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# Global versus local change effects on a large European river

M. Floury [a,*], C. Delattre [a], S.J. Ormerod [b], Y. Souchon [c]

[a] EDF R&D, Laboratoire National Hydraulique et Environnement, 6 Quai Watier, BP 49, 78401 Chatou, France
[b] Catchment Research Group, Cardiff School of Biosciences, Cardiff University, CF10 3AX, UK
[c] Irstea, UR MALY, Milieux Aquatiques, Ecologie et Pollutions, Pôle Hydroécologie Onema/Irstea, 3 bis Quai Chauveau, 69336 Lyon, CP 220, France

## HIGHLIGHTS

- ► This long-term multi-parametric study is one of the first of its kind.
- ► It illustrates the potential for complex environmental interactions in large rivers.
- ► It reveals how warming in Loire is consistent with recent atmospheric warming.
- ► Conversely, local management has larger effects on discharge and water quality.
- ► This work is expected to form a basis for assessing biological responses to changes.

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## ABSTRACT

Water temperature and discharge are fundamental to lotic ecosystem function, and both are strongly affected by climate. In large river catchments, however, climatic effects might be difficult to discern from background variability and other cumulative sources of anthropogenic change arising from local land and water management. Here, we use trend analysis and generalised linear modelling on the Loire, the longest river in France to test the hypotheses that i) long-term trends in discharge and river temperature have arisen from climate change and ii) climatic effects on water quality have not been overridden by local effects.

Over 32 years (1977–2008), discharge in the Middle Loire fell by about 100 $m^3/s$ while water temperature increased by 1.2 °C with greatest effects during the warm period (May–August). Although increasing air temperature explained 80% of variations in water temperature, basin-wide precipitation showed no long-term trend and accounted for only 18% of inter-annual fluctuations in flow. We suggest that trends in abstraction coupled with a potential increase in evapo-transpiration at the catchment scale could be responsible for the majority of the long-term discharge trend.

Discharge and water temperature explained only 20% of long-term variations in major water quality variables (conductivity, dissolved oxygen, pH, suspended matter, biochemical oxygen demand, nitrate, phosphate and chlorophyll-a), with phosphate and chlorophyll declining contrary to expectations from global change probably as a consequence of improved wastewater treatment.

These data partially support our first hypothesis in revealing how warming in the Loire has been consistent with recent atmospheric warming. However, local management has had larger effects on discharge and water quality in ways that could respectively exacerbate (abstraction) or ameliorate (reduced point-source pollution) warming effects. As one of the first case-studies of its kind, this multi-parametric study illustrates the potential for complex interactions between climate change and other environmental factors in large rivers.

## 1. Introduction

River thermal and hydrologic regimes are strongly influenced by climatic variations and potentially, therefore, global warming (Whitehead et al., 2009). In Europe, hydroclimatic models of warming predict a generalised rise in air and water temperatures and increasing variability in river flow, with discharge reduction during summer and increased drought risk likely in major European basins such as the Rhine, Danube or Volga (Webb, 1996; Arnell, 1999; EEA, 2007). Available data show already that warming trends are observable in rivers over a large geographical area (Langan et al., 2001; Daufresne et al., 2004; Hari et al., 2006; Moatar and Gailhard, 2006; EEA, 2007; Hammond and Pryce, 2007; Webb and Nobilis, 2007; Gosse et al., 2008; Pekarova et al., 2008; Zweimuller et al., 2008; Durance and Ormerod, 2009), with trends particularly pronounced since 1976 (IPCC, 2007). Although trends in discharge are more difficult to distinguish from background variability (Ziegler et al., 2005; Massei et al., 2011), retrospective

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* Corresponding author. Tel.: +33 1 30 87 79 75; fax: +33 1 30 87 80 86.
*E-mail addresses:* mathieu.floury@edf.fr (M. Floury), cecile.delattre@edf.fr (C. Delattre), ormerod@cardiff.ac.uk (S.J. Ormerod), yves.souchon@irstea.fr (Y. Souchon).

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studies and predictive models are currently consistent in revealing increasing discharge seasonality (Andersen et al., 2006; Webb and Nobilis, 2007; Whitehead et al., 2009). At least in high altitude, continental regions, this effect is largely explained by reduced snow cover, reduced spring thaw effects and a shift in winter precipitation from snow to rain (Arnell, 1999; Middelkoop et al., 2001; Nijssen et al., 2001; Eckhardt and Ulbrich, 2003).

Both thermal and hydrological changes in rivers have profound consequences. Temperature not only affects major processes in rivers such as gas dissolution (e.g. oxygen), the kinetics of solutes and pollutants (e.g. dissolution or precipitation) and evaporation, but it also plays a fundamental role in the survival, growth, metabolism, phenology, behaviour and interaction of organisms (Durance and Ormerod, 2010; Walther, 2010; Wilby et al., 2010; Woodward et al., 2010; Yvon-Durocher et al., 2010). Water temperature also affects primary production and litter decomposition thereby affecting river energetics along the entire river continuum (Vannote et al., 1980; Lecerf et al., 2007; Barlocher et al., 2008). Discharge variations also have fundamental effects on fluvial dynamics, solute flux and transport processes, while regulating the diversity, abundance and habitat conditions for organisms (Lake, 2000; Xenopoulos et al., 2005; Brown et al., 2007; Dewson et al., 2007).

Although climate change effects on rivers are now becoming apparent on at least three continents [e.g. Webb and Nobilis, 2007 (Europe); Chessman, 2009 (Australia); Kaushal et al., 2010 (North America)], under some circumstances they are exacerbated, confounded or potentially obscured by other sources of environmental change (Parmesan and Yohe, 2003; Daufresne et al., 2007; Durance and Ormerod, 2009). In large river basins, for example, river temperature and discharge pattern can also be severely affected by human activities that include river regulation for energy production, abstraction for irrigation or domestic and industrial purposes, thermal waste, urbanization, agricultural intensification and deforestation (Caissie, 2006; Webb et al., 2008; Wilby et al., 2010). These activities also affect river water quality either directly or by altering solute dilution (Limbrick, 2003; Bouraoui and Grizzetti, 2008). Some projections suggest that climate and land use will interact, for example through altered fluxes of nitrogen and phosphorus coupled with reduced dilution at low flow (Andersen et al., 2006; Whitehead et al., 2006; Jennings et al., 2009; Johnson et al., 2009). Under these circumstances, being able to distinguish the effects of climate change from other, local effects is an important priority, for example to diagnose the sources of change and guide management action. So far, however, investigations that attempt to make such distinctions are scarce.

In this paper, we use data from the Loire, France's longest river and one of the largest in Europe, to test the hypotheses that i) long-term trends in discharge and river temperature have arisen from climate change and ii) climatic effects on water quality have not been overridden by local effects. Hypothesis i) would be supported if local climatic data could explain trends in river temperature and discharge, while hypothesis ii) would be supported if physico-chemical trends revealed deteriorating water quality consistent with climate-change. In particular, eutrophication and trends in related-variables — typically an increase in biological oxygen demand and nitrate, phosphate and chlorophyll-a concentrations — are expected to be promoted by warmer temperatures and reduced discharge.

The Middle Loire has warmed over recent years, making it an ideal candidate river to test these hypotheses: Moatar and Gailhard (2006) showed that water temperature there has increased significantly by 2.4–3 °C in both spring and summer between 1976 and 2003. The Loire is also considered eutrophic, with warm period (spring–summer) chlorophyll peaks that can exceed 150 μg/L (Lair et al., 1998; Moatar and Meybeck, 2005). Other previous studies have reported on the thermal regime (Moatar and Gailhard, 2006; Gosse et al., 2008), hydrology (Bontron et al., 1999), chemical composition (Grosbois et al., 2001), nutrients (Meybeck et al., 1988) and plankton (Lair, 2001; Picard and Lair, 2005). To the best of our knowledge, however, this is the first study to consider all such factors together, describing long-term change over a period of three decades and analysing the relationships between observed trends.

## 2. Material and methods

### 2.1. Study area and data

The dataset (Appendix A) comes from Dampierre-en-Burly (47.4°N; 2.3°E) and Jargeau (47.5°N; 2.1°E) sites on the upstream Middle Loire (Fig. 1). Here, the Loire is 8th order river, with a catchment of 35,500 km$^2$, mean width of 300 m and mean low-water depth of about 1 m. Dampierre is at an altitude of 123 m, 110 km downstream of the confluence with the Allier and 550 km from the source. Jargeau is 40 km downstream of Dampierre, at 109 m. A preliminary climatic, hydrological and chemical study confirmed that the two sites were typical of all other measurement stations in the reach.

To test the main hypotheses, continuous measures of water temperature (Tw) and discharge (Q) were analysed by monthly steps over the period 1977–2008 using regulatory monitoring data from the Dampierre nuclear power station. Like the three other nuclear plants on the Middle Loire, Dampierre is equipped with an atmospheric cooling system which keeps the volume of diverted water and the temperature of discharge well within the long-term ranges of river temperature and discharge ($\leq$0.05 m$^3$/s removed for a 1300 MWe reactor and returned water heated by few tenths of a degree, respectively; see Vicaud, 2008), and thus there is no effect on the trends being studied here.

Specifically to test the first hypothesis, the effects of global climate change on the river's thermal and hydrological regimes were assessed using continuous measurement of air temperature (Ta) from Gien (10 km upstream of Dampierre), and of precipitation (Ptt), measured in the upstream basin. These data were available from the *Météo-France* national meteorology service at monthly steps for 1977–2008 (see Vidal et al., 2010).

Chemical data were available from both sites to test the second hypothesis. Regulatory monitoring at Dampierre includes continuous measurement of conductivity (Cdty), dissolved oxygen concentration ($O_2$) and pH for the period 1980–2008, reported monthly. Monitoring by the *Loire–Bretagne Basin Water Authority* at Jargeau provided monthly values for suspended matter contents (SM) since 1984, biochemical oxygen demand (BOD) since 1987, and concentrations of nitrate ($NO_3^-$), phosphate ($PO_4^{3-}$) and chlorophyll-a (Chloro) since 1980.

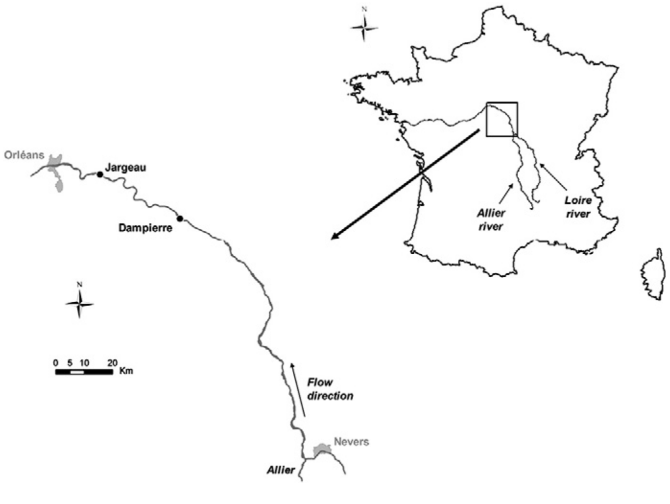

**Fig. 1.** Location of the Middle Loire and measuring stations.

### 2.2. Data analysis

All variables were first subject to a Grubbs' test to remove outliers (Grubbs, 1969), and then normalised to account for difference in measurement units. The resultant time series can be written as:

$$Series = Trend + Seasonal + Residuals.$$

To reduce the risk of spurious correlations and because the focus of analysis was on the origin of the trends, the *Seasonal* component was removed from each time series. In order to do this, each monthly average was converted to a deviation from the average for the same calendar month over the whole 32-year period. The resultant deseasonalized series are those used for the additional analyses.

#### 2.2.1. Trend analysis

The complete Tw and Q series were subject to a Mann–Kendall trend test as adapted by Hamed and Rao (1998). This method detects trends in temporal series after removing autocorrelations by Spearman rank correlation (Daufresne et al., 2004). The test was then implemented on the monthly series to identify months showing significant trends, thereby targeting the period mainly responsible for the overall evolution of Tw and Q. This key period was then selected for each of the 12 variables (Tw, Q, Ta, Ptt, Cdty, $O_2$, pH, SM, BOD, $NO_3^-$, $PO_4^{3-}$ and Chloro), and the series so formed were subject to the same trend test.

#### 2.2.2. Modelling relationships between variables

We used a model selection approach to quantify (i) the relative effects of atmospheric variables (Ta and Ptt) in the long-term trends observed for water temperature and discharge and (ii) the relative effects of water temperature and discharge in the long-term evolution of the 8 water quality variables. First, we performed a general linear modelling (GLM; Nelder and Wedderbu, 1972) on Tw and Q using the form:

$$Y \sim Ta + Ptt.$$

Second, we performed a GLM on the chemical variables (Cdty, $O_2$, pH, SM, BOD, $NO_3^-$, $PO_4^{3-}$ and Chloro) using the form:

$$Y \sim Tw + Q.$$

Because Y had a normal distribution (all series had been normalised), we used Gaussian models of GLM. The best model was selected for each Y according to Akaike's Information Criterion (AIC) and statistical significance was estimated by analysis of deviance between the null and selected models, validated by Fisher's F test (Fisher, 1950). Finally, the proportion of deviance explained by each explanatory variable retained in the selected model was extracted from the same analysis of deviance.

Only linear models were fitted because the effect of "deseasonalization" limited options for investigating non-linear effects. Moreover, preliminary investigation of non-linear effects using methods that were still possible after removing seasonal trends gave no significant improvements to model fit.

All analyses were performed using R software (R 2.12.0, R Development Core Team, 2010).

## 3. Results

### 3.1. Water temperature and discharge trend analysis

Water temperature increased significantly ($P<0.001$) over the 32-year period by about 1.2 °C between the first decade (1977–1986) and the last (1999–2008) (Table 1; Fig. 2a). Discharge declined ($P<0.05$) over the same period from 410 $m^3/s$ in 1977–1986 to 305 $m^3/s$ in 1999–2008, i.e. a decrease of 25% (Table 1; Fig. 2b).

Trend analysis on monthly data showed that water temperatures in May, June and August all increased significantly (Table 1), and were mainly responsible for the overall observed trend. Likewise, the months of May, June and July were responsible for most of the trend observed for Q (Table 1). All subsequent analyses therefore focused on this "warm period" of May–August of each year (Appendix B).

**Table 1**
Results of trend test applied to complete (All) and monthly (each month) deseasonalized time series for the water temperature (Tw) and discharge (Q) variables.

| Variable | Month | Trend | $\tau$ | *P* | Signif. |
|---|---|---|---|---|---|
| Tw | All | ↗ | 0.20 | <0.001 | *** |
| | May | | 0.45 | <0.001 | *** |
| | June | | 0.48 | <0.001 | *** |
| | August | | 0.25 | 0.048 | * |
| Q | All | ↘ | −0.16 | 0.011 | * |
| | May | | −0.26 | 0.035 | * |
| | June | | −0.34 | 0.006 | ** |
| | July | | −0.26 | 0.035 | * |

Only significant trends are shown; $\tau$ = Kendall tau; $^{***}P<0.001$, $^{**}P<0.01$, $^{*}P<0.05$.

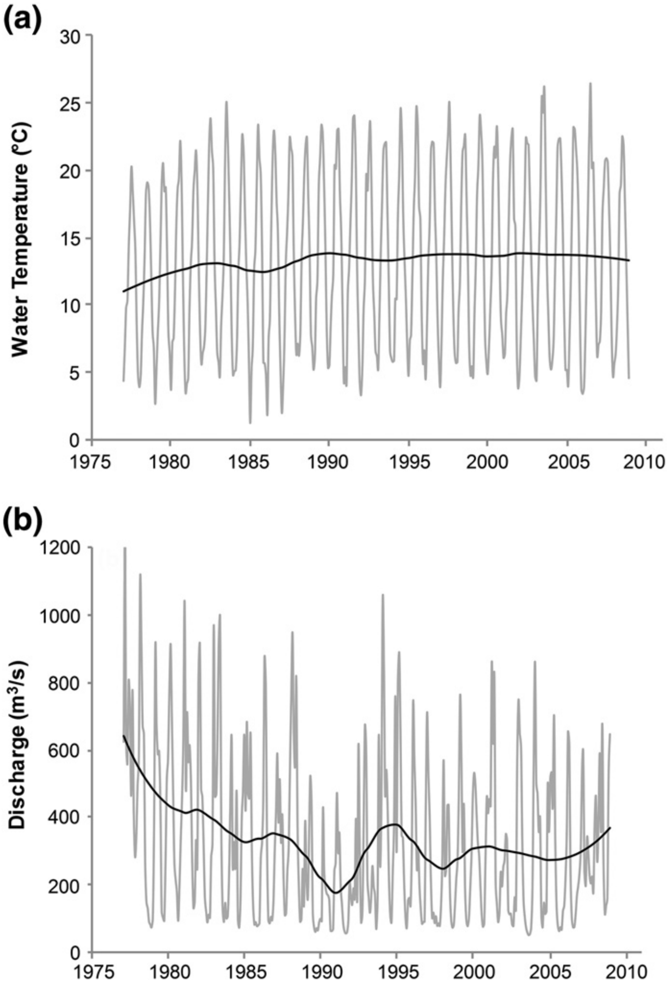

**Fig. 2.** Complete monthly data between 1977 and 2008 (grey curves) and long-term evolution indicated by LOESS (bold curves) for a) the water temperature and b) the discharge. The LOESS smoothing windows used span 30% of the data.

**Table 2**
Results of trend test applied to deseasonalized time series in warm period (May–August) for the 12 variables.

| | Variable | Trend | $\tau$ | $P$ | Signif. |
|---|---|---|---|---|---|
| Atmospheric | Ta | ↗ | 0.31 | <0.001 | *** |
| | Ptt | – | – | 0.797 | o |
| Hydroclimatic | Tw | ↗ | 0.35 | <0.001 | *** |
| | Q | ↘ | −0.25 | 0.001 | ** |
| Chemical | Cdty | – | – | 0.385 | o |
| | $O_2$ | ↘ | −0.23 | 0.002 | ** |
| | pH | ↘ | −0.24 | 0.035 | * |
| | SM | ↘ | −0.27 | 0.004 | ** |
| | BOD | ↘ | −0.36 | <0.001 | *** |
| | $NO_3^-$ | ↗ | 0.24 | 0.014 | * |
| | $PO_4^{3-}$ | ↘ | −0.43 | <0.001 | *** |
| | Chloro | ↘ | −0.30 | 0.012 | * |

$\tau$ = Kendall tau; ***$P<0.001$, **$P<0.01$, *$P<0.05$, o$P>0.05$.

### 3.2. Warm period trends

Trends in water temperature and discharge were stronger in the May–August warm period than in the overall time series (higher absolute $\tau$-coefficient values and significance levels; Table 2). Between the first ten years and the last ten, these results correspond to a rise of 2 °C in mean water temperature (from 19.1 °C to 21.1 °C) and a 40% fall in mean discharge from 322 to 192 $m^3$/s.

Among atmospheric variables, only air temperature changed significantly ($P<0.001$; Table 2), increasing during the warm period by about 1.6 °C between the first and last decades (from 15.9 °C to 17.5 °C, respectively).

Among chemical variables (Table 2), $O_2$, pH and SM declined slightly but significantly through time, with dissolved oxygen concentration decreasing by about 0.8 mg/L from 1977–1986 to 1999–2008 (from 11.0 to 10.2 mg/L), pH by 0.3 (from 8.7 to 8.4) and suspended matter by 2.3 mg/L (from 29.1 to 26.8 mg/L). Likewise, biochemical oxygen demand fell ($P<0.001$) by 2.7 mg/L from 1988–1997 to 1999–2008 (from 5.7 to 3.0 mg/L). Against the expectation of eutrophication, however, $PO_4^{3-}$ and Chloro fell significantly ($P<0.001$ and $P<0.05$, respectively; Fig. 3) respectively by two-thirds (from 0.15 to 0.05 mg/L) and more than 30 μg/L (from 88.6 to 56.0 μg/L) between the first decade (1977–1986) and the last (1999–2008). In contrast, $NO_3^-$ increased ($P<0.05$) by about 1.5 mg/L (from 3.6 to 5.1 mg/L). Conductivity showed no significant trend ($P>0.05$), with values fluctuating around 256 ± 27 μS/cm.

### 3.3. Effect of atmospheric conditions on Tw and Q

In GLM, air temperature accounted for more than 80% of the deviance in water temperature (Table 3; Fig. 4a) and, on the AIC criterion, the best model did not include Ptt. While precipitation was the strongest explanatory variable for deviance in flow (18%; Table 3), Ta accounted for only 4%, and the best model based on atmospheric predictors explained only 22% of the overall deviance compared to 80% for Tw.

### 3.4. Effect of Tw and Q on river chemistry

In GLM, discharge (Q) was an explanatory variable in all significant models for river chemistry (Table 4) explaining between 9% (BOD) and 32% (pH) of deviance in chemical variables. Tw had significant effects in the models for $NO_3^-$, $PO_4^{3-}$ and Chloro (Table 4), but in all cases accounted for less than 9% of the deviance (cf 11–23% for Q). In combination, Tw and Q explained, at best, just over a third of the deviance in any water quality variable ($PO_4^{3-}$; $P<0.001$). Neither had any effect on SM ($P>0.05$; Table 4). On average, the best models significantly explained only 20% (±9) of initial deviance in chemical variables (Table 4).

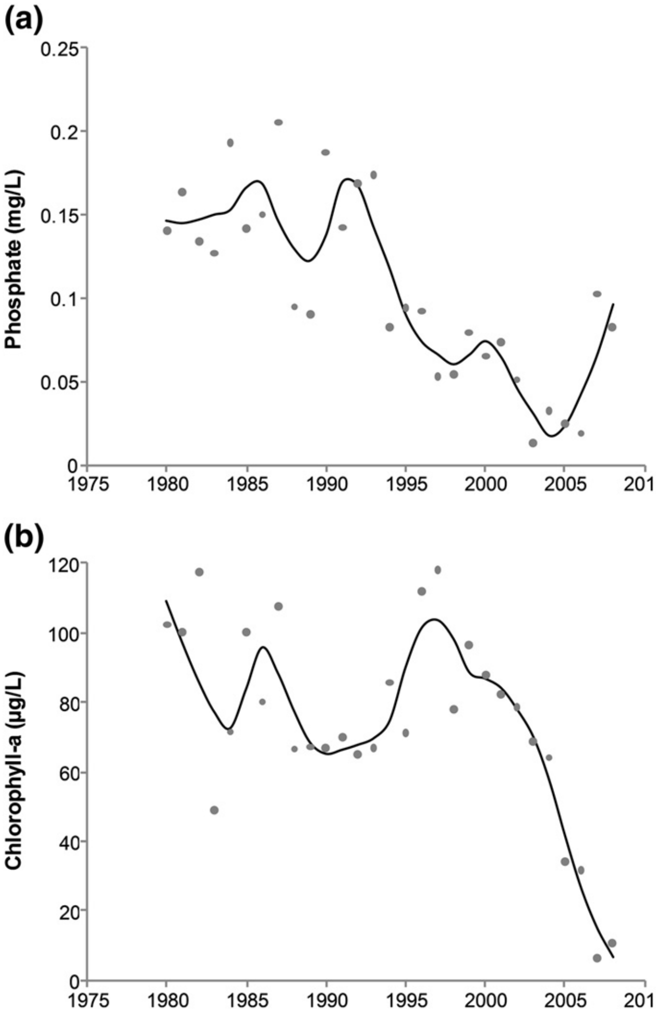

**Fig. 3.** Annual data in warm period between 1980 and 2008 (grey dots) and long-term evolution indicated by LOESS (bold curves) for a) the phosphate concentration and b) the chlorophyll-a concentration. The LOESS smoothing windows used span 30% of the data.

## 4. Discussion

These data from the Middle Loire partially support our first hypothesis that warming has occurred over recent decades in the Loire River, and that a large proportion of this trend can be explained by atmospheric warming (Fig. 2a). This result is in agreement with Moatar and Gailhard (2006) for the same river over the period 1976–2003 while the extent of overall warming (c. 1.2 °C over 3 decades) is consistent with other large European rivers (e.g. 1.4 °C to 1.7 °C rise over the 20th century on the Danube and tributaries; Webb and Nobilis, 2007). Moreover, these analyses indicate a major contribution to

**Table 3**
Results of GLM performed on Tw and Q: Null = null deviance, %Ta = percentage of deviance explained by Ta, %Ptt = percentage of deviance explained by Ptt, Residual = residual deviance, % explained = total percentage of deviance explained by the model, F = Fisher F and P = P-value.

| Variable | Deviance | | | | | Statistics | |
|---|---|---|---|---|---|---|---|
| | Null | %Ta | %Ptt | Residual | % explained | $F$ | $P$ |
| Tw | 8.64 | 80.1 | – | 1.72 | 80.1 | 254.256 | <0.001 |
| Q | 60.70 | 4.0 | 18.0 | 47.35 | 22.0 | 11.749 | <0.001 |

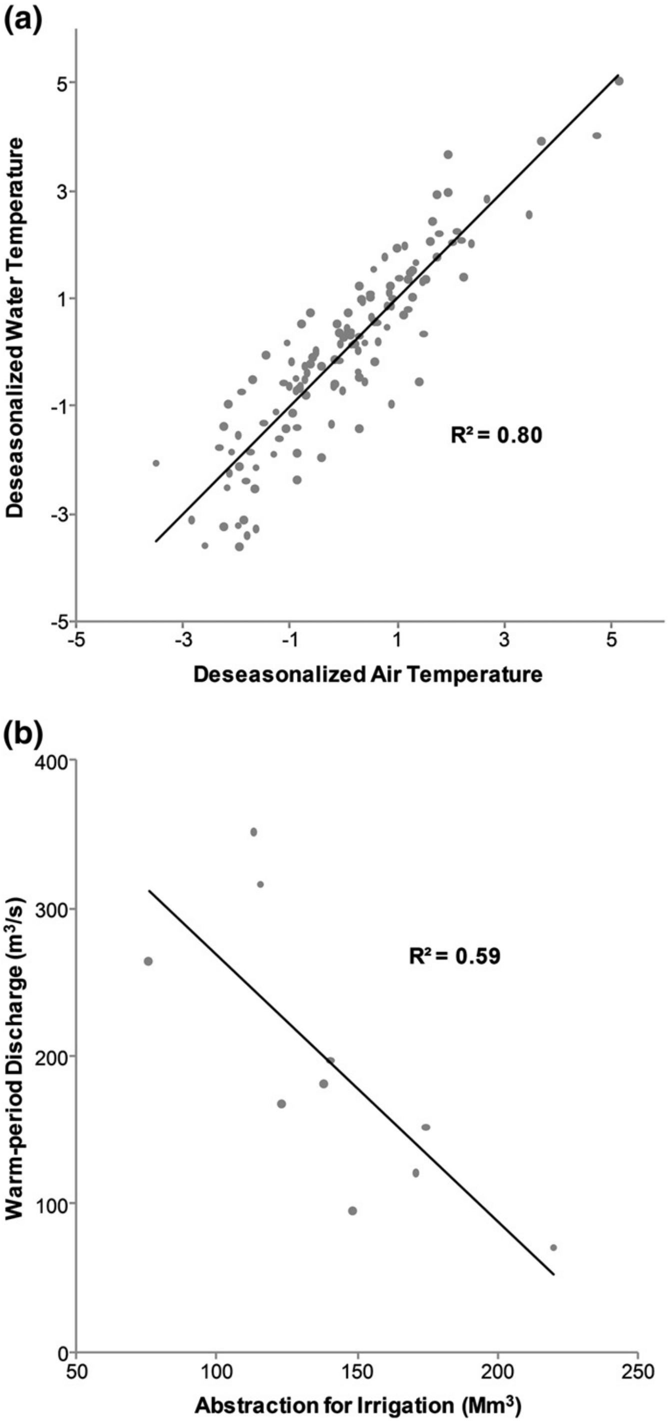

**Fig. 4.** Main factors identified as responsible for the hydroclimatic evolution of the Middle Loire River. a) Relationship between water temperature and air temperature over the 1977–2008 period (deseasonalized series in warm period). b) Relationship between mean annual discharge in warm period and annual abstraction for irrigation (data from the *Loire–Bretagne Basin Water Authority*) over the 1999–2008 period. Links between variables are shown by the black lines and associated $R^2$ coefficients derived from simple linear regressions.

warming from the hottest period of the annual cycle, with the mean temperature in the Middle Loire for May–August rising by about 2.0 °C over 32 years.

**Table 4**
Results of GLM performed on chemical variables: Null = null deviance, %Tw = percentage of deviance explained by Tw, %Q = percentage of deviance explained by Q, Residual = residual deviance, % explained = total percentage of deviance explained by the model, *F* = Fisher F and *P* = *P*-value.

| Variable | Deviance | | | | | Statistics | |
|---|---|---|---|---|---|---|---|
| | Null | %Tw | %Q | Residual | % explained | *F* | *P* |
| Cdty | 67.46 | – | 17.5 | 55.64 | 17.5 | 11.256 | <0.001 |
| $O_2$ | 131.24 | – | 13.5 | 113.53 | 13.5 | 8.266 | 0.001 |
| pH | 64.70 | – | 32.3 | 43.79 | 32.3 | 25.299 | <0.001 |
| SM | 72.01 | – | 4.5 | 68.78 | 4.5 | 2.302 | 0.105 |
| BOD | 87.95 | – | 9.0 | 80.00 | 9.0 | 3.976 | 0.023 |
| $NO_3^-$ | 24.28 | 4.0 | 13.2 | 20.10 | 17.2 | 7.679 | <0.001 |
| $PO_4^{3-}$ | 45.43 | 9.0 | 23.4 | 30.70 | 32.4 | 17.744 | <0.001 |
| Chloro | 77.08 | 3.5 | 10.9 | 65.96 | 14.4 | 6.233 | <0.001 |

As with water temperature, discharge exhibited stronger changes during the warmest months, falling through time and, again, these trends are consistent with the Danube (Webb and Nobilis, 2007; Pekarova et al., 2008) or the Rhône (Souchon et al., 2011). In this case, however, trends in precipitation explained only part of the discharge trend so that our first hypothesis is supported only partially. For water quality, climatically-mediated characteristics of the Loire had only minor effects on river chemistry, and some trends were contrary to the expectations of climate-change implying that local factors within the catchment must have been more important. Our second hypothesis is therefore falsified. We expand on these findings below.

Atmospheric trends over the Loire catchment have been consistent with the predictions of global warming (IPCC, 2007). In the Middle Loire, May–August air temperatures have increased by about 1.6 °C between 1977–1986 and 1999–2008. Moreover, the strong relation between Ta and Tw (Fig. 4a) confirmed the well-known link between air temperature and river water temperature (Webb et al., 2003, 2008; Caissie, 2006). Solar radiation heats both air and water through similar processes, but long-term warming trends in rivers are also likely to reflect heat transfers and thermal balance at the air/water interface. In the Middle Loire, these processes in total appear to account for more than 80% of the rise in temperature over the study period. Surprisingly, however, results showed that the river is warmer than the atmosphere (both in absolute and trend values), when the latter is supposed to contribute to the warming of the former. These unusual data may be simply due to the measurement frequency, with daily averages calculated from hourly values. Intra-day variations in air temperature are greater owing to a weaker specific heat capacity and nocturnal values, thus tending to downweight mean values more strongly for the atmosphere. It could be argued that water temperatures are affected by radiant heating, groundwater exchange and evaporative cooling as well as heat exchange with the atmosphere, so that a mechanistic approach using heat budgets is required to assess trends in more detail.

In contrast to river temperature, atmospheric warming was only weakly implicated in the long-term decrease in the river discharge, with less than 5% of hydrological patterns directly accounted for by rising temperature. Evaporation could be involved, and might even be underestimated by predictions using air temperature alone. Unfortunately, detailed data about evapo-transpiration processes were not available at the spatial and temporal scales investigated. Whereas precipitation was the main variable explaining river discharge in the GLM model (around 18%), precipitation showed no significant trend over the 32-year period, so that any relationship between air temperature, discharge and precipitation appeared to reflect inter-annual fluctuations rather than continuous long-term trend. This could explain why the trend for discharge was relatively weak and highly dependent on the period under consideration, in contrast to the gradual and constant evolution observed for water temperature. More in-depth assessment of temporal variations in hydrologic regime, based on specific measures, might disclose any significant trends for extreme events (floods or droughts), as suggested by several studies (Arnell, 1999; Middelkoop et al., 2001; Eckhardt and Ulbrich, 2003; Whitehead et al., 2009), but such assessments were outside our scope.

In the absence of large climate-change effects on flow, the next likely candidate for the cause of progressively declining discharge is local, human management of water flow through the Loire basin. Annual data on abstraction for irrigation purposes show a strong correlation with mean warm period discharge (c. 60%; Fig. 4b). Although these annual data were available only for a limited period (since 1999), they give an indication of the potential impact of human activities on the Loire's discharge pattern. According to the *Loire–Bretagne Basin Water Authority*, abstraction for irrigation represents a mean annual withdrawal of about 142 million $m^3$ during the last decade (1999–2008).

As with large European rivers, global climate changes are bound to be expressed in the Middle Loire alongside other anthropogenic alterations across the basin as a whole — notably land use change and water abstraction. The resulting effects on the Loire are likely to be through complex but predictable interactions. First, summer precipitation is forecast to fall strongly in Europe under the influence of global warming (Arnell, 1999; Eckhardt and Ulbrich, 2003), and water temperature is expected to continue to rise with the highest averages and maxima in summer. Second, these are exactly the same periods in which almost all water abstraction for irrigation takes place (about 98% of total annual volume, according to the *Loire–Bretagne Basin Water Authority*), further amplifying the phenomenon. Nonetheless, the volume abstracted during the warm period never exceeded 10% (in 2003) of the total water volume flowing in the Loire over the same period. Thus, while abstraction could contribute, on its own it is insufficient to be the main cause of discharge reduction in the Loire River observed here. Given that no trend was detected in precipitation, increased evaporation and/or transpiration in the Loire Basin remains the most plausible explanation for the majority of the long-term decline in discharge. Therefore, global and local factors affecting hydrological trends now require more detailed investigation, scenario-setting and modelling to guide future planning for adaptation.

In addition to affecting discharge, local reach- or catchment-scale processes have large potential to affect water quality either directly or through interaction with climate change. In the Middle Loire, phosphate and chlorophyll levels have declined over time, with the former falling almost continuously between 1980 and 2008, from about 0.15 mg/L to values oscillating around 0.05 mg/L during the last 10 years (Fig. 3a). Mean chlorophyll concentrations fluctuated at 60–120 μg/L until the mid-1990s and then fell strongly to <10 μg/L during the last years of the series (Fig. 3b). BOD also declined progressively from 1987. Not only are these trends contrary to expectations from global warming, they also run contrary to expectations from the observed locally reduced discharge and increased temperature. In particular, discharge reduction should have been sustained by greater groundwater exports discharged to the river, which exhibit high loads of dissolved solutes (Bouraoui and Grizzetti, 2008). Likewise, reduced flow and warmed waters were expected to promote physical habitat conditions and metabolic rates for phytoplankton organisms (Picard and Lair, 2005). Hydroclimatic variables, therefore, explained only a small proportion of deviance in river chemistry.

As a result, local water quality management is strongly implicated in these observed trends. Key points are the increasing number and improved performance of wastewater treatment plants (as a consequence of the Urban Wastewater Treatment Directive of 1991, 91/271/EEC) and the ban on phosphorus in washing powders (driven by a French Convention of 1989 and more recently the National Decree no. 2007-491 of the 29th March, 2007) that have helped to reduce phosphorus input into river water. For example, the number of households connected to the water-treatment network in the Loire basin increased between 1980 and 2008 from about 900,000 to 4,200,000 population equivalents, according to the *Eaux Résiduaires Urbaines 2009* database, and this has accounted for more than 80% of the fall in mean annual phosphate concentration (Fig. 5a), in agreement with the recommendations made by Mainstone and Parr (2002). Reduced phosphorus concentrations would then be expected to limit phytoplankton development during the warm period. The limitation is apparently sufficient in this case to reduce chlorophyll-a concentration by 35% over three decades with clear benefits to reduced organic load, when eutrophication is

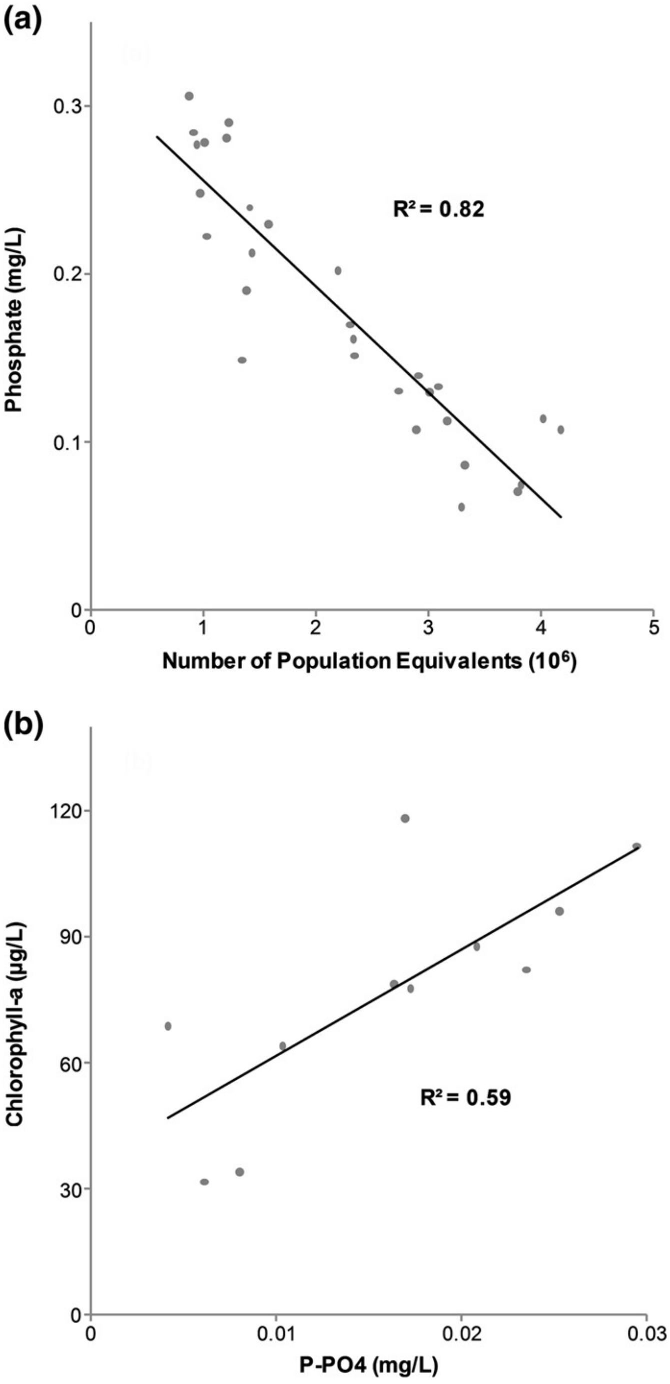

**Fig. 5.** Main factors identified as responsible for the water quality evolution of the Middle Loire River. a) Relationship between mean annual phosphate concentration and number of population equivalents connected to the sewerage network (data from the *Eaux Résiduaires Urbaines 2009* database) over the 1980–2008 period. b) Relationship in warm period between mean annual chlorophyll-a concentration and mean annual P–$PO_4$ concentration over the 1996–2006 period. Links between variables are shown by the black lines and associated $R^2$ coefficients derived from simple linear regressions.

**Appendix A. Annual statistics for the 12 complete time series. See Section 2.1 for abbreviations. Σ = synthesis for the entire period (1977–2008), SD = standard deviation, n = number of observations**

| Year | Ta (°C) | | | Ptt (mm/day) | | | Tw (°C) | | | Q (m$^3$/s) | | | Cdty (μS/cm) | | | O$_2$ (mg/L) | | | pH | | | SM (mg/L) | | | BOD (mg/L) | | | NO$_3^-$ (mg/L) | | | PO$_4^{3-}$ (mg/L) | | | Chloro (μg/L) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n |
| 1977 | 9.8 | 4.8 | 12 | 2.7 | 1.0 | 12 | 12.1 | 5.4 | 12 | 612 | 254 | 12 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 |
| 1978 | 9.4 | 5.5 | 12 | 2.0 | 1.1 | 12 | 11.6 | 5.5 | 12 | 403 | 370 | 12 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 |
| 1979 | 9.7 | 6.0 | 12 | 2.5 | 1.0 | 12 | 12.1 | 6.1 | 12 | 438 | 256 | 12 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 |
| 1980 | 9.1 | 6.0 | 12 | 1.9 | 0.7 | 12 | 12.2 | 6.6 | 12 | 436 | 266 | 12 | 230 | 39 | 10 | 11.2 | 1.0 | 10 | 8.3 | 0.5 | 10 | – | – | 0 | – | – | 0 | 4.3 | 2.8 | 6 | 0.31 | 0.17 | 6 | 55.0 | 58.0 | 11 |
| 1981 | 9.8 | 6.0 | 12 | 2.4 | 1.5 | 12 | 12.6 | 6.2 | 12 | 491 | 279 | 12 | 217 | 71 | 12 | 10.5 | 1.0 | 11 | 8.1 | 0.2 | 12 | – | – | 0 | – | – | 0 | 7.9 | 2.4 | 12 | 0.28 | 0.11 | 11 | 60.4 | 52.8 | 10 |
| 1982 | 10.8 | 6.0 | 12 | 2.3 | 1.1 | 12 | 14.0 | 6.6 | 12 | 363 | 304 | 12 | 342 | 37 | 12 | 10.3 | 1.0 | 12 | 8.5 | 0.6 | 12 | – | – | 0 | – | – | 0 | 5.3 | 4.0 | 12 | 0.28 | 0.13 | 12 | 61.5 | 56.5 | 12 |
| 1983 | 10.4 | 6.8 | 12 | 2.1 | 1.2 | 12 | 13.0 | 7.2 | 12 | 386 | 323 | 12 | 294 | 48 | 12 | 11.1 | 1.4 | 12 | 8.1 | 0.3 | 12 | – | – | 0 | – | – | 0 | 6.3 | 3.1 | 11 | 0.25 | 0.14 | 11 | 41.4 | 48.4 | 9 |
| 1984 | 9.6 | 6.0 | 12 | 2.3 | 1.3 | 12 | 12.8 | 6.2 | 12 | 352 | 194 | 12 | – | – | 0 | – | – | 0 | – | – | 0 | 28.9 | 9.6 | 12 | – | – | 0 | 6.4 | 3.7 | 12 | 0.28 | 0.10 | 11 | 36.6 | 31.2 | 12 |
| 1985 | 9.5 | 7.1 | 12 | 1.8 | 0.9 | 12 | 12.4 | 7.3 | 12 | 295 | 234 | 12 | 297 | 43 | 12 | 11.4 | 0.7 | 12 | 8.5 | 0.5 | 12 | 25.7 | 11.4 | 12 | – | – | 0 | 6.8 | 4.1 | 12 | 0.22 | 0.14 | 12 | 67.8 | 64.7 | 12 |
| 1986 | 9.9 | 6.7 | 12 | 2.2 | 1.0 | 12 | 12.6 | 7.2 | 12 | 320 | 266 | 12 | 260 | 38 | 12 | 11.4 | 1.3 | 12 | 8.4 | 0.6 | 12 | 32.2 | 13.1 | 12 | – | – | 0 | 8.4 | 5.3 | 12 | 0.28 | 0.14 | 12 | 60.1 | 47.5 | 12 |
| 1987 | 9.9 | 6.8 | 12 | 2.2 | 1.0 | 12 | 12.9 | 7.1 | 12 | 347 | 157 | 12 | 243 | 19 | 12 | 10.5 | 1.1 | 12 | 8.3 | 0.5 | 12 | 41.5 | 11.6 | 12 | 2.6 | 0.7 | 3 | 7.8 | 4.3 | 12 | 0.29 | 0.11 | 12 | 60.9 | 59.6 | 12 |
| 1988 | 10.4 | 5.7 | 12 | 2.5 | 1.1 | 12 | 13.4 | 6.2 | 12 | 438 | 301 | 12 | 246 | 32 | 12 | 10.5 | 1.4 | 12 | 8.0 | 0.5 | 12 | 41.9 | 13.5 | 12 | 3.8 | 2.3 | 12 | 3.8 | 2.5 | 12 | 0.15 | 0.07 | 12 | 45.6 | 54.5 | 12 |
| 1989 | 10.9 | 6.0 | 12 | 1.7 | 0.9 | 12 | 13.8 | 6.9 | 12 | 185 | 159 | 12 | 276 | 28 | 12 | 12.4 | 1.1 | 12 | 8.4 | 0.6 | 12 | 33.5 | 12.6 | 12 | 4.6 | 3.2 | 11 | 4.4 | 3.8 | 12 | 0.19 | 0.13 | 12 | 66.8 | 48.4 | 11 |
| 1990 | 10.9 | 6.3 | 12 | 2.0 | 1.0 | 12 | 14.3 | 6.7 | 12 | 179 | 107 | 12 | 262 | 33 | 12 | 11.2 | 0.8 | 12 | 8.4 | 0.8 | 12 | 32.3 | 12.8 | 12 | 3.9 | 1.6 | 12 | 6.6 | 5.2 | 12 | 0.24 | 0.11 | 12 | 55.6 | 32.3 | 12 |
| 1991 | 10.1 | 6.9 | 12 | 1.7 | 0.8 | 12 | 13.5 | 7.3 | 12 | 181 | 133 | 12 | 264 | 21 | 12 | 11.3 | 0.6 | 12 | 8.3 | 0.7 | 12 | 31.6 | 12.1 | 12 | 4.3 | 2.5 | 11 | 7.4 | 6.0 | 12 | 0.21 | 0.09 | 12 | 44.4 | 35.5 | 12 |
| 1992 | 10.3 | 6.1 | 12 | 2.5 | 1.3 | 12 | 13.3 | 6.8 | 12 | 316 | 213 | 12 | 248 | 32 | 12 | 10.6 | 1.4 | 12 | 8.0 | 0.7 | 12 | 28.8 | 10.9 | 12 | 3.5 | 1.6 | 12 | 8.0 | 4.9 | 12 | 0.23 | 0.11 | 12 | 42.7 | 34.5 | 12 |
| 1993 | 10.0 | 5.9 | 12 | 2.2 | 1.3 | 12 | 13.3 | 6.6 | 12 | 237 | 160 | 12 | 264 | 43 | 12 | 11.8 | 1.6 | 12 | 8.2 | 0.6 | 12 | 25.7 | 12.2 | 12 | 3.9 | 2.0 | 12 | 7.3 | 4.3 | 12 | 0.20 | 0.11 | 12 | 46.1 | 39.9 | 12 |
| 1994 | 11.3 | 6.0 | 12 | 2.4 | 1.0 | 12 | 13.6 | 6.4 | 12 | 452 | 300 | 12 | 247 | 27 | 12 | 11.5 | 1.2 | 12 | 8.1 | 0.6 | 12 | 40.0 | 16.1 | 12 | 3.3 | 2.5 | 12 | 8.6 | 3.8 | 12 | 0.17 | 0.07 | 12 | 43.4 | 43.5 | 12 |
| 1995 | 10.6 | 6.0 | 12 | 2.3 | 0.8 | 12 | 13.8 | 6.9 | 12 | 349 | 284 | 12 | 257 | 20 | 12 | 12.3 | 1.0 | 12 | 8.1 | 0.7 | 12 | 29.8 | 16.2 | 12 | 3.6 | 2.4 | 12 | 7.5 | 4.0 | 12 | 0.16 | 0.08 | 12 | 43.7 | 40.3 | 12 |
| 1996 | 9.9 | 5.7 | 12 | 2.3 | 1.1 | 12 | 13.3 | 6.5 | 12 | 338 | 241 | 12 | 246 | 24 | 12 | 10.4 | 0.7 | 12 | 8.2 | 0.5 | 12 | 28.6 | 10.3 | 12 | 4.2 | 2.7 | 12 | 7.3 | 5.0 | 12 | 0.15 | 0.09 | 12 | 62.6 | 56.6 | 12 |
| 1997 | 11.1 | 5.8 | 12 | 2.0 | 1.0 | 12 | 14.6 | 6.9 | 12 | 184 | 147 | 12 | 279 | 30 | 12 | 10.7 | 1.0 | 12 | 8.5 | 0.4 | 12 | 30.5 | 19.2 | 11 | 5.1 | 3.0 | 12 | 6.2 | 5.3 | 12 | 0.13 | 0.11 | 12 | 62.0 | 48.8 | 11 |
| 1998 | 10.3 | 6.2 | 12 | 2.1 | 1.3 | 12 | 13.2 | 6.8 | 12 | 248 | 158 | 12 | 254 | 28 | 12 | 10.6 | 1.3 | 12 | 8.4 | 0.5 | 12 | 28.4 | 13.2 | 12 | 3.3 | 1.9 | 12 | 7.9 | 4.8 | 12 | 0.11 | 0.06 | 12 | 49.3 | 34.0 | 12 |
| 1999 | 10.6 | 6.5 | 12 | 2.5 | 0.6 | 12 | 13.8 | 7.2 | 12 | 329 | 218 | 12 | 240 | 22 | 12 | 10.9 | 1.1 | 12 | 8.2 | 0.5 | 12 | 32.2 | 13.3 | 12 | 1.4 | 0.7 | 12 | 8.0 | 4.9 | 12 | 0.14 | 0.07 | 12 | 52.4 | 55.1 | 12 |
| 2000 | 10.9 | 5.8 | 12 | 2.4 | 1.3 | 12 | 14.1 | 6.5 | 12 | 306 | 162 | 12 | 250 | 17 | 12 | 10.2 | 1.5 | 12 | 8.3 | 0.5 | 12 | 25.9 | 9.6 | 12 | 2.7 | 1.4 | 12 | 8.2 | 4.0 | 12 | 0.13 | 0.07 | 12 | 47.8 | 43.7 | 12 |
| 2001 | 10.5 | 6.4 | 12 | 2.3 | 1.2 | 12 | 13.1 | 6.7 | 12 | 369 | 270 | 12 | 259 | 32 | 12 | 10.5 | 0.9 | 12 | 7.9 | 0.5 | 12 | 34.4 | 16.0 | 12 | 3.9 | 2.5 | 12 | 8.7 | 2.4 | 12 | 0.13 | 0.07 | 12 | 41.5 | 46.7 | 12 |
| 2002 | 11.0 | 5.1 | 12 | 2.4 | 1.1 | 12 | 14.0 | 6.2 | 12 | 256 | 214 | 12 | – | – | 0 | – | – | 0 | – | – | 0 | 25.2 | 12.6 | 12 | 2.2 | 0.8 | 12 | 8.4 | 4.2 | 12 | 0.11 | 0.06 | 12 | 36.1 | 32.8 | 12 |
| 2003 | 11.4 | 7.6 | 12 | 1.9 | 0.9 | 12 | 14.5 | 8.0 | 12 | 242 | 235 | 12 | 272 | 32 | 12 | 11.3 | 0.8 | 12 | 8.1 | 0.6 | 12 | 31.4 | 12.5 | 12 | 2.3 | 1.1 | 12 | 7.7 | 6.0 | 12 | 0.06 | 0.06 | 12 | 38.1 | 29.4 | 12 |
| 2004 | 10.4 | 6.4 | 12 | 2.0 | 1.2 | 12 | 13.5 | 6.9 | 12 | 334 | 236 | 12 | 270 | 35 | 12 | 10.7 | 0.7 | 12 | 7.9 | 0.5 | 12 | 30.5 | 17.8 | 11 | 2.0 | 0.7 | 12 | 10.3 | 5.2 | 12 | 0.09 | 0.07 | 12 | 32.0 | 29.0 | 12 |
| 2005 | 10.2 | 7.2 | 12 | 1.6 | 0.6 | 12 | 13.4 | 7.6 | 12 | 266 | 227 | 12 | 277 | 33 | 12 | 10.5 | 0.9 | 12 | 7.9 | 0.6 | 12 | 18.8 | 6.4 | 12 | 2.5 | 0.9 | 12 | 8.5 | 4.1 | 12 | 0.07 | 0.06 | 12 | 16.6 | 13.9 | 12 |
| 2006 | 11.2 | 7.0 | 12 | 2.1 | 0.8 | 12 | 13.8 | 7.7 | 12 | 253 | 197 | 12 | 273 | 28 | 12 | 10.8 | 1.1 | 12 | 7.9 | 0.5 | 12 | 25.3 | 7.3 | 12 | 1.5 | 0.8 | 12 | 8.9 | 4.5 | 12 | 0.07 | 0.05 | 12 | 17.4 | 12.2 | 12 |
| 2007 | 10.6 | 5.5 | 12 | 2.1 | 0.9 | 12 | 13.7 | 6.1 | 12 | 310 | 135 | 12 | 263 | 23 | 12 | 9.9 | 1.3 | 12 | 7.7 | 0.3 | 12 | 25.8 | 22.7 | 12 | 1.4 | 0.7 | 12 | 10.0 | 4.2 | 12 | 0.11 | 0.06 | 12 | 4.8 | 3.5 | 8 |
| 2008 | 10.3 | 5.7 | 12 | 2.6 | 0.8 | 12 | 13.1 | 6.5 | 12 | 383 | 200 | 12 | 260 | 31 | 12 | 10.3 | 1.2 | 12 | 7.8 | 0.3 | 12 | 15.8 | 11.4 | 12 | 2.0 | 0.0 | 12 | 9.1 | 1.9 | 12 | 0.11 | 0.05 | 12 | 6.8 | 7.6 | 8 |
| Σ | 10.3 | 6.0 | 384 | 2.2 | 1.0 | 384 | 13.3 | 6.5 | 384 | 331 | 244 | 384 | 263 | 40 | 322 | 10.9 | 1.2 | 321 | 8.2 | 0.6 | 322 | 29.8 | 14.1 | 298 | 3.1 | 2.1 | 253 | 7.5 | 4.4 | 341 | 0.17 | 0.12 | 339 | 45.5 | 44.3 | 332 |

**Appendix B. Annual statistics for the 12 time series during the warm period (May–August). See Section 2.1 for abbreviations. Σ = synthesis for the entire period (1977–2008), SD = standard deviation, n = number of observations**

| Year | Ta (°C) | | | Ptt (mm/day) | | | Tw (°C) | | | Q ($m^3/s$) | | | Cdty (µS/cm) | | | $O_2$ (mg/L) | | | pH | | | SM (mg/L) | | | BOD (mg/L) | | | $NO_3^-$ (mg/L) | | | $PO_4^3$ (mg/L) | | | Chloro (µg/L) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n | Mean | SD | n |
| 1977 | 14.6 | 2.5 | 4 | 3.4 | 0.7 | 4 | 17.5 | 2.5 | 4 | 693 | 156 | 4 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 |
| 1978 | 15.0 | 2.8 | 4 | 1.8 | 0.9 | 4 | 17.4 | 2.6 | 4 | 297 | 240 | 4 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 |
| 1979 | 15.9 | 2.8 | 4 | 2.0 | 0.9 | 4 | 18.1 | 2.7 | 4 | 315 | 244 | 4 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 | – | – | 0 |
| 1980 | 14.9 | 3.2 | 4 | 2.1 | 0.9 | 4 | 18.9 | 2.7 | 4 | 187 | 73 | 4 | 260 | 8 | 4 | 12.0 | 0.8 | 4 | 8.8 | 0.1 | 4 | – | – | 0 | – | – | 0 | 1.7 | 1.1 | 2 | 0.14 | 0.00 | 2 | 102.3 | 50.4 | 4 |
| 1981 | 15.6 | 2.9 | 4 | 2.5 | 1.4 | 4 | 18.6 | 2.9 | 4 | 383 | 220 | 4 | 215 | 42 | 4 | 10.0 | 1.4 | 4 | 8.2 | 0.2 | 4 | – | – | 0 | – | – | 0 | 5.4 | 2.2 | 4 | 0.16 | 0.08 | 4 | 100.2 | 47.9 | 4 |
| 1982 | 17.1 | 3.1 | 4 | 2.2 | 0.6 | 4 | 21.2 | 2.7 | 4 | 121 | 33 | 4 | 356 | 35 | 4 | 11.0 | 1.1 | 4 | 9.1 | 0.3 | 4 | – | – | 0 | – | – | 0 | 1.3 | 1.3 | 4 | 0.13 | 0.05 | 4 | 117.3 | 26.4 | 4 |
| 1983 | 17.2 | 4.8 | 4 | 2.5 | 1.4 | 4 | 20.3 | 4.9 | 4 | 391 | 419 | 4 | 268 | 22 | 4 | 11.7 | 1.8 | 4 | 8.3 | 0.5 | 4 | – | – | 0 | – | – | 0 | 3.8 | 2.3 | 4 | 0.13 | 0.10 | 4 | 48.8 | 62.0 | 2 |
| 1984 | 15.5 | 4.3 | 4 | 2.1 | 1.5 | 4 | 19.4 | 3.5 | 4 | 224 | 186 | 4 | – | – | 0 | – | – | 0 | – | – | 0 | 30.2 | 3.6 | 4 | – | – | 0 | 3.0 | 2.3 | 4 | 0.19 | 0.12 | 4 | 71.5 | 19.4 | 4 |
| 1985 | 15.9 | 3.7 | 4 | 2.2 | 1.1 | 4 | 19.3 | 3.9 | 4 | 295 | 256 | 4 | 275 | 15 | 4 | 11.4 | 0.2 | 4 | 8.8 | 0.4 | 4 | 27.9 | 14.4 | 4 | – | – | 0 | 4.9 | 3.5 | 4 | 0.14 | 0.08 | 4 | 100.2 | 56.1 | 4 |
| 1986 | 16.8 | 2.2 | 4 | 1.5 | 0.8 | 4 | 20.2 | 3.1 | 4 | 319 | 330 | 4 | 239 | 23 | 4 | 10.1 | 1.3 | 4 | 8.9 | 0.6 | 4 | 29.1 | 14.6 | 4 | – | – | 0 | 5.2 | 4.2 | 4 | 0.15 | 0.12 | 4 | 80.0 | 49.3 | 4 |
| 1987 | 15.7 | 3.8 | 4 | 2.5 | 1.0 | 4 | 19.4 | 3.3 | 4 | 266 | 130 | 4 | 230 | 11 | 4 | 10.5 | 1.3 | 4 | 8.8 | 0.4 | 4 | 46.3 | 8.5 | 4 | – | – | 0 | 3.9 | 2.2 | 4 | 0.21 | 0.09 | 4 | 107.4 | 37.2 | 4 |
| 1988 | 16.4 | 2.5 | 4 | 2.8 | 1.2 | 4 | 20.0 | 2.8 | 4 | 369 | 321 | 4 | 234 | 32 | 4 | 10.8 | 1.7 | 4 | 8.3 | 0.5 | 4 | 46.8 | 1.0 | 4 | 4.5 | 3.0 | 4 | 1.5 | 0.9 | 4 | 0.09 | 0.04 | 4 | 66.4 | 57.0 | 4 |
| 1989 | 17.6 | 2.3 | 4 | 1.3 | 0.3 | 4 | 21.4 | 2.1 | 4 | 174 | 183 | 4 | 265 | 15 | 4 | 13.6 | 0.4 | 4 | 8.9 | 0.3 | 4 | 41.9 | 5.5 | 4 | 5.1 | 3.5 | 3 | 1.5 | 1.1 | 4 | 0.09 | 0.04 | 4 | 67.2 | 18.0 | 4 |
| 1990 | 17.6 | 2.6 | 4 | 2.0 | 1.1 | 4 | 21.6 | 1.6 | 4 | 139 | 52 | 4 | 234 | 15 | 4 | 10.5 | 0.2 | 4 | 9.1 | 0.1 | 4 | 31.7 | 3.0 | 4 | 4.7 | 1.0 | 4 | 2.4 | 1.2 | 4 | 0.19 | 0.06 | 4 | 66.6 | 10.1 | 4 |
| 1991 | 16.8 | 4.6 | 4 | 1.4 | 0.8 | 4 | 20.8 | 3.9 | 4 | 85 | 39 | 4 | 254 | 9 | 4 | 11.3 | 0.7 | 4 | 9.0 | 0.3 | 4 | 31.3 | 8.9 | 4 | 6.1 | 1.7 | 3 | 1.7 | 2.1 | 4 | 0.14 | 0.05 | 4 | 70.0 | 37.5 | 4 |
| 1992 | 17.0 | 2.7 | 4 | 2.9 | 1.0 | 4 | 20.9 | 2.2 | 4 | 290 | 236 | 4 | 225 | 28 | 4 | 9.7 | 1.6 | 4 | 8.7 | 0.7 | 4 | 34.3 | 12.2 | 4 | 4.7 | 1.7 | 4 | 3.2 | 2.6 | 4 | 0.17 | 0.14 | 4 | 65.0 | 24.0 | 4 |
| 1993 | 16.7 | 2.3 | 4 | 2.6 | 0.7 | 4 | 20.8 | 2.1 | 4 | 171 | 78 | 4 | 225 | 18 | 4 | 10.3 | 0.9 | 4 | 8.7 | 0.5 | 4 | 27.5 | 6.9 | 4 | 5.3 | 1.9 | 4 | 3.3 | 2.1 | 4 | 0.17 | 0.13 | 4 | 66.9 | 26.2 | 4 |
| 1994 | 17.9 | 3.4 | 4 | 2.1 | 0.7 | 4 | 20.8 | 3.5 | 4 | 210 | 152 | 4 | 247 | 24 | 4 | 11.4 | 1.1 | 4 | 8.8 | 0.5 | 4 | 35.7 | 10.2 | 4 | 5.9 | 2.6 | 4 | 4.8 | 3.5 | 4 | 0.08 | 0.05 | 4 | 85.5 | 40.1 | 4 |
| 1995 | 17.1 | 3.5 | 4 | 1.7 | 0.6 | 4 | 21.1 | 3.5 | 4 | 179 | 120 | 4 | 259 | 6 | 4 | 12.3 | 0.8 | 4 | 8.9 | 0.4 | 4 | 29.9 | 16.1 | 4 | 5.6 | 2.6 | 4 | 4.0 | 3.7 | 4 | 0.09 | 0.05 | 4 | 71.1 | 32.9 | 4 |
| 1996 | 16.3 | 2.7 | 4 | 2.0 | 1.1 | 4 | 20.3 | 3.0 | 4 | 181 | 99 | 4 | 245 | 6 | 4 | 10.4 | 0.7 | 4 | 8.6 | 0.6 | 4 | 38.2 | 3.2 | 4 | 6.7 | 2.3 | 4 | 3.0 | 3.0 | 4 | 0.09 | 0.06 | 4 | 111.7 | 46.6 | 4 |
| 1997 | 17.1 | 2.8 | 4 | 2.6 | 0.8 | 4 | 21.8 | 2.7 | 4 | 96 | 18 | 4 | 270 | 14 | 4 | 9.9 | 1.2 | 4 | 8.8 | 0.1 | 4 | 46.7 | 17.2 | 4 | 8.7 | 1.2 | 4 | 1.3 | 1.0 | 4 | 0.05 | 0.01 | 4 | 118.1 | 15.6 | 4 |
| 1998 | 17.3 | 2.3 | 4 | 1.6 | 0.4 | 4 | 20.8 | 2.3 | 4 | 197 | 167 | 4 | 259 | 34 | 4 | 9.6 | 1.3 | 4 | 8.9 | 0.2 | 4 | 28.2 | 18.9 | 4 | 4.8 | 2.1 | 4 | 3.9 | 3.1 | 4 | 0.05 | 0.01 | 4 | 77.8 | 14.4 | 4 |
| 1999 | 17.4 | 2.1 | 4 | 2.4 | 0.6 | 4 | 21.4 | 2.7 | 4 | 197 | 168 | 4 | 247 | 13 | 4 | 10.9 | 1.0 | 4 | 8.7 | 0.5 | 4 | 33.4 | 6.4 | 4 | 1.9 | 1.1 | 4 | 3.5 | 3.2 | 4 | 0.08 | 0.04 | 4 | 96.2 | 50.1 | 4 |
| 2000 | 17.2 | 2.0 | 4 | 2.2 | 0.8 | 4 | 21.2 | 1.7 | 4 | 168 | 95 | 4 | 242 | 9 | 4 | 9.8 | 1.3 | 4 | 8.7 | 0.3 | 4 | 30.4 | 7.7 | 4 | 3.8 | 1.6 | 4 | 4.2 | 1.9 | 4 | 0.07 | 0.02 | 4 | 87.7 | 25.9 | 4 |
| 2001 | 17.4 | 2.3 | 4 | 2.4 | 0.5 | 4 | 20.5 | 3.1 | 4 | 316 | 342 | 4 | 252 | 29 | 4 | 10.4 | 1.2 | 4 | 8.4 | 0.6 | 4 | 36.8 | 10.9 | 4 | 6.1 | 3.3 | 4 | 6.6 | 1.6 | 4 | 0.07 | 0.05 | 4 | 82.1 | 53.3 | 4 |
| 2002 | 16.6 | 2.8 | 4 | 2.5 | 0.4 | 4 | 20.9 | 2.3 | 4 | 96 | 19 | 4 | – | – | 0 | – | – | 0 | – | – | 0 | 29.8 | 4.3 | 4 | 3.1 | 0.2 | 4 | 3.9 | 2.1 | 4 | 0.05 | 0.00 | 4 | 78.6 | 9.7 | 4 |
| 2003 | 20.0 | 3.9 | 4 | 1.6 | 0.2 | 4 | 23.5 | 3.5 | 4 | 71 | 24 | 4 | 273 | 13 | 4 | 11.1 | 1.4 | 4 | 8.7 | 0.2 | 4 | 32.3 | 4.6 | 4 | 3.7 | 0.7 | 4 | 2.5 | 2.5 | 4 | 0.01 | 0.00 | 4 | 68.6 | 12.1 | 4 |
| 2004 | 17.1 | 3.0 | 4 | 2.0 | 1.4 | 4 | 20.7 | 2.9 | 4 | 181 | 148 | 4 | 277 | 24 | 4 | 10.7 | 0.7 | 4 | 8.3 | 0.2 | 4 | 30.8 | 20.9 | 4 | 2.9 | 0.4 | 4 | 5.8 | 1.9 | 4 | 0.03 | 0.03 | 4 | 64.1 | 14.0 | 4 |
| 2005 | 17.7 | 2.5 | 4 | 1.6 | 0.3 | 4 | 21.3 | 2.7 | 4 | 152 | 124 | 4 | 280 | 14 | 4 | 9.9 | 0.6 | 4 | 8.4 | 0.3 | 4 | 18.7 | 1.6 | 4 | 3.1 | 0.3 | 4 | 5.3 | 2.4 | 4 | 0.03 | 0.02 | 4 | 34.0 | 6.1 | 4 |
| 2006 | 17.9 | 3.9 | 4 | 2.1 | 0.6 | 4 | 21.5 | 4.0 | 4 | 121 | 79 | 4 | 272 | 11 | 4 | 10.9 | 1.2 | 4 | 8.5 | 0.3 | 4 | 26.3 | 9.8 | 4 | 2.4 | 0.7 | 4 | 4.3 | 2.8 | 4 | 0.02 | 0.02 | 4 | 31.6 | 9.3 | 4 |
| 2007 | 16.5 | 1.8 | 4 | 3.1 | 0.4 | 4 | 20.2 | 1.0 | 4 | 265 | 66 | 4 | 248 | 21 | 4 | 8.6 | 0.3 | 4 | 7.6 | 0.3 | 4 | 18.8 | 4.8 | 4 | 1.5 | 0.8 | 4 | 7.1 | 0.3 | 4 | 0.10 | 0.07 | 4 | 6.6 | 4.2 | 4 |
| 2008 | 16.9 | 1.9 | 4 | 2.7 | 0.8 | 4 | 20.3 | 2.1 | 4 | 352 | 239 | 4 | 260 | 39 | 4 | 9.6 | 0.4 | 4 | 7.9 | 0.3 | 4 | 10.8 | 6.9 | 4 | 2.0 | 0.0 | 4 | 7.4 | 1.2 | 4 | 0.08 | 0.07 | 4 | 10.8 | 9.5 | 4 |
| Σ | 16.8 | 2.8 | 128 | 2.2 | 0.9 | 128 | 20.4 | 2.8 | 128 | 234 | 205 | 128 | 256 | 33 | 108 | 10.7 | 1.4 | 108 | 8.6 | 0.5 | 108 | 31.7 | 12.3 | 100 | 4.4 | 2.4 | 82 | 3.8 | 2.7 | 114 | 0.10 | 0.08 | 114 | 74.7 | 40.6 | 114 |

recognised as the main effect of pollution in continental waters at the present time (Mainstone and Parr, 2002; Hilton et al., 2006). Recently, in the UK, Bowes et al. (2011) described similar water quality responses following a reduction in phosphorus input from wastewater treatment plants. Interestingly, changes in chlorophyll-a during the mid-1990s coincided with a fall in mean $P–PO_4$ concentrations during May–August below 30 μg/L, which several studies (e.g. Westlake, 1981; Dodds et al., 2002) report as a threshold below which phosphorus levels begin to limit algal biomass development in freshwaters. This is confirmed by the $<30$ μg/L $P–PO_4$ concentrations during 1996–2006 explaining around 60% of the reduction in phytoplankton during the warm period (Fig. 5b). The years 2007 and 2008 were hydrologically exceptional across large areas of Western Europe, with elevated flow rate then constituting the main limiting factor on algal production in large rivers like the Loire (P. Gosse, pers. comm.).

A possible further explanation for altered chlorophyll concentrations in the Loire may be the pressure of biological grazing. The bivalve *Corbicula* sp. has colonised all of the large hydrographic basins of France in just 20 years (Mouthon, 2000; Brancotte and Vincent, 2002) and since the early 2000s has been found in the Middle Loire under increasingly favourable flow and temperature conditions. Previous works show that the filtration rate in this bivalve (around 25 ml/g/h) can significantly reduce algal density (Cohen et al., 1984; Hwang et al., 2004). Alongside local catchment changes, the effects of such invasive non-native species are a further complication in understanding climate-change effects on rivers.

In contrast to phosphate, nitrate concentrations have increased in the Loire, but links with the above quality changes are highly likely through reduced algal production and N incorporation into algal biomass (Schneider and Melzer, 2003; Jarvie et al., 2006; Johnson et al., 2009). Given that nitrate inputs are described as rising on the Loire catchment (Bouraoui and Grizzetti, 2011), the balance between greater input and weaker consumption may account for the significant increase in nitrate concentrations, notably as of the 1990s, only weakly if at all related to the evolution of hydroclimatic variables. Moreover, the reduction in photosynthetic activity associated with the reduction in phytoplankton seems to affect dissolved gas levels: the dissolved oxygen concentration shows a significant downward trend and pH tends towards slightly greater acidity, probably due to increasing $CO_2$ levels (Neal et al., 1998; Bowes et al., 2011). Finally, reduced oxygen solubility as a result of higher water temperatures could be a further explanation for lower $O_2$ concentrations.

## 5. Conclusion

In total, these data illustrate how the Middle Loire basin has undergone progressive atmospheric warming over recent decades with the direct consequences for increasing water temperature, especially during summer. In contrast, trends in summer precipitation have been weak and insufficient to be implicated in the observed decrease in discharge in the Loire, even though evapo-transpiration effects might have been underestimated. Instead, these changes are partially explained by abstraction for irrigation over the basin, which occurs mainly during this period of the year.

Despite some evidence of global climate change effects similar to those in other large European river basins, organic load (i.e. nutrients and phytoplankton) in the Loire have apparently ameliorated. Improved wastewater treatment appears to have reduced phosphate concentrations in the Loire, limiting phytoplankton development and mediating trends in other chemical variables. One implication is that phosphorus reduction policies might have helped offset potentially negative effects of climate change on water quality.

Whatever their origin, an important need is to assess the ecological consequences of climatic and water quality trends. To extend understanding of trends in the Loire, ecological dimensions must be taken into account so as best to guide and adapt management and restoration policy. We expect that the current assessment of physico-chemical trends can now form a basis for analysing the mechanisms involved in any local biological response to changes in water temperature, discharge and water quality. More significantly, however, these data reveal some of the complexities and difficulties in clearly identifying climate-change effects on the physico-chemical character and ecology of large rivers where complex interactions are likely between global and local sources of change.

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