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RESEARCH ARTICLE

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From a continuous thermal profile to a stepped one: The effect of run of river hydropower plants on the river thermal regime

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Abstract

Both reservoirs and run of river power plants affect the thermal regime of rivers but despite the higher number of the latter few studies have focused on their effect. In this study, we investigated the water thermal regime of Serio River (Northern Italy), a subalpine river regulated by a reservoir and characterized by a cascade system of run of river power plants. Water temperature has been monitored continuously for more than 4 years at the extremes of 4 stretches subjected to water diversion and thermal alterations have been quantified. Our results show that hydroelectric power plants act locally causing a considerable thermal alteration that increases with the distance from the diversion weir. Indeed, within the by-passed stretch, the rate of warming doubles the natural gradient (0.47°C/km vs. 0.19°C/km annually) with peaks in summer (0.73–0.90°C/km on average). By contrast, the run of river power plants keep the water temperature almost constant in the diversion channels. Thus, a cascade system of run of river plants shifts the overall riverine thermal regime from a continuous to a "stepped" longitudinal profile. Results highlight that the thermal effects of run of rivers plants are not negligible and should be considered and monitored continuously. Since there are thousands of hydropower plants powered by flowing waters it is time to consider their thermal impacts in environmental flow policies and bioassessment programs.

KEYWORDS
bioassessment, climate change, e-flow, flow regulation, renewable energy, thermal alterations

1 | INTRODUCTION

Rivers are complex and dynamic ecological systems with a strong influence on the territory. The key drivers in the riverine processes are the flow and the thermal regimes (Chinnayakanahalli et al., 2011). The river flow controls habitat availability and suitability of fish, benthic production, trophic web relationships as well as spatiotemporal patterns of macroinvertebrate communities (McIntosh et al., 2002). Furthermore, flow regulates the transport of solutes and sediments and the fate of organic matter, and shapes the riverbed morphology affecting the riparian zone and the connectivity with the terrestrial environment (Gintz et al., 1996; Mao et al., 2009). Temperature influences the ecosystem functioning (Coutant, 1999; Cummins, 1974; Karr & Dudley, 1981; Odum, 1973) controlling primary production, degradation of organic matter and solubility of chemical species (Cairns et al., 1975; Jacobsen et al., 2003; Lamberti & Steinman, 1997; Morin et al., 1999; Robinson et al., 2001). Moreover, it shapes the spatiotemporal patterns of aquatic biota constraining the ecological niche of the species (Céréghino et al., 2002; Cox & Rutherford, 2010; Elliott & Elliott, 2010). Regarding macroinvertebrates, the temperature is related to several life traits such as metabolism, life cycle, fitness and, behavior (Bonacina et al., 2022). Water temperature is so important for biological pathways that, for instance, it has been used as the main criterion for the definition of the fish riverine zonation. In Italy the Salmonid area, the Cyprinid area with deposition on the rocky substratum, and the Cyprinid area with deposition on aquatic plants have been defined according to the following range: $T < 16°C$, $17 < T < 20°C$, and $21 < T < 25°C$, respectively (Zerunian, 2002). However, an overall survey of the river network thermal regime at a regional or macroregional scale has never been done, so the zonation is approximate.

Despite the recognized biological importance of both flow and thermal regimes, research and environmental flow (e-flow) policies have been focused primarily on water quantity (Olden & Naiman, 2010; Webb et al., 2008).

Indeed, specific metrics have been developed to investigate the ecological effects of hydrological alteration (Lancaster & Downes, 2010; N. Leroy Poff & Zimmerman, 2010, Poff et al., 2017) and European countries have adopted various tools to manage water abstractions and maintain a flow consistent with a good ecological status (Water Framework Directive) without considering the associated thermal alteration.

The natural drivers that control the riverine water thermal regime are well known and include atmospheric conditions, hydrological factors, topography, and channel morphology (Caissie, 2006; Webb & Walling, 1997). However, anthropic activities such as thermal effluents, variations in the flow regime, reservoirs, and water diversions can play a crucial role (Caissie, 2006; Petts & Gurnell, 2005). Regarding hydroelectricity production, some studies have focused on the thermal impact caused by penstocks and diversion coming from reservoirs, while plants installed along the river are less documented although their number is higher and constantly increasing (Lange et al., 2018; Zarfl et al., 2015). Most of such plants are represented by the run of river (ROR) plants; they divert the water from the river and drive it to the turbines throughout channels or penstocks and then release it again into the river. The volume of the diverted water is generally higher than the volume left in the riverine channel (the e-flow) and runs into channel/penstocks long from a few hundred meters to some kilometers depending on the specific environmental context. In Northern Italy the plants powered from reservoirs/basins are 225 while plants powered from flowing waters are 1422. They provide 19,264 and 13,026 GWh, respectively, corresponding to 60.6% and 39.4% of the hydroelectric production (Permanent Secretariat of the Alpine Convention, 2009). Similarly, in Switzerland, where 55% of total electricity is produced by the hydroelectric sector, there are 100 hydroelectric plants powered from reservoirs and 566 hydroelectric plants powered from flowing waters. They supply 16,650 and 18,830 GWh respectively, that is, 47% and 53% of the total hydroelectric production (Permanent Secretariat of the Alpine Convention, 2009). Other types of diversion include nuclear, and fossil fuelled bypass sections that bring water to cool the plants and then release it again into the river. Such plants are located mostly along lowland rivers. Often ROR plants are located sequentially and coupled with the presence of a reservoir upstream that permanently ensures water to the whole hydroelectric system. In such cases, multiple infrastructures affect the water temperature, and the overall riverine thermal regime depends on the interaction of their impacts, as in the study hereafter presented.

While several studies investigated the thermal impact induced by low river flow downstream of reservoirs and small dams at different scales (Casado et al., 2013; Chandesris et al., 2019; Maheu et al., 2016; Seyedhashemi et al., 2021; Xu et al., 2021) very few addressed the thermal impacts in by-passed stretches subjected to power plants. Among them, Wawrzyniak et al. (2012) investigated the longitudinal and temporal thermal pattern of the Rhone River (France) in relation to hydroelectric and nuclear power plant diversions and Gibeau and Palen (2020) surveyed the ROR thermal impact in by-passed reaches of Douglas and Fire creeks (British Columbia, Canada).

The present study reports the results of an intensive survey of water temperature undertaken along the Serio River (Northern Italy), a subalpine regulated river characterized by a cascade system of ROR plants. We addressed the following questions:

- Which is the impact of ROR plants on the riverine thermal regime at seasonal and daily scales in the by-passed stretches?
- Which are the main drivers that control the thermal regime of a subalpine river affected by ROR plants' impacts?
- Which is the overall effect of a cascade system of ROR plants on the riverine longitudinal thermal profile

2 | MATERIALS AND METHODS

2.1 | Study area

This study was conducted in the upper part of Serio River in the Orobic Alps (Northern Italy). The upper Serio catchment covers 383 km^2 and lays between ~400 and 3050 m a.s.l; the river is regulated upstream by a high-altitude reservoir located at 1862 m.a.s.l. and having a volume of 18.5×10^6 m^3. The water is channeled in penstocks and falls for about 1000 meters on the turbines of the Dossi hydroelectric power plant (43 MW). Then, it is released in a compensating basin and from that to Serio River at 840 m.a.s.l. (Figure 1a). 7 ROR plants are located in sequence along the upper Serio, so that the river flow is diverted through a weir in a lateral channel that conveys the water to the turbine and then returns it into the river, mixing it with the e-flow left in the main channel until the following hydroelectric intake structure withdrawing it again (Figure 1b). 4 ROR plants were considered in this study and the monitoring sites were located at the extremes of each stretch, that is, upstream (just downstream the hydroelectric weir) and downstream (just upstream the release of water coming from the power plant) (Figure 1b). With respect to the effects of ROR plants, upstream sites were considered "not altered" while downstream sites were considered "altered" since the reduction of water flow due to ROR diversion was supposed to deviate the water temperature from the natural condition. Flows were typically

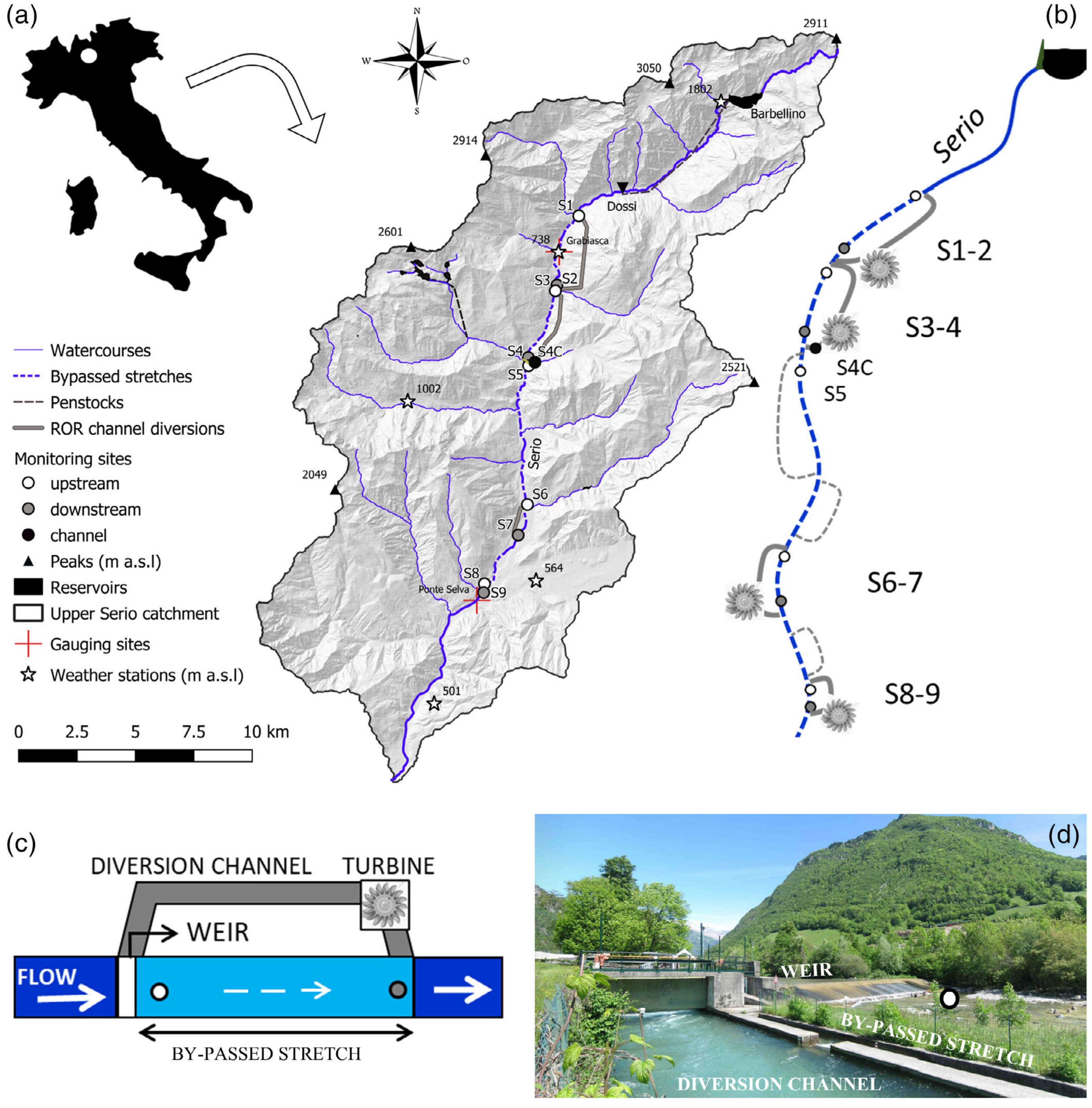

FIGURE 1 Map of the upper Serio catchment (a), schematic representation of the cascade system of the considered ROR plants with the monitoring sites (ROR plants not considered in the research are shown with grey dot lines) (b), schematic representation of a ROR plant (c) and picture of site S8 showing the weir, the diversion channel, and the beginning of the by-passed stretch (d). [Color figure can be viewed at wileyonlinelibrary.com]

diverted to run through the turbines day and night as long as the river flow was enough to generate power and to comply with the requirements for e-flow in the by-passed stretches. Such requirements for e-flows (Q_e) change across stretches, ranging between 0.47 and 1.36 m^3/s, and correspond approximately to 10% of the mean annual flow. Flow diversion occurred for almost all the year, except for occasional interruptions of few days due to low flows or floods. ROR plants can swirl at most a flow corresponding to the diversion grant limit (Q_d) (Table 1). From July 2018 to January 2020 the first power plant was inactive, so the first riverine stretch (S1-2), in that period, represented the undisturbed condition, namely the absence of the ROR plants' impact (hereafter identified as S1-2*). An additional monitoring site (S5) was located downstream of the second hydropower release (downstream S4) to assess the overall effect of two

TABLE 1 List of the monitoring sites in the Serio River.

Monitoring sites	Altitude (m a.s.l.)	Distance from reservoir (m)	Length of the stretch (m)	Slope %	Position in the diverted stretch	e-flow = Q_e (m^3/s)	Diversion grant limit (m^3/s) = Q_d
S1	784.03	9196	3703	2.905	Upstream	0.47	6
S2	676.47	12,899			Downstream		
S3	671.88	13,014	3315	1.349	Upstream	0.55	9.7
S4	627.17	16,329			Downstream		
S4C*	630	/	/	/	/	/	/
S5	623.84	16,466					
S6	511.09	22,959	1528	0.648	Upstream	1.133	12
S7	501.19	24,487			Downstream		
S8	474.35	27,365	379	1.201	Upstream	1.361	10.3
S9	469.8	27,744			Downstream		

*S4C site is located in the diversion channel of the S3-4 stretch.

consecutive ROR hydropower plants on the river thermal regime. Another site (S4C) was located at the same altitude of S4 but in the diversion channel to assess the effect of ROR plants on the temperature of the diverted water for one complete year (September 2020–September 2021).

Topographic data were elaborated through a Geographic Information System analysis (Qgis 3.4.14) and include the altitude of the monitoring sites, the distance from the reservoir, the length of the river stretches and their slope (Table 1).

2.2 | Water temperature

Water temperature was monitored in each site for more than 4 years (July 2018–September 2022) with two different types of data loggers (iButton-1921Z: range −5 to 26°C, resolution: ±0.125°C, accuracy: ±1.0°C, measurement interval: 60 min and iButton-1925: range: −5 to 26°C, resolution: ±0.0625°C, accuracy: ±0.5°C measurement interval: 10 min). The data loggers were cross-calibrated to ensure reliable comparisons, synchronized using the 1-Wire® software, and then fixed on the riverbed of each monitoring site. Water temperature data were downloaded and a linear interpolation between consecutive measurements was performed to obtain a continuous series of the water temperature (one value per minute) and lastly the daily mean, maximum and minimum values. When water temperature data were lacking due to sensor failure or loss (~30% of the data) the values were estimated separately for each site from air temperature by Generalized Additive Models (GAM) using daily water temperature (mean, maximum, and minimum) and air temperature (mean) time series plus the week number as an extra smoothing parameter (see Krajenbrink et al. (2021) for details) to have a continuous data set. GAMs were developed by "mgvc" (Wood, 2022) R package using a Gaussian distribution and provided an excellent performance (Root Mean Square Error [RMSE] ~0.82°C, see Table 1A). For site S2 we performed two different models based on water data collected when the power plant was off (S2*) and on (S2). In S9, few data were collected and were not reliable since water temperature was locally influenced by a small intermittent spring coming from the river shore, so we did not consider them in the analyses.

2.3 | Air temperature

Mean daily air temperatures of the five meteorological stations located in the upper Serio catchment were obtained from the Regional Environmental Protection Agency website (www.arpalombardia.it) and used to estimate air temperatures in the monitoring sites throughout an interpolation based on altitude as described in Fiorenzo et al. (2008). Thus, we calculated the mean monthly gradient (lapse-rate) of the 2011–2020 decade in the upper Serio catchment using a linear interpolation that correlates the mean monthly temperature of each meteorological station with the altitude as proposed by Garen and Marks (2005). Then, the daily air temperatures monitored by the meteorological station were reported to the sea level using the calculated vertical gradient of the considered month and averaged. Finally, the air temperature was retransferred to the elevation of the monitoring site using the lapse-rate of the considered month (Waring & Running, 1998).

2.4 | Flow data

Mean daily flows in each riverine stretch have been reconstructed using the daily flow data monitored by the gauging sites, the diversion rates, and the residual flow provided by the hydropower's operator. The residual flow (Q_r) is the flow left by the plants in the by-passed stretches and usually correspond to the e-flow (Q_e). The gauging sites were located at the extremes of the study area: the first, Grabiasca, downstream of S1 while the second, Ponte Selva, about 500 m downstream of S9, as shown in Figure 1a. In addition, on several occasions, the riverine current speed was measured (collecting data every 0.5–1 m by the HACH-FH950 electromagnetic flowmeter) and data were used to calculate the discharge flow by both mid and mean section methods (averaged) (Gore & Banning, 2017; Miraudа et al., 2011). These values were used to better calibrate the flow estimations. Indeed, the total flow in each stretch was estimated by scaling the gauging site flow measurements on the watershed area of each stretch. Thus, the flow in the stretches (Q_s) affected by ROR diversions consisted of the residual flow (Q_r) when the total flow estimation (Q_t) was smaller or equal than the hydroelectric grant limit; in the other case, it resulted from the difference between the estimated total flow and the hydroelectric grant limit (Q_d, see Table 1). The same procedure proved to be robust in a previous study where a high correlation between the instantaneous flow measured at each site ($n = 85$) and the estimated mean daily flow was observed [$r = 0.75$, $p < 0.001$; Figure S1 Supplementary material of Fornaroli et al. (2019)].

$$Q_s = Q_r \text{ if } Q_t < Q_d$$

$$Q_s = Q_t - Q_d \text{ if } Q_t > Q_d$$

2.5 | Serio water thermal regime

To describe the water thermal regime of each site, we plotted the annual thermal profile based on daily values (mean, maximum, and minimum) averaged for the 4 years of the survey (July 2018–July 2022). One-way ANOVA followed by the multiple comparisons Tukey's HSD test was performed to compare daily water thermal mean and range (maximum-minimum) of each monitoring site through seasons and point out possible significant differences. Similarly, the significance of the differences between water temperature downstream and upstream of each stretch (both daily means and maxima), normalized for the stretch length was tested. These analyses were conducted separately for each season, identified as winter (December–January–February), spring (March–April–May), summer (June–July–August), and autumn (September–October–November).

2.6 | Drivers of water thermal regime

To identify the main drivers that control the water thermal regime of Serio River explanatory variables related to meteorology, topography, and flow were selected and their respective contribution was assessed to describe the water temperature using model selection and optimization. Stochastic models were preferred to deterministic ones as they require fewer input data and are relatively simple in implementation and application. Thus, daily water temperatures were analyzed using the GAM model as previously described (Section 2.1). However, in this case, other variables (see Table 2) that allow us to better describe the water temperature along the whole upper Serio were included. The relevant variables were selected by a forward procedure starting with a model based only on daily air temperature (T_a) and adding one more variable step by step. At each step, the performance of the model was assessed using the RMSE. The selection stopped when the addition of a new variable did not improve the accuracy of the result by at least 0.05°C (Table 2A). The optimal model was fitted using 70% of the data (homogenously distributed among seasons and sites) and validated with the remaining dataset (30% of the data) in each site using the RMSE and the adjusted R^2 parameter (R^2_{adj}). The thermal sensitivity (Kelleher et al., 2012) was assessed at each site correlating daily air and water temperatures and analyzing the slope of the regression ($s = \Delta Twater/\Delta Tair$). All the analyses were performed in *R* project software.

3 | RESULTS

3.1 | Thermal regime of Serio River

The annual water thermal profiles were plotted to compare the thermal patterns in not-altered (upstream) and altered (downstream) sites as shown in Figure 2.

Annual thermal profiles exhibited a seasonal pattern ranging from 3 to 5°C in December–February to 10–16°C in July–August (on average) with water temperatures increasing with increasing distance from the headwater (from S1 to S9), especially in summer. Downstream sites (S2*, S2, S4, S7) were warmer than their upstream counterparts, especially S2 and S4 that showed sharp differences between the maximum and the mean (Figure 2 graphs B, C).

As shown in Figure 3a water temperature was significantly different between unaltered and altered sites both at annual and seasonal scale except for S6-S7 during summer and autumn. Site S4C (diverted water) was generally more similar to S1 site (both annually and seasonally) than to the adjacent sites (in particular S3, S5). The daily water temperature range presented marked seasonal patterns, with

TABLE 2 Variables identified as potential drivers for the upper Serio water thermal regime with mean, standard deviation, and range.

Variable	Type of variable	Acronym	Unit	Mean	Sd	Range
Mean daily air temperature	Meteorology short term	Ta	°C	10.88	7.54	−6.59 to 28.68
Week number	Meteorology long term	Wn		26.59	15.06	1–53
Distance from the reservoir	Topography distance from the source	D	m	18,008.62	6039.14	9344.5–27,579.5
Length from the weir	Topography effect of ROR plant	L	m	888.74	1387.48	0–3703
Mean daily flow in the by-passed stretch	Hydrology	Q_s	l/s	5421.29	5958.41	313–101,747.18
Mean daily flow in the diverted channel	Hydrology	Q_d	l/s	1346.90	2541.15	0–11,955

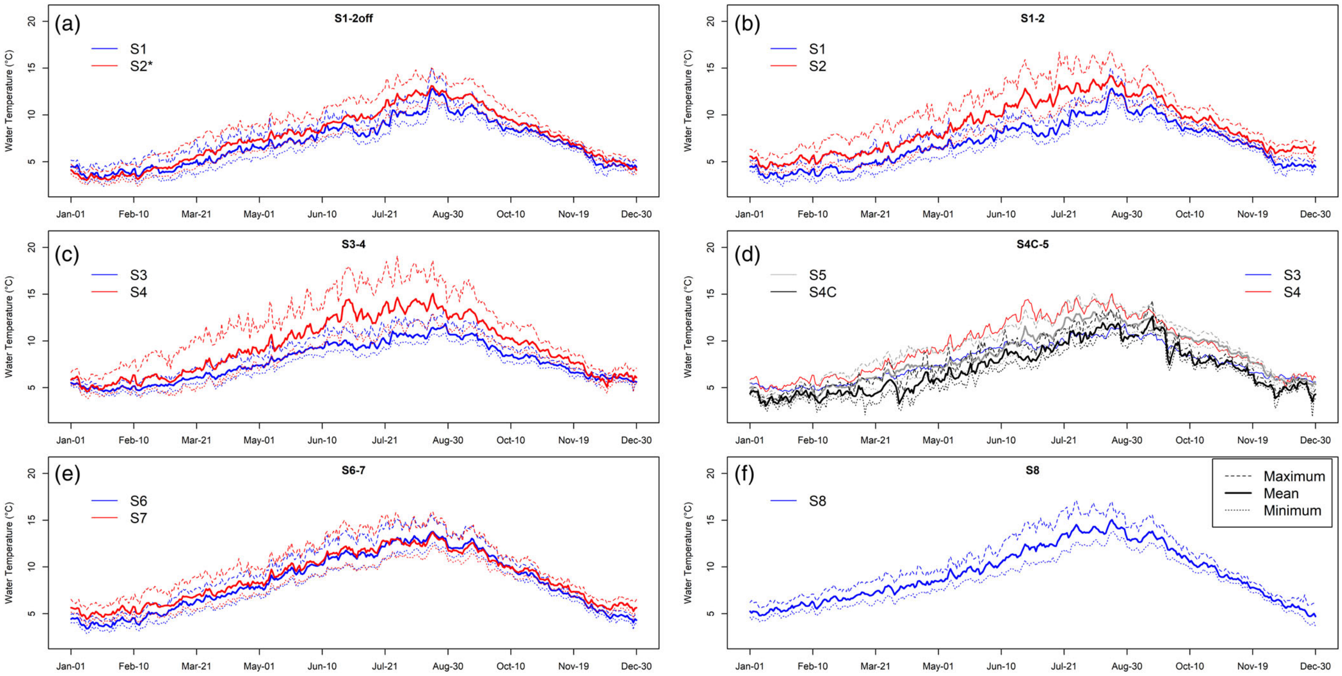

FIGURE 2 Water thermal regime in the monitoring sites of the upper Serio River averaged on 4 years (July 2018–July 2022). Upstream (blue lines) and downstream (red lines) water temperature (daily minimum, mean and maximum) are reported per each by-passed stretch (graphs a, b, c, e). For the last stretch (graph f) only the upstream temperatures are indicated. Graph d compares the thermal profiles of the diverted water (S4C), of the river water downstream the ROR release (S5), upstream and downstream the by-passed stretch (S3 and S4 respectively). [Color figure can be viewed at wileyonlinelibrary.com]

smaller variations in winter (generally below 2.5°C) than in the rest of the year. All altered sites have a significantly higher daily variation compared to their unaltered counterparts, both annually and seasonally. Such variation reached a daily range up to 6–8°C in sites S2 and S4 unlike S1 and S3 (<5°C) (Figure 3b). The diverted water had the same temperature (or even lower) along its running way (from S3 to S4C) while the river water temperature increased from S3 to S4 and decreased after the input of the diverted water in S5 (Figure 3a). Site S4C had the smaller range of daily variation (<3°C) and seasonal variation (Figure 3b).

3.2 | ROR plants thermal alteration in the diverted stretches

The first power plant was inactive in the period July 2018–January 2020 allowing the estimation of the longitudinal natural thermal gradient in the stretch S1-S2* (0.19°C/km in average) that was significantly lower than the altered stretches at annual scale (0.47, 0.48, and 0.30°C/kmS1-2, S3-4 and S6-7 respectively, Figure 4a year). This is particularly clear in summer when temperature variation in the stretches S1-2 and S3-4 was greater (0.73 and 0.90°C/km in S1-2, S3-4 vs. 0.32°C/km in S1-S2*, respectively) as shown in Figure 4a Summer. The differences in the thermal gradient assessed with maximum daily temperatures were even sharper, with gradients of 0.25, 0.63, 0.87, and 0.53°C/km in S1-2*, S1-2, S3-4, S6-7 respectively (Figure 4b Year) and peaks of 2–3°C/km in S1-2 and S3-4 (daily mean, Figure 4b Summer). The variation in S6-7 was smaller than in S1-2 and S3-4 (Figure 4a,b Year) with a marked seasonal pattern ranging from 0.69°C/km in winter and 0.09°C in summer and autumn (Figure 4a). However, it was still significantly different from the natural gradient measured in S1-2* both for means and for maxima (Figure 4a,b Year).

3.3 | Drivers of water thermal regime

Based on the stepwise regression it was possible to identify the main drivers that control the water thermal regime of the upper Serio River. Indeed, according to the forward selection the most explicative variables are air temperature (Ta), week number (Wn), distance from the headwater (D) and distance from the weir (L) (see Tables 2A and 3A):

$$\mathrm{Tw} \sim \mathrm{s(Ta)} + \mathrm{s(Wn)} + \mathrm{poly(D,3)} + \mathrm{poly(L,2)}$$

The model provides an overall excellent performance (RMSE < 0.8°C and R^2_{adj} > 0.92) and can be successfully used to predict water temperature along the entire upper Serio River since the predictive capacity is high in all sites (RMSE < 1°C and R^2_{adj} > 0.79, Table 4A). Daily air temperature (Ta) was the most explicative variable of water temperature explaining the 77% of the total observed variance (Table 2A). However, the correlation Tw ~ Ta alone varies among sites with higher values in downstream sites (0.37 and 0.39 in S2 and S4) than in the downstream ones (0.28 and 0.26 in S1 and S3)

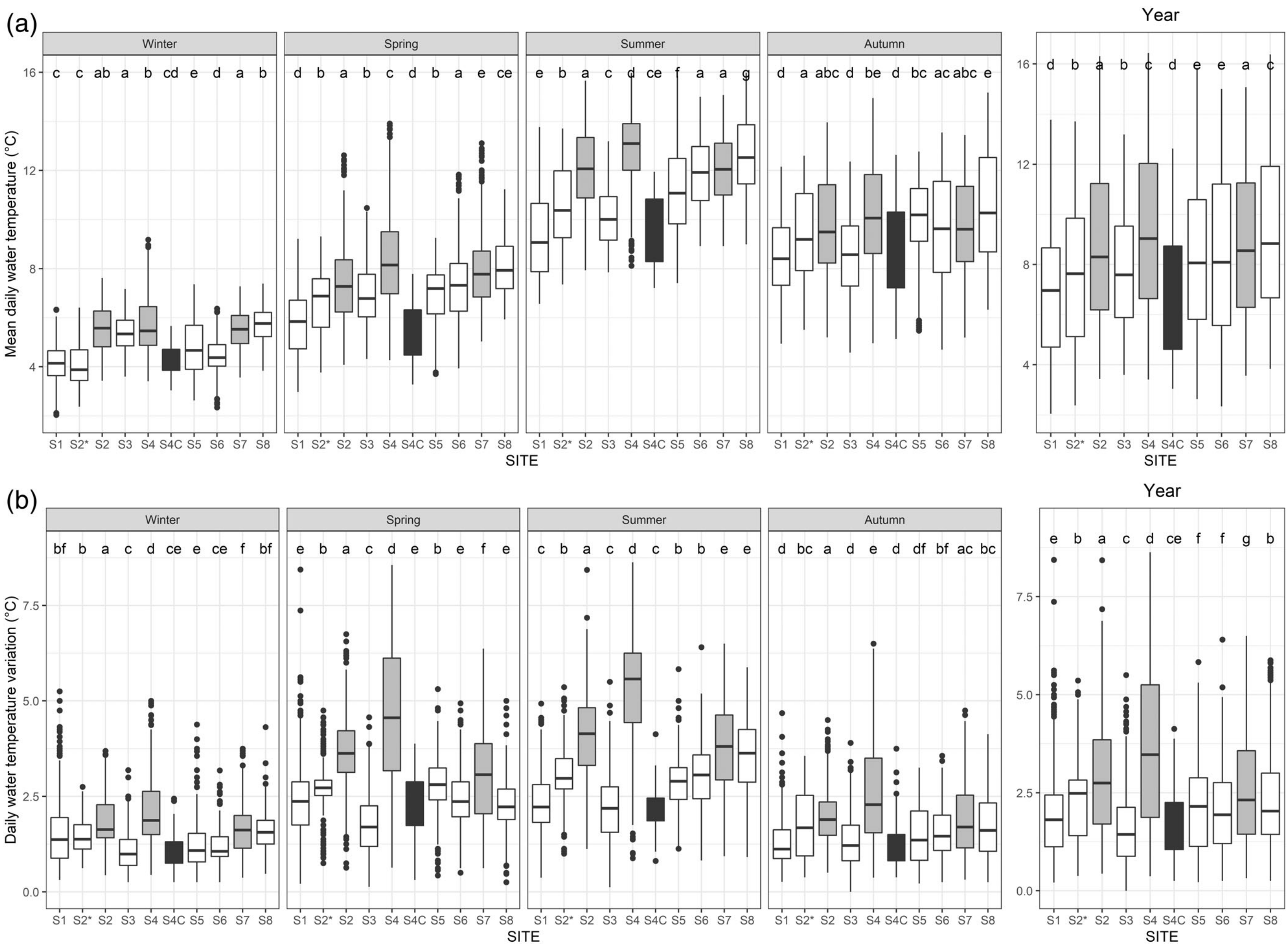

FIGURE 3 Mean (a) daily water temperature and (b) temperature range in the monitoring sites of Serio River in the different seasons. Different lowercase letters indicate significant differences among sites in the same season (Tukey's multiple-comparison test, $p < 0.001$). White and grey colors indicate not altered and altered sites respectively, while black identifies diversion channel.

(Figure 5) pointing out the possible influence of ROR plants on the relationship between air and water temperature. Nevertheless, the thermal sensitivity ($s = 0.39$) in the unaltered site S6 was similar to that one of the altered sites.

The other explicative variables were related to the period of the year (Wn) and the topography (D and L) while flows (Q_s and Q_d) were not retained as they did not improve significantly the model fit (Table 2A). The effect of ROR plants can be disentangled by the L variable, indeed the sites whose thermal regime is not influenced by ROR plants have a distance from the weir equal to zero.

4 | DISCUSSION

4.1 | Water thermal regime

The water thermal regime of Serio River is characterized by consistent seasonal (~8–12°C) and daily variations (from 1 to 2°C in winter to 6 to 7°C in summer in altered sites) as well as by site variations (Figure 2), in line with other similar rivers as the Noce River (Trentino, Italy, Zolezzi et al., 2011). According to Piccolroaz et al. (2016), Serio can be defined as a "resilient" river concerning thermal sensitivity because, due to the high-reservoir regulation, the dependence of water on the atmospheric conditions (ΔTwater/ΔTair $= 0.33$, considering the whole upper Serio) is below 0.55, the threshold separating thermally resilient and thermally reactive rivers. In addition, its sensitivity is close to 0.30, the typical value of reservoir regulated rivers estimated at a regional scale. Similarly, the thermal gradient of the upper Serio is around 0.21°C/km (from S1 to S8) which is a typical value for intermediate responsive rivers (Caissie, 2006) and is slightly below the natural rate of 0.25–0.27°C/km, estimated in the Douglas Creek (British Columbia, Canada; Gibeau & Palen, 2020). The water thermal regime of the upper Serio depends mainly on meteorological conditions (daily mean air temperature and period of the year) but also on the presence of hydropower plants (both high-altitude reservoir and ROR plants) whose influence, according to our model, is related to the distance from the reservoir and the ROR weir (D and L respectively). The flow was not retained as an explicative variable of the water thermal regime as the topography was already sufficient to obtain reliable estimates. Thus, in this case, thermal alteration seems

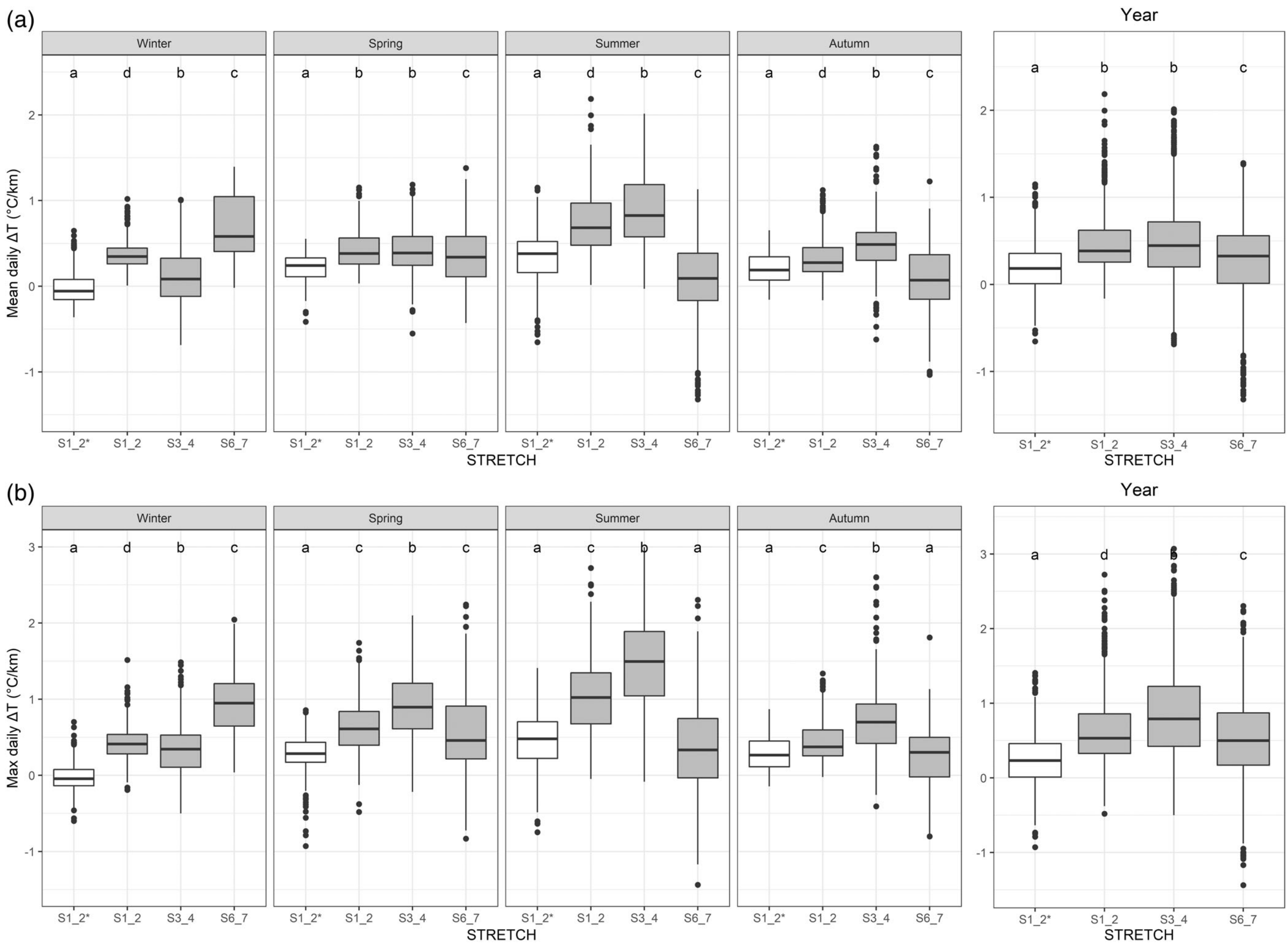

FIGURE 4 Mean (a) and maximum (b) daily water temperature variations between downstream-upstream sites. White color indicates the first stretch when the ROR plant was inactive. Different lowercase letters indicate significant differences among sites in the same season and in the whole period (Tukey's multiple-comparison test, $p < 0.001$).

related to riverine structural features as stretch length and distance from the headwater rather than to flow management. This makes the water temperature prediction more feasible since data referring to the flow released by ROR plants are generally not available (at least not for all plants). It must be noted that within the by-passed stretches the flow is almost always (>300 days/year) the e-flow.

4.2 | ROR plants' thermal alterations

According to the results (Figures 2 and 4), ROR plants alter the thermal regime in the by-passed stretches, especially in S1-2 and S3-4. Indeed, the rate of warming double in the presence of water diversion than in "natural" conditions (~0.47 vs. 0.19°C/km in S1-2* annually) and even larger in summer and considering the daily maxima (~0.8 vs. 0.3°C/km summer mean; ~0.8 vs. 0.25°C/km annual maximum; ~1.5 vs. 0.5°C/km summer maximum) (Figure 4). ROR plants, reducing considerably the flow in the by-passed stretch (~1/10 of the diverted flow on average, Table 1), increase water temperature from air temperature (Figure 5 Tw/Ta in altered vs. unaltered sites) causing a sharp thermal variation (mostly warming but also cooling) within each stretch. The maximum daily water thermal alterations occurred during the summer heat waves when the warm air and the prolonged drought exacerbated the thermal impact of the ROR plants. In these periods the daily variation reached about 0.73–0.90°C/km (in S1-2 and S3-4 on average) with peaks over 2.5°C/km. For example, site S4 was around 4°C warmer than S3 (14 vs. 10°C Figure 2) on average with maxima differing more than 8°C (in ~3 km). Such variations were in line with the one estimated by Gibeau and Palen (2020) for the by-passed stretches of Douglas and Fire creeks (0.46 and 0.33°C/km the annual average up to 0.86–1.24°C/km in summer). By contrast, no marked alterations were observed in the Rhone River (France) where the thermal gradient in the by-passed stretches and in the unaltered ones was comparable (~0.05°C/km). In that case, the differences between the by-passed stretches and the diversion channels were +0.5–0.6°C in summer and −0.6 to (−0.2)°C in winter (in 12–14 km), considerably lower than in Serio River (2–3°C in summer and 0–1.5°C in winter in 3–4 km).

However, such sharp alterations were observed especially in S1-2 and S3-4 stretches while the thermal gradient in S6-7 differed significantly from the S1–S2* one only in winter and spring. Moreover, the thermal sensitivity in S6 was comparable to the one observed in the other downstream sites (~0.34–0.39 in S2, S4, and S7). This could be explained by (i) the inflow of a tributary stream (Ogna) between S6 and S7 that, despite its low flow (<1 m^3/s) might contribute to cool the water, especially in summer, (ii) the groundwater upwelling due to the change of the lithology from siliceous to limestone downstream of S5, and (iii) the shorter length of the stretch (1.6 km vs. 3–3.7 km). The inflow of Ogna could also explain the sharp winter thermal gradient since, in winter, the temperature is higher in Ogna than in Serio in S6 (Bonacina, personal observation). The observed effect of ROR plants (~2.7°C in summer in S1-2 and S3-4) agreed with the one reported by Prats et al. (2010) for Ebro River (2.3°C). In that case the primary cause was the input of high temperature effluents from nuclear plants which, however, had a heating effect all year long while ROR plants cause both water heating and cooling.

4.3 | From a continuous water thermal profile to a stepped one

ROR hydropower plants withdraw water to produce energy and then, discharge it again into the river. The temperature of the water released through the turbines is similar (or even colder) to the upstream water temperature (Figures 2 and 3, S4C vs. S3 sites) because the diverted channels are often underground or shaded and the flow velocity is high (2–3 m/s). As the ratio between the two flows (diverted and residual) is around 10:1, the mixing mitigates the thermal variation occurred within the by-passed stretch. In the case of a cascade system of ROR plants, the overall impact (both in the by-passed stretches and in the diverted channel) must be defined comparing the longitudinal thermal profile with the thermal profile of a reference river not affected by ROR plants. Thus, we used Eq4 to compare the water temperature longitudinal profile of Serio River with or without all seven ROR plants. (Figure 6).

As shown in Figure 6, in the absence of ROR plants the longitudinal water thermal profile follows a continuous pattern typical of headwater streams (Fullerton et al., 2015) while with ROR plants it exhibits a "stepped" profile with sharp drops downstream the releases from ROR plants, especially for the longer stretches (S1-2, S3-4, and S5-5A).

Indeed, ROR plants act in two opposite ways: on one side they cause marked local heating due to the flow reduction in the river channel, on the other side they cause cooling in the diverted channel. Overall, a cascade system of ROR plants shifts the whole riverine thermal regime from a continuous to a "stepped" profile.

4.4 | Ecological implications of ROR thermal alteration and e-flow policies

Thermal variation in the observed range (1–8°C) could affect the aquatic biota as shown by (Lessard & Hayes, 2003) studying the effect

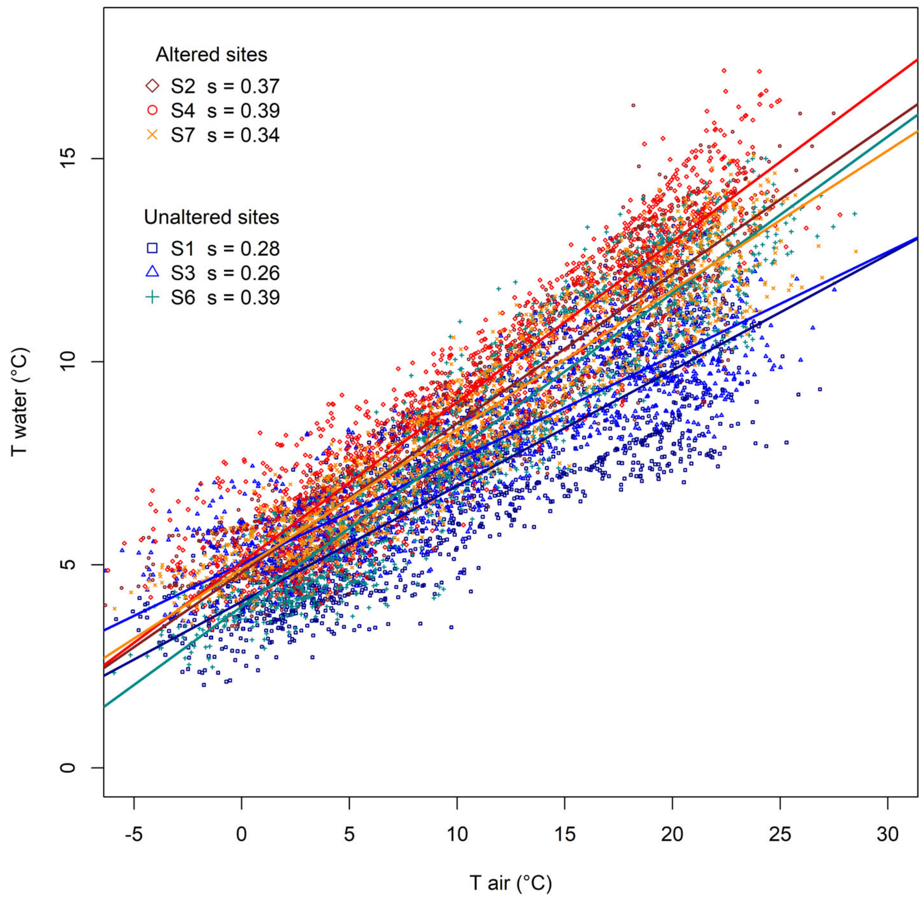

FIGURE 5 Correlation between daily air and water temperatures. Altered and unaltered sites were identified by red and blue colors respectively. The slope of the regression (s = ΔTwater/ΔTair) is indicated. [Color figure can be viewed at wileyonlinelibrary.com]

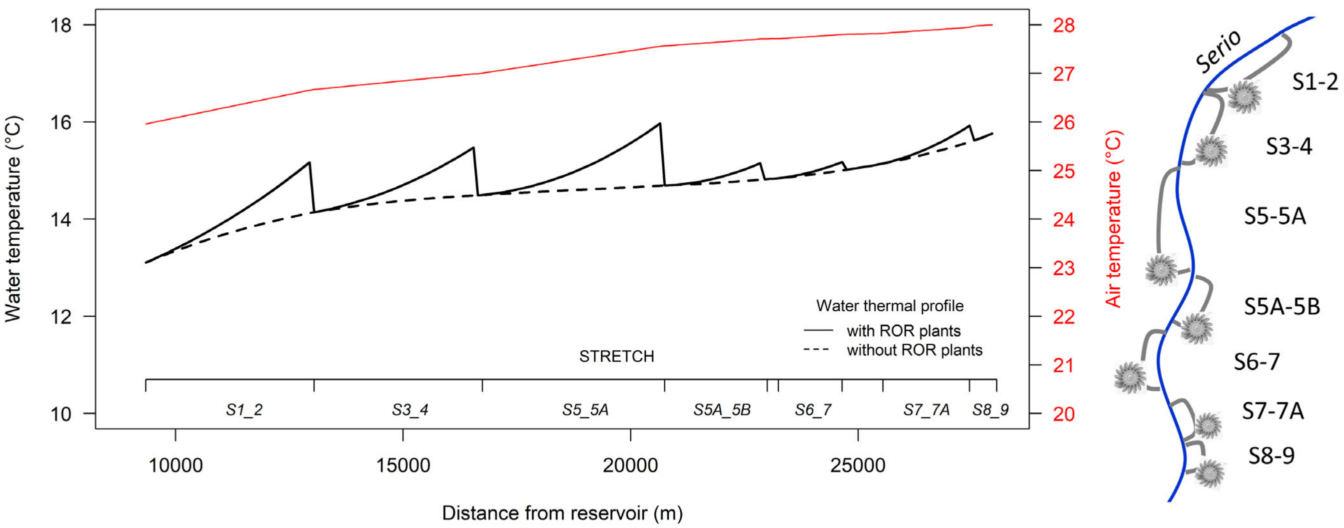

FIGURE 6 Longitudinal water thermal profile (daily mean) of the upper Serio River with or without ROR plants in the 35th week (T air at Ponte Selva = 28°C). [Color figure can be viewed at wileyonlinelibrary.com]

of thermal alteration caused by small dams with superficial discharge. Indeed, they observed that small dams warmed the water downstream causing shifts in macroinvertebrate community composition, an increase in fish species richness, and a reduction in the densities of brown trout, brook trout, and slimy sculpin populations. Thus, we can suppose differences in macroinvertebrate assemblage composition at the extremes of the stretches driven by an increase in water temperature and similarly between upstream and downstream of the ROR water release due to the sharp thermal drop. Similarly, the contrasting thermal conditions may affect the growth of fish (in our case *Salmo trutta* dominated) since the cumulated degree-day substantially differ (i.e., ~3161, 4211, and 3433°C/year in S3, S4, and S5 respectively) as discussed by (Gibeau & Palen, 2020). Such possible changes should be investigated by disentangling the effect of water temperature from other factors such as hydrology and water quality, already integrated into the e-flow bioassessments.

In light of the presented results, the temperature monitoring laid down by Directive 2006/44 (Parliament, 2006) seems pretty inadequate to detect ROR thermal impacts because the thermal regime has daily and seasonal variations not detectable with a weekly sampling. The monthly sampling established by the Italian transposition (D.Lgs 152/2006) is obviously even more inadequate. Moreover, according to the Directive the thermal alteration must not exceed 1.5°C with respect to the natural conditions (in salmonid waters). Probably ROR plant diversions cannot be identified as "thermal discharges"; however, their indirect impacts in the by-passed stretch can easily overcome the threshold of 1.5°C. Rising temperatures have been observed in rivers in the last years (Bonacci et al., 2008; Hari, 2006; Michel, 2020) and dry periods are expected to be more frequent and intense due to global warming, in particular in the Alps (Viganò et al., 2015), so the thermal alterations could have important ecological effects on lotic systems in the close future and should be investigated deeply (Fuso et al., 2023). To properly quantify possible impacts of ROR thermal alteration specific indicators should be elaborated as it has been done to assess thermopeaking caused by hydropeaking (Carolli et al., 2015; Vanzo et al., 2016).

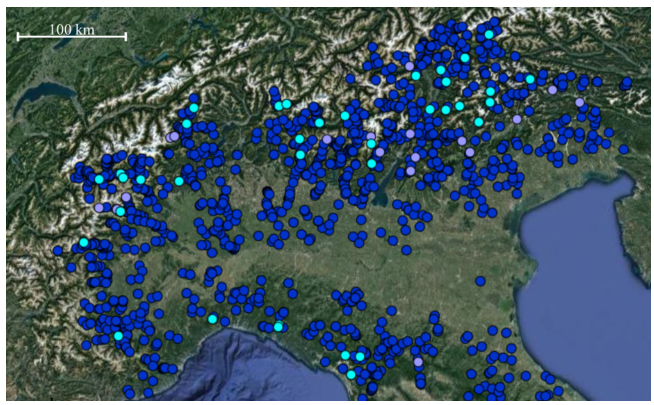

FIGURE 7 Hydropower plants powered by storage/reservoir (violet and light blue) and by flowing waters (blue) in Northern Italy (Italian Energy Services Manager, GSE S.p.A: www.gse.it). [Color figure can be viewed at wileyonlinelibrary.com]

To the author's knowledge this is the first study highlighting the thermal effect of a cascade system of ROR plants on a subalpine river and only few studies (Gibeau & Palen, 2020; Wawrzyniak et al., 2012) investigated the effect of single ROR plants in different geographical contexts. As, especially in mountain regions, there are thousands of plants powered from flowing waters (Figure 7), further research, at a larger scale, should attempt a rigorous investigation of the thermal alterations induced by ROR plants. Indeed, local factors such as channel morphology, tree canopy, dam characteristics, and management practices could display different thermal patterns.

5 | CONCLUSION

This study showed that the thermal regime of Serio River depends firstly on the meteorological conditions and secondarily on the anthropogenic impact caused by hydropower plants. Two different impacts are acting on the upper Serio water thermal regime in opposite ways and at different spatial scales. In the by-passed stretches where the flow is reduced by water withdrawal for ROR plants, the dependence between air and water temperature is strengthened, especially at the maximum distance from the weir. Hence, locally, the rate of warming (cooling) is higher in the stretches subjected to ROR plants diversion than in the "natural" stretches. On the other hand, ROR plants reduce the dependence between air and water temperature in the diverted channels. Thus, altogether, a cascade system of ROR plants shifts the overall riverine thermal regime from a continuous to a "stepped" profile.

Similarly to the development of flow-ecology relationships that have been done in the last twenty years regarding e-flow policies, now emphasis must be placed on the temperature-ecology relationship. This information could allow to predict/describe thermal alterations and to assess their impacts on the aquatic biota. Indeed, possible interventions on the management of e-flow, on the length of the by-passed stretches, on the vegetation shading and on the channel morphology could mitigate such alterations also from a global warming mitigation perspective.

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CONFLICT OF INTEREST STATEMENT

Authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Figshare at 10.6084/m9.figshare.22303219.

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APPENDIX A

TABLE 1A Performance of GAM models used to predict water temperature for the whole monitoring period (July 2018–July 2022) expressed with the root-mean-square error (RMSE) and the R^2_{adj} for each site.

	RMSE (°C)			R^2_{adj}		
SITE	T mean	T max	T min	T mean	T max	T min
S1	1.03	1.24	1.04	0.87	0.84	0.86
S2*	0.45	0.68	0.54	0.98	0.96	0.96
S2	0.95	1.22	0.93	0.92	0.90	0.91
S3	0.93	1.03	1.01	0.86	0.86	0.83
S4	1.24	1.44	1.26	0.88	0.89	0.84
S5	0.82	0.92	0.85	0.94	0.93	0.93
S6	0.63	0.78	0.69	0.96	0.96	0.95
S7	0.74	0.98	0.77	0.94	0.92	0.92
S8	0.66	0.79	0.75	0.95	0.95	0.93
Mean	0.82	1.00	0.86	0.92	0.91	0.91

*From July 2018 to January 2020 the first power plant was inactive, so in that period S2 site was not subjected to the impact of the first ROR plant.

TABLE 2A Selection of the variable through a forward approach.

GAM models	RMSE (°C)	R^2_{adj}
Tw ~ s(Ta)	**1.369**	0.778
Tw ~ s(Ta) + s(Wn)	**1.009**	0.879
Tw ~ s(Ta) + s(Wn) + poly(D, 3)	**0.846**	0.915
Tw ~ s(Ta) + s(Wn) + poly(D, 3) + poly(L, 2)	**0.775**	0.929
Tw ~ s(Ta) + s(Wn) + poly(D, 3) + poly(L, 2) + (s(Qs) + s(Qd))	**0.764**	0.931

Note: RMSE (in bold) values were used to select the optimal model.

TABLE 3A Water thermal regime model presented with the intercept, the average slope of each factor with the standard error and the *p*-value.

Parametric coefficient	Estimation	Standard error	*p* value
Intercept	8.484517	0.009195	<0.001
poly(L, 2)1	31.364518	0.849883	<0.001
poly(L, 2)2	6.44114	1.00246	<0.001
poly(D, 3)1	42.089232	0.9145	<0.001
poly(D, 3)2	−7.365209	0.838301	<0.001
poly(D, 3)3	16.193198	0.89854	<0.001
Smooth terms:			
Ta	7.82	8.661	<0.001
Wn	8.849	8.993	<0.001

Note: The equation is: Tw ~ s(Ta) + s(Wn) + poly(D, 3) + poly(L, 2).

TABLE 4A Performance of model expressed with the root-mean-square error (RMSE) and the R^2adj assessed in each site.

	RMSE (°C)	R^2_{adj}
S1	0.907	0.849
S2	0.718	0.933
S3	0.927	0.797
S4	0.966	0.888
S5	0.745	0.927
S6	0.638	0.955
S7	0.604	0.945
S8	0.695	0.946
Mean	0.775	0.905