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Hydrological response to climate variability at different time scales: A study in the Ebro basin

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SUMMARY

In this study we analyzed the response of monthly runoff to precedent climatic conditions at temporal scales of 1–48 months in 88 catchments of the Ebro basin (northeast Spain). The standardized precipitation evapotranspiration index (SPEI) was used to summarize the climatic conditions at different time scales, and was correlated with the standardized streamflow index (SSI) calculated at the mouth of each catchment. The Ebro basin encompasses a gradient from Atlantic to Mediterranean climates, and has remarkable complexity in topography, geology and land cover. The basin is highly regulated by dams, which were built to produce hydropower and supply water for agriculture. These characteristics explain why sub-basins of the Ebro River basin respond in differing ways to precedent climatic conditions. Three main sub-basin groups were distinguished on the basis of the correlation of their streamflow responses to different time scales of the SPEI: (1) sub-basins correlated with short SPEI time scales (2–4 months), which generally corresponded to unregulated headwater areas; (2) sub-basins correlated with long SPEI time scales (10–20 months), where groundwater reserves play a major hydrological role; and (3) sub-basins correlated with medium SPEI time scales (6–10 months). The latter occur in the lower sectors of the Ebro basin and its tributaries, which receive river flows from the other two sub-basins, and where dam regulation has a significant influence on the hydrological characteristics. In addition to the three main sub-basin groups, other streamflow responses associated with seasonal factors were identified, particularly those related to snowpack and the various management strategies applied to reservoirs.

1. Introduction

Streamflow is an integrated response to basin inputs (climate), water transfer, water losses by evapotranspiration storage processes, and the effects of human activities on natural water flows. Prior to reaching the stream network a large proportion of precipitation is stored in various hydrological subsystems (including snowpack, soil moisture, groundwater reserves, reservoir storages) that respond to climatic conditions at different time scales (Vicente-Serrano and López-Moreno, 2005; McGuire and McDonnell, 2006). The results of previous research have shown that the catchment response time to precedent climatic conditions is highly variable among regions, as it depends on of the physical attributes of the catchments (geology, topography, soils and vegetation), climatic conditions (evapotranspiration rates, snow cover, rainfall intensity) and dam operations (Post and Jakeman, 1996; Soulsby et al., 2006; Lorenzo-Lacruz et al., 2010; McDonnell et al., 2010; Fleig et al., 2011). The hydrological response to climate has also been shown to be seasonally dependent because the relative effects of different water sources, climatic conditions, hydrological processes and water management vary throughout the water year (Tallaksen, 1995; García-Ruiz et al., 2008). For instance, in the Pyrenees it has been found that a 42% of the spring runoff are explained by the climatic conditions that occurred during winter (López-Moreno and García-Ruiz, 2004). It has also been demonstrated that water released downstream of dams largely depend on the storage levels required at various times of the year. For example, the amount of water released during autumn from reservoirs built to supply water for agriculture during the dry season (late spring and summer) depends on the amount of water remaining at the end of the irrigation period (late September), while the releases in winter depend on the magnitude of inflows during autumn. In such cases the downstream flows show a much more marked response to climate at long time scales than at shorter ones (García-Ruiz et al., 2011). The maintenance of ecological flows during summer explains why no correlations are found between climatic conditions and river flows in most regulated rivers (i.e. López-Moreno et al., 2004). Other sources of seasonal variability

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are associated with the different characteristics of the recession curves during the year. Thus, Tallaksen (1995) found that steeper recession curves are generally typical of the summer period, especially in areas with shallow groundwater tables and extensive vegetation. This has been confirmed in small catchments in mountainous areas, where Hortonian flows dominate the runoff generation processes during summer and early autumn, in contrast with the remainder of the year when most of the surface runoff results from saturation excess processes and lateral runoff (García-Ruiz et al., 2008; Latron and Gallart, 2008).

The spatial and seasonal variability in the patterns of water storage and residence time make it difficult to identify scale-invariant climatic controls on runoff generation (Beven, 2002). For this reason it is important to analyze the response of river flows to climate at various time scales. Advances in this field are necessary to improve the assessment and short-term forecasting of water resource availability, to better understand how river flows have reacted to past climatic trends and predict their response to various climate change scenarios.

The main objective of this study was to analyze the response of monthly runoff to precedent climatic conditions at various temporal scales (1–48 months). The study included 88 catchments of the Ebro basin (northeast Spain). For this purpose we used the standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano et al., 2010), which has been used to summarize climatic conditions at various time scales and has been shown to have the capacity to explain temporal fluctuations in hydrological series in differing environments (Lorenzo-Lacruz et al., 2010). We investigated the main explanatory time scales of the SPEI for different months and sub-basins, and assessed spatial variability in the climate–runoff relationships. This involved correlation of the SPEI (calculated for 1–48 months) with monthly anomalies of river flows, quantified using the standardized streamflow index (SSI; Vicente-Serrano et al., 2011). The correlations were conducted for continuous series from October 1950 to September 2007, but also separately for each month. The curves that relate the change in correlation coefficient with the various time scales of the SPEI were used to assess the response time of each sub-basin to antecedent climatic conditions. The shapes of these curves were objectively classified to discriminate areas with a common hydrological response time.

The study represents a novel approach to the analysis of the response time of river flow conditions to precedent climatic conditions at the basin scale. The Ebro basin is an excellent site for such a research. It encompasses a gradient from Atlantic to Mediterranean climatic conditions, and has remarkable complexity in topography, geology and land cover. The basin is highly regulated by dams that were built to produce hydropower and supply water for agriculture. In addition, the high density of gauging stations facilitates analysis of the hydrological response time to climate in undisturbed headwater areas, and aggregation of the effect of reservoir operations on the runoff response time in downstream sectors of the river.

2. Study area

The study area comprises approximately 83,000 km^2 in northeast Spain. The relief of the basin is very contrasted. The main unit is the Ebro valley, a depression through which the Ebro River runs. The valley is surrounded to the north and south by high mountain ranges that drain major tributaries (Fig. 1). The valley is enclosed to the north by the Cantabrian Range and the Pyrenees (maximum altitudes >2000 and 3000 m a.s.l., respectively) and to the south by the Iberian Mountains (maximum altitude 2000–2300 m a.s.l.), while to the east and parallel to the Mediterranean coast the valley is sharply enclosed by the Coastal Range (maximum altitude 1000–1200 m a.s.l.).

The heterogeneous topography, contrasting influences of Atlantic and Mediterranean conditions, and the influence of various large scale atmospheric patterns (Vicente-Serrano and López-Moreno, 2005) generate an irregular distribution of climate parameters and variability in precipitation and temperature throughout the region (Ninyerola et al., 2007). Thus, long-term mean annual precipitation varies from 307 to 2451 mm yr^{-1} between different sub-regions of the basin. The center of the Ebro basin is the driest sector, whereas the most humid areas are found in the Pyrenees and in the Atlantic headwaters (West of the Ebro basin). Autumn and spring receives most of precipitation (García-Ruiz et al., 2001. The summer is relatively dry (with occasional rainstorms), as is the winter, when extended periods of anticyclonic conditions occur. However, in the westernmost part of the study area the winters are more humid because of continuous exposure to the passage of Atlantic fronts. The long-term average annual temperature varies from 0.8 to 16.2 °C. Elevation in the basin explains most of the spatial differences in temperature.

The contrasting topography and climatic characteristics within the basin explain the high variability of the river regimes among different sub-basins. Fig. 2 shows marked differences in the long-term (1950–2005) monthly runoff measured at six gauging stations located in different parts of the study area. This shows that in general high flows are recorded in winter or spring, whilst summer produces the lowest discharges. Peak flows in spring are recorded mainly in the Jaca and Collegats rivers (Pyrenees), whereas maximum flows in winter are observed in those areas where snow plays a minor role (Daroca) or the climate is dominated by Atlantic influences (the Ebro River in Miranda de Ebro). Downstream sectors of the Ebro basin (Zaragoza and Tortosa) also have maximum river flows during winter, but they maintain substantial discharge during spring as a consequence of the contribution of Pyrenean tributaries and water stored in large reservoirs. Summer flows are relatively high in areas of Atlantic climate (i.e. the Ebro River in Miranda de Ebro) or in the basins where groundwater makes a significant contribution to total runoff, as occurs in the Jiloca River in Daroca.

The humid conditions of the mountainous areas, especially the Pyrenees, are in stark contrast to the dry characteristics of large areas of the Ebro River valley, emphasizing the importance of mountains in the hydrology and water resources of the entire basin (López-Moreno et al., 2011). The relative abundance of water in the area led to the construction of numerous dams to regulate the main rivers, and this has caused major alterations to river regimes and reduced flood occurrences (López-Moreno et al., 2004).

3. Data and methods

The present study involved calculation of Pearsońs coefficients between long-term monthly river discharge series in different catchments of the Ebro basin with an index that represented the climate variability of each drainage area, determined at various time scales. Climatic data was provided by the Spanish Meteorological Agency (AEMET). Monthly series of precipitation (429) and temperature (55) were used. Observatories are located within the Ebro basin or in its immediate surroundings. The climate series were obtained from an original dataset of 1583 observatories through a process that included reconstruction, gap filling (only series with a maximum of 5% of missing data; they were filled using linear regression with neighboring stations which exhibited a correlation $r > 0.9$), quality control and homogenization testing with independent reference series (see Gonzalez-Hidalgo et al., 2009; Kenawy et al., in press). River flow evolution was analyzed at 88 gauging stations managed by the Ebro River Hydrographic Administration (Confederación Hidrográfica del Ebro, CHE). As for