ECOHYDRAULICS:
linkages between hydraulics, morphodynamics & ecological processes in rivers

15-17 June 2011

Extended Abstracts

maison des sciences de l'homme

4 rue Ledru
Clermont-Ferrand, France
Ecohydraulics: linkages between hydraulics, morphodynamics and ecological processes in rivers

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Clermont-Ferrand, France, 15-17 June, 2011
Imprint

EUROMECH Colloquium 523
Ecohydraulics: linkages between hydraulics, morphodynamics and ecological processes in rivers
15-17 June 2011, Maison des Sciences de l’Homme, Clermont-Ferrand

This colloquium is organized under
of the EUROMECH - European Mechanics Society - Council.

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Sponsors
European Mechanics Society (EUROMECH) German Research Foundation (DFG)
Netherlands Organisation for Scientific Research (NWO) DFG-NWO project number DN66-149
University Blaise-Pascal, Clermont-Ferrand MSH Clermont-Ferrand

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Effects of Paso de las Piedras Dam on the thermal regime of Sauce Grande River, Argentina

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ABSTRACT. It has been well demonstrated that dams and reservoirs represent source major of hydrological disturbance by regulating fluvial processes downstream of the impoundment. In assessing the hydrological and ecological impacts of such river regulation, recent research has evaluated the role of reservoirs in altering spatial and temporal patterns of river water thermal behaviour. Water temperature is the most important physical property of streams and rivers. It exerts a strong influence on the complex hydrological, chemical and biological processes of the river system, with significant implications for water quality and stream ecology. This study aims to identify the effects of Paso de las Piedras Dam on river temperature variability during summer for the Sauce Grande River. A 30-day set of continuous hourly data was analysed for a total of 9 stations (2 climate stations and 7 stream temperature sites) deployed above and below the reservoir. Time-series span the hottest period recorded during summer 2009, from late February to late March. Methods were divided into two linked sections: (i) analysis of absolute differences in daily air and stream temperature and (ii) classification of diurnal regimes of air and stream temperature with respect to shape (timing). The longitudinal patterns of stream temperature suggested a significant dam-induced thermal regulation between upstream and downstream reaches. Differences between mean seasonal values were of up to 2.5°C, becoming significantly higher when considering maximum records (up to 4°C). Immediately below the dam, temperatures showed an outstanding warming trend. Farther downstream, regimes exhibit even cycles as the flow becomes more dominated by groundwater contribution and weather conditions.

KEYWORDS: Paso de las Piedras Dam, Sauce Grande River, river temperature, hydrological regulation.

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1. Introduction

Despite the value of dams for water resources management, dam construction and reservoir operation represent the greatest source of hydrological interference by human activities, creating artificial river flow regimes downstream and interrupting the transfer of sediments from headwater source areas (Brandt, 2000; Graf, 2005; Magilligan & Nislow, 2005; Petts & Gurnell, 2005). Regulation influences the full range of flows over timescales ranging from hours to years; and, at present, few rivers are in natural or semi-natural conditions (Suriyan & Rinaldi, 2003).

Since dams and reservoirs profoundly affect river hydrology, considerable recent research evaluates the hydrological and ecological cost of river impoundment (Nilsson & Berggren, 2000; Mccartney et al., 2001; Kondolf & Batalla, 2005; Magilligan & Nislow, 2005). Concern about the ecological integrity of impounded rivers motivated several studies focusing on the role of reservoirs in inducing a regulated pattern of river thermal behaviour downstream (Webb & Walling, 1997a; Preece & Jones, 2002; Steel & Lange, 2007; Wright et al., 2009).

River water temperature is arguably the most important physical property of streams and rivers as it influences the hydrological, chemical and biological processes of the river system, with significant implications on the stream ecology and water quality (Webb, 1996; Caisse, 2006; Bonacci et al., 2008; Haag & Luce, 2008). Dams are effective thermal regulators, as they release water from the deepest layers of the reservoir with thermal characteristics that typically differ from ambient conditions in an unregulated river (Webb, 1996; Webb et al., 2008).

This study aims to identify summer patterns of stream temperature within Sauce Grande River, upstream and downstream from Paso de las Piedras Dam. The goal here is not to provide a definitive analysis but to test a classification method to evaluate stream temperature behaviour during the summer season, its spatial variability and its sensitivity to prevailing weather conditions and dam-induced hydrological regulation.

2. Methods

2.1. Study area

Paso de las Piedras Dam and its reservoir are located on the middle section of the Sauce Grande River Basin in the SW of Buenos Aires province, Argentina (Fig. 1). The area is located in a temperate sub-mountain plain. Rainfall concentrates in spring season, exhibiting inter-annual variability that strongly depends on El Niño (heavy rains) and La Niña (extended drought) events. Hence, the Sauce Grande River flow regime is very variable. Annual mean flow is 4.54 m³/s but peak flows can reach 670 m³/s in 12 hours for a 25 mm rainfall event.

Completed in 1978, Paso de las Piedras reservoir has a surface area of 36 km² and a capacity of 328 hm³ at maximum water level (165 m). Its primary purpose is water supply to a population of about 500 000 people; therefore, dam management attempts to maintain a top full reservoir. Consequently, the magnitude, length and frequency of water release depend on reservoir volume, and so the downstream flow regime is highly irregular.

2.2. Data sources

Hourly observations of air temperature were obtained from two meteorological stations (MS): MS Saldungaray (A1) and MS Paso de las Piedras (A2), located upstream and next to the reservoir, respectively (Fig. 1).

Eight temperature data loggers (ONSET Computer Corporation) recorded water temperature every 15 min from January to March 2009. They were deployed within the main channel along upstream (W1 and W2) and downstream (W3 to W7) reaches (Fig. 1). Additionally, one logger was installed on a small channel draining water from reservoir leakages, as a proxy for dam water release temperatures. A 30-day-dataset of continuous hourly data was assembled for all sites. It spans the hottest period recorded during summer 2009, ranging from late February (day 58) to late March (day 87). Hereafter,
dates will be referred to using the Julian day of the year and time will be quoted in local time.

![Figure 1. Layout map of the study area.](image)

### 2.3. Time series assessment

Summer patterns for air and stream temperature time-series were examined by absolute differences in daily data. Several metrics were calculated: (i) daily mean, maximum and minimum records (magnitude), (ii) day of occurrence of extreme values (timing), and (iii) period of time associated to extreme values (duration). Extreme values were defined as those lying above ($D_{\text{max}}$) and below ($D_{\text{min}}$) the mean plus or minus two standard deviations, respectively. Furthermore, station-to-station differences in water temperature records were inspected using longitudinal profiles of average values for the season, and the hottest and the coldest days.

### 2.4. Classification of diurnal regime shape

A hierarchical cluster analysis (HCA) was applied to classify air and stream temperature time-series by relative differences in the shape (timing) of the diurnal regimes. This procedure was firstly developed by Hannah et al. (2000), and then applied in several studies (Harris et al., 2000; Bower et al., 2004; Kanskar et al., 2004; Hannah et al., 2005). The 'shape' classification identifies station-days with a similar regime form, regardless of the absolute magnitude. The 24 hourly observations within each day for the 30-day period and over the 9 sites (270 station-days) were standardized using z-scores (mean = 0, standard deviation = 1). Air and stream temperature records were classified together into groups of similar diurnal thermograph form. Classification was achieved by Ward's linkage method as it gave relatively dense clusters with small within-group variance.

### 3. Time series assessment

Table 1 summarises the magnitude, timing and duration of air and stream temperature summer patterns. Air temperature series exhibit high daily variability, attaining maximum diurnal ranges of up to 18°C (A1) and 15°C (A2). Intra-seasonal variability is also considerable. High-temperature extremes ($N_{\text{max}}$) have occurred frequently (4 to 5 days) but with short duration (1 to 2 days), attaining maximum records on Julian day 58. Air temperature at both sites cooled on Julian day 73 and low-temperature extremes ($N_{\text{min}}$) were occurred over two consecutive days.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Air temp.</th>
<th>Stream temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W1</td>
<td>W2</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>21.0</td>
<td>21.6</td>
</tr>
<tr>
<td><strong>Var</strong></td>
<td>3.1</td>
<td>4.3</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>33.0</td>
<td>34.1</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>6.1</td>
<td>9.3</td>
</tr>
<tr>
<td>$D_{\text{max}}$</td>
<td>55</td>
<td>57</td>
</tr>
<tr>
<td>$N_{\text{max}}$</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td><strong>ML</strong></td>
<td>122</td>
<td>102</td>
</tr>
<tr>
<td><strong>R</strong></td>
<td>18.4</td>
<td>15.3</td>
</tr>
</tbody>
</table>

$D =$ Day, $N =$ Number, $ML =$ Maximum length, $R =$ Range
Variability on stream temperature series is highly correlated to air temperature (average Spearman’s rho = 0.64). The sites warmed on Julian day 59, i.e. 1-day delay relative to air temperature, and cooled on Julian day 75 (2-day delay). Most sites also experienced considerable daily temperature fluctuations, reaching in some cases maximum ranges of up to 4°C (W1, W6 and W7).

Variability in stream temperature patterns is also related to the spatial distribution of the sites. Differences in thermal patterns between sites located above the impoundment (W1 and W2) are not much significant, although station W1 exhibits higher daily ranges and greater occurrence of high-temperature extremes. Below the dam, water temperatures increase in a downstream direction (W3→W7). Differences in average values were +1.5°C, and were notably higher (+3.7°C) in maximum records. Diurnal ranges increase as well, from 1.6°C (W3) to 3.4°C (W7), and consequently, the frequency and duration of high and low-temperature extremes appear to be more significant as the stations lie farther downstream.

To highlight this spatial variability in water temperatures, longitudinal profiles across stations were inspected (Fig. 2). The spatial distribution of mean values for the season (S), the hottest (HD) and the coldest (CD) day suggests a significant dam-induced thermal regulation between upstream and downstream reaches. Differences in seasonal means between station W2 (immediately upstream) and station W3 (immediately downstream) were of up to 2.5°C, and notably higher on the hottest day (3.5°C).

Whilst upstream sites show thermal stability, stream temperatures below the dam exhibit an outstanding warming trend in the downstream direction. Station-to-station thermal gradients (TG) illustrate the rates of increase of water temperature with distance (Fig. 2). Warming rates are considerably high between the dam closure and the station W3 (+1°C/km), and decrease farther downstream. It suggests that the reservoir may induce an immediate thermal effect on the sites situated below the dam that does not persist beyond the close vicinity of the impoundment. It is beyond the scope of this study to understand the differences in rates of increase between sites as a result of external control factors such as topography, shading effect or groundwater contribution.

4. Classification of the diurnal thermal regime ‘shape’

Air and stream temperature records were standardised and then classified together into groups of similar diurnal temperature regime form (shape). Inspection of the cluster dendrogram and agglomeration schedule plot suggested that four clusters would provide an informative classification of the summer data set (Fig. 3). The clusters give a classification as follows:

- **Class A**: Early diurnal cycle that shows a gentle onset with peak at 5 pm, relatively long peak duration and gentle cessation (57 station-days).
- **Class B**: Steep rise towards an early peak at 3 pm, short duration and rapid cessation (65 station-days).
- **Class C**: Early peak at 4 pm and long cessation towards low temperatures (68 station-days).
- **Class D**: Late rise into an extended peak at 6 pm with gradual cessation (80 station days).

The main difference between the four classes is in the timing and length of the peaks. Whilst classes B and C exhibit early and steep peaks, classes A and D reveal gentle onset and cessation with a longer duration. Additionally, diel cycles for classes C and
D₅ appear to be uneven across the day, illustrating a cooling and a warming trend, respectively.

Figure 3. Standardised (z-scores) hourly temperature values for all station-days within air and stream temperature regime shape clusters. The thick black line shows the average value for each shape class.

Summary statistics of diurnal temperature regime shape classes by station are given in Table 2. Air temperature regimes exhibit mostly steep and early peaks (Class B₃ and Class C₃). Regime class B₅ also dominates for water temperature sites W6 and W7, whereas it never occurs for the rest of the water stations. Later and extended peaks (Class D₅) illustrate the most frequent diurnal regime shape for station W1, and clearly dominate in station W3. Farther downstream, seasonal patterns for stations W4 and W5 exhibit gentle and even diel cycles (Class A₅). The distribution of the dominant classes across the water temperature stations reveals spatial differentiation in diurnal regime forms, especially below the impoundment. Extended peaks illustrating a warming trend are found immediately below the dam (station W3). Farther downstream, water temperatures increase and regimes experience more even diel cycles, as it is observed for stations W4 and W5 (Class A₅). Dam effects seem disappear within the distal stations (W6 and W7), since they experience similar dominant patterns as ambient conditions (Class B₃).

<table>
<thead>
<tr>
<th>Station</th>
<th>A₅</th>
<th>B₅</th>
<th>C₅</th>
<th>D₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>A₁</td>
<td>1</td>
<td>11</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>A₂</td>
<td>2</td>
<td>15</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>W₁</td>
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<td>0</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>W₂</td>
<td>2</td>
<td>15</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>W₃</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>W₄</td>
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<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>W₅</td>
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<td>3</td>
<td>0</td>
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<tr>
<td>W₆</td>
<td>2</td>
<td>1</td>
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<td>0</td>
</tr>
<tr>
<td>W₇</td>
<td>2</td>
<td>19</td>
<td>9</td>
<td>0</td>
</tr>
</tbody>
</table>

5. Conclusions

The analysis of absolute differences in daily records illustrated that water temperature time-series are correlated to air temperature. However, spatial differentiation in water temperature patterns suggested a significant dam-induced thermal regulation between upstream and downstream reaches. Classification of stream temperature diurnal regime shape underlined the thermal effects of the impoundment. Immediately below the dam, the sites describe a warming trend that leads to more even cycles, as the flow becomes more dominated by groundwater contribution and weather conditions. This study has evaluated stream temperature behaviour in a regulated river using limited data sets. Further research requires exploring more extended data sets to better understand the thermal patterns of flow and their sensitivity to prevailing weather conditions and dam-induced hydrological regulation. Moreover, hydrological records and land cover layers are also required in assessing the thermal dynamics of the river system.
References


