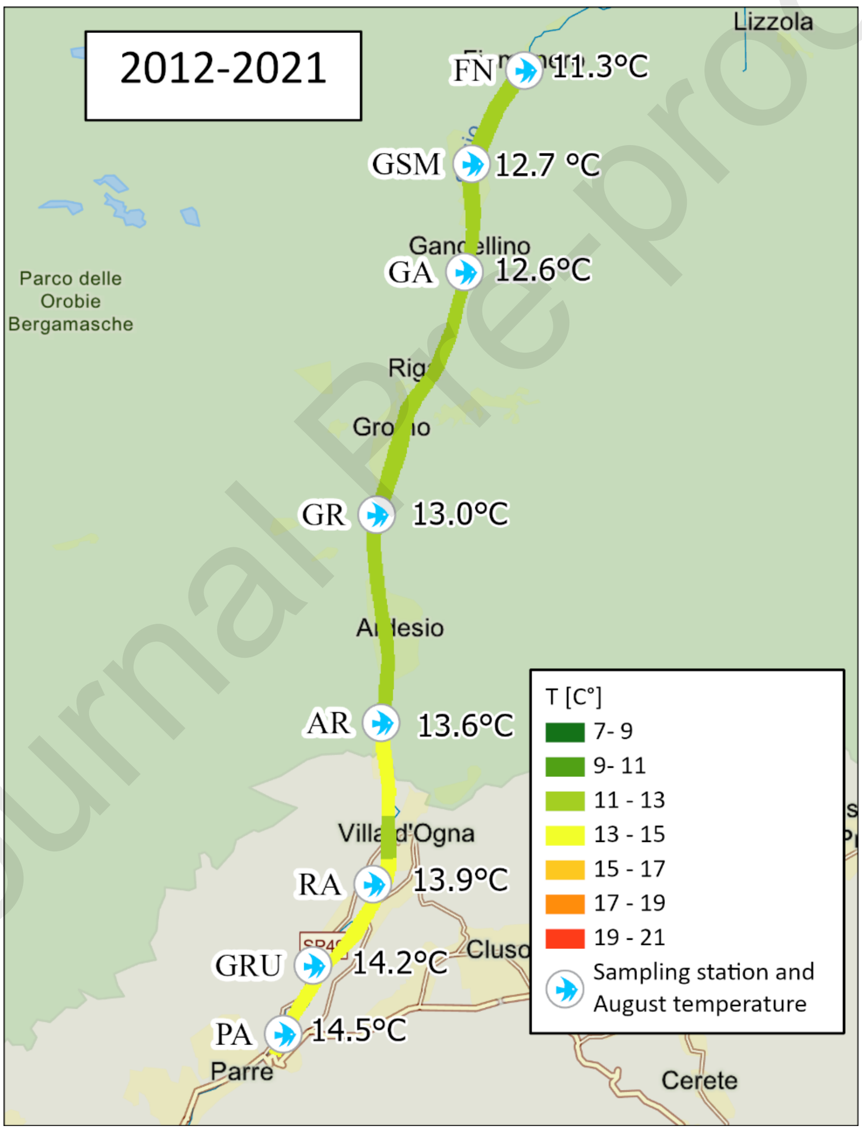

Figure 6. Average water temperature during the CR period (2012-2021) for the whole stretch (color scale) and the sampling stations (text).

3.4. Habitat suitability

With *Poli-Hydro* model we simulated daily discharges within the 8 sampling locations, and we evaluated the corresponding PD in each station. In Figure 7 we reported the number of days per year, averaged along CR period, when trout PD falls in each of the two classes that we defined, i.e. good or poor, based upon the maximum value of daily potential density PD_{max}. We can see that PD is characterized by higher variability between the upstream and downstream sections, mainly for adults and juvenile, than for fry. But for adults, differently from fry and juvenile, most of the downstream sections show seemingly little suitable habitat conditions, in almost all seasons. Contrarily, for young trout, one finds low habitat suitability only in the two upstream sections, while overall quite acceptable flow conditions are found. This is true also for fry, except in downstream sections where habitat is sometimes less suitable.

	CR 2012-21																							
	winter						spring						summer						fall					
	ad		fry		juv		ad		fry		juv		ad		fry		juv		ad		fry		juv	
FN	90	0	92	0	18	73	90	0	92	0	44	48	92	0	92	0	91	1	91	0	91	0	74	17
GSM	84	6	92	0	4	86	67	23	92	0	37	55	40	52	92	0	68	24	71	20	91	0	28	63
GA	84	6	91	1	88	3	88	2	89	3	92	0	89	3	92	0	91	1	90	1	83	8	91	1
GR	1	89	92	0	90	0	3	87	92	0	92	0	12	80	92	0	92	0	9	82	91	0	91	0
AR	4	86	92	0	83	7	37	53	92	0	88	4	60	32	92	0	84	8	25	66	91	0	81	10
RA	87	4	89	4	90	0	62	28	65	27	92	0	49	43	92	0	92	0	73	18	73	18	91	0
GRU	90	0	89	4	88	2	90	0	67	25	91	1	92	0	92	0	90	3	91	0	74	18	90	1
PA	49	41	88	4	90	0	54	36	63	30	92	0	82	10	92	0	92	0	84	7	72	19	91	0

Figure 7. Total number of days per year when trout density in each sample station falls within each class, i.e. good (green bar), and poor (red bar), for each season, averaged along the CR period, for each life stage of the trout. Bar width visually indicates the length of the period (over the length of the season, ca. 90 days).

3.5. River stress

We reported in Figure 8 the river stress indicator, for each sampling site, and trout life stage, averaged over the CR. Since temperature is nearly always below the PKD critical threshold, the stress conditions for the river are mainly due to poor habitat suitability. One can see the (negative) contribution of temperature to RS only in downstream sections and in summer months, where sporadic exceedance of the thermal threshold is found.

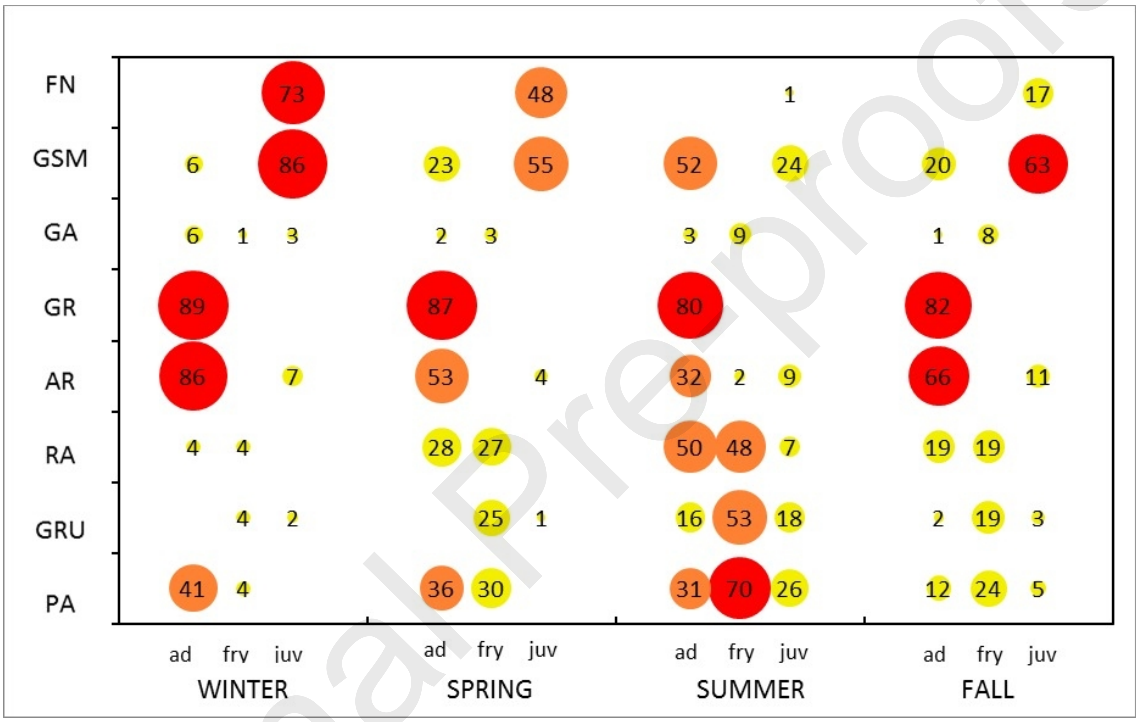

Figure 8. River Stress index, expressed in number of days per year, for each season, averaged along the CR period, for each life stage of the trout, at each sampling point. Days 0-30 (yellow), days 30-60 (orange), days 60-90 (red).

3.6. Future thermal suitability

Our modelled water temperature in future scenarios is reported for the whole stretch in Figure 9 using average values of the 6 GCM models only for SSP126, and SSP585, as respectively the more optimistic, and pessimistic ones, in P1 and P2. One finds that in the worst-case scenario, the model estimated an increase up to +6.5 °C during August, which is again the most critic month, with likely severe consequences on trout health. Indeed, as water temperature would increase, PKD outburst would become more and more frequent, and more severe. In Figure 10 we report the average number of days per year when temperature would be above PKD threshold during CR, under all future scenarios. All scenarios exhibit possible outbreaks. However, while for mid-century P1 spreading of PKD would be limited to most downstream sections, during P2, under the worst scenarios PKD threshold would be exceeded for most of the summer, possibly leading to high mortality in downstream sections, and low mortality elsewhere in the reach.

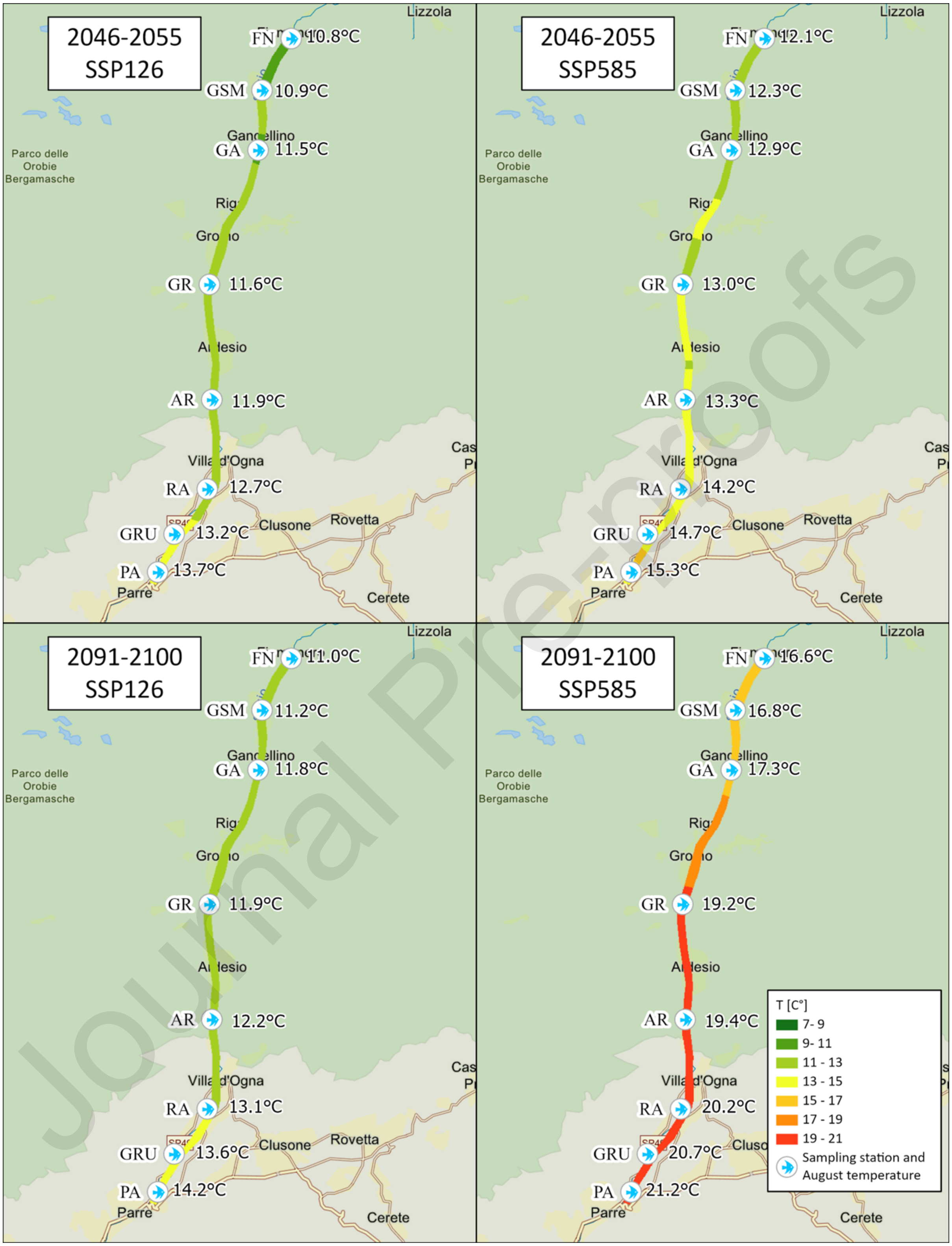

Figure 9. Average August water temperature for P1 and P2, and 2 scenarios, i.e. SSP 126 in 2046-55, SSP 585 in 2046-55, SSP 126 in 2091-2100, SSP 585 in 2091-2100.

		CR	2046-55				2091-2100			
		2012-2021	SSP 126	SSP 245	SSP 370	SSP 585	SSP 126	SSP 245	SSP 370	SSP 585
Possible Outbreak (T > 15 °C for over 14)	FN								54	60
	GSM								57	66
	GA								68	73
	GR							2	82	83
	AR							5	84	85
	RA	4				2		22	94	93
	GRU	6			4	6		35	100	99
	PA	13		11	12	22		64	104	104
Low mortality (T > 15 °C for over 29)	FN								53	60
	GSM								54	63
	GA								64	73
	GR								82	83
	AR							3	84	85
	RA	4						11	93	93
	GRU	4			4			23	99	99
	PA	5		3	5	9		53	103	104
High mortality (T > 18 °C for over 26)	FN									
	GSM									
	GA								4	7
	GR								10	13
	AR								11	14
	RA								33	41
	GRU								47	56
	PA								62	65

Figure 10. Outbreak of PKD in present and future scenarios in 8 considered stations, e.g., average days per year in critical conditions. Darker tones of red indicate worse conditions.

To assess hydro-morphological suitability, we evaluated PD for the 8 sampling sites during P1 and P2, for the two scenarios SSP126, and SSP585, thus providing the lower and the upper bound of the future suitability assessment. Then, we evaluated number of days per year, averaged along the CR, P1, and P2, when such weighted PD for the river would fall within each class, for each season (Figure 11). Because winter discharge would increase in future scenarios (Figure 4), water level would also increase, and accordingly adult fish would find more suitable conditions. This projected condition would be confirmed by the slight decrease, in future winters, of the number of days when PD for adult trout would be in "poor" class. On the contrary, in spring and fall, the number of days in "poor" class would remain almost constant, while in summer the critical days would slightly increase. No evident trends are observed for juvenile and fry stages, that may face less criticalities.

P1 SSP 126

	winter						spring						summer						fall					
	ad		fry		juv		ad		fry		juv		ad		fry		juv		ad		fry		juv	
FN	71	19	90	0	45	45	49	43	92	0	73	19	28	64	92	0	92	0	71	20	71	20	71	20
GSM	80	10	90	0	15	75	71	21	92	0	52	40	50	43	92	0	92	0	80	11	80	11	80	11
GA	8	82	87	3	89	1	27	65	86	6	89	3	43	49	74	18	74	18	8	83	8	83	8	83
GR	6	84	90	0	90	0	17	75	92	0	92	0	32	60	92	0	92	0	6	85	6	85	6	85
AR	15	75	90	0	81	9	49	43	92	0	81	11	62	31	92	0	92	0	15	76	15	76	15	76
RA	83	7	84	6	90	0	71	21	75	17	92	0	57	35	59	33	59	33	83	8	83	8	83	8
GRU	90	0	85	5	89	1	92	0	77	15	88	4	92	0	62	30	62	30	90	1	90	1	90	1
PA	57	33	84	6	90	0	70	22	73	19	92	0	74	18	57	35	57	35	57	34	57	34	57	34

P1 SSP 585

	winter						spring						summer						fall					
	ad		fry		juv		ad		fry		juv		ad		fry		juv		ad		fry		juv	
FN	67	23	90	0	59	31	52	40	92	0	77	16	41	51	92	0	92	0	67	24	67	24	71	20
GSM	74	16	90	0	25	65	74	18	92	0	47	45	66	26	92	0	92	0	74	17	74	17	80	11
GA	15	76	83	7	89	1	21	71	88	4	87	5	28	64	82	10	82	10	15	77	15	77	8	83
GR	12	78	90	0	90	0	11	81	92	0	92	0	19	73	92	0	92	0	12	79	12	79	6	85
AR	25	65	90	0	81	9	43	49	92	0	79	13	46	46	92	0	92	0	25	66	25	66	15	76
RA	76	14	77	13	90	0	79	13	81	11	92	0	71	21	73	19	73	19	76	15	76	15	83	8
GRU	90	0	78	12	87	3	92	0	84	8	87	5	92	0	76	16	76	16	90	1	90	1	90	1
PA	76	14	74	16	90	0	72	20	76	16	92	0	78	14	69	23	69	23	76	15	76	15	57	34

P2 SSP 126

	winter						spring						summer						fall					
	ad		fry		juv		ad		fry		juv		ad		fry		juv		ad		fry		juv	
FN	69	21	90	0	51	39	43	49	92	0	77	15	32	60	92	0	92	0	69	22	69	22	69	22
GSM	78	12	90	0	20	71	68	24	92	0	59	33	51	41	92	0	92	0	78	13	78	13	78	13
GA	10	80	84	6	90	0	35	57	85	7	87	5	42	50	78	15	78	15	10	81	10	81	10	81
GR	8	82	90	0	90	0	20	72	92	0	92	0	29	63	92	0	92	0	8	83	8	83	8	83
AR	29	61	90	0	82	8	63	29	92	0	85	7	67	25	92	0	92	0	29	62	29	62	29	62
RA	80	10	81	9	90	0	64	28	68	24	92	0	60	32	64	28	64	28	80	11	80	11	80	11
GRU	90	0	81	9	87	3	92	0	73	19	88	4	92	0	67	25	67	25	90	1	90	1	90	1
PA	56	34	81	9	90	0	71	21	69	23	92	0	79	13	61	31	61	31	56	35	56	35	56	35

P2 SSP 585

	winter						spring						summer						fall					
	ad		fry		juv		ad		fry		juv		ad		fry		juv		ad		fry		juv	
FN	53	38	90	0	74	16	61	31	92	0	85	7	69	23	92	0	92	0	53	39	53	39	53	39
GSM	69	21	90	0	40	50	75	17	92	0	39	53	82	10	92	0	92	0	69	22	69	22	69	22
GA	23	67	79	11	89	2	14	78	88	4	89	3	10	82	89	4	89	4	23	68	23	68	23	68
GR	18	72	90	0	90	0	8	84	92	0	92	0	7	85	92	0	92	0	18	73	18	73	18	73
AR	48	42	90	0	80	10	44	48	92	0	78	15	42	50	92	0	92	0	48	43	48	43	48	43
RA	68	22	69	21	90	0	82	10	83	9	92	0	84	8	85	7	85	7	68	23	68	23	68	23
GRU	90	0	71	19	87	3	92	0	85	7	88	4	92	0	86	6	86	6	90	1	90	1	90	1
PA	79	11	65	25	90	0	75	17	80	12	92	0	85	7	83	9	83	9	79	12	79	12	79	12

Figure 11. Total number of days per year when PD along the river falls within each class, i.e. good (green), and poor (red), for each season, averaged on the three decades, CR, half century and end of century, for each life stage of the trout. Bar width visually indicates the length of the period (over the length of the season, ca. 90 days).

3.7. Future river stress

In Figure 12 we report the RS index during P1 and P2, for the two scenarios SSP126, and SSP585. Differently from the findings for the CR period (Figure 8), here the combination of the habitat and thermal suitability seem crucial, since it would lead to a worsening of river conditions when considering both the suitability functions, with respect to the approach of dealing with them separately (Figure 10, Figure 11). Whereas for adult the projected habitat suitability along the river would be undermined under all scenarios both in P1 and P2, for juvenile and fry the findings would be slightly less alarming (Figure 11). Contrarily, the RS index, by combining habitat suitability with the effect of projected water temperature increase, would project a picture with larger stress, leading under the worst-case scenarios to the highest stress conditions, in summer and fall seasons.

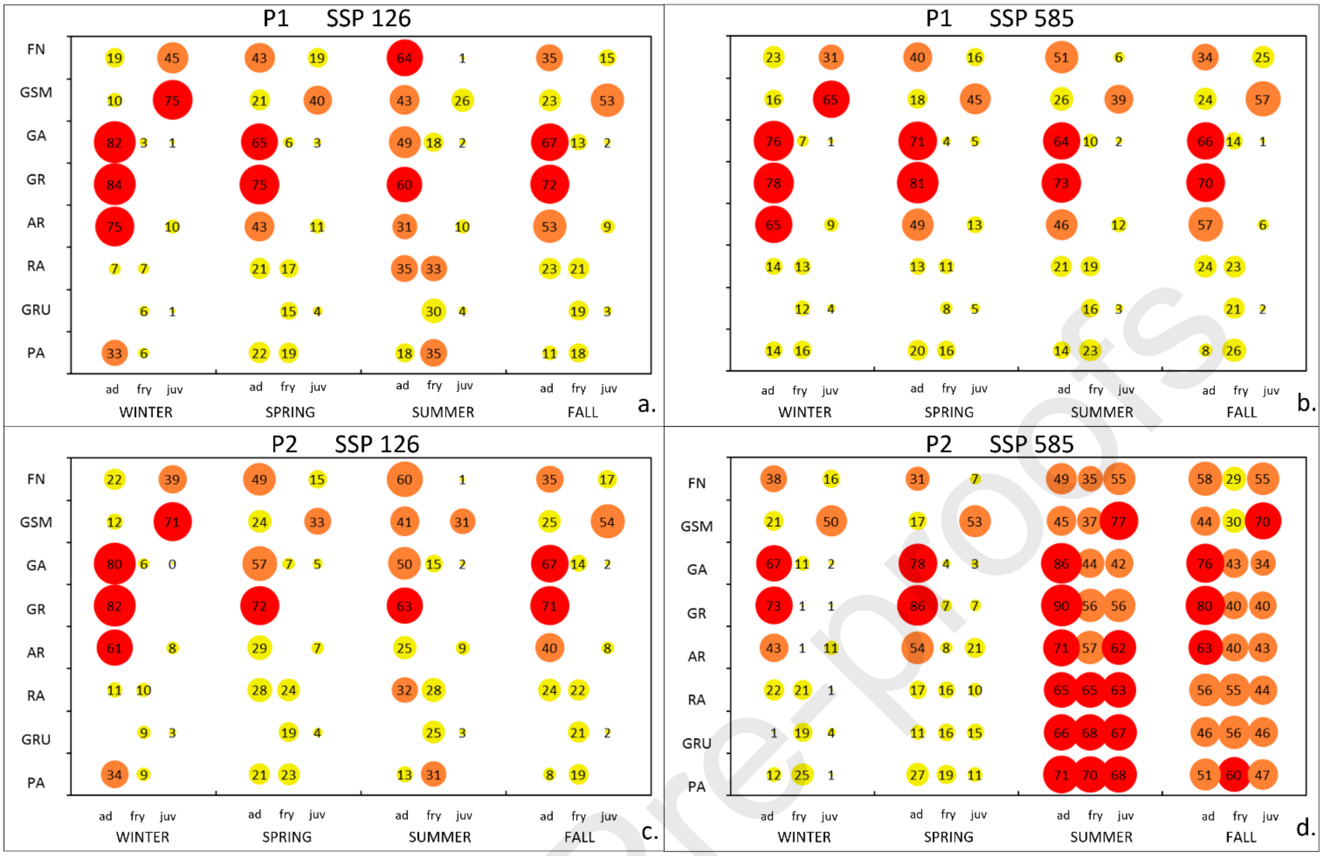

Figure 12. River Stress index, expressed in number of days per year, for each season, for each life stage of the trout, at each sampling point., averaged on P1 and P2, for 2 scenarios, i.e. (a) SSP 126 in 2046-55, (b) SSP 585 in 2046-55, (c) SSP 126 in 2091-2100, (d) SSP 585 in 2091-2100. Days 0-30 (yellow), days 30-60 (orange), days 60-90 (red).

4. Discussion

Suitability indexes depending upon stream flow magnitude, and timing are largely adopted to evaluate the effect of climate change on riverine habitat (Viganò et al., 2016, Ayllòn et al., 2009). However, assessment of water temperature is likely essential, due to its effects upon physiology and behaviour of trout (Elliot J. M. and Elliot J. A., 2010). The assessment of water temperature requires proper modelling, particularly in rivers exploited by human activity, where alteration of the thermal regime as due to withdrawal, and release is still poorly understood (Dickson et al., 2012). We used here a physically based model, *Poli-Wat.Temp*, depending upon factors directly affecting thermal dynamics. We modelled daily water temperature, obtaining a *Bias* mod/obs smaller than 1°C in each water temperature station, that is consistent with similar studies in nearby areas (Toffolon et Piccolroaz, 2015).

In future worst scenarios, we projected a significant temperature increase for water in most downstream areas during August, over +6.5°C, which is even higher than the increase of air temperature as projected. This result is coherent e.g. with a recent study in Columbia basin (Flickin et al., 2014), where the lack of cold water coming from snow would lead to similar temperature outbreaks, and it is also consistent with the historic trend of Swiss streams temperature as observed, nearby +0.37 C° per decade *vs* +0.13 C° per decade for air temperature (Auer et al., 2007). Nevertheless, in other studies projected temperature increase would be milder (Michel et al., 2022, Agnetti et al., 2018), especially when using empirical models, possibly less recommended for projections in future scenarios (Leach et al., 2019). In these models, generally water temperature is linearly dependant on air temperature with slopes smaller than one (Erickson et al., 1996). However, in physical models the link with air temperature can be more complex, given the presence of other variables also depending upon air temperature, i.e. upstream water temperature like here, and the link between air/water temperatures is less predictable. Here we considered spatial dependence, thus water temperature is affected by upstream boundary conditions, e.g. water temperature in Barbellino lake, with its average linked linearly to annual air temperature. We did not consider here boundary/initial conditions as possibly given by other, smaller reservoirs in the high Serio valley, e.g. Valmorta, Avert. We nevertheless consider this choice as the best option here, since we do not possess data thereby for water temperature assessment. Furthermore, regarding the assessment of Barbellino temperature, the apparent lack of physical modelling of lake heating dynamics, crucial to correctly assess downstream temperature, possibly limits our analysis here. Indeed, most studies concerning lake temperature are related to *epilimnion* (i.e. the lake surface), where more data are available, and remote sensing can be used (Pareeth et al., 2016). Few studies try to model hypolimnion temperature (Prats et al., 2019), and we are not aware of any studies attempting to model lake temperature considering the effect of withdrawal upon lake mixing. Indeed, the morphology of the hydraulic structure impacts lake mixing, and so vertical temperature profile is also affected.

According to our predictions of hydro-morphological suitability, we do not foresee very large trends therein for the next future. Like previous studies in the area (Viganò et al., 2016), small flow variations are projected in winter, when a slight increase of discharge, due to larger shares of liquid precipitation, would positively affect adult trout. We observed that potential trout density would never decrease below -40% of its maximum in our simulations, thus dramatic conditions linked to lack of water would not be encountered in Serio River, under our hypotheses. Moreover, the critical periods in response to hydrological and thermal conditions, i.e. winter and summer respectively, do not coincide. Thus, the combined indicator RS highlights that the critical periods in the year may be longer than when considering the two suitability indexes separately, as it would be expected. It is important to point out that *RS* we used here was calculated by merging the number of days when PD falls in "poor" class, and the number of days when water temperature is above the threshold for the possible outbreak of PKD. If we had considered the intersection of the two sets, or a different criterion to define the critical threshold for temperature, probably the results would be less critical. However, we considered the lowest temperature threshold for PKD because it is the one likely to be most sensitive to climate change. Three years of water temperature monitoring (2018-2021) in the Upper Serio catchment revealed an acceptable thermal habitat for *Salmo trutta*, since water temperature was always below the chosen critical thresholds. The future projections show continuous, and evident worsening of the thermal habitat for trout, in particular for most downstream stations (RA, GRU, PA).

Other studies recently demonstrated the worsening of thermal conditions in temperate rivers due to climate change. Santiago et al. (Santiago et al., 2016) studied the effects of climate change upon the thermal niche of brown trout in the Iberian Duero River basin. They showed that in the worst scenario (RCP 8.5), loss of habitat of brown trout may reach -30% in the upstream part of the basin, at the end of the century. The thermal niche was assessed using a threshold based on the exceeding of +18°C (daily mean), and projections showed an increase of ca. 3 and 9 folds of the number of consecutive days above the threshold, with RCP 4.5, and 8.5 respectively. Similarly, Borgwardt et al. (2020) projected the effects of climate change on Austrian brown trout at country scale, assessing both physiological stress, and potential emergence of diseases. Overall, they found that at the end of the century, RCP 8.5 would show an increase of both high mortality (+25%) and low mortality (+20%) conditions. In our case study, high mortality (T_w > 18°C) is seldom, if ever, predicted since we studied a cold Alpine river. However, our results clearly show that the habitat of brown trout would face a more dramatic condition, with headwater areas becoming the only optimal niche for the conservation of the species.

We consider the PKD as the most likely risk factor for trout, preliminarily neglecting a possible negative effect as due to lack of food, or hypoxia. Indeed, several studies demonstrated that increasing temperatures enhance disease prevalence, severity and distribution, and PKD-related mortality (Okamura 201; Waldner et al., 2019). By contrast, rising temperatures do not seem to adversely affect food availability, because secondary productivity of benthos generally increases (Albertson et. al., 2018; Bonacina, 2022). Furthermore, as aforementioned, oxygen rate in the Serio River was always found at saturation level, likely due to flow turbulence, and the maximum temperatures projected in the worst scenario (approximately +21°C) did not visibly cause a decrease in oxygen below the concentration needed by trout (7 mg/l). Sub-Alpine and Alpine rivers are profoundly impacted by human infrastructures, both for hydroelectric and irrigation purposes, affecting the riverine thermal regime

(Cassie, 2006). For this reason, we included here hydropower diversion in our study. To further explore climate change impacts upon fish communities, more detailed investigation covering the effects of plants and dams on the thermal regime should be carried out at a regional scale.

This study helps to understand the magnitude of thermal impacts and explores measures to mitigate the effects of global warming. For instance, an increase of the minimum flow discharge, especially during summer heat waves, could increase the thermal inertia of the river and reduce warming, decreasing the number of critical days, possibly at the cost of reducing hydropower production. Moreover, other strategies to reduce temperature raising could be implemented, such as the increase of vegetation cover along the river to enhance the shading and reduce the effect of solar radiation.

Here we considered as a target species the *Salmo trutta*, since it is regarded as a most abundant, and economically viable fish species in Serio River. However, the marble trout (*Salmo marmoratus*), indigenous and subendemic of the Po Valley (Zerunian, 2003), has the same habitat preferences of the allopatric brown trout, and it may survive to higher temperature thresholds, so in the future it might likely face less criticalities. Marble trout is included in the Habitat Directive (92/43/CEE), and in the IUCN Red List of Threatened species (Crivelli, 2006). Another endemic species of the Po Valley is *Cottus gobio* (Elliot J. et Elliot A., 1995) also included in the Habitat Directive (92/43/CEE), as well in the IUCN Red list of vertebrate animals (Rondinini et al., 2013), and it has more flexible thermal preference compared to *Salmo trutta.* Thus, the conservation of the endangered species *Salmo marmoratus* and *Cottus gobio* may be fundamental to maintain healthy fish communities on subalpine rivers like Serio here, also under a climate change adaptation perspective.

5. Conclusions

This study introduces a new physical model to assess river water temperature with the presence of hydropower plants, and a synthetic *River Stress* index to consider both the effects of change in discharge and water temperature on riverine habitat. The proposed methodology was applied to alpine Serio River in present and IPCC future scenarios, where future hydraulic habitat suitability is not expected to highlight large criticalities, while projections of stream temperature show apparently more alarming findings.

This methodology can be applied to other Alpine rivers, also exploited for human activities and requiring quality assessment, pending basic information availability of hydrology, thermal regime, and fish abundance, as reported here. Even in lack of information, some findings may be portable to other areas, e.g. fish density functions for similar target species. Such analysis may help in i) evaluating seasonal criticalities for fish species, and ii) providing more sustainable withdrawal strategies and, thus outlining a background for planning adaptation strategies.

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Supplementary material

Parameter	Unit	Description	Value	Method
DDS	[mmd^{-1} °C^{-1}]	Degree Day Snow	5	Literature [42]
t_g, t_s	[h]	Lag times, ground/surface	50, 400	Calibration, Hydrograph shape
n_g, n_s	[-]	Reservoirs, ground/surface	3, 3	Literature [41]
K	[mmd^{-1}]	Saturated conductivity	3	Calibration, flow volumes
k	[-]	Ground flow exponent	0.5	Calibration, flow volumes
θ_w, θ_s	[-]	Water content, wilting, field capacity	0.15, 0.45	Literature [41]

Table 1. Parameters for Poli-Hydro calibration.

Parameter	Unit	Value
α	$[JK^{-1}m^{-3}]$	20.94
β	$[s]$	41.87

Table 2. Calibration parameter of the thermal model, Eq. (2)

Parameter	Unit	Value
γ	[-]	0.35
ω	[-]	0.5
Lag	[day]	105

Table 3. Calibration parameter of the Barbellino lake temperature model, Eq. (6)

- Climate change is leading to hydro-thermal river regimes unsustainable to salmonids.
- We couple a new physically based thermal model, *Poli-Wat.Temp* with hydrological model *Poli-Hydro*, to assess water temperature as a function of air temperature, and river discharge.
- We constrain habitat suitability against water temperature, by assessing a synthetic River Stress index
- With respect to a solely habitat based assessment, the Rivers Stress index highlights longer critical periods per year.
- The increase in water temperature will result into worse conditions for trouts in summer.