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Dam effects on droughts magnitude and duration in a transboundary basin: The Lower River Tagus, Spain and Portugal

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[1] This study examines the effects of a large dam on hydrological droughts in the transboundary Tagus River, central Spain and Portugal. The magnitude and duration of droughts are analyzed by comparing a monthly drought index calculated for the flow series upstream and downstream of the Alcántara reservoir. The dam was built in 1969, and the reservoir is the second largest in Europe (3,162 hm^3). Water management in the area is complex because of large seasonal and interannual variability in the flow regime, which is characteristic of Mediterranean environments. This paper demonstrates that, as a result of exploitation of the Alcántara reservoir, (1) during periods of water scarcity, the releases in winter and spring are reduced dramatically and the magnitude and duration of summer low flow show a slight increase and (2) the nature of droughts along the Tagus river basin downstream of the dam has shown severe changes since construction of the dam. In fact, during the predam period (1943–1969), droughts were longer and more intense in the Spanish part of the basin than that in the Portuguese part. Since the construction of the Alcántara dam, however, the Portuguese part of the basin has experienced more severe droughts than did the upstream part in terms of both magnitude and duration.

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1. Introduction

[2] Reservoirs are key infrastructures for various water supplies and hydropower generation. The role of reservoirs is particularly relevant in regions that experience seasonal water scarcity, such as those under a Mediterranean climate, where flow regimes are characterized by marked seasonality, high interannual variability, and periodic floods and droughts. Moreover, reservoirs may also be used to control the river flow during extreme periods such as floods and droughts. During droughts, some of the stored water is released to maintain ecological flow, as well as meet basic water requirements; however, there commonly exists an operational conflict between the main purpose of the reservoir (irrigation, water supply, or hydropower production) and its function in hazard mitigation or environmental regulation. The main purpose of the reservoir is commonly given priority over other considerations, and the nature of the downstream effects of reservoir operation is often debatable from an integrated water management viewpoint [*McCully*, 2001; *López-Moreno et al.*, 2004].

[3] Recent decades have seen the emergence of a clear scientific interest in reservoir management practices and their impacts. Other issues have received little attention, including the role of reservoir management during periods of drought. Drought is a major hydroclimatic hazard that leads to numerous economic, environmental, social, and even political problems. Hence drought management should be a key issue in risk-based decision processes as part of reservoir operation [*Huang and Chou*, 2008]. Droughts are a highly complex phenomena that commonly start with long periods of low precipitation, resulting in water scarcity that progressively propagates throughout the hydrological system, affecting the soil moisture content, groundwater storage, river discharge, and reservoir storage [*Changnon and Easterling*, 1989]. Among the different components of droughts (climatic, environmental, agricultural, etc.), the hydrological component is the most important given the high dependence of many activities (e.g., agriculture, industry, hydropower generation, and urban supply) on surface water resources. In the case of regulated rivers within transboundary basins, water management during drought events becomes a complex issue in which national legislation and international conventions must be observed.

[4] The present study considers the case of the Tagus, a transboundary river shared by Spain and Portugal. More specifically, the study focuses on the influence of the Alcántara reservoir on the downstream hydrological droughts. Hydrological droughts are referred here to those events affecting flow discharge, so they are not strictly

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climatic droughts but river droughts. The magnitude and duration of droughts are analyzed by comparing a monthly drought index calculated for the flow series upstream and downstream of the dam. The reservoir, built in 1969, is located about 10 km from the border between the two countries. Being the second largest reservoir in Europe, it determines to a great extent the discharge of the Tagus River in the Portuguese sector of the basin.

2. Study Area

[5] The Tagus River, located in the center of the Iberian Peninsula, flows from east to west for 1009 km, draining an area of 80,100 km^2 (Figure 1). About 73% of its length and 69% of its catchment area are in Spain, with 27% and 31% in Portugal, respectively. The river is one of the main surface water bodies in the Iberian Peninsula: about 15% of the Spanish population and 30% of the Portuguese population live within the river basin.

[6] The climate of the basin varies from Mediterranean with strong continental influences in eastern areas to Atlantic conditions in western areas, particularly in the Portuguese part of the basin. The average annual precipitation varies significantly along the basin, ranging from 450 mm in the middle reaches to 870 in the Portuguese part of the basin to 1500 in the Central Ranges in Spain. The upper zones of the tributaries that emerge from the northern and westernmost sectors of the basin (i.e., from the Central Ranges in Spain) contribute more than 1500 mm of rainfall per year. The Portuguese tributaries contribute a significant amount of water to the river; they have a relatively regular seasonal regime due to the Atlantic influence, and tend to show noticeable peak flows in winter. Some of these tributaries are regulated by dams constructed for hydropower generation.

[7] The Tagus River provides water for urban supply (e.g., Madrid and Lisbon), the irrigation of large agricultural areas (230.000 ha), and industrial uses (e.g., cooling of nuclear and thermal plants). There is also a large fishery in the Tagus estuary and adjacent coastal sectors, and this industry is dependent on the level of freshwater flow. Interbasin water transfer between the Tagus and Segura rivers in the upper reaches of the Tagus is undertaken to solve the problem of the near-chronic water deficit experienced in coastal areas of the Spanish Mediterranean. Since construction of the interbasin channel in 1979, the annual discharge of the Tagus has been generally below the historical average, and water transfer has only been able to supply about 40% of the planned volume of 600 hm^3 a^{-1} [*Morales et al.*, 2005]. The process of determining the amount of water available for transfer during dry years causes severe social and political conflicts in Spain. The transboundary nature of the Tagus Basin also leads to difficulties in management of the flow, mainly during large floods and drought periods [*Azevedo et al.*, 2004].

[8] The Alcántara reservoir, located close to the border between Spain and Portugal, has a gross storage capacity of 3,162 hm^3, being the second largest reservoir in Europe. The long-term average runoff (1943–2003) is 6850 hm^3. The temporal series shows a downtrend evolution, mainly associated to afforestation in headwater areas, and aggravated by the Tagus Segura Water transfer [*Gallart and Llorens*, 2002]. Thus the mean runoff has decreased from 7,515 hm^3 a^{-1} during the predam period (1943–1969) to 6208 hm^3 a^{-1} for the postdam period (1970–2003). Tagus River in Alcántara shows a marked Atlantic regime, with a clear winter peak (November–February and low flows in summer (see inflows to the reservoir, Figure 4a). The dam, which is 135 m high, was built in 1969 for hydropower generation. Because of its large capacity (representing about 46% of the mean annual flow), the reservoir the reservoir has a large potential to modify the river regime downstream in Portugal, where the water is mostly used for agricultural purposes and industrial and domestic supply.

3. Methods

3.1. Database Preparation

[9] We analyzed various hydrological series obtained from the Spanish Tagus Water Authorities (*Confederación Hidrográfica del Tajo*) and the Portuguese Water Institute (*Instituto da Água*). The Spanish record consisted of monthly series recorded at the Alcántara gauging station (see Figure 1), which began to operate in 1915. Gaps in the series, which affect less than 5% of the data since 1940, were filled by regression analysis using a regional series created from available gauging stations in the upstream sector of the Tagus River. The regional series was developed in three steps [*Beguería et al.*, 2003]: (1) normalization of the original monthly series by subtracting the long-term mean and dividing by the long-term standard deviation; (2) calculation of the regional monthly averages; (3) normalization of the averaged time series.

[10] The record from the Alcántara gauging station was used until 1969, when the Alcántara reservoir was first exploited. Given that the Alcántara gauging station is located 1 km downstream of the Alcántara dam, it no longer reflects the natural hydrological regime of the Tagus River. For the period after 1969, the natural monthly inflow series was derived from the mass balance between the measured discharge from the dam and the amount of water stored in the reservoir. This approach has been used to reconstruct reservoir inflow data in other studies conducted in the Iberian Peninsula, yielding high-quality monthly data [*López-Moreno et al.*, 2004]. This approach is the most suitable for the Alcántara reservoir because the nearest present-day gauging station is located 150 km upstream (Valdecañas) along a section of river with much lower discharge than that at Alcántara (the section of the Tagus River at Valdecañas has two important tributaries, the Alagón (from the north) and the Almonte (from the south), which since 1969 have flowed directly into the Alcántara reservoir.

[11] For the Portuguese sector, we used the longest time series available (1943–1992): that recorded at the Santarém gauging station (see Figure 1). To extend the monthly flow records until 2003, we used data from the gauging station at Almourol, located 25 km downstream from Santarém. The ratio between annual discharge in Santarem and Almourol is 0.96. The flow series recorded at Almourol consists of a continuous record from 1973 until the present. The two gauging stations have a common recording period of 19 years, thus enabling the calculation of a relationship based on linear regression between monthly flows. This relationship proved to be extremely strong for all months of the year, with values of the correlation coefficient (Pear-

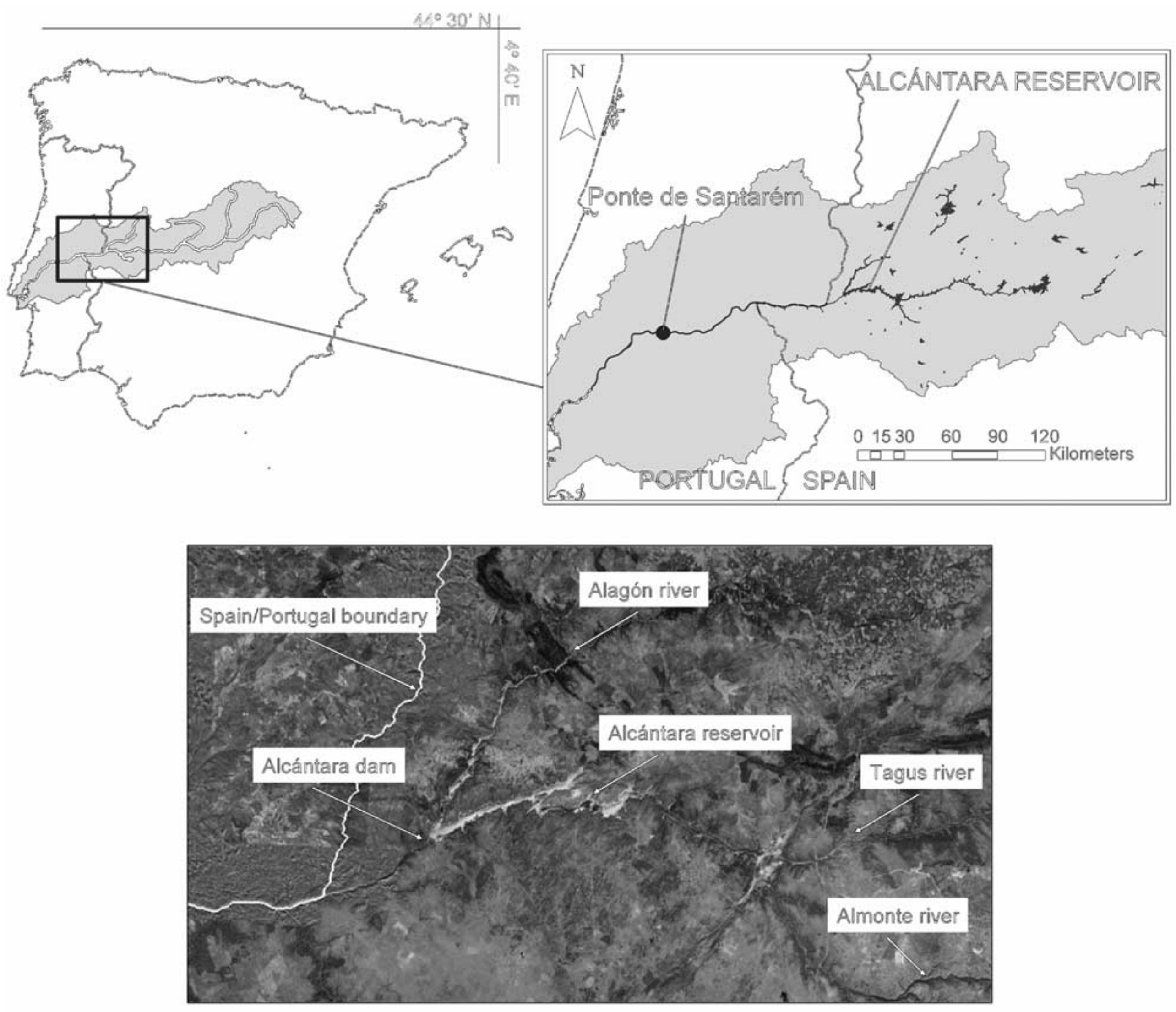

Figure 1. Location map of the Tagus River and Alcántara reservoir. The shaded area shows the extent of the Tagus river basin.

son's *r*) always higher than 0.96. On the basis of this relationship, we reconstructed the series of monthly discharge at Santarém gauging station until 2003 based on the record from Almourol gauging station.

[12] Tributaries located between the Alcántara dam and the Santarém gauging station contribute an average of $\approx$3000 hm^3 a^{-1} to the discharge of the Tagus River. This contribution results in an increase in the total annual flow volume from 6850 hm^3 at Alcántara to 9755 hm^3 at Santarém. To understand the possible contribution of the tributaries and (in the absence of reliable discharge data) to discriminate the influence of the Alcántara reservoir on the Tagus discharge at Santarém from that of the tributaries, we generated a synthetic time series of the contribution of the tributaries based on the difference between the discharge series recorded in Santarem minus the discharge recorded at the foot of the Alcántara dam.

3.2. Calculation of Drought Index

[13] There are several approaches available in studying hydrological droughts based on daily hydrological records [*Fleig et al.*, 2006]. A common procedure is to identify drought periods via a constant discharge threshold [*Tallaksen et al.*, 1997; *Fleig et al.*, 2006]. This enables the identification of low-discharge periods, when water scarcity presents a threat to water needs. This criterion does not take into account the seasonality of the discharge, a fact that usually leads to classify naturally low summer flows as low-flow periods. This is especially a problem under highly seasonal regimes, as with Mediterranean rivers.

[14] In the present paper, drought periods were identified according to the monthly discharge anomalies with respect to average conditions [*Dracup et al.*, 1980]. A drought index commonly used to analyze climatic droughts, the standardized precipitation index (SPI), was used to quantify the discharge anomalies. The advantages of the SPI are its theoretical basis, robustness, and versatility in drought analysis. SPI values are comparable in both time and space, and is not affected by geographical or topographical differences. The SPI allows determining the duration, magnitude and intensity of droughts. This index was developed by *McKee et al.* [1993] to identify nonnormal dry and humid periods based on precipitation records. Although the SPI has been widely applied to precipitation records in different

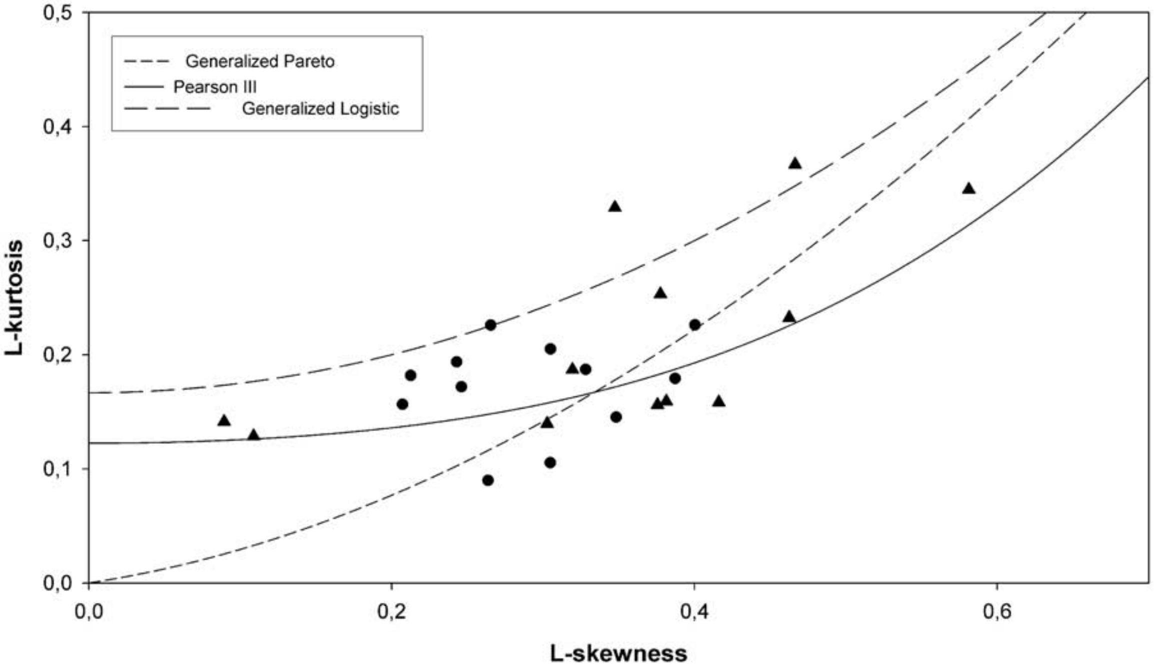

Figure 2. L- moment ratios diagram, showing the empirical distribution of monthly discharge upstream (circles) and downstream (triangles) of the Alcántara reservoir. Also shown are candidate probability distributions (lognormal, solid line and long dashed line; Pearson III, short dashed line).

regions [e.g., *Bordi et al.*, 2004; *López-Moreno and Vicente-Serrano*, 2008], it has yet to be applied to river discharge data.

[15] For a given observation, the SPI is the number of standard deviations with respect to the long-term average of the whole series. Since hydrological series commonly do not follow a normal distribution, being highly biased, it is necessary to adjust the records to a different probability distribution. In considering discharge data, few studies have investigated the optimal probability distribution to ensure the correct standardization of the series. For data from northwest Europe, *Zaidman et al.* [2001] showed a relatively good adjustment of the discharge series to the lognormal distribution. For the present study, a comparison among several skewed probability distributions, based on the L moments ratios diagram [*Greenwood et al.*, 1979; *Sankarasubramanian and Srinivasan*, 1999] was performed. This plot enables a graphical comparison of the L coefficients of skewness and kurtosis of the data with that of a set of candidate probability distributions [*Hosking*, 1990, 1991]. Figure 2 shows the L moment ratios diagrams corresponding to the monthly discharge series upstream and downstream of the Alcántara reservoir. In general, the statistical values of the discharge series oscillate around the theoretical curve of the Pearson III distribution, which was therefore selected to calculate the hydrological drought index.

[16] The probability density function of a Pearson III distributed variable is written as

$$f(x) = \frac{1}{\alpha\Gamma(\beta)}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x-\gamma}{\alpha}\right)}$$

where α, β and γ are scale, shape, and origin parameters, respectively, for discharge values $x > 0$. $\Gamma(\beta)$ is the Gamma function of β. The parameters were estimated using the L moment method.

[17] The cumulative probability distribution function of x is given by

$$F(x) = \frac{1}{\alpha\Gamma(\beta)}\int_{\gamma}^{x}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x-\gamma}{\alpha}\right)}$$

[18] Once $F(x)$ has been calculated, it is normalized such that the mean is zero and the standard deviation is 1. This normalized variable is interchangeable with the SPI and is comparable with other SPI values over time and space. An SPI of zero indicates that the discharge corresponds to 50% of the accumulated probability according to the Pearson III distribution, which corresponds to the mean value.

[19] To transform $F(x)$ and obtain the SPI, the approach formulated by *Abramowitz and Stegun* [1965] is used

$$SPI = W - \frac{C_0 + C_1W + C_2W^2}{1 + d_1W + d_2W^2 + d_3W^3}$$

$$W = \sqrt{-2\ln(P)} \text{ for } P \leq 0.5$$

P is the probability of exceeding a determined D value, $P = 1 - F(x)$
If $P > 0.5$, P is replaced by $1 - P$ and the sign of the resultant SPI is switched.
The constants are: $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$.

[20] A most complete review about the SPI and detailed formulation of the SPI calculation according to the Pearson III distribution and the L moment method can be found in the work of *Vicente-Serrano* [2006b] and *López-Moreno and Vicente-Serrano* [2008].

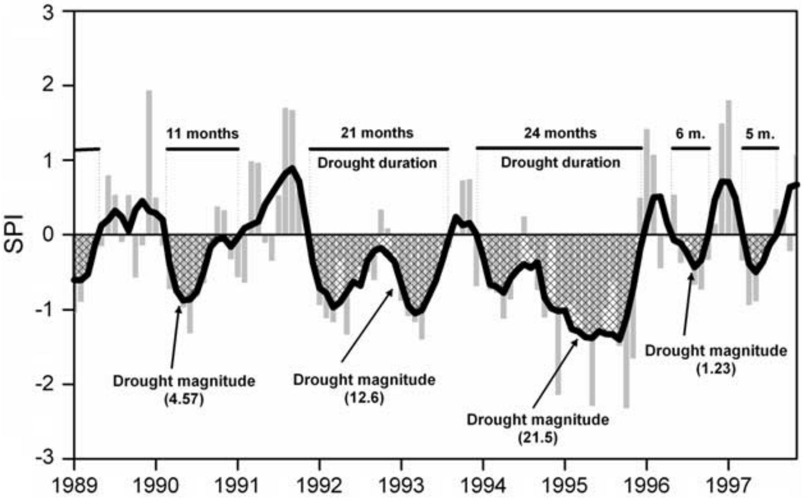

Figure 3. Example of the smoothing procedure employed for standardized precipitation index (SPI) series and calculation of drought magnitude and duration.

[21] SPI series were calculated for the upstream and downstream discharge series, and also for the series for Portuguese tributaries and release from the Alcántara reservoir (1970–2003). In addition, a precipitation-based drought index (SPI) at a time scale of 12 months was calculated from a regional series of precipitation using 13 precipitation stations (8 in Spain and 5 in Portugal), with the purpose of comparing the occurrence of hydrological and climatic droughts. SPI at 12 months is an appropriate time scale for analyzing hydrological implications of regulated river basin, as it usually shows the highest correlation values [*Vicente-Serrano and López-Moreno*, 2005].

3.3. Drought Event Analysis

[22] Drought events can be directly identified based on discharge series [*Tallaksen and van Lanen*, 2004] or drought indices [*Vicente-Serrano et al.*, 2004]. Although a standard criterion is lacking in identifying drought events, they are commonly defined as a sustained and regionally extensive occurrence of below-average water availability [*Tallaksen and van Lanen*, 2004]. Using hydrological and climatic time series, droughts are identified as periods during which the precipitation/discharge drought indices are below a certain threshold, following the theory of runs [see *Yevjevich*, 1967]. Several criteria are used in selecting a threshold. Although it would be optimum to fix a threshold with an economic, physical and/or ecological significance, in practice this is usually difficult because natural and social demands differ and vary in time and space. For this reason, statistical criteria based on percentiles [*Tarhule and Wo*, 1997; *Fleig et al.*, 2006], percentages of the mean [*Tallaksen et al.*, 1997], and probabilities [*Agnew*, 2000; *Vicente-Serrano et al.*, 2004] are commonly employed. Given the objective of the present study, an SPI value of zero was selected as a threshold to ensure a sufficient sample of events. Other commonly used criteria (5%, 10%, or 20% of accumulated probability) would reduce the sample size to such a degree to preclude reliable comparisons.

[23] In addition to threshold selection, two other problems must be solved to successfully identify drought events: the occurrence of minor droughts and mutually dependent droughts [*Fleig et al.*, 2006]: (1) minor droughts are events characterized by both: short duration and, at the same time, low magnitude; these are of little hydrological importance and may disturb the analysis; (2) mutually dependent drought events can occur when short periods with discharge above the threshold level divide a long period of low discharge into several drought events.. These smaller events cannot be considered mutually independent, and it is advisable to combine them into a single large event to capture the true severity of the drought. Various procedures have been proposed to combine mutually dependent droughts [*Tallaksen et al.*, 1997]; we chose the moving average procedure in which a low-pass filter of 5 months is applied to smooth the original drought index series. This procedure combines mutually dependent droughts into a single drought event; it also filters out the minor droughts, providing better results than other methods [*Fleig et al.*, 2006]. Obviously, the analysis of hydrological or ecological processes sensitive to short and frequent droughts cannot be conducted using filtered series.

[24] Figure 3 shows the smoothing procedure and the identification of drought events. It illustrates that a 5-month smoothing permits identifying all main drought spells, grouping-dependent periods of negative anomalies interrupted by very short and low positive anomalies (see years 1994 and 1995). Drought events were defined according to the zero SPI threshold from the filtered SPI series (upstream and downstream of the reservoir, Portuguese tributaries, and release from the Alcántara reservoir). Two main components from each drought event were chosen for further analysis [*Tarhule and Wo*, 1997]: (1) drought magnitude (accumulated deficit below a certain threshold, which is the sum of negative SPI anomalies belonging to the same drought event); (2) and drought duration (number of months or years below a certain threshold).

4. Results

4.1. Management Pattern at the Alcántara Reservoir

[25] Figure 4a shows the average monthly water storage in the Alcántara, as well as inflow and outflow since the

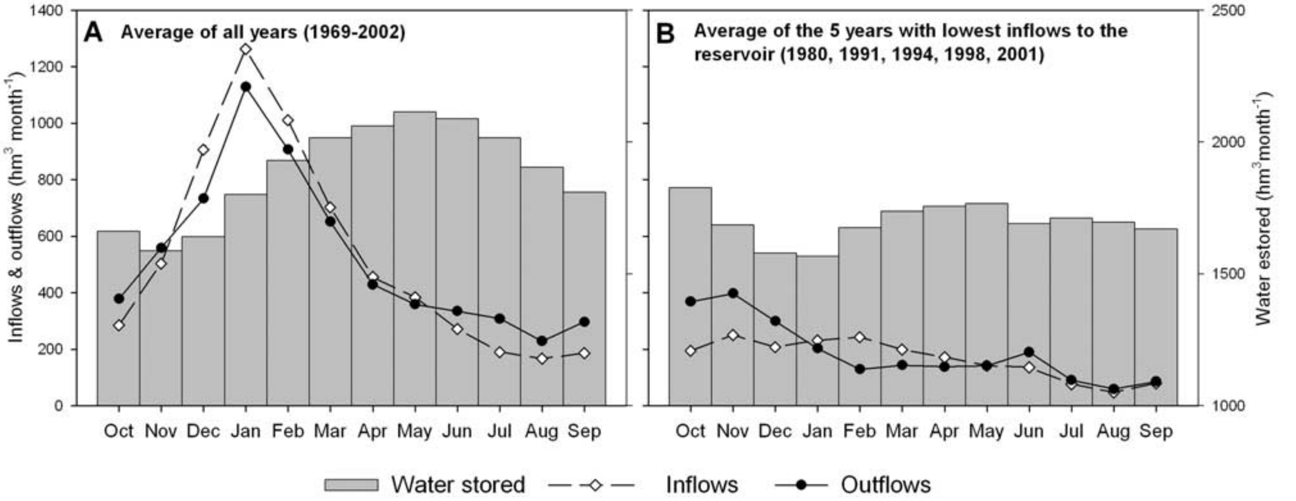

Figure 4. Mean inflow, outflow, and stored volume in the Alcántara reservoir. (a) All years. (b) Average of the 5 years with lowest inflows.

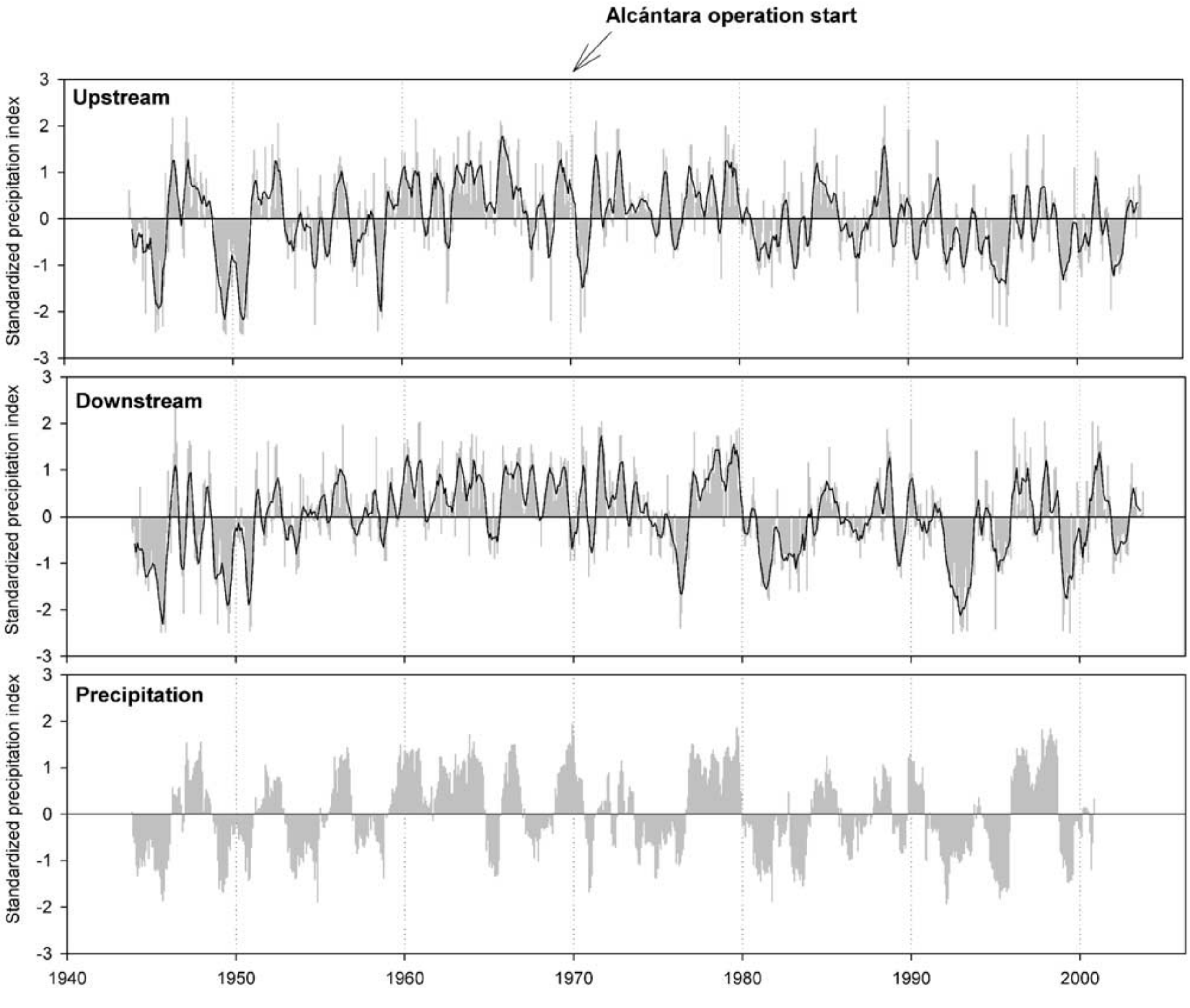

Figure 5. Time series of standardized precipitation index (SPI) for the Tagus River upstream of the Alcántara reservoir and at Santarém and regional precipitation SPI for the entire Tagus basin. Solid lines are the series after applying a low-pass filter of 5 months to smooth the original drought index series.

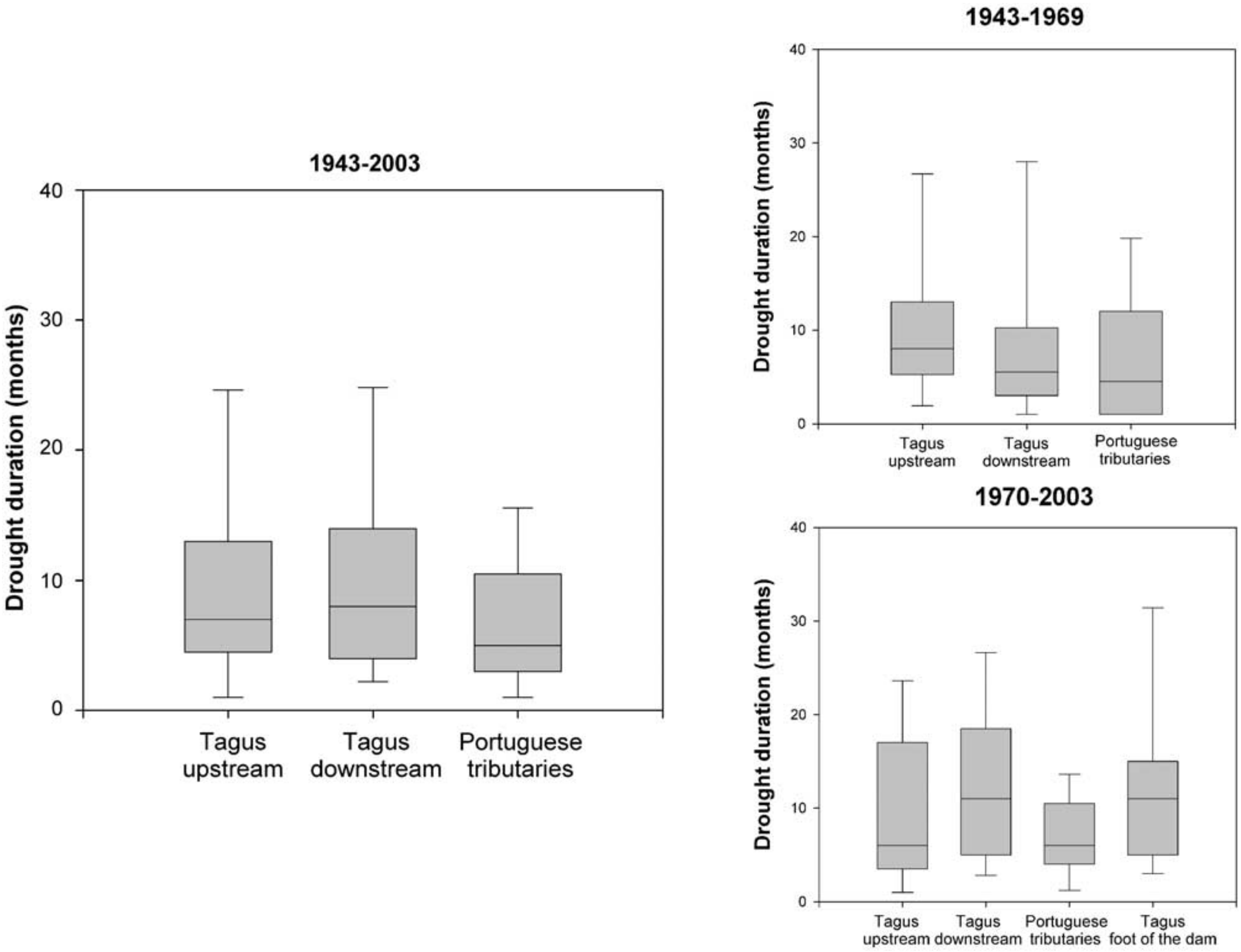

Figure 6. Boxplots of the duration of drought events upon the Tagus River at Alcántara reservoir (upstream), at Santarém gauging station (downstream), in the Portuguese tributaries, and at the foot of the Alcántara dam. The upper and lower parts of the boxes are the 75th and 25th percentiles, respectively; the whiskers indicate the 90th and 10th percentiles; and the lines within the boxes are the median values.

dam began operating in 1970. Figure 4b shows the same information for the 5 years with the lowest annual inflow to the reservoir.

[26] Under average conditions, the inflow curve exceeds the outflow curve from October to May, in particular from October until February. Filling of the reservoir is accomplished by storing the maximum annual flows of early winter, which also enables the maintenance of significant outflows downstream of the dam, as electricity demand results in high rates of release. From March onward, the differences between inflows and outflows are minimal, but enable the continued accumulation of water up to the maximum annual storage level (around 2100 hm^3) by the end of May. Outflow exceeds inflow during summer due to the release of water for the maintenance of the established ecological discharge, industrial and irrigation use, and urban supply in the Portuguese part of the basin. The minimum storage level (1662 hm^3) occurs in September. As a result of exploitation of the reservoir, the Portuguese section of the Tagus River still exhibits a seasonal pattern that resembles the natural pattern, although noticeably more smoothed, as a component of the winter peak flows is stored in the reservoir and summer low flows are enhanced downstream of the dam. This pattern may change markedly when hydrological conditions are far from average. Thus, during dry years (i.e., very low inflow and a complete lack of high flows during winter, Figure 4b), the water release during winter and early spring is reduced dramatically. This procedure enables the attainment of a maximum storage of close to 1700 hm^3 in May. This volume is maintained during summer by releasing water from the reservoir in similar volumes to that of inflow.

4.2. Downstream Effects on Magnitude and Duration of Hydrological Droughts

[27] Figure 5 shows the time series of the hydrological drought index (SPI) upstream and downstream of the dam, and the SPI of the regional precipitation series for the entire Tagus basin. Comparison of the hydrological series suggests that they are generally similar (r = 0.71) despite the runoff contribution of several important Portuguese tributaries. For both Spain and Portugal, the most severe droughts were recorded in the 1940s, 1980s, and 1990s; while the wettest were the 1960s and 1970s, with the 1950s showing an average behavior. There is generally a high correspondence

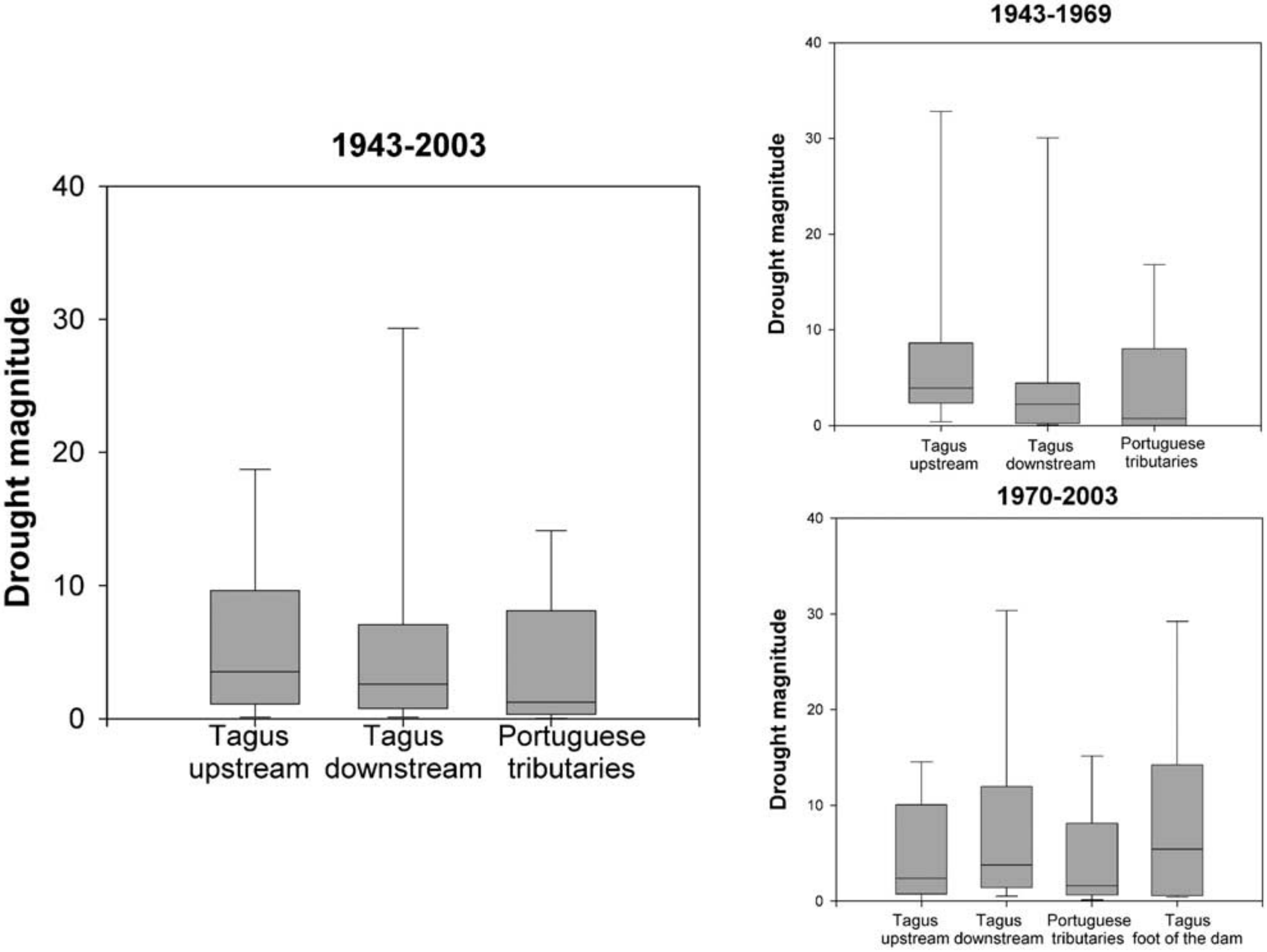

Figure 7. Boxplots of the magnitude of drought events (accumulated negative anomalies per event) recorded along the Tagus River, at Alcántara reservoir (upstream), at Santarem gauging station (downstream), in the Portuguese tributaries, and at the foot of the Alcántara dam. The upper and lower parts of the boxes are the 75th and 25th percentiles, respectively; the whiskers indicate the 90th and 10th percentiles; and the lines within the boxes are the median values.

between periods with anomalous precipitation and those with anomalous runoff. This finding indicates the modest role, in the middle and lower sectors of the Tagus river basin, of upstream regulation in the hydrological response to the climatic signal. Thus both runoff series show a rather linear response to precipitation across the entire basin (correlation coefficients r = 0.58 and r = 0.60 for upstream and downstream series, respectively). Similarities in the anomalies apparent in the two hydrological series are especially clear when we focus on drought occurrence, i.e., periods of negative anomalies at the Spanish and Portuguese sites show a clear match. Despite these similarities, differences are apparent in the length and magnitude of comparable drought periods.

[28] Moreover, Figure 5 shows that drought occurrence in the Tagus, as well as in the regional precipitation, does not show clear trends during the analyzed period. Thus the same number of drought events (13) has occurred during the predam and postdam periods. Highest drought duration and magnitude where found at the beginning and the end of the time series (1940–1950s and 1980–1990s decades).

4.3. Drought Duration and Magnitude Before and After Construction of the Alcántara Dam

[29] Figure 6 shows the duration of drought events recorded in the Tagus River upstream of Alcántara reservoir (“Tagus upstream”), downstream at the Santarém gauging station (“Tagus downstream”), the Portuguese tributaries (“Portuguese tributaries”), and immediately downstream of Alcántara dam (“foot of the dam”). When the period (1943–2003) is considered, the distribution, the distribution of drought duration upstream of the dam is similar to that observed downstream. In both cases the mean drought duration is close to 7 months and the 90th percentile is around 25 months. Droughts in the Portuguese tributaries have a lower duration than those in the main river. Figure 6 (right) shows clear differences in drought duration between the predam (1943–1969) and postdam (1970–2003) periods. The predam period is characterized by a longer duration of droughts upstream (mean duration, 8 months) than downstream (mean duration, 5.5 months), probably due to the shorter duration of droughts in the Portuguese tributaries (these tributaries have different flow regimes

Table 1. Number of Months With SPI Anomalies Within Different Ranges of Intensity Upstream and Downstream the Dam and Change (in Percentage) for the Predam (1943–1969) and the Postdam (1970–2003) Periods

	Predam Period (1943–1969)			Postdam Period (1970–2003)		
SPI Magnitude	Upstream	Downstream	Change (%)	Upstream	Downstream	Change (%)
$-0.5 < \mathrm{SPI} < -1$	44	40	−9.1	76	65	−14.5
$-1 < \mathrm{SPI} < -1.5$	12	22	83.3	36	35	−2.8
$-1.5 < \mathrm{SPI}\ -2$	12	7	−41.7	3	14	366.7
$\mathrm{SPI} < -2$	17	11	−35.3	6	11	83.3

from those in Spain because of their strongest Atlantic influences, a fact that mitigates the climatic influence on the flow regime). The opposite trend is observed for the period since the reservoir came into operation: droughts are noticeably longer downstream of the dam (mean duration in Santarem, 11.5 months) than upstream (mean duration at the inflow into the Alcántara reservoir, 6 months). In recent decades, droughts in the Portuguese tributaries have shortened in duration (mean duration, 6 months), probably due to river regulation, and they are clearly shorter than those recorded downstream (in Santarem). Since 1970 the duration of droughts has been markedly longer at the foot of the dam than upstream the reservoir, indicating that management of the Alcántara reservoir has led to an increase in the duration of droughts downstream. The effects of the dam are not compensated downstream by the evolution of the behavior of incoming Portuguese tributaries.

[30] Figure 7 shows similar data to that in Figure 6, although for the magnitude of drought events. As for the data on duration, the magnitudes of droughts for the entire period are similar in Spain (upstream) and in Portugal (downstream). Drought events within the Portuguese tributaries are generally of lower magnitude than those either upstream or downstream of the dam. During the predam period, the magnitude of upstream droughts clearly exceeds that of downstream droughts because of the smoothing role of the Portuguese tributaries. Nevertheless, the opposite trend is observed for the period after construction of the dam, with higher-magnitude droughts in downstream areas. The magnitude of droughts in the Portuguese tributaries has slightly decreased following construction of the dam. Exploitation of the reservoir emerges as the only possible explanation of the observed change in the pattern of upstream versus downstream drought magnitude. The fact that the magnitude of droughts is markedly higher at the foot of the dam than upstream of the dam (average values of 5.4 and 2.3, respectively) suggests that operation of the dam has served to accentuate the magnitude of droughts.

[31] Table 1 confirms that the Alcántara reservoir strongly influences the occurrence of drought in the lower section of the Tagus River. During the predam period, the downstream sector recorded a similar number of months with slight negative ($0.5 < \mathrm{SPI} < -1$) SPI values to the upstream sector (44/40 upstream/downstream, respectively), a higher occurrence of months with anomalies in the range $-0.5 < \mathrm{SPI} < -1$, and a lower occurrence of months with large negative anomalies ($\mathrm{SPI} < -1.5$). However, since the reservoir has come into operation, the number of months with large negative anomalies (3/14 for $-1.5 < \mathrm{SPI} < -2$ and 6/11 for $\mathrm{SPI} < 2$) is noticeably higher than in the Portuguese stretch of the Tagus.

[32] The above results are confirmed by the data in Table 2, which lists the statistics (duration, total magnitude, mean monthly magnitude, and maximum magnitude) of drought events upstream and downstream of the Alcántara dam, as well as the sign of change in upstream-downstream drought characteristics. The data show a marked shift in the upstream-downstream drought characteristics since the Alcántara reservoir was first exploited. During the predam period, droughts in the Portuguese sector of the Tagus River were shorter and less intense, whereas since 1970 they have become longer and more intense.

[33] Finally, Figure 8 shows examples (for four different periods) of how exploitation of the Alcántara reservoir can explain observed differences in the duration and magnitude of droughts upstream and downstream of the dam. Figures 8a and 8b show long periods with negative SPI values for the Tagus River; during both periods, the drought in the downstream stretch was more intense and longer than that in the upstream stretch. During these months, outflow from Alcántara was reduced to increase water storage in the reservoir. This strategy was applied even during months with pronounced negative SPI anomalies in the upstream sector of the river. Figure 8c shows a different situation, in which the magnitude of downstream droughts was controlled by increasing the outflow from the Alcántara reservoir, hence reducing the amount of water stored. During 1998–1999, under conditions of severe water scarcity in upstream areas, the exploitation practices of the Alcántara reservoir led to increased water storage, causing several peaks of high drought intensity in downstream areas (Figure 8d).

5. Discussion and Conclusions

[34] The main objective of the study was to characterize the role of dam operations on the magnitude and duration of hydrological droughts in the downstream sector of the Tagus river basin. The main conclusions are summarized as follows.

[35] 1. The standardized precipitation index, which has not been previously used for runoff series, appears as a promising tool for analyzing duration and magnitude of hydrological droughts.

[36] 2. Despite an apparent similar evolution of the hydrological series for areas upstream (Spain) and downstream (Portugal) of the Alcántara reservoir, noticeable

Table 2. Statistics of Drought Events Upstream and Downstream of the Alcántara Reservoir and the Relationship[a] Between Upstream and Downstream Events

		Upstream (Spain)				Downstream (Portugal)				Downstream-Upstream Relationship			
	Event	Duration (Days)	Magnitude	Mean Mag.	Maximum Mag.	Duration (Days)	Magnitude	Mean Mag.	Maximum Mag.	Duration (Days)	Magnitude	Mean Mag.	Maximum Mag.
Predam period (1943–1969)	1	26	22	0.85	1.93	25	2.9	0.12	2.3	×	–	–	+
	2	27	37	1.37	2.17	31	31	1.00	1.89	+	–	–	–
	3	11	4.14	0.38	0.68	14	4.98	0.36	0.8	+	+	×	+
	4	13	5.7	0.44	1.07	1	0.05	0.05	0.05	–	–	–	–
	5	7	3.6	0.51	0.81	3	0.25	0.08	0.03	–	–	–	–
	6	13	6.4	0.49	1.02	9	1.92	0.21	0.4	–	–	–	–
	7	9	9.4	1.04	1.99	5	2.2	0.44	0.65	–	–	–	–
	8	5	2.27	0.45	0.63	0				–	–	–	–
	9	0				9	3.68	0.41	0.53	+	+	+	+
	10	6	2.46	0.41	0.66	3	0.1	0.03	0.064	–	–	–	–
	11	6	3.08	0.51	0.83	0				–	–	–	–
	12	0				6	2.3	0.38	0.69	+	+	+	+
	13	11	9.8	0.89	1.49	6	2.6	0.43	0.77	–	–	–	–
	Average	10.3	9.6	0.7	1.2	8.6	4.7	0.3	0.7	1×, 4+, 8–	0×, 3+, 10–	1×, 2+, 10–	0×, 4+, 9–
Postdam period (1969–2003)	14	6	1.37	0.23	0.37	11	2.83	0.26	0.44	+	+	+	+
	15	9	3.54	0.39	0.67	16	12.41	0.78	1.67	+	+	+	+
	16	1	0.1	0.10	0.1	5	1.52	0.30	0.38	+	+	+	+
	17	37	19.39	0.52	1.02	41	30.55	0.75	1.56	+	+	+	+
	18	22	7.65	0.35	0.84	22	4.68	0.21	0.51	×	–	–	–
	19	6	2.37	0.40	0.6	9	5.87	0.65	1.05	+	+	+	+
	20	11	4.57	0.42	0.87	12	1.87	0.16	0.34	×	–	–	–
	21	21	12.6	0.60	1.04	24	32.7	1.36	2.12	+	+	+	+
	22	24	21.15	0.88	1.4	17	11.17	0.66	1.17	–	–	–	–
	23	6	1.22	0.20	0.42	0				–	–	–	–
	24	5	1.38	0.28	0.49	5	1.36	0.27	0.38	×	×	×	–
	25	25	15	0.60	1.31	21	18.4	0.88	1.74	–	+	+	+
	26	13	10.27	0.79	1.23	12	7.08	0.59	0.81	×	–	–	–
	Average	14.3	7.7	0.4	0.8	15.0	10.9	0.6	1.0	4×, 6+, 3–	1×, 7+, 5–	1×, 7+, 5–	0×, 7+, 6–

[a] ×, upstream ≈ downstream (±5%); +, downstream exceeds upstream; –, upstream exceeds downstream. Magnitude: accumulated SPI anomalies; mean mag., mean SPI magnitude; max. mag., magnitude of SPI (standard deviations from long.-term mean) for the month with lowest discharge during the drought event.

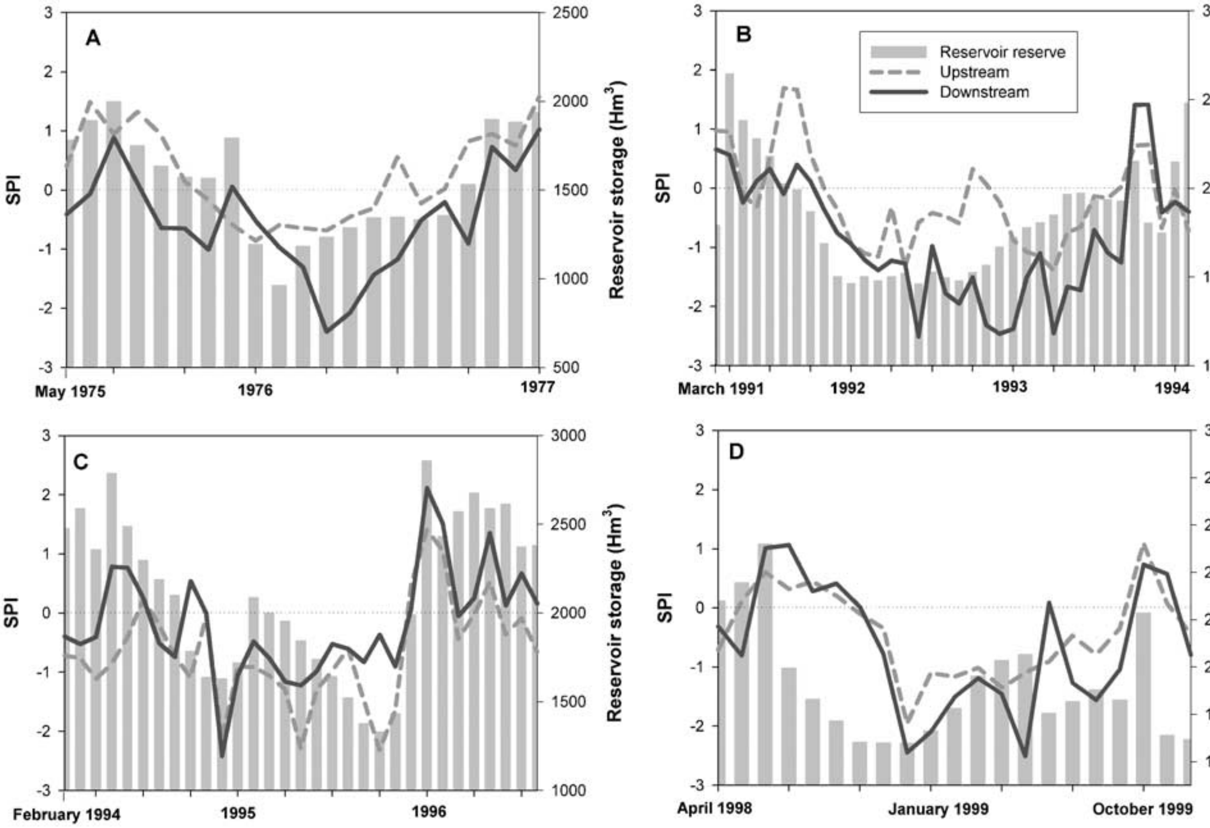

Figure 8. Evolution of the standardized upstream and downstream river flows (SPI) in relation to water storage levels in Alcántara reservoir for four selected drought events.

differences emerged as a consequence of the management of the Alcántara reservoir.

[37] 3. Under normal conditions, the Alcántara reservoir diminishes the natural seasonal variability of the Tagus River regime, reducing the winter high flows and leading to increased discharge during the dry summer season. As a result of reservoir exploitation, releases during winter and spring are severely reduced under periods of water scarcity, while summer low flows may exhibit a slight increase.

[38] 4. Characteristics of downstream droughts along the Tagus River have changed since the Alcántara dam was built in 1969. During the 1943–1969 period, droughts were longer and more intense in the upstream (Spanish) sector of the Tagus River than in the downstream sector (Santarem, Portugal). In contrast, from 1970 onward the Portuguese sector has experienced more severe droughts than the Spain sector, in terms of both drought duration and magnitude. These results demonstrate that the observed changes can be attributed to the management practices of the Alcántara reservoir as the evolution of Portuguese tributaries has reduced the length and magnitude of their droughts.

[39] The standardized precipitation index (SPI) had shown to be a useful indicator of climatic droughts [*McKee et al.*, 1993]. In this study, the application of SPI to hydrological analysis has demonstrated that it offers several advantages to more traditional techniques such as constant thresholds or percentage of cumulated probability. Main advantages of SPI are: (1) the possibility to compare river flow series of different magnitude; (2) the non influence of natural seasonal oscillations; (3) and the possibility to minimize the impact of minor and mutually dependent events [*Fleig et al.*, 2006] in analysis of drought magnitude and duration. Pearson III appears as the most suitable probability distribution function for the analyzed series. However, this finding cannot be generalized for all runoff series since it may change in basins subjected to different hydroclimatic conditions.

[40] The results achieved in this work highlight the capacity of dams to modify the hydrologic regime of highly regulated rivers. When water is abundant, the Alcántara reservoir is filled completely, with an accompanying release of water for hydropower generation or other uses in the Portuguese part of the basin. During such wet periods the water release from Alcántara may also contribute to an increase in downstream summer flows. A similar pattern of management has been reported at others reservoirs located in the Iberian Peninsula or Mediterranean climatic conditions (in Pyrenees [*López-Moreno et al.*, 2004]; the whole Ebro basin [*Batalla et al.*, 2004]; Sacramento River [*Bliss-Singer*, 2007]). Under drought conditions, the Alcántara reservoir is maintained at a minimum level, with a reduction in or even elimination of winter and spring high outflows, thereby amplifying the drought conditions downstream. Before construction of the dam, the Atlantic regime of the Portuguese tributaries appeared to reduce the duration and magnitude of downstream droughts compared with those in the Spanish part of the basin; however, management of the reservoir has led to a general increase in drought severity in the downstream sector.

[41] The present results indicate that exploitation of the Alcántara reservoir is responsible for the increase in drought severity. In fact, similarities in drought characteristics upstream of the dam during predam and postdam periods suggest that few of the observed changes when upstream-downstream series are compared can be ascribed to changing climatic conditions within the basin or upstream regulation. The role of the Alcántara reservoir in accentuating droughts is somehow compensated by the inflow of tributaries to the Tagus River between the Alcántara reservoir and the gauging station at Santarém, as the severity of droughts in these tributaries is noticeably lower than that in the Tagus River, especially in recent years. Probably, the reduction in drought severity may be related to increasing regulation of some tributaries (i.e., in the Zezere river, Portugal), as recent climatic evolution, included droughts, has not shown noticeable changes in this sector of the Iberian Peninsula [*Vicente-Serrano*, 2006a]. Droughts measured at the foot of the dam are markedly amplified compared with those resulting from incoming flows to the reservoir. In fact, the arrival of new tributaries to the main channel contributed to alleviating the pronounced changes induced by operation of the reservoir. It explains the slight reduction in drought severity observed in Santarem compared to the duration and magnitude of droughts recorded at the foot of the dam.

[42] The reduction in river flows that occurs during periods of water scarcity might affect several ecological and economical aspects of the lowest sector of the Tagus River. Previous studies have reported a deterioration in the composition and integrity of riparian vegetation in Portugal over the period since the Tagus River became strongly regulated [e.g., *Aguiar and Ferreira*, 2005]. Moreover, a previous study found that river discharge has a strong impact on estuarine and coastal fisheries [*Loneragan and Bunn*, 1999]. *Costa et al.* [2007] found that the relationship between fish species abundance and river flow in the Tagus River differs among species, but that in general fish density shows marked differences between dry and wet years.

[43] Problems arising from management of the Alcántara reservoir are critical because of their transboundary context, and management of the reservoir, in particular during flood crises, has already received criticism [*Azevedo et al.*, 2004]. Since February 2000, the management of international waters shared by Portugal and Spain has been regulated by a new bilateral agreement termed the "Albufeira Convention." For the Tagus River and others shared between the two nations, the convention establishes minimum flows and the necessity of communication during exceptional floods or drought conditions. Despite this positive outlook, questions remain concerning the effectiveness of the convention. In fact, during the most recent water shortage, difficulties arose to implement the protocol defined to meet increasing demands with the available water resources by the drought management plans [*Garrote et al.*, 2007].

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