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Temporal variability in the thermal regime of the lower Ebro River (Spain) and alteration due to anthropogenic factors

Jordi Prats [a,*], Rafael Val [b], Joan Armengol [c], Josep Dolz [a]

[a] Hydraulic, Maritime and Environmental Engineering Department, Technical University of Catalonia, C/ Jordi Girona, 1-3, 08034 Barcelona, Spain
[b] Department of Hydraulics, Faculty of Engineering, UNAM, Ciudad Universitaria, 04510 México DF, Mexico
[c] Department of Ecology, Faculty of Biology, University of Barcelona, Avda. Diagonal 645, 08034 Barcelona, Spain

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SUMMARY

The Ebro River is one of the longest rivers in Spain and it also has the greatest discharge. Its lower part is highly regulated and includes a system of three reservoirs (Mequinensa, Riba-roja and Flix). The water temperature is altered because of the release of hypolimnetic water and the use of water for cooling at the Ascó nuclear power plant. The thermal regime of the lower Ebro River on different time scales and the changes caused by anthropogenic factors, especially the system of reservoirs and the thermal effluent of the nuclear power plant, have been studied by installing a net of water temperature measuring stations and by using historical water temperature data provided by the thermal power plant at Escatrón. An increase of 2.3 °C in the mean annual water temperature could be demonstrated in the period 1955–2000 at this site. The effects of the system of reservoirs and of the nuclear power plant were the usual for this kind of structures and could be detected many kilometres downstream. In the summer, the cooling effect of the reservoirs and the warming effect of the nuclear power plant compensated each other. In winter, the warming effect of both summed up.

1. Introduction

Water temperature is a key factor in the physical, biological and chemical processes of fluvial ecosystems (Allan, 1995). The thermal regime of a fluvial ecosystem determines the species that can be found in it (Vannote and Sweeney, 1980; Hellawell, 1986). Thermal cues play an important role in the biological cycles of many aquatic organisms (e.g. Rodriguez-Ruiz and Granado-Lorencio, 1992; White and Knights, 1997). Water temperatures affect the development of organisms (e.g. Lutz, 1968; Pritchard et al., 1996; Watanabe, 1998), their growth rates, metabolic rates (e.g. Sweeney, 1977; Barko and Smart, 1981; Santamaria and van Vierssen, 1997), fecundity (Vannote and Sweeney, 1980), heavy metal uptake (Fraysse et al., 2000), etc. The competitive ability of some fish species also depends on water temperature (Baltz et al., 1982; Reeves et al., 1987; Taniguchi et al., 1998). As a result, changes in the water temperature regime can change the structure of the community.

Throughout the years, the human being has made use of fluvial ecosystems. Some actions have caused changes in the thermal regimes of rivers (e.g. Alberto and Arrúe, 1986; Preece and Jones, 2002). Reservoirs and the use of water for cooling are often the most important sources of water temperature modifications caused by humans. The use of water for cooling, usually by power plants, causes the water to become warmer (Hellawell, 1986). Wastewater can also have a similar effect (Kinouchi et al., 2007). This is often called "thermal pollution" and its effects can be local or extend over a long stretch of the river depending on factors such as the difference in water temperature respect to natural conditions, the volume of the thermal inflow respect to the total river discharge and the actual river discharge. Reservoirs can also cause various effects, depending on various factors such as the climate, the size of the impoundment, the residence time, the stability of the thermal stratification and the depth of the outlet (Wotton, 1995; Lessard and Hayes, 2003). Provided that thermal stratification occurs, the water from deep-release reservoirs is cooler in the summer and warmer in the winter than it would be without the reservoir (Ward, 1985; Webb and Walling, 1993). Water diversions can also alter water temperature regimes because they reduce discharge, which causes water temperature range to increase throughout the year (Meier et al., 2003). Irrigation is also known to decrease discharge and increase water temperature (Verma, 1986).

* Corresponding author. Address: Hydraulic, Maritime and Environmental Engineering Department, Building D1, Office 208, Technical University of Catalonia, C/ Jordi Girona, 1-3, 08034 Barcelona, Spain. Tel.: +34 93 401 19 63; fax: +34 93 401 73 57.

E-mail addresses: jordi.prats-rodriguez@upc.edu (J. Prats), rvals@iingen.unam.mx (R. Val), jarmengol@ub.edu (J. Armengol), j.dolz@upc.edu (J. Dolz).

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The effects of changes on water temperature in Spanish regulated rivers have been reviewed by García de Jalón et al. (1992) and García de Jalón (1996). Water temperature in regulated Spanish rivers has often been studied as part of research aimed at determining the downstream effects of reservoirs (Garcia de Jalon et al., 1988; Casado et al., 1989; Camargo and Garcia de Jalon, 1990) or general ecological studies (Muñoz, 1990). With respect to the Ebro River the earliest studies of the thermal regime are those by Arrúe and Alberto (1986) and Alberto and Arrúe (1986), who studied the thermal regime of the entire Ebro River basin by using monthly water quality measurements. They found a linear relationship between mean annual water temperature and altitude and between water temperature and air temperature at Escatrón (Arrúe and Alberto, 1986). However, they also showed that some types of floods (mainly those caused by ice-melt) could induce water temperature decreases even at Escatrón, at more than 600 km from the source of the river (Arrúe and Alberto, 1986). They also studied some alterations of the thermal regime in different points of the Ebro River, including the alterations caused by the Mequinensa, Riba-roja and Flix reservoir system, and they observed an increasing trend of 0.08 °C/yr in the annual weighted mean of water temperature at Escatrón in the period 1955–1978 (Alberto and Arrúe, 1986). The weights were the relative discharges. The thermal pollution caused by the Ascó nuclear power plant in the summers of 1990 and 1997 were studied by DEHMA (1990) and Limnos (1997), respectively, showing an increase in water temperature of 2–4 °C. Negative effects on the fauna and flora of the river caused by this increase were not observed (Limnos, 1997; Ibàñez, 1998). Dolz et al. (1994) dealt with the effects of the Mequinensa, Riba-roja and Flix reservoir system on water temperature in the summer of 1990. An important decrease in water temperature, a decrease in daily water temperature range and a displacement of the phase of the daily water temperature pattern were observed at the exit of the system of reservoirs. Water temperature increased downstream of the reservoirs. But the first detailed study on the effect of the reservoirs of Mequinensa, Riba-roja and Flix with measurements all year round was Val's (2003) PhD thesis, which has provided part of the field data presented in this paper. Val (2003) studied the downstream effects of the reservoirs on water temperature in the years 1998–1999. The results he obtained in the annual time scale were presented by Prats et al. (2004a). They also described the effect of the nuclear power plant of Ascó in 1998–1999 and discussed the possible effects of the water temperature alterations on the fauna and flora of the river. The alterations of the daily water temperature patterns produced by the reservoirs in 1998–1999 were dealt with in Prats et al. (2004b) by analysing the processes that took place inside the system of reservoirs.

In this paper the thermal regime of the lower Ebro River is studied on different time scales, from hours to years, and the changes caused by anthropogenic factors, especially the Mequinensa, Riba-roja and Flix reservoir system and the thermal effluent of the Ascó nuclear power plant. The description of the daily and annual water temperature patterns downstream from the reservoirs has been extended to the period 1998–2003, so that the inter-annual variability can be taken into account. A more detailed analysis of the data of the years 1998–1999 obtained by Val (2003) has been made and the effect of each individual reservoir of the system has been dealt with separately. This paper also completes the work of Alberto and Arrúe (1986) on long-term water temperature trends by adding recent data to the annual water temperature series published by them and reanalysing the new data series. In consequence, a more accurate description of the thermal regime in the lower Ebro River has been made.

2. Study area

The Ebro River is located in north-eastern Spain and is one of the biggest rivers in this country, its length being 910 km. The study area comprises the lower part of the Ebro River (Fig. 1), from Escatrón to Miravet, at about 260 and 80 km from the mouth, respectively. At Escatrón, there is a thermal power station that uses water from the river (a concession of 9.1 m^3/s) for cooling. At the time of the realization of the study it used coal, although nowadays it burns natural gas. According to Limnos (1998), this plant had no appreciable effect on water temperature. In the mainstem of the Ebro River upstream from this point, there are no major reservoirs or power stations for 470 km. However, there are many weirs for irrigation and hydroelectric purposes.

Downstream from Escatrón there is a system of three reservoirs, Mequinensa ($1500 \times 10^6\ m^3$), Riba-roja ($210 \times 10^6\ m^3$) and Flix ($11 \times 10^6\ m^3$), that regulate the hydrologic regime of the lower part of the river until it reaches the sea. The Mequinensa and Riba-roja reservoirs were finished in the late 1960s (in 1966 and 1969, respectively), while the Flix reservoir was completed in 1945. The dams have overflow spillways, bottom outlets, hydroelectric intakes, and additional outlets at different depths. However, only hydroelectric intakes and overflow spillways (in case of great discharges) are normally used.

Downstream from Flix the river flows approximately from north to south and its width is of 50–200 m. The landscape crossed by the river consists mainly on agricultural land and some small urban areas. Some islands can be found in the river. The riparian vegetation is composed of tamarisk (*Tamarix* sp.), poplar (*Populus nigra*), white poplar (*Populus alba*) and willows (*Salix* sp.). There are also formations of giant-reed (*Arundo donax*), reed (*Phragmites australis*) and reedmace (*Typha* sp.). Riparian vegetation is limited to a stretch at each riverside, broken at some places (Limnos, 1998).

About 5 km downstream from the Flix reservoir is the Ascó nuclear power plant, which began its activity in December 1984. The two reactors of the power plant in total have a gross electrical power output of about 2050 MWe and a thermal reactor power of about 5800 MWt. A concession of 72.30 m^3/s Ebro River's water is granted to the power plant for cooling (minimum river flows in the area are around 100 m^3/s). In addition, the power plant also has two parallel sets of forced-draught cooling towers and a 160 m high natural-draught cooling tower. Legal limitations have been imposed on the allowed water temperature increase caused by the nuclear power plant. When river discharges go below a level such that the use of the open cooling system (taking river water to the condensers and returning it warmed to the river) would cause a water temperature increase higher than the allowed one, the cooling towers are put into service (www.anav.es). Warm water released from the nuclear power plant floats on the river's water, forming a thermal plume, until some kilometres downstream the mixing is complete and no lateral differences in water temperature can be detected (Limnos, 1997).

Table 1 shows the annual mean discharges for the period of study in several of the gauge stations in the study area. Mean annual discharge downstream from the reservoirs during the study period was 320 m^3/s, from which approximately a 30–40% came from the Segre and Cinca Rivers. Fig. 2 shows the distribution of mean monthly flows in the lower Ebro River before and after the construction of the reservoirs of Mequinensa and Riba-roja. While in the wetter months discharge was higher before the construction of reservoirs, in the driest months (July–September) discharge increased slightly after their construction. The cause for this is the need to maintain a minimum flow for the cooling of the nuclear plant and the irrigation channels in the Ebro Delta.