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Influence of dam-induced hydrological regulation on summer water temperature: Sauce Grande River, Argentina

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ABSTRACT

This study quantifies for the first time the influence of flow regulation on the river thermal behaviour of an ungauged basin located in central-eastern Argentina. A 30-day data set of continuous summer hourly data was assembled for eight water temperature gauging sites deployed along the main channel upstream and downstream from the impoundment. Analysis methods include descriptive statistics of daily temperature data, classification of diurnal regimes by relative differences in the 'shape' and the 'magnitude' of the thermographs (RSMC), and quantification of the climatic sensitivity of water temperature regimes using a sensitivity index. Results revealed that temporal fluctuations in water temperatures were linked to meteorological drivers; however, spatial variability in the shape and the magnitude of the thermographs revealed the effects of the dam in regulating river thermal behaviour downstream. Water temperatures immediately below the dam were reduced notably; diurnal cycles were reduced in magnitude, delayed in timing, and revealed overall climatic insensitivity and high temporal stability in regime shape. Dam effects persisted along the 15-km stretch monitored, although declined in the downstream direction. These findings provide new scientific understanding about the river water quality and inform river management about potential shifts in summer water temperature with great implications for the diversity and lifecycles of Neotropical river fauna. The use of the RSMC and sensitivity index approaches in water temperature assessment is novel and has wider applicability for quantifying river thermal regimes and their sensitivity to drivers of change over a range of temporal and spatial scales. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS river water temperature; thermographs; flow regulation; ungauged basins; regime shape and magnitude classification (RSMC); sensitivity index (SI)

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INTRODUCTION

River water temperature (RWT) is the most important physical property of streams and rivers (Webb, 1996; Caissie, 2006; Haag and Luce, 2008; Webb *et al*., 2008). It influences strongly the hydrological, chemical, and biological processes within the river system (Hannah *et al*., 2008b) and hence, has great significance for water quality and stream ecology (Webb 1996; Poole and Berman, 2001; Caissie, 2006). Flow regulation by dams is the greatest cause of hydrologic alteration of streams and rivers (Petts and Gurnell, 2005) and has direct influence on the thermal regime of the river downstream (Olden and Naiman, 2010) by inducing changes in the flow thermal capacity and heat load (Webb, 1996; Poole and Berman, 2001).

Considerable research has evaluated the role of dams in affecting the spatial and temporal patterns of RWT downstream (e.g. Ward and Stanford, 1979; Cowx *et al*., 1987; Webb and Walling, 1988; 1993; 1995; 1997; Preece and Jones, 2002; Steel and Lange, 2007; Archer, 2008; Wright *et al*., 2009; Olden and Naiman, 2010; Poirel and Gailhard, 2010). These studies revealed that changes occur to all aspects of the river thermal regime, involving the magnitude (e.g. decrease in summer maxima and increase in winter minima) and the timing of the thermograph (e.g. delay in the annual cycle), the frequency and duration of temperature extremes (e.g. capped or ameliorated minima and maxima), and the rate of change (e.g. decrease in diurnal fluctuations). Such changes were reported to be significant immediately below the dam and, in many regulated rivers, persisted over several tens of kilometres downstream.

Although the effects of flow regulation on RWT may be hypothesized, the magnitude and the extent to which dams modify the river thermal regime downstream may vary considerably from one dam to another depending on the dam operational procedures (i.e. patterns of flow release and outlet height; Ward and Stanford, 1979), the reservoir limnology (Ward, 1985; McCartney *et al*., 2001), and the dam position with respect to the longitudinal stream profile (Ward and Stanford, 1983; 1995). In addition, the thermal regime of rivers responds to a number of atmospheric and hydrological drivers of heat exchange to and from the river (Webb, 1996; Poole and Berman, 2001; Caissie, 2006; Hannah *et al*., 2004, 2008a; Webb *et al*., 2008). In the absence of detailed information on heat fluxes, air temperature has

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been used widely as surrogate measure of net heat exchange at the water–air interface to assess river thermal variability and predictability (e.g. Webb and Walling, 1997; Mohseni and Stefan, 1999; Ozaki *et al*., 2003; Webb *et al*., 2003; Caissie *et al*., 2005; Bonacci *et al*., 2008).

The Paso de las Piedras Dam on the Sauce Grande River, Argentina, is the focus of this study. Despite the vital importance for water supply and large capacity of the impoundment, the effects of the dam on the river environment remain poorly evaluated. This paper provides the first assessment of the influence of flow regulation upon the thermal behaviour of the river below the impoundment. It quantifies patterns of daily water temperature at multiple sites during a summer period to understand the complex response of RWTs to the following: (i) dam operational procedures inducing regulated patterns of flow and (ii) hot weather conditions that may cause thermal stress for river ecology. In addition to providing new information on the thermal behaviour of regulated rivers and on the thermal effects of impoundment on the Sauce Grande River specifically, this paper represents the first application of a regime shape and magnitude classification scheme (RSMC; after Hannah *et al*., 2000) and a climatic sensitivity index (SI; after Bower *et al*., 2004) to RWT assessment.

STUDY AREA

The Sauce Grande River drains a basin area of 4650 km^2 within a temperate sub-mountain plain located in south-western Buenos Aires, Argentina (Figure 1). Dominant land uses are rain-fed agriculture and livestock grazing of unimproved grasslands; population density is very low. The river flow regime is flashy; mean annual flow is $4{\cdot}54\,m^3\,s^{-1}$, and peak flows may reach $520\,m^3\,s^{-1}$ for 25-mm rainfall excess (Luque *et al*., 1979). Rainfall occurs mainly in austral spring and summer, defining a 'wet season' that extends from October to April (Campo *et al*., 2004). Mean annual precipitation is 760 mm, with high inter-annual variability linked to *El Niño* (heavy rains) and *La Niña* (extended drought) episodes (Scian, 2000). Sequences of anomalous dry (or wet) climate conditions are frequent and impact very seriously on major human activities (Troha and Forte Lay, 1993; Forte Lay et al., 2008; Penalba and Llano, 2008; Andrade *et al*., 2009; Bohn *et al*., 2011).

The Paso de las Piedras Dam has impounded the middle river section since 1978 for water supply to a population that today reaches about 400 000 people. At full supply, its reservoir has a surface area of 36 km^2, depth of 25 m, and maximum capacity of 328 hm^3 (Schefer, 2004). Climate variability and population growth combine to generate low resilience to deficiencies in local water resources; accordingly, dam operational procedures seek to store and conserve a maximum volume of water to assure supply in periods of drought. Reservoir evacuation occurs only in periods of water excess (i.e. full reservoir). Water diversions are conducted either through the bottom gate (controlled hypolimnetic release) or through the overflow spillway (uncontrolled epilimnetic release). Controlled flow release averages $10\,m^3\,s^{-1}$ from a 0·15-m sluice gate (Schefer, 2004).

Downstream base flows may persist for much of the year or even for several consecutive years; at present, the river has exhibited residual flows since April 2005. Immediately below the dam, flow averages $0{\cdot}25\,m^3\,s^{-1}$ and originates from reservoir seepage below the dam embankment structure. Further downstream, groundwater inflows contribute to increase mean flows up to $0{\cdot}35\,m^3\,s^{-1}$. Except for

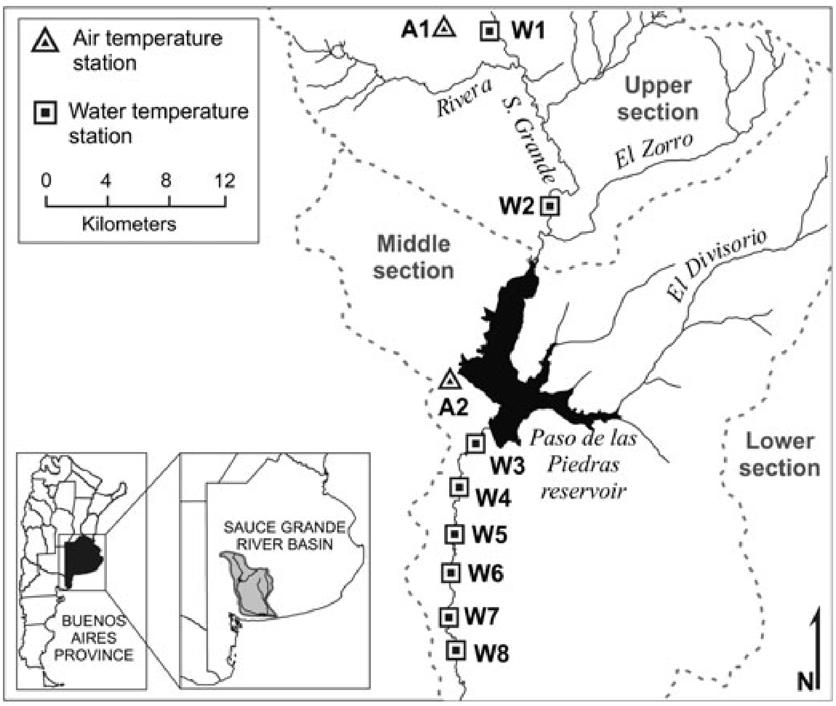

Figure 1. Map of the study area and location of water and air temperature gauging sites.

some short and unsteady reaches, the Sauce Grande River receives no tributary inputs until its confluence with Cañada de los Leones Creek in the lowest section.

DATA AND METHODS

Data collection. Eight temperature dataloggers (Hobo Pendant Temperature, ONSET Computer Corporation) were deployed within the main channel above (W1 and W2; Figure 1) and below the impoundment (W3 to W8; Figure 1). Additionally, one logger was installed in the weir draining reservoir seepage into the main river channel. Water temperature sampling sites were selected on the basis of distance from the dam, site accessibility, channel morphology, and riparian vegetation. The dataloggers were cross-calibrated and clock-synchronized (Hannah *et al*., 2009) to record water temperature every 15 min during summer 2009. Concurrent hourly observations of air temperature were provided by the Autoridad del Agua de la Provincia de Buenos Aires (ADA) for two meteorological stations, A1 and A2, located upstream and adjacent to the reservoir, respectively (Figure 1). The use of two stations was considered appropriate to highlight any meteorological variability due to differences in altitude and exposure along the river. Hourly records of rainfall and flow discharge were also provided by the ADA; however, flow variability over the monitoring period was very low (Figure 2), and so these data were excluded from the analysis. Rainfall during the monitoring period was 55 mm; river flow averaged 3·27 $m^3 s^{-1}$ upstream and 0·33 $m^3 s^{-1}$ downstream, with little fluctuation (standard deviation of 0·09 and 0·01 $m^3 s^{-1}$, respectively).

A 30-day data set of continuous hourly data was assembled for all air and water temperature gauging sites. The time series spanned the hottest period recorded during austral summer 2009 (day 58–87) and thus allowed variations in RWT to be evaluated under strong meteorological influence.

Time series assessment and thermal metrics. Patterns in air and water temperature over the monitoring period were inspected by using a set of thermal metrics adapted from Chu *et al*. (2010) and on the basis of those proposed by Poff *et al*. (1997) to characterize the five ecologically critical components of the river flow regime (magnitude, timing, duration, frequency, and rate of change; Table I); note, HGHT and LOWT correspond to the third and first quartiles, respectively. Spatial variations in RWT were evaluated by plotting the 30-day mean, maximum, and minimum temperature by site versus distance from the dam.

Classification of diurnal air and water temperature regimes. Daily patterns in air and water temperature were inspected using a classification method based on relative differences in the shape (timing) and the magnitude (size) of diurnal regimes (RSMC). The RSMC was developed by

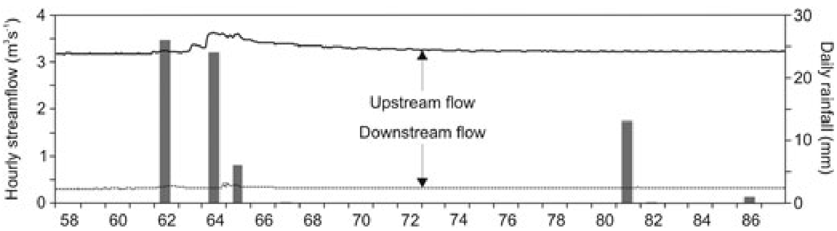

Figure 2. Hourly discharge and daily precipitation series for the 30-day monitoring period.

Table I. Metrics used in the characterization of patterns of air and water temperature.

Thermal regime component	Ecological and water quality relevance	Temperature metric	Abbreviation
Magnitude	Absolute thermal values defining specific biological, physical, and chemical reactions/responses	Mean daily temperature (°C)	MNT
		Maximum daily temperature (°C)	MAXT
		High daily temperature (°C)	HIGHT
		Median temperature	MEDT
		Low daily temperature (°C)	LOWT
		Minimum daily temperature (°C)	MINT
Frequency	How often thermal events of a particular magnitude occur	Area under the mean seasonal temperature of all gauging stations (°C)	$AUMNT_{GS}$
Timing	When do temperatures of a certain magnitude occur, having specific ecological and water quality implications	Day of maximum (Julian day)	DMAXT
		Day of minimum (Julian day)	DMINT
		Start of high daily temperature (Julian day)	STHGHT
		Start of low daily temperature (Julian day)	STLOWT
Duration	Period associated with temperature of a certain magnitude	Length of high temperature (number of days)	LGHGHT
		Length of low temperature (number of days)	LGLOWT
Rate of change	How quickly temperature changes in magnitude	Mean daily range (°C)	MNR
		Maximum daily range (°C)	MAXR
		Minimum daily range (°C)	MINR

Hannah *et al.* (2000) and has been evaluated in a number of studies assessing river flow and climate regimes (e.g. Harris *et al.*, 2000; Bower *et al.*, 2004; Kansakar *et al.*, 2004; Hannah *et al.*, 2005). This study represents the first application of the RSMC technique to RWT regime classification.

Hourly records of air and water temperature over the 30-day monitoring period and across the 10 gauging sites were classified together; this gave a data set of 300 station-days. To identify station-days with similar regime shape, hourly temperature observations were standardized (z-scores) over the diurnal cycle at each site; diurnal patterns by site were then classified into groups of similar thermograph form. To classify the regime magnitude, the daily mean, maximum, minimum, and variance were standardized by site over the 30-day period; the four standardized indices by station-day were classified into groups of similar thermograph size. Hierarchical cluster analysis was used to classify regime shape and magnitude using Ward's algorithm. Ward's method was selected because it produced relatively dense clusters with small within-group variance (cf. Hannah *et al.*, 2005). The structure of the cluster dendrogram and breaks of slope in the agglomeration schedule plot were used to estimate the appropriate number of clusters (regime classes).

Quantification of the stability and climatic sensitivity of diurnal water temperature regimes. This paper tests the utility of the novel *SI* devised by Bower *et al.* (2004) to quantify water–air temperature associations considering regime shape and magnitude attributes separately. The *SI* is calculated in two stages. Firstly, the stability of each water and air temperature regime is quantified by computing an equitability index (*EI*) that considers the probability of occurrence of one regime class against all the possible regime classes (Equation (1)). Secondly, the associations between water and air temperature regime classes are evaluated as the conditional probability, $P(Y_j|X_i)$, of observing a particular water temperature regime, Y_j, as conditioned by each air temperature regime, X_i, and vice versa, i.e. $P(X_i|Y_j)$.

$$EI = \frac{-\sum_{i=1}^{n} P_i \ln P_i}{\ln n} \tag{1}$$

The *SI* is computed on the basis of the ratio of equitability (E) between water and air temperature regimes ($E[Y]:E[X]$). If $E(Y) > E(X)$, Equation (2) is used to produce a value between 0 and +1 (positive scenario); if $E(Y) < E(X)$, Equation (3) is used to give a value between -1 and 0 (negative scenario).

$$SI = \frac{1}{2(n_x n_y)}\left(-\sum_{i=1}^{n_x}\left(\frac{P(Y_j/X_i)\ln P(Y_j/X_i)}{\ln n_y}\right)+\left(\frac{P(X_i/Y_j)\ln P(X_i/Y_j)}{\ln n_x}\right)\right) \tag{2}$$

$$SI = -1 - \frac{1}{2(n_x n_y)}\left(\sum_{i=1}^{n_x}\left(\frac{P(Y_j/X_i)\ln P(Y_j/X_i)}{\ln n_y}\right)+\left(\frac{P(X_i/Y_j)\ln P(X_i/Y_j)}{\ln n_x}\right)\right) \tag{3}$$

Positive and negative scenarios represent the direction of sensitivity (Figure 3). Negative values indicate that a limited number of water temperature regimes occur under a variety of air temperature conditions. Conversely, positive values indicate that a variety of water temperature regimes are observed under similar air temperature conditions. *SI* values approaching -1 or +1 both designate insensitivity; the difference is in the direction of the associations. Values closer to 0 indicate a sensitive situation, where a single water temperature regime is observed under particular air temperature conditions (Bower *et al.*, 2004).

RESULTS

Time series assessment and thermal metrics

Air temperature sites revealed strong fluctuations in both temporal and diurnal thermal patterns (Table II). Four short duration episodes of high temperature (in two consecutive days) occurred simultaneously at both sites A1 and A2. The hottest episode started on day 71, with MAXT attained

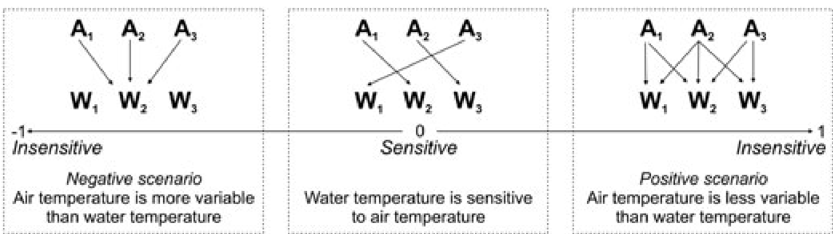

Figure 3. Conceptual scheme illustrating scenarios of climatic (in)sensitivity of water temperature regimes. Modified from Bower *et al.* (2004).

Table II. Thermal patterns by air temperature site and water temperature site.

Metric	Air temperature		Water temperature							
	A1	A2	W1	W2	W3	W4	W5	W6	W7	W8
MNT	21·0	21·6	21·3	21·4	18·8	18·9	19·5	19·9	20·0	20·3
MAXT	33·0	34·1	25·3	24·6	20·5	21·5	22·0	22·9	23·6	24·2
HGHT	24·5	24·6	22·2	22·6	19·5	19·9	20·4	20·9	21·0	21·4
MEDT	20·6	21·3	21·5	21·7	18·9	19·0	19·8	20·1	20·1	20·3
LOWT	17·8	18·7	20·5	20·3	18·2	18·1	18·8	19·1	19·2	19·3
MINT	6·1	9·3	18·2	17·2	16·0	15·3	15·6	15·7	15·7	15·8
$AUMNT_{GS}$	0·50	0·40	0·40	0·37	1·00	1·00	1·00	0·07	0·17	0·20
DMAXT	72	72	72	72	72	72	72	72	72	72
DMINT	73	73	76	76	74	74	75	76	76	76
STHGHT	58; 71; 78; 86	58; 71; 78; 86	58;70; 85	58;70; 84	58;70; 84	58;70; 84	58;71; 84	58;71; 85	58;70; 86	58;70; 86
STLOWT	61; 66; 73	61; 66; 73	62; 74	62; 74	62; 73	61; 73	62; 73	62; 73	62; 73	62; 73
LGHGHT	2; 2; 1; 2	2; 2; 1; 2	3; 3; 1	3; 3; 1	3; 3; 1	3; 3; 1	3; 2; 2	3; 2; 2	3; 3; 1	3; 3; 1
LGLOWT	2; 2; 4	3; 1; 4	2; 6	2; 6	1; 7	2; 6	2; 6	2; 6	2; 6	2; 6
MNR	12·2	10·2	1·6	2·1	1·6	1·9	2·0	2·4	3·0	3·4
MAXR	18·4	15·3	4·5	3·1	2·6	3·1	3·3	3·5	4·4	4·7
MINR	5·3	4·9	0·5	0·9	0·9	1·1	0·7	0·6	1·1	1·2

on day 72. Both sites cooled markedly on day 73, and daily temperature remained low over four consecutive days. Daily fluctuations were up to 18 °C (A1) and 15 °C (A2) and averaged 12 and 10 °C, respectively. Between-station differences in the absolute magnitude of diurnal thermographs may be explained by the geographical situation of the sites: Cooler temperatures at site A1 may be explained by its higher elevation, whereas smaller diurnal ranges at site A2 were possibly related to its close proximity to the reservoir lake (thermal moderation).

Temporal fluctuations in RWT were synchronized broadly with those observed for air temperature, especially the timing and duration of high temperatures. All water temperature sites attained MAXT on day 72 and cooled on day 73 (as did air temperature), except for sites W1 and W2 that cooled on day 74. MINTs were attained on days 74–76 (1–3 days lag compared with air temperature), and the period associated with low temperatures was longer and steadier than for air temperature sites (six consecutive days). Inter-comparison of thermal patterns across sites revealed spatial differentiation in the absolute magnitude of the thermographs for sites located upstream and downstream of the impoundment.

To highlight the effects of the dam on RWT downstream, longitudinal profiles of mean, maximum, and minimum temperatures were inspected (Figure 4); outlet temperatures were measured in the weir draining reservoir seepage to the main river channel. MNT in site W3 (immediately downstream) was 2·6 °C cooler than that in site W2 (immediately upstream); MAXT (MINT) in site W3 was 4·1 °C (1·2 °C) cooler than in site W2. A warming trend in the downstream direction (W3 → W8) was evidenced clearly, especially regarding mean and maximum temperatures. The warming rate between the dam barrage and site W3 (river kilometre 1·7) was 1·6 °C in MNT, 1·9 °C in MAXT, and 1·1 °C in MINT. Water temperatures between sites W3 and W4 (river kilometre 4·2) remained relatively steady, although a decrease of −0·2 °C km^{-1} was observed for MINT. Downstream from W4, water temperatures described a steady increase, with the exception of a small decline in MINT between sites W4 and W5 (river kilometre 8·3).

Classification of air and water temperature diurnal regimes

Prior to classification, air and water temperature series were inspected. The diurnal thermographs showed that the daily

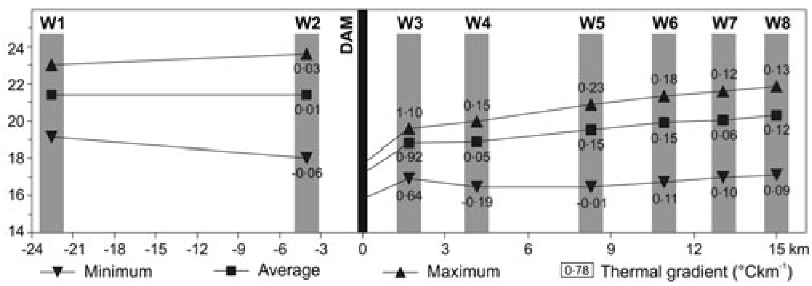

Figure 4. Longitudinal profiles of mean, maximum, and minimum temperatures recorded over the 30-day monitoring period. Numbers indicate station-to-station thermal gradients (°C km^{-1}).

minima occurred typically just before sunrise and the maxima after solar noon; hence, diurnal cycles were demarcated to begin at 0800 h for all station-days. This ensured that the rising limb, the peak, and the falling limb of diel cycles were encapsulated on the 'thermal response day' for analysis. Regimes are referred to by the day in which they begin.

Diurnal regime 'shape'. Inspection of the cluster dendrogram and agglomeration schedule plot suggested that four clusters provided an informative classification of the data sets (Figure 5). The regime shape classes were identified as follows:

Class A → Symmetrical diurnal cycle with gradual onset, broad peak at 1700 h, and gentle cessation (117 station-days).

Class B → Steep rise towards an early peak at 1500 h, short duration peak, and rapid cessation (99 station-days).

Class C → Early peak at 1600 h followed by long recession (36 station-days).

Class D → Late rise into an extended peak at 1800 h with gradual cessation (48 station days).

The main difference between regime shape classes was in the timing and duration of the peaks. Whereas classes B and C exhibited early and steep peaks, classes A and D revealed gentle onset and cessation with a longer duration. Diurnal cycles for classes C and D appeared to be uneven across the day, indicative of a long-term (multiday) cooling and warming, respectively (Figure 5).

Analysis of class frequency by site (Table III) revealed clear dominance of one 'typical' regime shape class by site, and spatial correspondence of dominant classes permitted to assemble water temperature sites into groups of similar diurnal regime shape, especially for sites located below the dam. Site W3 revealed a clear dominance of class D, which also prevailed for site W1. Class A was observed to dominate from sites W4 to W6, revealing relative homogeneity in the river thermal behaviour after a distance of about 4 km below the dam and similarity with unregulated conditions (site A2). Spatial constancy in dominant patterns of diurnal regime shape was also observed for sites W7 and W8, which were similar to dominant patterns for air temperature (class B) indicating potential equilibration and resynchronization of downstream water temperatures with the atmosphere.

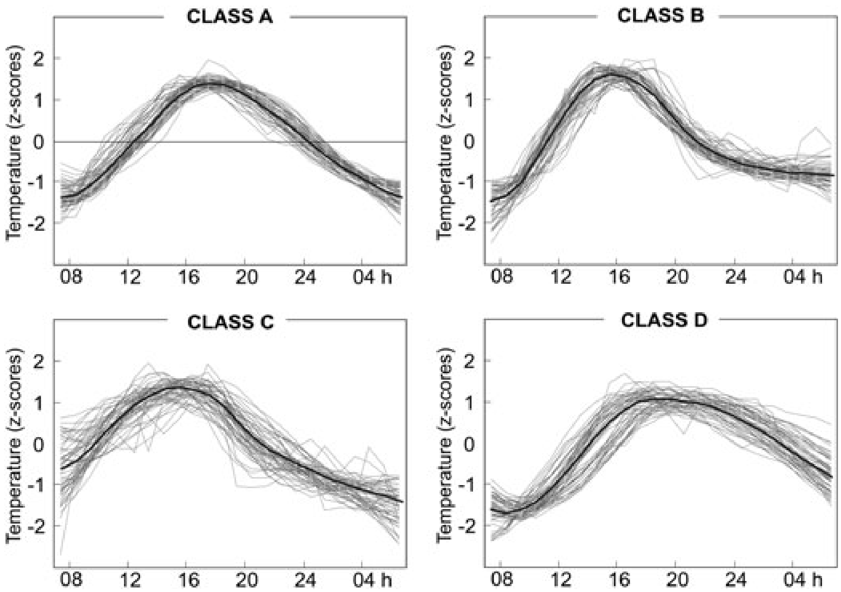

Figure 5. Standardized (z-scores) hourly records of air temperature (60 station-days) and water temperature (240 station-days) by regime shape class. The thick black line shows the average value for each shape class.

Table III. Frequency (as fractional proportion of days) of diurnal regime 'shape' classes by air temperature site and water temperature site; bold numbers indicate the dominant class by site.

	Air temperature		Water temperature							
Shape class	A1	A2	W1	W2	W3	W4	W5	W6	W7	W8
A	—	0·13	0·13	**0·73**	0·13	**0·90**	**0·83**	**0·90**	0·07	0·07
B	**0·73**	**0·63**	0·10	0·07	—	0·03	—	—	**0·87**	**0·87**
C	0·27	0·23	0·10	0·13	0·07	0·07	0·10	0·10	0·07	0·07
D	—	—	**0·67**	0·07	**0·80**	—	0·07	—	—	—

Diurnal regime 'magnitude'. On the basis of the cluster dendrogram and agglomeration schedule plot, four clusters provided a robust classification of the magnitude of air and water temperature diurnal regimes. Table IV presents summary statistics for each regime magnitude class, and Figure 6 presents the box plots of magnitude indices by regime magnitude class. The regime magnitude classes can be arranged to give a relative temperature classification as follows:

Class 1 → Cool day with the lowest minimum and maximum temperature (56 station-days).
Class 2 → Warm day with moderate minimum and maximum temperature (74 station-days).
Class 3 → Hot day with relatively low minimum temperature, high maximum temperature, and hence high variance (73 station-days).
Class 4 → Very hot day with the highest minimum and maximum temperature (97 station-days).

Regime magnitude classification did not reveal clear spatial or temporal patterns; the four classes exhibited broadly the same frequencies across all water and air temperature sites (Table V) with slight preponderance of hot days (classes 3 and 4). This suggested sequencing and synchrony of change in the relative magnitude of diurnal regimes within and between sites regardless of temporal and spatial variations in absolute temperatures.

Table IV. Average temperature (°C) by index and regime 'magnitude' class for air temperature sites and water temperature sites.

	Air temperature					Water temperature				
	Magnitude class				Mean	Magnitude class				Mean
Index	1	2	3	4		1	2	3	4	
T_{min}	10·7	15·4	15·9	18·4	15·6	16·7	18·8	19·2	19·8	18·8
T_{max}	22·6	24·3	28·2	30·2	26·8	19·2	20·6	21·9	22·3	21·2
T_{mean}	16·9	19·8	23·2	23·4	21·3	18·1	19·7	20·8	20·8	20·0
T_{var}	3·9	2·7	4·6	3·2	3·6	0·8	0·6	1·0	0·7	0·8
N	11	14	16	19	60	45	60	57	78	240

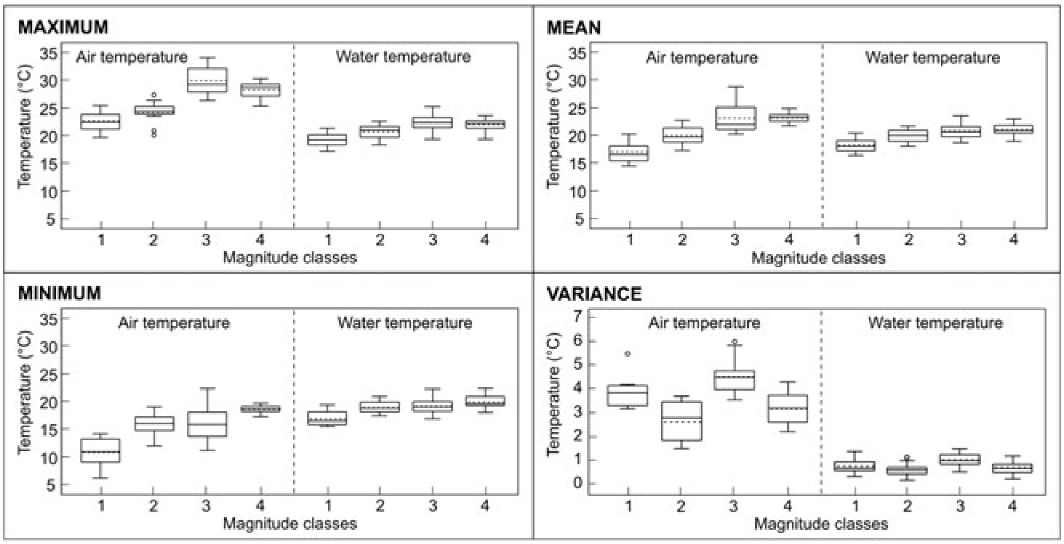

Figure 6. Box plots of the mean, variance, minimum, and maximum daily air and water temperatures by regime magnitude class.

Table V. Frequency (as fractional proportion of days) of diurnal regime 'magnitude' classes by air temperature site and water temperature site; bold numbers indicate the dominant class by station.

Magnitude class	Air temperature		Water temperature							
	A1	A2	W1	W2	W3	W4	W5	W6	W7	W8
1	0·20	0·17	0·23	0·20	0·20	0·20	0·17	0·17	0·17	0·17
2	0·23	0·23	0·27	0·23	**0·30**	0·27	0·23	0·23	0·23	0·23
3	0·23	**0·30**	0·17	0·27	0·20	0·23	0·23	0·27	0·27	0·27
4	**0·33**	**0·30**	**0·33**	**0·30**	**0·30**	**0·30**	**0·37**	**0·33**	**0·33**	**0·33**

Composite classification. A composite classification was produced by combining regime shape and magnitude classes Analysis of the spatial distribution of dominant regime composite classes (Figure 7) revealed similar inter-site behaviour for air temperature regimes, with clear dominance of hot temperatures and steep diurnal cycles (class 4B). Comparison between *water temperature* sites showed great contrast in the dominant patterns of diurnal regime and evidenced the effects of the impoundment on the thermal behaviour of the river downstream. Both upstream sites (W1 and W2) were dominated by relative high temperatures; the difference between sites was in the dominant shape of the thermographs (late peak with gradual cessation in site W1 and more even diurnal cycles in site W2). Immediately downstream from the impoundment (site W3), the relative magnitude of dominant diurnal regimes was notably lower than that for the upstream sites, revealing the effects of the dam in reducing diurnal maxima and in moderating diurnal fluctuations. Dominance of cool to warm temperatures persisted over a distance of about 4 km (site W4), although the dominant shape of diurnal regimes was more even across the day and in synchrony with sites W5 and W6, which revealed dominance of hot and even diurnal regimes the same as the unregulated site W2. Dominating patterns of water temperature at the distal sites (W7 and W8) were similar to those observed for air temperature (class 4B).

Quantification of the temporal stability and climatic sensitivity of water temperature regimes. Building on analysis in the preceding sections, we quantified the temporal stability (day-to-day switching) of air and water temperature diurnal regimes by using a regime EI (Table VI). Additionally, an *SI* was used to summarize the strength and direction of water–air temperature regime associations (Table VI). These analyses were conducted for regime shape and magnitude separately.

Equitability and sensitivity indices for *water temperature regime shape* identified clearly two different scenarios for sites located above or below the dam (Table VI; Figure 8).

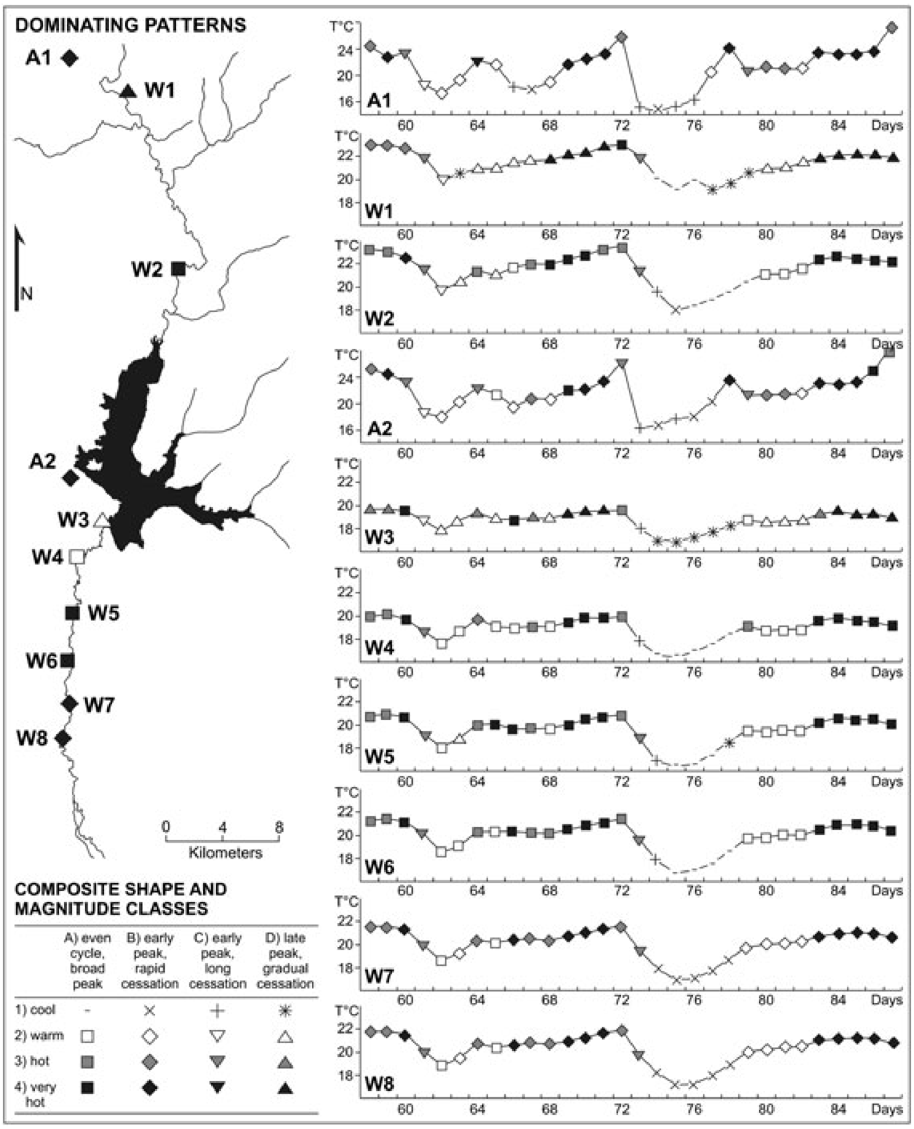

Figure 7. Distribution of composite shape and magnitude classes over curves of daily mean temperature by site (right) and spatial distribution of the dominant composite regime classes of air and water temperature (left).

Table VI. Equitability of diurnal regime shape and magnitude classes by air and water temperature site, and climatic sensitivity of the shape and the magnitude of water temperature regimes by site.

Station	Equitability index		Sensitivity index	
	Regime shape	Regime magnitude	Regime shape	Regime magnitude
A1	0·53	0·99	-	-
W1	0·72	0·98	0·46	−0·16
W2	0·62	0·99	0·37	0·79
A2	0·82	0·97	-	-
W3	0·45	0·99	−0·65	0·44
W4	0·28	0·99	−0·59	0·40
W5	0·41	0·97	−0·63	−0·42
W6	0·23	0·98	−0·68	−0·42
W7	0·35	0·98	−0·66	−0·42
W8	0·35	0·98	−0·66	−0·42

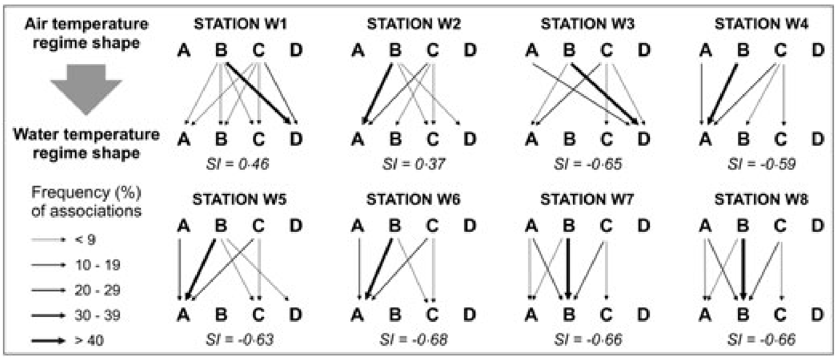

Figure 8. Direction and frequency of associations between air and water temperature regime shape classes.

Positive *SI* values for upstream sites (W1 and W2) indicated that water temperature regimes were more variable than air temperature regimes and hence more equitable ($0{\cdot}62 < EI < 0{\cdot}72$). However, moderate *SI* values suggested that variability in water temperature was very sensitive to air temperature, especially at site W2 ($SI = 0{\cdot}37$). Negative *SI* values for downstream sites suggested that water temperature regimes were less variable than air temperature and so less equitable ($0{\cdot}23 < EI < 0{\cdot}45$). This indicates that a limited number of water temperature classes occurred under a broader range of air temperature regimes. Moderate to moderately high *SI* values ($-0{\cdot}59 < SI < -0{\cdot}68$) suggested that the shape of water temperature regimes was climatically insensitive.

Water temperature regime magnitude exhibited high overall sensitivity to air temperature (Table VI; Figure 9). Except for station W2, all sites experienced low to moderate *SI* values, either positive ($0{\cdot}40 < SI < 0{\cdot}44$) or negative ($-0{\cdot}16 < SI < -0{\cdot}42$). This suggested that relative patterns in water temperature were influenced by meteorological conditions even though absolute values were affected by impoundment. This interdependence could be expected, as air and water temperature regime magnitude revealed high temporal equitability ($0{\cdot}97 < EI < 0{\cdot}99$) and hence high temporal variability. Moreover, the direction and frequency of water–air associations revealed strong links between similar regime magnitude classes.

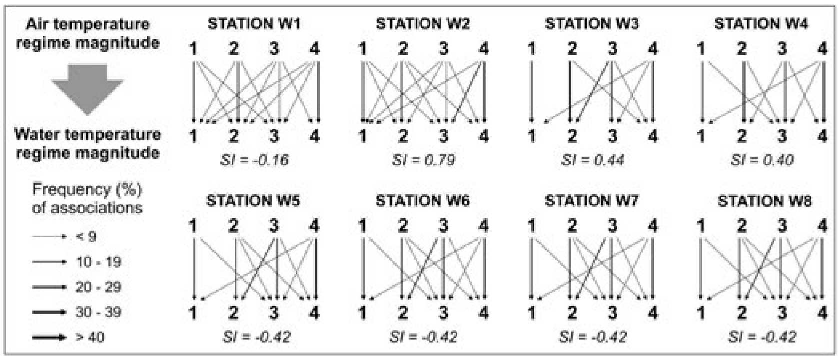

Figure 9. Direction and frequency of associations between air and water temperature regime magnitude classes.

DISCUSSION

Potential impacts of the dam on summer river water temperature. Although the dam affected primarily the absolute magnitude of the river water thermographs, the frequency, timing, and duration of temperature extremes across sites were influenced by ambient conditions without significant differences between the unregulated and regulated sites. Overall, the main effects of the dam were similar to those found for temperate rivers (Ward and Stanford, 1979; 1983; 1995) and included (i) reduction in daily mean, maxima, and minima, and (ii) reduction in diurnal fluctuations.

Downstream maximum thermal differences with respect to the unregulated river upstream were −3 °C in MNT, −4 °C in MAXT, −1 °C in MINT, and −0·5 °C in MNR. Comparable magnitudes of thermal depression during summer were reported, for example, in the Ain River below the Vouglans Dam, France (−2 °C; Poirel and Gailhard, 2010) and in the River Tyne below the Kielder Dam, UK (−3 °C; Archer, 2008). Also in the UK, Webb and Walling (1993; 1995; 1997) found that the main effects of the Wimbleball Dam upon the thermal regime of the upper Haddeo River were both depressed summer maxima (2 °C in average) and diurnal fluctuations in all seasons (up to 60% reduction in maximum daily range). In comparison with this study, significantly greater magnitudes of summer thermal depression were reported for regulated rivers in Australia, which are comparable in terms of physical setting. For example, the summer water temperature in the Macquarie River below the Burrendong Dam and in the Mitta Mitta River below the Dartmouth Dam was reduced by 8 and 10 °C, respectively (reviewed by Preece and Jones, 2002), and the temperature maxima in the Naomi River below Keepit Dam was reduced by 5 °C (Preece and Jones, 2002).

In contrast to dams where cooling trends during summer months are related to flow release from the bottom of thermally stratified reservoirs (e.g. Preece and Jones, 2002; Wright et al., 2009; Olden and Naiman, 2010), the cooling effect induced by the Paso de las Piedras Dam was related to the canalization of reservoir seepage below the dam embankment. The dam effects were most marked over a distance of about 8 km and declined downstream thereafter; however, the mean water temperature at site W8 (river kilometre 15) was 1·3 °C cooler than the unregulated river (site W2). Similar patterns were found by Webb and Walling (1988; 1993) for different river sites in south-west England (20 km; 40 km in conditions of hot weather) and by Cowx *et al.* (1987) for three river sites in Wales (30 km). However, the distance for thermal recovery below the dams has been reported to vary considerably (e.g. 60 km, Archer, 2008; 100 km, Preece and Jones, 2002; 260 km, Zhong and Power, 1996) as it depends primarily on the dam structure and operational procedures (Ward and Stanford, 1979), on the energy contributions from the atmosphere and the streambed (Webb, 1996; Caissie, 2006), and on a number of factors moderating heat exchange to and from the river (e.g. riparian cover, Hannah *et al.*, 2008a; groundwater inflows, Webb and Walling, 1997; among many others).

The response of diurnal regimes of water temperature to regulated patterns of flow and hot weather conditions showed different behaviour regarding the shape and the magnitude of the thermographs. *Regime shape* analysis revealed strong class dominance by site, i.e. each site had a 'typical' form of diurnal regime during the monitoring period and clear differentiation in the spatial distribution of dominant classes downstream related systematically to the effects of the dam. Conversely, *regime magnitude* analysis revealed high within-site variability and strong between-site synchrony, i.e. changes in the relative magnitude of diurnal regimes occurred at the same time across all sites. This revealed that water temperature regimes were more sensitive to change in the relative size than in the timing of the diurnal cycles, which in turn were affected by the impoundment.

On the basis of the frequency and the spatial distribution of dominating classes of regime shape and magnitude, the river thermal behaviour over the monitoring period may be simplified into four combinations of composite classes of diurnal regime (Table VII) highlighting contrasts of major ecological significance (cf. Harris *et al.*, 2000). The unregulated 'natural' river thermal regime revealed relatively symmetrical diurnal cycles and preponderance of sequencing of high temperatures (class *i*). These thermal patterns showed a major shift directly below the dam: Diurnal cycles were delayed in timing and reduced in amplitude (class *ii*), and the recurrence of relative cool to warm temperatures persisted over about 4 km downstream (class *iii*). Diurnal regimes recovered to 'natural' behaviour (class *i*) after a distance of about 8 km but changed again downstream from river kilometre 13, with stronger diurnal

Table VII. Simplified classes of diurnal water temperature regime and spatial distribution along the Sauce Grande River.

Simplified class	Description	Spatial distribution
i	Relatively symmetrical diurnal cycles with broad peak at 1700–1800 and preponderance of high relative magnitude	Upstream unregulated river; 8–11 km downstream from the dam
ii	Late and extended peak at 1800 h with gradual cessation and preponderance of low relative magnitude	2 km downstream from the dam
iii	Symmetrical diurnal cycles with broad peak at 1700 h and preponderance of low relative magnitude	4 km downstream from the dam
iv	Steep and early peak at 1500 h with rapid cessation and preponderance of high relative magnitude	13 km downstream from the dam

fluctuations and higher magnitude (class *iv*), which were more in synchrony with air temperature regimes than upstream unregulated flow conditions.

Regime shape and magnitude classification provided the basis for assessing temporal stability of regimes by site (*EI*) and for quantifying the linkages between water and air temperature regimes (*SI*). Sensitivity analysis for water–air temperature associations revealed two contrasting scenarios for sites located above and below the impoundment. The shape and the magnitude of water temperature regimes within the upstream 'natural' river were climatically sensitive and temporally equitable; downstream, the form (timing) of water temperature regimes revealed overall climatic insensitivity and high constancy of a single class across sites (regime stability), although water–air associations regarding the regime magnitude revealed higher sensitivity and equitability. This suggested that relative sequencing of size of response was broadly driven by prevailing weather conditions, although the timing and absolute size of the thermographs were affected by the dam.

Ecological implications. A number of studies have demonstrated that summer cooling of river waters below the dams may have serious implications for aquatic ecosystems related to changes in the ecological niche (e.g. extirpation of native species and species turnover, Olden and Naiman, 2010; Osmundson, 2011) and to disruption in life cycles (e.g. increased trout development, Webb and Walling, 1995; reduced spawning success of several fish species, Preece and Jones, 2002; and delayed salmonid smolting, Archer, 2008). Within the Sauce Grande River, the most serious ecological threat of river summer cooling is conceivably related to potential shifts in stream habitat characteristics from temperate subtropical (Pampasian-like) conditions to cold temperate (Patagonian-like) conditions. The river flows within the Pampean ecological province (Lopez *et al*., 2008), which contains lotic and lentic Neotropical species of the Brazilian subregion (Casciotta *et al*., 1999). Most species have wide environmental tolerance (Lopez *et al*., 2002); however, the Sauce Grande River flows near the southern limit for Neotropical diversity (Negro River, Almirón *et al*., 1997; Colorado River, Lopez *et al*., 2008) and so near the northern limit for the Austral kingdom (Lopez *et al*., 2008). Hence, summer cooling of river waters below the dam may cause reductions in water temperature below suitable thresholds for native Neotropical fish species. Shifts from temperate subtropical conditions to cold temperate conditions have major implications for the fish community structure (e.g. increase in biomass and body size; Mello *et al*., 2012) and composition (e.g. decrease in species richness and density; Rosso and Quiros, 2010).

The overall biodiversity of the Sauce Grande River is poorly known, and so the effects of the dam upon the ecological integrity of the river system are difficult to estimate with certainty. Nevertheless, studies on native fish composition within the upper Sauce Grande revealed abundance of 'madrecita' [*Jenynsia lineata or multidentata* (Jenyns)] and 'panzudito' (*Cnesterodon decemmaculatus*) along the water course (Menni *et al*., 1988; Lopez Cazorla *et al*., 2003b) and abundance of 'pejerrey' (*Odontesthes bonariensis*) in both the upper river environment (Lopez Cazorla et al., 2003a) and the lentic systems within the lowest section (Gomez *et al*., 2007). The annual cohort of Jenyns are born in late spring–early summer when water temperature ranges from 20 to 26 °C (Lopez Cazorla *et al*., 2003b) The pejerrey produce two annual cohorts: one during September–October and the other during March–April, with optimum incubation range between 16 and 21 °C and maximum birth percentage at 24 °C (Gomez *et al*., 2007). A potential reduction of more than 4 °C in maximum daily summer temperature below the dam may be below the physiological optima for fish performance and growth, especially for Jenyns.

Furthermore, depression in summer temperature extremes (seasonal constancy) and reduction in diel fluctuations (diurnal constancy) may delay the emergence and maturation of macroinvertebrates (Ward and Stanford, 1979; 1982), which may result in significant reductions in the abundance and diversity of insect fauna (Lehmkuhl, 1972; Anderson, 1989; Webb and Walling, 1995, Jackson *et al*., 2007). Diurnal regimes immediately below the dam were reduced and delayed and revealed to be dominated by relative cool to warm temperatures (class *ii*); this may have direct implications for hatching and growth of Ephemeroptera *Baetis* and *Ulmenitus*, which constitute 92% of the total diet taxa for Jenyns (Lopez Cazorla *et al*., 2003a).

The applicability of the RSMC and SI approaches to water temperature assessment. The RSMC approach provided easily interpretable information on two key attributes of the river thermal regime influencing river ecology: the size and the timing of the thermograph. The method allows the analysis of both key regime attributes separately and jointly (Harris *et al*., 2000; Kansakar *et al*., 2004), and so aggregated patterns of water temperature regime can be identified simply. Additionally, the RSMC procedure is relative at a station, and so it provided information on the regime variability within (time) and between (space) sites. The major benefits of this technique are that (i) it may be applied to any variable exhibiting a cycle for a given time length and resolution (Harris *et al*., 2000; Bower *et al*., 2004) and (ii) the flexibility of the classification procedure allows modification for a range of applications (Hannah *et al*., 2000). Thus, the RSMC represents a potentially powerful tool for regime analysis in a variety of variables, contexts, and time scales.

The use of the *SI* to assess the climatic sensitivity of water temperature regimes is novel and provided useful summaries of the complex linkages between water temperature regimes, flow regulation, and weather conditions during a critical period of water and thermal stress. The major contribution of the *SI* was that it summarized the strength and the direction of water–air temperature associations into a single, concise value that allowed comparison in space and time. Arguably, the *SI* provides less information about the direction and frequency of single class associations. However, this may be evaluated by cross-tabulation of values of conditional entropy for a given location. By simply plotting these results (Figures 8 and 9), meaningful complementary information may be yielded. Furthermore, as the *SI* quantifies relationships between two variables subject to any nominal regime classification (Bower *et al*., 2004), it may be applied to link classes for a wide range of variables affecting water quality and stream ecology (e.g. flow discharge, water conductivity, and dissolved oxygen), and thus, it has great potential utility as a tool for ecohydrological analysis.

CONCLUSIONS

This paper has investigated in detail the influence of flow regulation on the thermal behaviour of the Sauce Grande River during a summer period. The effects of the Paso de las Piedras Dam in depressing daily mean, maximum, and minimum RWTs and in reducing diurnal fluctuations were identified clearly over a distance of about 15 km downstream. Besides disrupting physiological optima for life cycles of aquatic organisms, potential summer shifts in the river thermal regime may involve reductions in the stream productivity (Caissie, 2006) and changes in the composition of riverine biota (Olden and Naiman, 2010). However, the ecological implications of altered patterns of water temperature within the Sauce Grande River are still to be investigated directly.

This study provided the very first assessment of the broad-scale impacts of the Paso de las Piedras by focusing on summer river thermal variability, an ecohydrologically relevant variable. The new understanding yielded herein serves as an important platform to enable further research to assess the health of the river ecosystem and to inform the sustainable management of water resources. As well as yielding new information to underpin further ecohydrological research, this study applied for the first time a novel classification scheme and a climatic SI to water temperature assessment. Combined, these approaches provided substantial information on temporal (in)stability and spatial variability of diurnal regimes of air and water temperature and gave a robust measure of the strength and direction of water–air temperature associations over time. Both methods are widely transferable to assess a variety of ecohydrological variables, as well as their sensitivity to climate and other drivers of change over a range of spatial and temporal scales.

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