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Development of a new methodology for the creation of water temperature scenarios using frequency analysis tool

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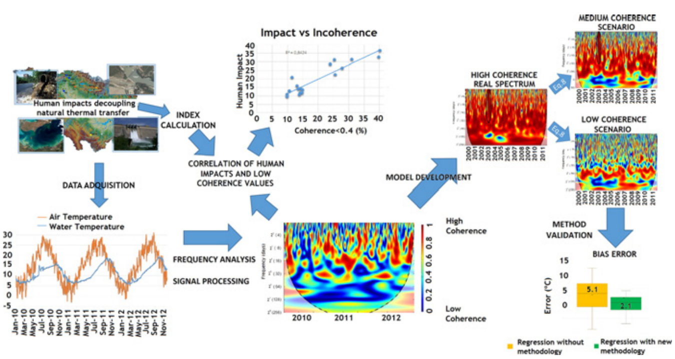
HIGHLIGHTS

- We developed a new methodology for the calculation of water temperature scenarios.
- A correlation of $r^2 = 0.84$ between human impacts and temperature incoherence was found.
- Stream impact in the 128 days frequency is due to agricultural flow management.
- The new method reduced the stream temperature prediction error in >2 °C.

GRAPHICAL ABSTRACT



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ABSTRACT

Thermal quality in river ecosystems is a fundamental property for the development of biological processes and many of the human activities linked to the aquatic environment. In the future, this property is going to be threatened due to global change impacts, and basin managers will need useful tools to evaluate these impacts. Currently, future projections in temperature modelling are based on the historical data for air and water temperatures, and the relationship with past temperature scenarios; however, this represents a problem when evaluating future scenarios with new thermal impacts. Here, we analysed the thermal impacts produced by several human activities, and linked them with the decoupling degree of the thermal transfer mechanism from natural systems measured with frequency analysis tools (wavelet coherence). Once this relationship has been established we develop a new methodology for simulating different thermal impacts scenarios in order to project them into future. Finally, we validate this methodology using a site that changed its thermal quality during the studied period due to human impacts. Results showed a high correlation ($r^2 = 0.84$) between the decoupling degree of the thermal transfer mechanisms and the quantified human impacts, obtaining 3 thermal impact scenarios. Furthermore, the graphic representation of these thermal scenarios with its wavelet coherence spectrums showed the impacts of an extreme drought period and the agricultural management. The inter-conversion between the scenarios gave high morphological similarities in the obtained wavelet coherence spectrums, and the validation process clearly showed high efficiency of the developed model against old methodologies when comparing with Nash-Stucliffe criterion. Although there is need for further investigation with different climatic and anthropic management conditions, the developed frequency models could be useful in decision-making processes by managers when faced with future global change impacts.

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1. Introduction

Stream temperature is a fundamental property of river habitats that shapes biological communities and determines ecosystem services. Despite atmospheric conditions, topography and streambed are usually the most important factors responsible for the heat exchange processes that take place in water surfaces (Caissie, 2006; Magnuson et al., 1979), there are a couple of human activities that can alter directly (e.g. dams or industrial spills (Olden and Naiman, 2010; Prats et al., 2012)) or indirectly (e.g., land uses (Poole and Berman, 2001)) water temperatures.

It is anticipated in the near future that as a result of climate change, temperatures and water cycles are going to be severely altered (IPCC, 2014). The main impacts will be higher water temperatures and greater flow fluctuations, which are likely to influence many physical, chemical and biological processes governing water quality (Dale, 1997; Thorne and Fenner, 2011; Val et al., 2016a). This implies that humans will be forced to manage these changes in order to adapt them.

The prediction of stream water temperature is the main goal for many basin managers to address water resource problems, such as thermal spills, water quality and ecosystem requirements. A better understanding of the natural thermal regime of river systems is also very important in the management of fisheries resources, some agricultural needs and even some industrial activities (Deas, 2000). Thus, the first step in the overall understanding of the stream thermal regimes is to be able to study and predict the natural variations in stream water temperature.

For these purposes, basin managers and researchers use several water temperature modelling methods, such as; regression models (Johnson, 1971; Mackey and Berrie, 1991; Mohseni et al., 1998; Smith, 1981), stochastic models (Caissie et al., 1998; Cluis, 1972), deterministic models (Kim and Chapra, 1997; Sinokrot and Gulliver, 2000; Vugts, 1974; Younus et al., 2000) or advanced algorithms (Arganis et al., 2009; El-Jabi et al., 2009). All these models, except the deterministic models, are based on the high correlation of air-water temperature, and use mainly air temperatures to predict water temperatures. However, the air-water temperature relationship could be altered due to several human impacts (dams, spills, land uses, etc.), causing an error in the calculations of water temperatures with these models (Prats et al., 2012).

On the other hand, deterministic models and other mixed models (deterministic + empirical (Buendia et al., 2015)) are better adapted to this problem, because they consider the different energy fluxes and mixing zones within the river. These methods use a set of variables (solar radiation, wind speed, air temperature, spill inputs, dams, discharges, etc.) that allow the quantification of the total energy flux experienced by the river, and then fit the total energy flux to the observed changes in water temperatures. However, these methods require many parameters with a high data volume, which implies that long future projections for each of these parameters would result in a higher error.

Then, coming back to the non-deterministic models, the main problem with their use for future projections is that these models are based on previous conditions and are projecting only the same scenario at where they have been developed. This fact could be a limitation in the decision-making by managers under the upcoming changing conditions caused by climate change.

All these models focus in the study of time series, in this study, the term “signal” is used as a meaning close to “time series”. These signals analyses are about the study of observations of one variable through time (Box et al., 2015). The classical analysis of time series is attained in the time domain, and based on statistic models like moving averages, autocorrelation and autoregression. However, frequency domain or spectral approaches are more acquainted in the analysis in signal processing or system engineering fields, determining how much energy is contained within a time series by estimating the frequency spectrum (periodogram) or time-frequency spectrum (scalogram). Then, it is important to realize that the two approaches can be applied to identify natural system models in a complementary way, and by modelling the periodogram we can develop different scenarios, that we could apply in future projections.

Here we analysed 19 air-water temperature signals (1996–2012) relationships at the Ebro River Basin by using frequency analysis tools, showing a link between the air–water temperature coherence and the human management degree of each water body. Then, we established several management scenarios, and made a validation for this new methodology when applying them into future temperature projections.

2. Materials and methods

2.1. Study sites

This study has been developed at the Ebro River Basin, which is located at the North-East of Spain, comprising an area of 86,100 km^2. Its climate is complex and presents a great heterogeneity in its topography, as it is influenced by the Atlantic climate system situated at the northwest and by the Mediterranean climate from the southeast. In addition, it is highly influenced by several global weather patterns, such as the North Atlantic Oscillation, the Mediterranean Oscillation and Western Mediterranean Oscillation (Vicente-Serrano et al., 2009; Vicente-Serrano and Lopez-Moreno, 2006), generating a complex spatial distribution of climatic patterns. There are large variations in rainfall and evapotranspiration (Ninyerola et al., 2007), with rainfall ranging from 307 to 2451 mm yr^{-1}, and average annual temperatures from 0.8 °C to 16.2 °C.

The Ebro basin has a high flow regulation capacity. Ebro Hydrographic Confederation (CHE), through the 187 existing dams is able to manage >85% of the annual average flow of the whole basin. The main destination for the dammed water is irrigation, with an area of 906,000 ha, and an annual total water demand of approximately 7793 hm^3/year. The other main use of water from this basin is the production of hydroelectric energy, where 458 power stations use around 38,000 hm^3/year to produce about 9400 GW/h (Batalla et al., 2004; Magdaleno and Fernandez, 2011).

This study was carried out with daily average temperature time series from 1996 to 2012. Water temperature data were obtained from 19 automatic sampling stations from the Ebro management body (CHE), and air temperature data were obtained from the nearest meteorological stations from the Spanish meteorological Agency (AEMET) (Fig. 1).

CHE sampling stations are equipped with temperature sensors model ADASA™, P102. (More information about the data collection of water temperature is available in the Supporting information appendix 1).

2.2. Frequency analysis

Although wavelet analysis covers a wide range of methods and applications, fundamental operations are wavelet transforms, which are appropriate for the many natural phenomena that present high frequency events happening during short durations such as the changes in temperatures. Wavelet transform provides the frequencies contained in the signal and sheds light about the moment at which each frequency is present (Mallat, 1999). Wavelets are well appropriated for analysing signals that hold local nonlinearities and singularities. The continuous wavelet transform (CWT) $f(t)_{s,\tau}$ of a function f(t), on the base of the wavelet mother $\psi_{s,\tau}$ is defined as the inner product $\langle f(t),\psi_{s,\tau}\rangle$ in the measurable and square integral spaces (Daubechies, 1990) as is set out in Eqs. (1) to (3):

$$[W_\psi f](s,\tau)=\int_{-\infty}^{\infty} f(t)\psi^*_{s,\tau}(t)\mathrm{d}t \tag{1}$$

$$\psi_{s,\tau}(t)=\frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right) \tag{2}$$

where ψ^* is the complex conjugate. The mother wavelet $\psi(t)$ is