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The impact of droughts and water management on various hydrological systems in the headwaters of the Tagus River (central Spain)

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SUMMARY

The influence of climate variation on the availability of water resources was analyzed in the headwaters of the Tagus River basin using two drought indices, the standardized precipitation index (SPI) and the standardized precipitation evapotranspiration index (SPEI). This basin is highly regulated and strategic, and contains two hyperannual reservoirs that are the origin of the water supply system for Mediterranean areas of southeast Spain. The indices confirmed that drought conditions have prevailed in the headwaters of the Tagus River since the 1970s. The responses in river discharge and reservoir storage were slightly higher when based on the SPEI rather than the SPI, which indicates that although precipitation had a major role in explaining temporal variability in the analyzed parameters, the influence of temperature was not negligible. Moreover, the greatest response in hydrological variables was evident over longer timescales of the climatic drought indices. Although the effect of climate variability on water resources was substantial during the analyzed period, we also showed a major change in hydrological–climatic relationships in regulated systems including reservoir storage and outflow. These were closely related to changes in external demand following commencement of the water transfer system to the Júcar and Segura basins after the 1980s. The marked reduction in water availability in the basin, which is related to more frequent droughts, contrasts with the amount of water transferred, which shows a clear upward trend associated with increasing water demand in the Mediterranean basin.

Introduction

An effect of global change on environmental conditions in the western Mediterranean region is increasing uncertainty in water resource availability (García-Ruiz et al., submitted for publication). The projections of climate models are for a general decrease in precipitation and increasing temperatures in the region (Giorgi and Lionello, 2008), which may markedly reduce river flows (*e.g.*, Kilsby et al., 2007). Nevertheless, there are various sources of uncertainty in climate change simulations (Raisanen, 2007), and difficulties are associated with establishment of direct relationships between climate variability and water resources, as a consequence of the substantial influence of land cover (Llorens et al., 1995; Beguería et al., 2003; García-Ruiz et al., 2008) and water management strategies (López-Moreno et al., 2007) on the response of river flows to climate variability. Analysis of the temporal evolution of water resources in the Mediterranean area is complex, given the large natural climate variability of the region (Vicente-Serrano and Cuadrat-Prats, 2007; Lopez-Bustins et al., 2008; De Luis et al., 2009), land cover changes in headwaters (Vicente-Serrano et al., 2004; Lasanta et al., 2005; MacDonald et al., 2000; Sluiter and De Jong, 2007), and the intense water regulation necessary to meet high urban and agricultural demand (Batalla et al., 2004; López-Moreno et al., 2009). To understand the possible consequences of climate change processes on the future availability of water resources in the region, it is necessary to determine the current relationship between climate variability and water resources, taking account of different hydrological subsystems (*e.g.*, river discharge, reservoir storage) and the major role of dam and canal operations in the regulation of river flows.

In the western Mediterranean region the availability of water resources is critical during certain periods. River flows show strong seasonality characterized by low natural flow in summer; management of reservoirs is thus focused on meeting urban and irrigation demands during this season (Maneux et al., 2001; Snoussi et al., 2002). The high frequency of droughts in the area makes it necessary to improve management strategies during dry periods. To this

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end it is important to determine the empirical relationship between climatic and hydrological droughts, which will enable accurate assessment of the possible impact of environmental change processes.

Isolating the influence of climate is difficult because the response of hydrological systems to precipitation can vary markedly as a function of time (Changnon and Easterling, 1989; Elfatih et al., 1999; Pandey and Ramasastri, 2001), as a result of temporal differences in the frequencies of hydrological and climatic variables (Skøien et al., 2003). In a study in the central Spanish Pyrenees, Vicente-Serrano and López-Moreno (2005) showed very different timescale responses to precipitation accumulation between river discharge (short timescale) and reservoir storage (long timescale). A similar pattern was found by Szalai and colleagues (2000) in Hungary. In Greece, Vasiliades and Loukas (2009) reported different response times for soil moisture and river discharge to two Palmer drought indices, with variations in soil moisture occurring at higher frequency than river discharge. This was more marked for groundwater level, which responds to precipitation only following long-term accumulation (Khan et al., 2008). Thus, the effect of climatic droughts on groundwater shows distinct temporal inertia (Peters et al., 2005).

Reservoir regulation and water transfer disrupt climate–hydrology relationships, sometimes dramatically, making it difficult to determine the role of precipitation variability on availability of water resources. In addition, several studies have shown that recent temperature increases (Jones and Moberg, 2003) are having a negative effect on the availability of water resources, as a consequence of water losses caused by evapotranspiration (Nicholls, 2004; Cai and Cowan, 2008; Gerten et al., 2008). To date, no studies have analyzed this issue in the western Mediterranean region.

Few empirical analyses have related hydrological records to climate indices, or tested the usefulness of various drought indices for monitoring water resources in different systems. The main objective of this study was to determine the relationship between two different multi-scalar drought indices (the standardized precipitation index, SPI; and the standardized precipitation evapotranspiration index, SPEI) and three hydrological variables (river discharge, reservoir storage, and reservoir release) in the headwaters of the Tagus River. This is a highly regulated and strategic basin that has two hyperannual reservoirs (*i.e.*, where the storage capacity exceeds the annual discharge from a regulated river) that are the origin of a water transfer system supplying the Mediterranean areas of southeast Spain. Additional objectives of the study were: (i) to identify the best drought index and timescale for monitoring water resources in the different subsystems, and, (ii) to assess the influence of water management and warming processes on temporal changes in climate–hydrological relationships.

Study area

Water resources are intensively regulated in the *Alto Tajo* region, which comprises the headwaters of the Tagus River, between the Iberian Range and the Plateau of Castille. The river basin is in a mountainous area ranging in altitude from 600 m at the Bolarque reservoir to 1935 m at the eastern extremity of the basin, and has a surface area of 7417 km^2. The relief is dominated by moorlands, the main structural unit, which descend gradually over a limestone base from the foot of the Orihuela and Albarracín ranges. Below 1000 m a marl substrate is evident, and the valley opens up and provides a suitable area for the retention of water.

The spatial distribution of precipitation follows a topographic pattern. Mean annual precipitation decreases from 1000 mm in the Albarracín Range (east) to about 500 mm in low-altitude areas. Precipitation is strongly seasonal, with a peak in May and another in November; the area is also subject to the low summer rainfall typical of the Mediterranean region. Temperatures are characterized by extremes and oscillations given the continental nature of the climate. The maximum daily oscillation, 29.4 °C, was recorded in 1981. The mean annual temperature is less than 10 °C for most of the basin, but during winter the average temperature drops to 1–3 °C, making it one of the coldest regions on the Iberian Peninsula. In the hottest month (July) the average temperature is 21.9 °C.

The area has a dense hydrological network divided into two main components, the Tagus and Guadiela Rivers, whose waters are collected and regulated downstream (Fig. 1). The water is controlled to supply various water uses in the region, and to transfer water to the Mediterranean coastlands. The basin has two large reservoirs, the Entrepeñas and Buendía dams. The Entrepeñas has a capacity of 802 Hm^3 and the wall height of the dam is 87 m; it was built in 1956 to collect the waters of the Tagus River. The Buendía dam stores the waters of the Guadiela, Mayor, and Guadamejud Rivers. The dam was built in 1957, the wall height of the dam is 78 m, and has a maximum storage capacity of 1638 Hm^3. Both reservoirs act as a single storage unit, as they are connected by a tunnel. The Bolarque dam is located downstream of the discharge of the two main dams, at the convergence of the Tagus and Guadiela Rivers. The dam was built in 1910, but underwent several modifications that were not finalized until 1951. The main function of the dam is distribution of the water collected upstream in the Entrepeñas and Buendía dams; some is sent to the Tajo-Segura water transfer and the Bolarque-Jarama irrigation supply systems, and the remainder flows a few kilometers down the main stream of the Tagus River to the Zorita reservoir, which was built in 1947 for hydroelectric production.

Two principal land cover types exist in the study area: above 1000 m the predominant land cover are the forests, composed mainly by conifers, which occupy 42.5% of the study area. Dry-farmed cropland covers 43.9% of the surface, mainly in the flat areas. Other important land cover types in the study area are thicket (9.9%) and grasslands (2.3%). Irrigated lands, urban areas and agro-forestry occupy percentages lower than 1% of the study area.

The area is highly strategic in terms of water resources, as it provides water to the Tajo-Segura Transfer. The diversion of water to the Mediterranean region involves political decisions at a national level, and has been the focus of territorial conflicts, especially during drought periods (Garrote et al., 2007).

Dataset and methodology

Climate data

Data on monthly precipitation, and maximum and minimum temperatures between 1961 and 2006 were provided by the Spanish Meteorological Agency (AEMET). This consisted of 64 monthly temperature series and 147 monthly precipitation series within the study area and neighboring zones. The availability and quality of the series were variable; both precipitation and temperature series contained numerous discontinuities, and long continuous series were very rare. Therefore, for further analysis we selected only those series with <10% gaps (nine precipitation series and three temperature series; see Fig. 1). Gaps were filled using multiple linear regressions.

Among the different existing techniques to detect and adjust the temporal non-homogeneities of climate series, (see reviews in Peterson et al., 1998; Beaulieu et al., 2007), we have used the standard normal homogeneity test (SNHT; Alexandersson, 1986), which is widely used to homogenize temperature and precipitation series in different regions (*e.g.*, Alexanderson and Moberg, 1997; Begert and Schlegel, 2005). Following Peterson and Easterling