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WHAT DRIVES WARMING TRENDS IN STREAMS? A CASE STUDY FROM THE ALPINE FOOTHILLS

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ABSTRACT

We investigated the effects of climate warming and land-use changes on the temperature and discharge of seven Swiss and Italian streams in the catchment of Lake Lugano. In addition, we attempted to predict future stream conditions based on regional climate scenarios. Between 1976 and 2012, the study streams warmed by 1.5–4.3 °C, whereas discharge showed no long-term trends. Warming trends were driven mainly by catchment urbanization and two large-scale climatic oscillations, the North Atlantic Oscillation and the Atlantic Multidecadal Oscillation. In comparison, independent influences by radiative forcing due to increased atmospheric CO_2 were uncertain. However, radiative forcing was predicted to further increase stream temperature (to +3–7 °C), reduce summer discharge (to −46%) and increase winter discharge (to +96%) between the present and 2070–2099. These results provide new insights into the drivers of long-term temperature and discharge trends in European streams subject to multiple impacts. The picture emerging is one of transition, where greenhouse-gas forcing is gaining ground over climate oscillations and urbanization, the drivers of past trends. This shift would impress a more directional nature upon future changes in stream temperature and discharge, and extend anthropogenic warming to rural streams. Diffusing future impacts on stream ecosystems would require adaptation measures at local to national scales and mitigation of greenhouse-gas emissions at the global scale.
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KEY WORDS: Atlantic Multidecadal Oscillation; climate change; Lake Lugano; models; North Atlantic Oscillation; stream temperature; global change

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INTRODUCTION

Temperature and discharge are master variables that influence most physical and biological features of stream and river ecosystems. Temperature influences the distribution, abundance and development of aquatic organisms, as well as the rate of ecological functions such as biomass production and decomposition (Ward and Stanford, 1982; Peters *et al*., 1987; Briers *et al*., 2004; Acuña *et al*., 2008). Discharge influences habitat characteristics such as current velocity and substrate type, and may indirectly influence water temperature (Poff *et al*., 1997; Caissie, 2006). As a result, natural or human-induced changes in temperature or discharge almost certainly influence the structure and function of river ecosystems. Additionally, these changes can impact the services provided by rivers to human society. For example, in temperate regions, cold-water rivers provide hydroelectric power and support fisheries of recreational and economic interest. These services would be reduced or lost through decreases in discharge, which would reduce water availability for power production (Christensen *et al*., 2004; Payne *et al*., 2004), or increases in water temperature, which would render rivers inhospitable to cold-water fish (e.g. Eaton and Scheller, 1996; Hari *et al*., 2006).

In streams and rivers, temperature and discharge change over time scales spanning from minutes to centuries. Recently, there has been considerable interest in long-term changes, that is, the changes occurring over decades or centuries. Most of this interest stems from the realization that climate has warmed over much of the globe. For example, the Intergovernmental Panel on Climate Change has estimated that during the past century, the temperature of the Earth's surface has risen by 0.6–0.9 °C (IPCC, 2007). During the same time, streams and rivers around the world have displayed trends towards higher water temperature and reduced discharge (e.g. Daufresne *et al*., 2004; Durance and Ormerod, 2007; Dai *et al*., 2009; Kaushal *et al*., 2010). However, the causes of these patterns, as well as their relation to global warming, remain poorly understood. Although forcing due to increased concentrations of greenhouse gases may be involved, there are other influencing factors, including catchment urbanization, changes in water use and climate oscillations, such as the North Atlantic Oscillation (NAO; Durance and Ormerod, 2007; Kaushal *et al*., 2010). Research into long-term physical changes in rivers is therefore needed to disentangle the effects of these factors and separate anthropogenic from natural influences (Durance and Ormerod, 2007).

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The catchment of Lake Lugano, located in the southern Alpine foothills, offers valuable opportunities to explore long-term changes in temperature and discharge in streams during the last decades. Temperature and discharge of the main tributaries to the lake have been recorded since the 1970s, while local climate has been monitored since 1863. In this catchment, during the last 150 years, average air temperature has increased by approximately 1.5 °C, and the increase appears to have accelerated during the last 50 years (Meteosvizzera, 2012). In addition, whereas some sub-basins within the catchment have remained scarcely populated, others have been extensively urbanized (Ferrario, 2009). We investigated the effects of these changes on the temperature and discharge of the main tributaries to the lake and forecasted future scenarios. Our specific questions were as follows: [Q1] Did the tributaries display trends in water temperature and discharge since the beginning of the monitoring programme? [Q2] What are the drivers of the trends? [Q3] How will stream temperature and discharge change in the future?

METHODS

Study area

The catchment of Lake Lugano (614.5 km^2, 45° 59′ 0″ N, 8° 58′ 0″ E, Figure 1) lies in the southern Alpine foothills, across southern Switzerland and northern Italy. In addition to the lake (49.9 km^2, altitude at the surface: 271 m a.s.l.), the catchment includes mountains (Prealpi di Lugano and Prealpi Lombarde) that rise to 2245 m a.s.l. The catchment has an oceanic climate characterized by mild winters and wet weather for most of the year, but especially in spring and autumn. The average air temperature is 12.4 °C, and the average annual precipitation is 1559 mm (MeteoSvizzera, 2013).

This study focuses on seven major tributaries to the lake monitored for water temperature, discharge and chemical characteristics (Figure 1, Table I). The streams are fed by groundwater, rain and melting snow, in proportions that depend on watercourse, time of the year and distance from the source (Table I). Land use in the catchments mainly includes residential and industrial developments (lumped under 'urban' land use), woods and pastures (Table I). The extent of urban cover varies among catchments, with the catchments of the streams Cuccio and Magliasina being mostly rural and those of the streams Scairolo and Laveggio being heavily urbanized (Table I). At urbanized streams, sampling sites are located downstream of sewage-treatment plants. Temperature records from upstream sites (Ufficio della protezione e della depurazione delle acque, Bellinzona, Switzerland, *unpublished*) indicate that, currently, effluents from these plants warm the streams by approximately 1 °C (annual average).

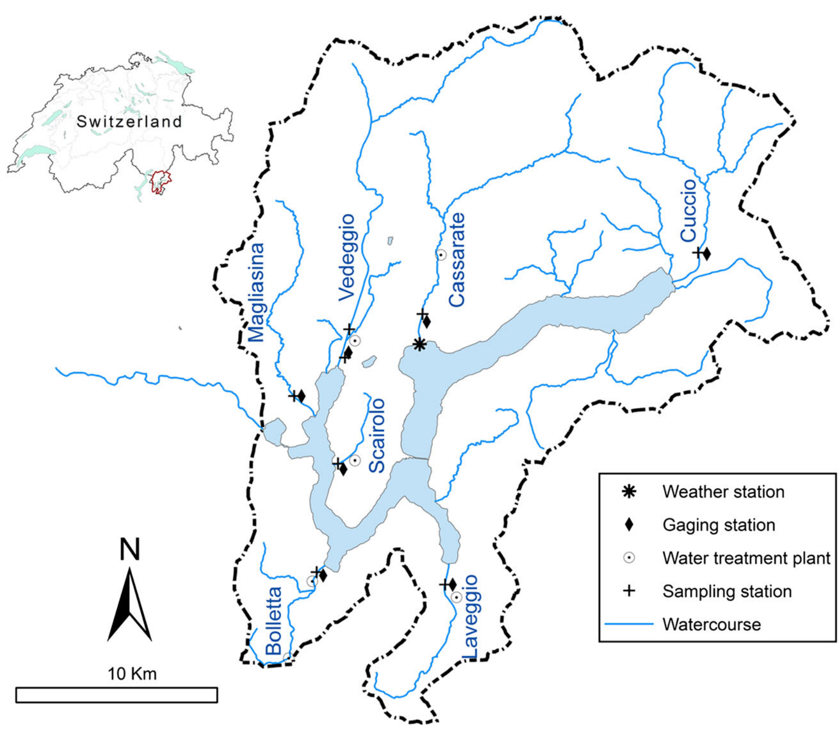

Figure 1. Map of the study area showing the location of the temperature sampling sites and the gauging stations. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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Table I. Study streams (tributaries to Lake Lugano), classified by degree of catchment urbanization (Ferrario, 2009), stream type (Dübendorfer *et al*., 2011) and regime (Pfaundler *et al*., 2011)

	Coordinates of sampling site	Altitude (m a.s.l.)	Catchment area (km^2)	Woodland (%)	Urban (%)	Meadows (%)	Stream classification	Reference temperatures	Regime
Urban									
Laveggio	+45° 53′ 47.20″ +8° 58′ 25.10″	276	31	49	25	1	Hyporhithron	T_{min} = 2–7 °C T_{max} = 14–21 °C	Southern pluvial
Scairolo	+45° 57′ 4.89″ +8° 54′ 23.34″	275	10	58	29	0	Hyporhithron	T_{min} = 2–7 °C T_{max} = 14–21 °C	Southern pluvial
Intermediate									
Bolletta	+45° 54′ 22.31″ +8° 53′ 44.68″	283	21	73	17	0	Hyporhithron	T_{min} = 2–7 °C T_{max} = 14–21 °C	Southern pluvial
Cassarate	+46° 1′ 14.30″ +8° 57′ 45.98″	292	81	62	14	13	Metarhithron (colline-montane)	T_{min} = 2–7 °C T_{max} = 14–20 °C	Southern pluvio-nival
Vedeggio	+45° 59′ 51.12″ +8° 54′ 31.49″	277	106	66	12	7	Metarhithron (colline-montane)	T_{min} = 2–7 °C T_{max} = 14–20 °C	Southern pluvio-nival
Non-urban									
Cuccio	+46° 1′ 50.95″ +9° 7′ 48.97″	275	54	46	3	41	Metarhithron (montane)[a]	T_{min} = 1–5 °C T_{max} = 12–20 °C	Southern pluvio-nival
Magliasina	+45° 58′ 54.57″ +8° 52′ 44.19″	302	35	75	5	8	Metarhitron (montane)[a]	T_{min} = 1–5 °C T_{max} = 12–20 °C	Southern pluvio-nival

Reference temperatures are the temperature expected in Swiss streams not impacted by human activities (Dübendorfer *et al*., 2011).
[a]Although the measuring station lies in the foothill zone, the source and a substantial part of the upper catchment lie in the montane-to-subalpine zone. The steep slope of the catchment means that climate in the lower catchment does not strongly influence the temperature.

A recent analysis of the regional climate indicates that air temperature around Lake Lugano has been rising at a rate of 0.1–0.2 °C per decade since 1900, and this rate has increased during the last 50 years (Meteosvizzera, 2012). Moreover, assuming no reductions in greenhouse-gas emissions, radiative forcing has been projected to warm the regional climate further, by up to +4 °C, by the end of the 21st century. In comparison, precipitation has shown a weak declining trend in the past (1900–2011), although summer precipitation is projected to decrease substantially, by up to −25%, by 2070–2099 (Meteosvizzera, 2012).

Availability and characteristics of historical temperature, discharge and weather data

The day-time water temperature of the major tributaries of Lake Lugano has been monitored since 1976 by governmental agencies and the University of Applied Sciences and Arts of Southern Switzerland (SUPSI). Temperature data consist of measurements collected with a frequency of approximately 1 month. On each sampling occasion, a water sample is collected at the monitoring site, and its temperature is immediately measured using an electronic digital thermometer (a mercury thermometer was used in the early years of the monitoring programme). We considered these temperatures to be accurate to within ±0.1 °C. Moreover, for this study, we assumed that these ‘spot’ measurements served as reasonable proxies for monthly means. This assumption was supported by two lines of evidence. First, temperature has been monitored continuously since 2002 or 2009 in four of our streams, and the monthly means obtained from this monitoring were highly correlated to the spot values used in this study ($r \geq 0.94$). Second, in our temperature models, expressing time in units of days or months produced nearly identical results, indicating that within-month variation in temperature was minor.

Discharge data were obtained from the Federal Office for the Environment and the Institute of Earth Sciences of SUPSI. The series examined in this study extend back to 1970–1986, depending on stream. Discharge data were available as daily values. We obtained monthly means by averaging daily values within months.

Data on air temperature and precipitation were obtained from the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss). These data were collected at a weather station in Lugano, which lies approximately in the centre of the catchment (Figure 1). Temperature and precipitation data used in this study are monthly values. Air temperature is the average monthly temperature measured 2 m above ground. Precipitation is the cumulative precipitation fallen within a month.

Analysis of trends in stream temperature and discharge (see Q1)

Our analysis of long-term trends in stream temperature and discharge focussed on a monthly time unit. The significance of any trends over time was assessed using regression models (Model 1, Table II). The dependent variables in the

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Table II. Regression models used to detect trends, identify drivers and project future values of water temperature (A) and discharge (B) in the study streams

(A) Temperature	
Model 1:	$T_w = \beta_0 + \text{trend} + \text{seasonal influence} + \varepsilon$
	Where: ▪ T_w = 'spot' water temperature (°C) ▪ Trend, or linear function of time $= \beta_1 \times t$ ▪ Seasonal influence $= \beta_2 \times \sin(2 \times \pi \times t) + \beta_3 \times \cos(2 \times \pi \times t)$ ▪ $\beta_{0\rightarrow 3}$: constants ▪ t: time (months) ▪ ε: error
Model 2:	$T_{w,\text{deseasonalized}} = \beta_0 + \beta_1 \times \text{NAO} + \beta_2 \times \text{AMO} + \beta_3 \times \text{MO} + \varepsilon$
	Where: ▪ $T_{w,\text{deseasonalized}}$: T_w-seasonal influence (from Model 1) ▪ $\beta_{0\rightarrow 4}$: constants ▪ NAO: North Atlantic Oscillation index ▪ AMO: Atlantic Multidecadal Oscillation index ▪ MO: Mediterranean Oscillation index ▪ CO_2-I: CO_2 index
Model 3:	$T_{w,\text{seasonal}} = \beta_{0+}\beta_1 \times T_{\text{air}} + \varepsilon$
	Where: ▪ $T_{w,\text{seasonal}}$: average seasonal water temperature (°C) ▪ T_{air} = average seasonal temperature(°C)
(B) Discharge	
Model 1:	$Q_{\text{deseasonalized}} = \beta_0 + \text{trend} + \varepsilon$
	Where: ▪ $Q_{\text{deseasonalized}}$: monthly discharge : seasonal index
Model 2:	$Q_{\text{deseasonalized}} = \beta_0 + \beta_1 \times \text{NAO} + \beta_2 \times \text{AMO} + \beta_3 \times \text{MO} + \varepsilon$
Model 3:	$Q_{\text{seasonal}} = \beta_{0+}\beta_1 \times P + \varepsilon$ Where: ▪ Q_{seasonal}: average seasonal discharge ($m^3 s^{-1}$) ▪ P: average seasonal precipitation (mm)

models were monthly spot temperatures or monthly deseasonalized discharge values. Spot temperatures were averaged where, because of irregularities in sampling, multiple measurements existed for a same month. Discharge data were deseasonalized by dividing monthly values by the seasonal index, that is, the median difference between each month's discharge and the average discharge for a 12-month period centred on that month, across the study period. The independent variables differed depending on model. The model for temperature included a linear function of time and a sinusoidal function to account for seasonal influences (Caissie, 2006). The model for discharge included only a linear function of time, because it was fit to deseasonalized data. Significant effects of the linear function of time were interpreted as evidence of long-term trends in temperature or discharge.

Linear regressions were chosen instead of more usual non-parametric approaches (e.g. the seasonal Mann Kendall test) because we had no *a priori* means to deseasonalize temperature data (the data series were incomplete and irregular; to use seasonal tests, we would have had to impute missing data, which may introduce bias, or delete incomplete years, which loses information). We checked for serial correlation and heterodasticity by examining model residuals and found no suggestion of either. In addition, we verified that any trends detected were indeed approximately linear and that the residuals were normally distributed.

Identification of the drivers of the trends (see Q2)

We considered climatic oscillations and greenhouse-gas forcing to be the main potential drivers of trends in temperature and discharge in our streams. In particular, we assessed the driving effects of a subset of climatic oscillations known to influence the climate of the Alpine region [the NAO, the Atlantic Multidecadal Oscillation (AMO) and the Mediterranean Oscillation (MO); Dokulil *et al.*, 2010] and radiative forcing due to greenhouse gases (Hofmann *et al.*, 2006). A difference between these potential drivers is that greenhouse-gas forcing causes directional warming at the global scale. By comparison, oscillations redistribute heat over the globe.

Analogous to the trend analysis, the identification of the drivers of the trends employed regression models and was based on a monthly time unit. The dependent variables in the models were deseasonalized monthly temperatures or discharge values. Deseasonalized temperatures were obtained by subtracting the seasonal influence (from Model 1) from monthly spot temperatures. Deseasonalized monthly discharge values were obtained as described earlier. The independent variables were the four potential drivers considered in this study, NAO, AMO, MO and CO_2 forcing. Because of a correlation between AMO and CO_2 forcing ($r = 0.7$ during 1976–2012), we did not assess the importance of the individual independent variables using a single multiple-regression model. Instead, we first modelled the dependent variables using the climatic oscillations as predictors (Model 2, Table II). In a second step, we examined whether variance in the residuals from this model could be explained by CO_2 forcing. A significant association between CO_2 forcing and the residuals was interpreted as evidence that CO_2 forcing had an independent effect on temperature and discharge, beyond the effects of climatic oscillations. A non-significant effect could indicate that CO_2 forcing did not influence temperature and discharge, or that its influence was indirect, via effects on climatic oscillations.

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The climatic oscillations considered in this study arise mostly from internal atmospheric processes, although anthropogenic influences on the NAO are possible (Hurrell *et al*., 2003; Knudsen *et al*., 2011). The NAO (Hurrell *et al*., 2003) is a see-saw pattern in the relative strength of a permanent low-pressure system located at high latitudes and a permanent high-pressure system located at mid latitudes over the North Atlantic. A positive NAO phase reflects a higher-than-average difference in pressure between the two systems, a negative phase a lower-than-average difference. During positive NAO phases, northern Europe experiences warmer air temperatures and wetter weather, whereas southern Europe often experiences drier conditions. During negative NAO phases, the pattern is reversed. For our analyses, the NAO was parameterized using the monthly NAO index provided by the Climate Prediction Center of the U.S. National Weather Service (available online at www.cpc.ncep.noaa.gov). This NAO index is calculated based on the rotated principal component analysis proposed by Barnston and Livezey (1987).

The AMO (Schlesinger and Ramankutty, 1994) consists in a 65–70 year band fluctuation in the surface water temperature of the North Atlantic. A positive AMO phase indicates higher-than-average surface temperatures, a negative phase lower-than-average temperatures. The temperature difference between extremes amounts to approximately 0.6 °C. The AMO was parameterized using the monthly AMO index provided by the National Oceanic and Atmospheric Administration of the U.S. Dept. of Commerce (available online at www.esrl.noaa.gov/psd/data/timeseries/AMO/). This index is essentially a smoothed, detrended index of the North Atlantic surface temperature.

The MO (Conte *et al*., 1989) is a pattern in the normalized pressure difference between Algiers and Cairo. This oscillation is one of the main teleconnection patterns (a recurrent large-scale anomaly in pressure and circulation) in the Mediterranean area (e.g. Dünkeloh and Jacobeit, 2003). The MO was parameterized using the daily index provided by the Climatic Research Unit of the University of West Anglia (available online at www.cru.uea.ac.uk/cru). Monthly records were obtained by averaging daily values.

Forcing due to greenhouse gases was parameterized using an index that converts changes in CO_2 abundance in the atmosphere relative to 1750 to radiative forcing (Butler and Montzka, 2013; available online at www.esrl.noaa.gov). Hereafter, we refer to this index as the CO_2 index. Although an aggregate index that accounts for all greenhouse gases exists (Butler and Montzka, 2013), we focussed on CO_2 because of the following: (i) this gas is the main responsible of total greenhouse-gas forcing (Hofmann *et al*., 2006); (ii) CO_2 forcing almost perfectly correlates with total forcing ($r = 0.995$ between 1979 and 2011); and (iii) contrary to the index of total greenhouse-gas forcing, the CO_2 index was available as a monthly value, consistent with the time unit of our analysis.

Prediction of future stream temperature and discharge (see Q3)

To project the effects of future climatic changes, we calibrated empirical models (Model 3, Table II) that predict stream temperature and discharge from air temperature and precipitation using historical data. The models consisted of linear regressions. The dependent variables were stream temperature or discharge. The independent variables were air temperature alone for the stream-temperature model and air temperature along with precipitation for the discharge model. Our predictive models were applied to seasonal data, to match the time unit adopted by local climate prediction analyses (Meteosvizzera, 2012). Seasonal temperature and discharge data were obtained by averaging data within years and seasons, with seasons defined as follows: winter = December–February, spring = March–May, summer = June–September and autumn = October–November. Once calibrated, the regression models were used to convert projected air temperature and precipitation for 2070–2099 (Meteosvizzera, 2012; see APPENDIX) into matching projections for stream temperature and discharge. These projections account only for increases in greenhouse-gas forcing. Climatic oscillations over the Atlantic are largely unpredictable, and therefore, their future effects could not be modelled.

Table III. Trends in monthly water temperature in the study streams, between 1976 and 2012

Stream	Trend	Model (1) fit
Non-urban		
Cuccio	$0.04 \pm 0.01^{***}$	$R^2 = 0.85$, $df = 3, 387$, $F = 725.00^{***}$
Magliasina	$0.06 \pm 0.01^{***}$	$R^2 = 0.85$, $df = 3, 410$, $F = 778.68^{***}$
Intermediate		
Bolletta	$0.08 \pm 0.01^{***}$	$R^2 = 0.85$, $df = 3, 385$, $F = 716.86^{***}$
Cassarate	$0.07 \pm 0.01^{***}$	$R^2 = 0.85$, $df = 3, 413$, $F = 774.42^{***}$
Vedeggio	$0.08 \pm 0.01^{***}$	$R^2 = 0.77$, $df = 3, 413$, $F = 449.66^{***}$
Urban		
Laveggio	$0.07 \pm 0.01^{***}$	$R^2 = 0.75$, $df = 3, 414$, $F = 423.97^{***}$
Scairolo	$0.12 \pm 0.01^{***}$	$R^2 = 0.82$, $df = 3, 398$, $F = 591.14^{***}$

Reported are the coefficient ± SE of the linear trend (coefficients from Model 1, Table II.A were multiplied by 12 to express trends in °C year^{-1}) and two measures of model fit (R^2 and F). The asterisks indicate the level of significance: $^{*} = p < 0.5$; $^{**} = p < 0.01$; $^{***} = p < 0.001$; ^{NS} = non-significant.

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In our models, precipitation was parameterized as liquid-only precipitation (essentially, rain and snowmelt), because liquid precipitation is more directly associated to runoff than total precipitation, which includes dry snow. Liquid-only precipitation was estimated for each stream based on total precipitation and air temperature following Hock (2003). Briefly, below 1 °C, all precipitation was considered dry snow. Above 1 °C, all precipitation was considered rain. Liquid-only precipitation was calculated as the sum of rain plus, in winter and spring, snowmelt from the snowpack, which was assumed to melt above 1 °C at a rate proportional to day-time temperature.

Projections of stream temperature and discharge were made for three scenarios of greenhouse-gas emission trends, namely A2, a high-emission scenario ('business as usual'); A1B, a medium high-emission scenario that assumes a reduction after 2060; and RCP3PD, a low-emission scenario that assumes a rapid reduction after a peak in 2020, essentially restoring 1900 emission levels by 2100 (IPCC, 2000; Moss *et al*., 2010; Meteosvizzera, 2012).

In this analysis, we considered only non-urban watercourses. Urban watercourses will probably be urbanized further, but we cannot predict to what extent or what effects future urbanization will have on river physical characteristics.

RESULTS

Trends in stream temperature and discharge

Between 1976 and 2012, the water temperature of all study streams displayed a warming trend, with warming rates ranging between 0.04 and 0.12 °C year^{-1} (Table III, Figures 2 and 3). In other words, during the last 36 years, the study streams warmed on average by 1.5 to 4.3 °C. Warming trends appeared to be more pronounced in urbanized

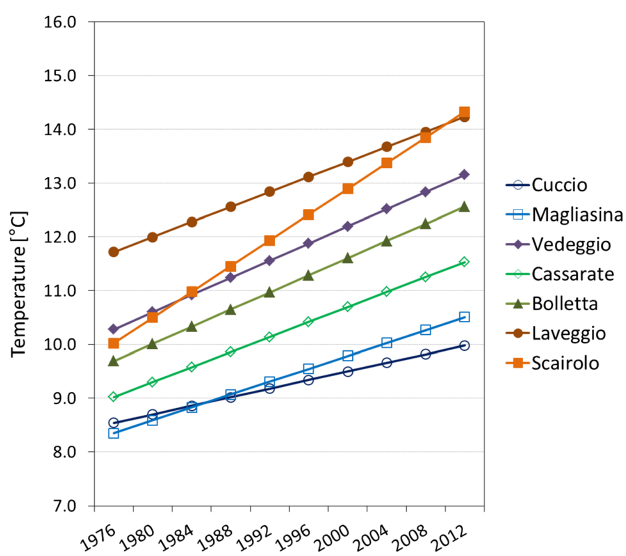

Figure 2. Trends in monthly water temperature in the study streams. For clarity, only linear trends (from Model 1, Table II) are illustrated. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

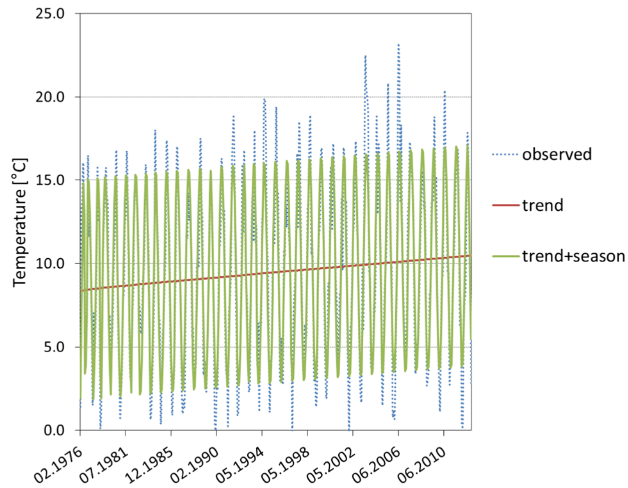

Figure 3. Trends in water temperature in the stream Magliasina. Illustrated are the observed temperatures, the temperatures predicted by the model used to detect trends in temperature (Model 1, Table II) and the linear trend. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

Table IV. Trends in monthly discharge in the study streams, between the period starting from 1970 to 1986 (depending on stream) and 2012

Stream	Trend	Model (1) fit
Non-urban		
Cuccio	0.00 ± 0.00^{NS}	$R^2 = 0.00$ $df = 1, 322$ $F = 0.06^{NS}$
Magliasina	0.00 ± 0.00^{NS}	$R^2 = 0.00$ $df = 1, 394$ $F = 0.06^{NS}$
Intermediate		
Bolletta	0.00 ± 0.00^{NS}	$R^2 = 0.01$ $df = 1, 322$ $F = 3.59^{NS}$
Cassarate	0.00 ± 0.00^{NS}	$R^2 = 0.01$ $df = 1, 514$ $F = 2.98^{NS}$
Vedeggio	0.00 ± 0.00^{NS}	$R^2 = 0.00$ $df = 1, 406$ $F = 0.97^{NS}$
Urban		
Laveggio	0.00 ± 0.00^{NS}	$R^2 = 0.00$ $df = 1, 418$ $F = 1.17^{NS}$
Scairolo	0.01 ± 0.00^{NS}	$R^2 = 0.01$ $df = 1, 370$ $F = 2.75^{NS}$

Conventions as in Table III.

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catchments. Further analysis confirmed that the warming rate correlated with the degree of catchment urbanization ($r = 0.78$; $p = 0.04$), with stream temperatures increasing at a faster rate in the more urbanized catchments.

The deseasonalized stream temperature also appeared to correlate with the degree of urbanization of the catchment (Figure 2). Streams in urbanized catchments (Scairolo and Laveggio) had temperatures up to 4 °C higher than the most natural streams (Cuccio and Magliasina).

In contrast with temperature, discharge did not display any significant linear trends during the study period (Table IV).

Drivers of the trends

The best predictors of monthly deseasonalized stream temperature were the NAO index and the AMO index (Table V). The effects of these indices were positive, indicating that positive phases of the NAO and AMO were associated with higher stream temperatures. The MO index, in contrast, had no effects. The CO_2-forcing index was unrelated to the residual temperature (after accounting for the effects of climatic oscillations) of the least urbanized stream (Cuccio). However, it was related to residual temperature in the other streams, with influence apparently increasing with the degree of catchment urbanization ($r = 0.88$, $p = 0.01$).

Although we detected no long-term trends in monthly deseasonalized discharge, we used regression models to explore if the NAO, AMO or MO explained variation in this parameter (Table VI). We omitted the CO_2-forcing index because this independent variable could explain only linear or quasi-linear trends. The results indicated that, at all sites, discharge was weakly ($r^2 \leq 0.13$) but significantly influenced by the NAO. Effects by the AMO and MO indices were also detected but were inconsistent across streams. All effects were negative, indicating that positive phases of the NAO, AMO and MO were associated with reduced discharge.

Future stream temperature and discharge

Our models projected increases in year-round temperatures for the two less urbanized study streams (Cuccio e Magliasina; Figure 4, APPENDIX). Not surprisingly, projected warming was most severe under the A2 ('business as usual') scenario. For example, according to this scenario, average winter temperature was projected to increase from 3 °C in 1976–1986, the first decade of the monitoring

Table V. Effects of three climatic oscillations (NAO, AMO and MO) on deseasonalized monthly stream temperature, and effect of CO_2 radiative forcing on residual temperature, between 1976 and 2012

Stream	Effect of oscillations on temperature	Model fit	Effect of CO_2-I on residuals	Model fit
Non-urban				
Cuccio	NAO: $0.27 \pm 0.10^{*}$	$R^2 = 0.04$	CO_2-I: 0.66 ± 0.38^{NS}	$R^2 = 0.01$
	AMO: $1.49 \pm 0.48^{**}$	$df = 3, 387$		$df = 1, 388$
	MO: 0.08 ± 0.25^{NS}	$F = 5.84^{***}$		$F = 2.97^{NS}$
Magliasina	NAO: $0.38 \pm 0.10^{***}$	$R^2 = 0.08$	CO_2-I: $0.88 \pm 0.38^{*}$	$R^2 = 0.01$
	AMO: $2.56 \pm 0.49^{***}$	$df = 3, 410$		$df = 1, 411$
	MO: -0.21 ± 0.25^{NS}	$F = 11.73^{***}$		$F = 5.35^{*}$
Intermediate				
Bolletta	NAO: $0.22 \pm 0.10^{*}$	$R^2 = 0.12$	CO_2-I: $1.22 \pm 0.35^{**}$	$R^2 = 0.03$
	AMO: $3.22 \pm 0.45^{***}$	$df = 3, 385$		$df = 1, 386$
	MO: -0.43 ± 0.23^{NS}	$F = 17.32^{***}$		$F = 11.76^{**}$
Cassarate	NAO: $0.42 \pm 0.10^{***}$	$R^2 = 0.11$	CO_2-I: $1.08 \pm 0.36^{**}$	$R^2 = 0.02$
	AMO: $2.72 \pm 0.46^{***}$	$df = 3, 413$		$df = 1, 414$
	MO: 0.06 ± 0.24^{NS}	$F = 17.05^{***}$		$F = 9.13^{**}$
Vedeggio	NAO: $0.50 \pm 0.10^{***}$	$R^2 = 0.19$	CO_2-I: $1.01 \pm 0.35^{**}$	$R^2 = 0.02$
	AMO: $4.03 \pm 0.45^{***}$	$df = 3, 413$		$df = 1, 414$
	MO: -0.13 ± 0.23^{NS}	$F = 31.52^{***}$		$F = 8.32^{**}$
Urban				
Laveggio	NAO: $0.39 \pm 0.10^{***}$	$R^2 = 0.10$	CO_2-I: $1.24 \pm 0.36^{**}$	$R^2 = 0.16$
	AMO: $2.97 \pm 0.47^{***}$	$df = 3, 414$		$df = 1, 415$
	MO: -0.11 ± 0.24^{NS}	$F = 16.25^{***}$		$F = 11.56^{**}$
Scairolo	NAO: $0.29 \pm 0.11^{**}$	$R^2 = 0.16$	CO_2-I: $2.18 \pm 0.40^{***}$	$R^2 = 0.07$
	AMO: $4.49 \pm 0.51^{***}$	$df = 3, 398$		$df = 1, 399$
	MO: -0.48 ± 0.26^{NS}	$F = 25.49^{***}$		$F = 30.08^{***}$

Conventions as in Table III. NAO, North Atlantic Oscillation; AMO, Atlantic Multidecadal Oscillation; MO, Mediterranean Oscillation; CO_2-I, CO_2 index.

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Table VI. Effect of three climatic oscillations (NAO, AMO and MO) on deseasonalized monthly discharge, between the period starting from 1970 to 1986 (depending on stream) and 2012

Stream	Effect of oscillations on discharge	Model fit
Non-urban		
Cuccio	NAO: $-0.07 \pm 0.03^{*}$	$R^2 = 0.04$
	AMO: -0.23 ± 0.14^{NS}	$df = 3, 320$
	MO: -0.07 ± 0.07^{NS}	$F = 4.46^{**}$
Magliasina	NAO: $-0.12 \pm 0.04^{**}$	$R^2 = 0.08$
	AMO: -0.33 ± 0.19^{NS}	$df = 3, 392$
	MO: -0.25 ± 0.09^{NS}	$F = 10.57^{***}$
Intermediate		
Bolletta	NAO: $-0.13 \pm 0.04^{***}$	$R^2 = 0.13$
	AMO: -0.18 ± 0.18^{NS}	$df = 3, 320$
	MO: $-0.30 \pm 0.09^{**}$	$F = 15.59^{***}$
Cassarate	NAO: $-0.11 \pm 0.03^{**}$	$R^2 = 0.07$
	AMO: $-0.42 \pm 0.13^{***}$	$df = 3, 488$
	MO: $-0.18 \pm 0.07^{*}$	$F = 12.89^{***}$
Vedeggio	NAO: $-0.10 \pm 0.03^{**}$	$R^2 = 0.07$
	AMO: $-0.38 \pm 0.14^{**}$	$df = 3, 404$
	MO: -0.13 ± 0.07^{NS}	$F = 9.79^{***}$
Urban		
Laveggio	NAO: $-0.09 \pm 0.03^{**}$	$R^2 = 0.09$
	AMO: -0.17 ± 0.12^{NS}	$df = 3, 416$
	MO: $-0.20 \pm 0.06^{**}$	$F = 13.80^{***}$
Scairolo	NAO: $-0.07 \pm 0.03^{*}$	$R^2 = 0.07$
	AMO: -0.12 ± 0.14^{NS}	$df = 3, 368$
	MO: $-0.21 \pm 0.07^{**}$	$F = 9.34^{***}$

Conventions as in Table III. NAO, North Atlantic Oscillation; AMO, Atlantic Multidecadal Oscillation; MO, Mediterranean Oscillation.

programme, to 6–7 °C in 2070–2099 (a 100–133% increase). Over the same period, average summer temperature was projected to increase from 14–15 °C to 20–21 °C (a 29–30% increase). Projections under the A1B or A2 scenarios were similar, whereas projections under the RCP3PD scenario indicated a smaller change. Projections for spring and autumn temperatures were intermediate between those for winter and summer (*not shown*).

Summer discharge was projected to decrease substantially according to all scenarios, with predicted losses attaining 38% (Cuccio) and 46% (Magliasina) between 1986–1996 and 2070–2099 (Figure 5). In contrast, over the same time, winter discharge of the stream Magliasina was projected to increase (+96%) according to the A2 and A1B scenarios, consistent with an increase in liquid-only winter precipitation. Projections of winter discharge were not attempted for the stream Cuccio because, for this stream, we found no relationship between winter precipitation and discharge (APPENDIX). As for temperature, the A2 and A1B emission scenarios led to nearly identical projections, whereas projections under the RCP3PD scenario pointed towards smaller changes, especially in winter.

DISCUSSION

Trends in stream temperature and discharge

The trend towards higher stream temperatures in our study area accords with growing evidence that a majority of streams and rivers across the Northern Hemisphere has become warmer during the last century (e.g. Webb and Nobilis, 1994; Langan *et al*., 2001; Hari *et al*., 2006; Durance and Ormerod, 2007; Kaushal *et al*., 2010). For example, in the USA, 50% of the main streams and rivers for which historical temperature records are available have displayed warming trends during the last century (Kaushal *et al*., 2010). In Wales, UK, winter temperatures in upland streams have increased by 2.0–2.4 °C between 1981 and 2005 (Durance and Ormerod, 2007). In Switzerland, near the study area, 25 streams and rivers monitored for temperature showed a coherent increase of 0.1–1.1 °C between 1978–1987 and 1988–2002 (Hari *et al*., 2006). In the study area, however, warming rates (0.04–0.12 °C year^{-1}) were striking for their magnitude, which were among the highest reported in the literature. We suggest that there are three reasons. First, the study streams are not fed by glacier melt-water, which can decouple stream temperatures from regional climate (Hari *et al*., 2006). Second, the streams were small and shallow, which renders them highly exposed to atmospheric conditions (Caissie, 2006). Third, and probably most important, the temperature of the study streams was influenced not only by changes in air temperature (Meteosvizzera, 2012) but also by interacting impacts, including urbanization. In comparison, most previous work involved streams that were larger (e.g. Hari *et al*., 2006; Kaushal *et al*., 2010) and/or unaffected by urbanization (e.g. Durance and Ormerod, 2007). Small urbanized streams, therefore, are probably among the most sensitive to long-term changes in temperature owing to the combination of natural and anthropogenic causes.

In contrast to temperature, discharge showed no significant trend during the study period. Globally, during the last decades, a trend towards dryer climate and lower river discharge has been widespread at low-to-mid latitudes (Dai *et al*., 2009). In keeping with this pattern, precipitation in the study area showed a weak decreasing trend during 1961–2011 (Meteosvizzera, 2012). Therefore, a trend towards reduced runoff and stream discharge might have been expected. However, the study streams have flashy regimes and high month-to-month variation in discharge. This variation probably prevented the detection of any long-term trends in this study. Thus, while our results do not disprove that climate change or other impacts (e.g. urbanization) influenced discharge in the study area, they indicate that any effects would have been minor compared with the background variability.

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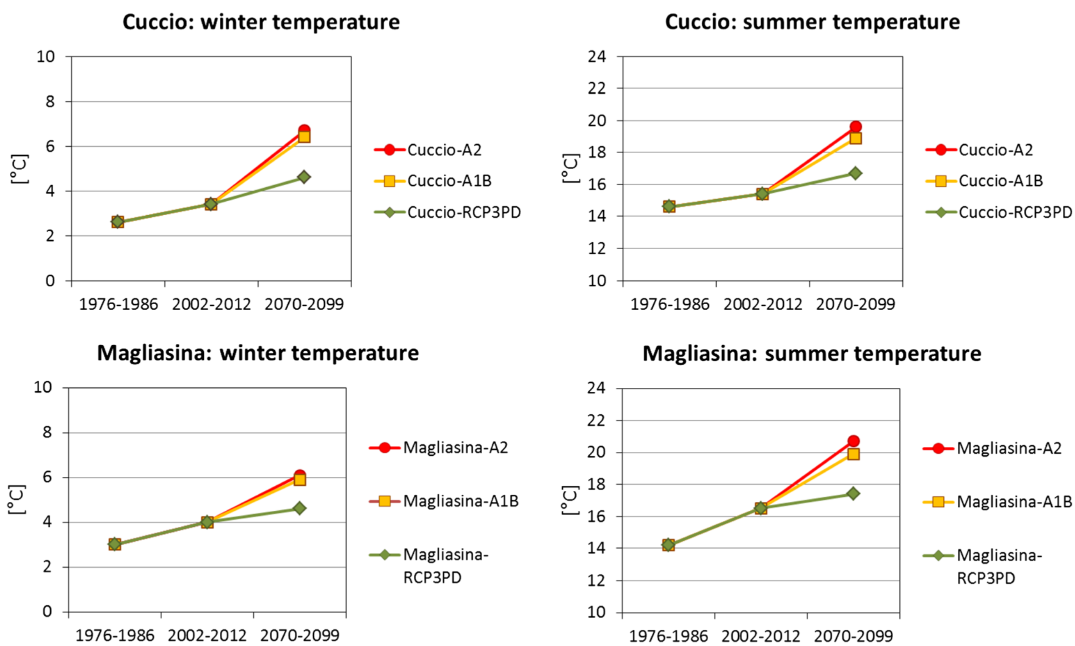

Figure 4. Winter and summer water temperature in 1972–1982 (observed), 2002–2012 (observed) and 2070–2099 (projected) of two non-urbanized study streams. Projections were made for three scenarios of future greenhouse-gas emission trends (see Methods).This figure is available in colour online at wileyonlinelibrary.com/journal/rra

Drivers of warming trends

Long-term warming of streams and rivers may by driven by greenhouse-gas forcing, changes in land/water use (including urbanization) and/or large-scale climatic oscillations (Durance and Ormerod, 2007; Kaushal *et al*., 2010). Of these factors, urbanization and climatic oscillations influenced our study streams, whereas the effect of

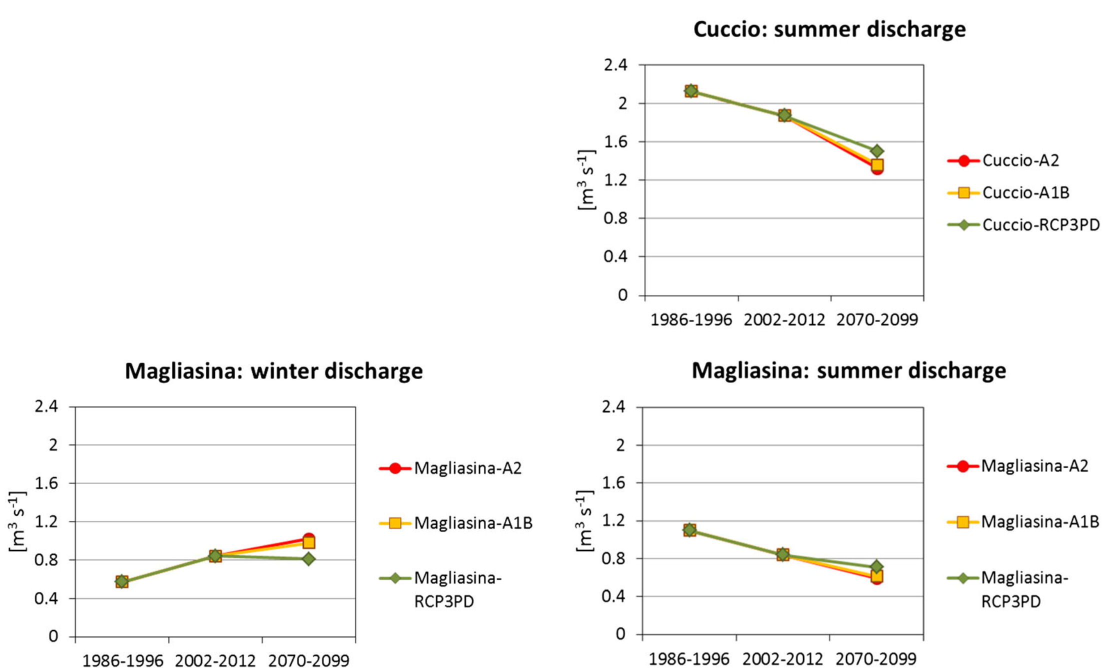

Figure 5. Winter and summer discharge in 1972–1982 (observed), 2002–2012 (observed) and 2070–2099 (projected) of two non-urbanized study streams. Projections were made for three scenarios of future greenhouse-gas emission trends (see Methods). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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greenhouse-gas forcing was ambiguous for the time period 1976–2012.

During the study period, streams draining urbanized catchments had deseasonalized temperatures up to 4 °C higher, and warmed up to three times faster, than the most rural streams. However, these differences may not be entirely attributed to urbanization. Urbanized streams in the study area originated at lower altitudes and belonged to different habitat types than the rural streams, so they might have been slightly warmer regardless of land use. Nonetheless, in Switzerland, natural differences between these stream types amount to no more than 2 °C (Dübendorfer *et al*., 2011; Table I), suggesting that the rest of the differences, up to 2 °C, stemmed from variation in catchment urbanization. Urbanization leads to stream warming through a variety of impacts, including removal of riparian canopy, domestic or industrial discharges of heated water, effluents of sewage-treatment plants or runoff from impervious surfaces (Kinouchi, 2007; Nelson and Palmer, 2007). While all these impacts occurred in the study area, at present, the influence of sewage-treatment plants explains as much as one extra degree (°C) in the urban streams (see Methods).

In Europe, contributions of the NAO to recent warming trends in streams and rivers are well known (e.g. Hari *et al*., 2006; Durance and Ormerod, 2007), but our study is among the first to indicate influences by the AMO. The contributions of the NAO and AMO to the warming trends in our streams are consistent with the patterns of these oscillations during the last decades. The NAO tended to remain in a positive phase from the 1960s to the 1990s, while the AMO index has displayed an increasing trend from the 1970s to present. Therefore, for most of the study period (1976–2012), these oscillations drove European climate towards warmer conditions in unison.

The precise mechanisms through which these climatic oscillations warmed the study streams have yet to be assessed but probably included changes in heat fluxes between streamwater, groundwater and the atmosphere. For example, in winter, a shift towards more positive NAO and/or AMO phases could mitigate convective heat losses from the streams to the atmosphere by reducing the number of days when air temperature drops below stream temperature. In other seasons, a shift towards a more positive AMO phase could result in warmer air and greater heat gains in streams. Moreover, warmer weather could induce a greater accumulation of heat in the ground during the warm seasons and, hence, a greater release of heat to streamwater through hyporheic exchange during the cold seasons (Caissie, 2006).

Contrary to the Atlantic oscillations, the MO had no influence on monthly variation in stream temperature. In Europe, the MO affects the temperature, the duration of the ice cover and the timing of the ice-out in lakes in eastern Austria and Hungary, but the influence of this teleconnection appears to decrease towards western and northern Europe (Dokulil *et al*., 2010). Therefore, in our study area, which lies roughly in the centre of continental Europe, the signal of the MO might have been too weak to be detected in patterns of streamwater temperature. Additionally, during most of the study period, the Atlantic influence was unusually strong (implied by high values of the NAO index), and its strength might have overshadowed the Mediterranean influence on the climate of the Alpine area.

Greenhouse-gas forcing, or more precisely CO_2 forcing, had no independent effects on the most rural stream (Cuccio) but had an apparent influence on temperature in the other streams, especially in the most urbanized ones. This result was perplexing because CO_2 forcing is a global phenomenon, so we expected it to affect urbanized and non-urbanized streams alike. Therefore, we suggest that the independent effect was spurious, because of a confounding association between the CO_2 index and the rate of urbanization of the catchments. In other words, we suggest that increasing catchment urbanization had an approximately linear warming effect, which our models attributed to the CO_2 index because this predictor also increased quasi-linearly during the study period.

It is possible that CO_2 forcing influenced stream temperature indirectly, via effects on climatic oscillations. Although the AMO and the NAO stem from intrinsic atmospheric processes, the apparent shift of the NAO towards a more positive phase during the last decades may have been influenced by greenhouse-gas forcing (as well as a loss of stratospheric ozone; Visbeck *et al*., 2001; Hurrell *et al*., 2003; Knudsen *et al*., 2011). However, the effects of human activities on the NAO are uncertain and probably explain only a small fraction of NAO variability (Hurrell *et al*., 2003). It is also possible that, because of the correlation between the AMO and CO_2-forcing indices, our models attributed true effects of CO_2 forcing to the AMO. However, the correlation between indices was moderate ($r = 0.7$), suggesting that the AMO index should not have entirely camouflaged any independent effects of CO_2 forcing, if the effects were strong. On the whole, we suggest that CO_2 forcing was not a major driver of the warming trends observed in this study.

Future stream temperature and discharge

While greenhouse-gas forcing might not have been a major driver of stream temperature and discharge until present, our projections suggest that its role will increase considerably before the end of the century. By 2070–2099, we predicted that greenhouse-gas forcing will cause shifts in temperature

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and discharge that are larger than the effects apparently caused by climate oscillations and urbanization during the last four decades. As a case in point, the summer temperature at our most rural stream (Cuccio) increased by 0.8 °C from 1976–1986 to 2002–2012, but was projected to increase by 3.5 °C between 2002–2012 and 2070–2099.

Increases in temperature or losses in discharge of the magnitude projected by this study would almost certainly alter biological communities, ecosystem processes and ecosystem services. For example, most study streams are used for recreational trout fishing and serve as conduits for the transport of treated sewage to Lake Lugano. However, the occurrence of trout, *Salmo trutta*, would be jeopardized by high summer temperature (Hari *et al*., 2006) and reduced flows, which could lead to toxic, poorly oxygenated water at urban sites. Reduced flows would also reduce the water renewal time of Lake Lugano and might hinder the lake's ongoing recovery from eutrophication.

Preventing these changes will require more than a rapid reduction in global greenhouse-gas emissions. A shift from high (A2 scenario) to medium-high (A1B scenario) emissions would have minor effects. Even attaining the most optimistic scenario (RCP3PD) would not reverse current warming trends for another century (IPCC, 2007). Therefore, if the existing ecosystem services provided by the study streams are to be maintained, the impacts of future warming have to be diffused before the effects of any declines in greenhouse-gas emissions will take effect. In the study area, non-urbanized streams offer little latitude for adaptation measures, because their overall ecological state is good. However, conditions at urban streams could be ameliorated by increasing riparian shading, restoring riparian buffers or reducing impervious surfaces (Beechie *et al*., 2013).

Conclusions

During the last decades, interest in climate change has drawn attention to long-term changes in temperature and discharge in streams and rivers, as well as on the causes of these changes. To date, warming trends have been reported throughout the Northern Hemisphere. However, the causes remain unclear, as attempts to relate these trends to underlying drivers have been rare (Durance and Ormerod, 2007). Furthermore, the contribution of anthropogenic forcing to these trends has not been addressed. Our study, based on unusually long and detailed stream temperature and discharge data, provided new insights. The picture emerging is one of transition. So far, in the study area, long-term changes in stream temperature and discharge have reflected mainly climate oscillations, a largely (although perhaps not exclusively) natural phenomenon (Hurrell *et al*., 2003; Knudsen *et al*., 2011), and urbanization, a local human impact. In the near future, in comparison, greenhouse-gas forcing, a global human impact, is predicted to assume greater importance. A shift towards increasing global human pressure would have important consequences for the study streams and our ability to manage them. For example, the shift would impress a more directional nature upon the changes in temperature and discharge. In addition, it will probably extend anthropogenic warming to rural streams, which were hitherto unaffected. Finally, the shift would hinder our ability to conserve streams and associated ecosystem services through local or regional management, including adaptive measures. More and more, in the future, conserving local ecosystems might require management at the global scale.

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APPENDIX A

Projected increases in (A) air temperature (in °C) and (B) precipitation (in mm) in the study area from 1980–2009 to 2070–2099, according to season and three scenarios (A2, A1B and RCP3PD) of future greenhouse-gas emission (Meteosvizzera, 2012). See Methods for definition of seasons and description of emission scenarios.

(A) Air temperature

	A2	A1B	RCP3PD
Winter	+3.8	+3.3	+1.4
Spring	+3.7	+3.1	+1.3
Summer	+4.8	+4.1	+1.8
Autumn	+3.8	+3.3	+1.4

(B) Precipitation

	A2	A1B	RCP
Winter	+23%	+20%	+8%
Spring	−10%	−9%	−4%
Summer	−27%	−23%	−10%
Autumn	−9%	−9%	−3%

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APPENDIX B

Models predicting (A) seasonal water temperature, T_w (in °C), and (B) seasonal discharge, Q, in two study streams (Cuccio and Magliasina) from air temperature (T_{air}, in °C) and precipitation (P, in mm) during the past (maximum extent 1976–2012; the beginning varies depending on stream and parameter, according to data availability). Significant models were used to project future (2070–2099) water temperature and discharge from projected changes in air temperature and precipitation (see APPENDIX A). The asterisks indicate the level of significance: $^{*} = p < 0.5$; $^{**} = p < 0.01$; $^{***} = p < 0.001$; ^{NS} = non-significant ($^{\dagger} = p < 0.10$). wi = winter; su = summer.

(A) Water temperature

River	Model	Model fit
Magliasina	$T_{w,wi} = 1.04 + 0.65 \times T_{air}$	$R^2 = 0.10$; $df = 1, 35$; $F = 3, 74^{NS\dagger}$
	$T_{w,su} = -7.69 + 1.10 \times T_{air}$	$R^2 = 0.56$; $df = 1, 35$; $F = 44.30^{***}$
Cuccio	$T_{w,wi} = -0.16 + 0.88 \times T_{air}$	$R^2 = 0.34$; $df = 1, 33$; $F = 16.60^{***}$
	$T_{w,su} = -4.92 + 0.95 \times T_{air}$	$R^2 = 0.40$; $df = 1, 33$; $F = 21.57^{***}$

(B) Discharge

River	Model	Model fit
Magliasina	$\mathrm{Log}_{10}Q_{wi} = -46 + 0.006 \times P$	$R^2 = 0.65$; $df = 1, 31$; $F = 57.68^{***}$
	$\mathrm{Log}_{10}Q_{su} = -0.58 + 0.003 \times P$	$R^2 = 0.52$; $df = 1, 31$; $F = 33.33^{***}$
Cuccio	$\mathrm{Log}_{10}Q_{wi} = 0.08 + 0.001 \times P$	$R^2 = 0.01$; $df = 1, 25$; $F = 0.27^{NS}$
	$\mathrm{Log}_{10}Q_{su} = -0.11 + 0.002 \times P$	$R^2 = 0.58$; $df = 1, 25$; $F = 33.86^{***}$

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