Alcántara dam in the Tagus River: a case study of the effect of a large reservoir in the droughts in a trans-boundary basin

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ABSTRACT

The effect on the hydrological droughts of the large reservoir created by the dam of Alcántara, located in the trans--boundary Tagus River, almost in the border between Portugal and Spain, is discussed. 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 results achieved show that, as a consequence of the exploitation of 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 Alcántara has shown severe changes since the 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. However, since the construction of the Alcántara dam the Portuguese part of the basin has experienced more severe droughts than did the upstream part in terms of both magnitude and duration

KEY WORDS: *Trans-boundary water management, SPI drought index, Alcántara dam, Tagus River .*

INTRODUCTION

Reservoirs are key regulatory infrastructures, in particularly in regions, such as those under a Mediterranean climate, where the flow regime is characterized by marked seasonality, high inter-annual variability, and periodic exceptional floods and droughts. Despite such circumstance the role of reservoir management during periods of drought has received little scientific attention. Droughts are 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 river discharge, the soil moisture content, the groundwater storage, and the reservoir storage. In the case of regulated rivers within trans-boundary basins, water management during drought events becomes a complex issue in which national legislation and international conventions must be observed.

The present study addresses the effect of Alcántara reservoir, the second largest reservoir in Europe, in the hydrological droughts meaning those droughts affecting the downstream flow discharges. Alcántara dam was built in 1969 and is located in the Tagus trans-boundary River, about 10 km from the border between Portugal and Spain. Due to the huge capacity of the reservoir the exploitation of Alcántara determines to a great extent the discharges of Tagus River in the Portuguese part of the basin. The magnitude and duration of the droughts are analyzed by comparing a monthly drought index calculated for the flow series upstream and downstream of the dam.

STUDY AREA AND HYDROLOGICAL DATA

The Tagus River is located in the centre of the Iberian Peninsula and drains an area of 80,100 km^2, 69% of which is located in Spain and the rest in Portugal. The river is one of the main surface water bodies in the Iberian Peninsula providing water for urban supply (including to the capitals of both countries), irrigation and industrial uses. About 15% of the Spanish population and 30% of the Portuguese population live within the river basin. The climate in the basin varies from Mediterranean with strong continental influences in the eastern areas to Atlantic in the 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 mm in the Portuguese part of the basin, and to 1500 mm in the Central Ranges in Spain.

The Alcántara dam, located close to the border between Spain and Portugal, was built in 1969. The dam creates a reservoir with a gross storage capacity of 3162 hm^3, being the second largest reservoir in Europe. Because of its large capacity (representing about 46% of the mean annual flow), the reservoir has a large potential to modify the river regime downstream in Portugal, where the water is mostly used for agriculture, industry, and domestic supply. The long-term average runoff at Alcántara section (1943–2003) is 6850 hm^3 though exhibiting a downtrend evolution from 7515 hm^3, during the predam period (1943–1969), to 6208 hm^3, in the postdam period (1970–2003).

The hydrological data that supported the analysis was obtained from the Spanish and Portuguese Water Authorities (*Confederación Hidrográfica del Tajo* and *Instituto da Água*, respectively). The Spanish records consisted of monthly flows recorded at Alcántara gauging station (located 1 km downstream of Alcántara dam) which began to operate in 1915. The procedure adapted to fill the gaps in the series, which affect less than 5% of the data since 1940, is described in López-Moreno *et al.* (2009). The natural inflows after the dam construction (1969) were derived from the mass balance between the measured

discharge from the dam and the amount of water stored in the reservoir (López-Moreno *et al.,* 2009). The Portuguese records consisted of monthly flows at Santarém gauging station, for the period of 1943 to 1992, extended, by reconstruction until 2003, based on the records at Almourol gauging station, located 25 km upstream (the ratio between annual discharges at Almourol and Santarém is 0.96). The flow series recorded at Almourol consists of a continuous record from 1973 onwards. 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 the months of the year, with values of the correlation coefficient (Pearson's r) always higher than 0.96 thus validating the flow reconstruction procedure.

As a result of the contribution of the tributaries located between Alcántara dam and Santarém gauging station the mean annual flow volume increases from 6850 hm^3 to 9755 hm^3. To understand the contribution of those tributaries a synthetic time series was generated based on the difference between discharges at Santarém and at the foot of Alcántara dam (López-Moreno *et al.,* 2009).

THE DROUGHT INDEX

The drought periods were identified by the monthly discharge anomalies with respect to average conditions. For that purpose the standardized precipitation index (SPI) (McKee *et al*., 1993) was applied to monthly stream flow data based on the Pearson III distribution with parameters given by the L-moment method (López-Moreno *et al.,* 2009). Though the advantages of the SPI and its theoretical basis, robustness, and versatility in drought analysis based on rainfall data are comprehensively documented (Vicente--Serrano, 2006b, López-Moreno and Vicente-Serrano, 2008, Santos *et al.,* 2010) there is little experience in the application of that index to river discharges (López-Moreno *et al.,* 2009, Santos and Portela, 2010).

The SPI series from 1970 to 2003 were calculated for the flow series (i) upstream of Alcántara dam, (ii) released from Alcántara dam (foot of the dam), (iii) downstream at Santarém, and (iv) of the Tagus Portuguese tributaries. 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 droughts, derived from the river discharges, and climatic droughts, derived from the precipitation records. SPI at 12 months is an appropriate time scale for analyzing hydrological implications of regulated river basin (López-Moreno *et al.,* 2009).

DROUGHT EVENT SELECTION

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. Several criteria are used in selecting the 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, percentages of the mean or probabilities are commonly employed. Given the objective of the present study, a 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.

In addition to the threshold selection, two other problems must be solved to successfully identify drought events: the occurrence of minor droughts and of mutually dependent droughts (Fleig *et al*., 2006). Minor droughts are events characterized by short duration and, at the same time, low magnitude. They have little hydrological importance and may disturb the analysis. 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. Among the various procedures that have been proposed to combine mutually dependent droughts, a 5-months moving average was selected and 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 (López-Moreno *et al.,* 2009). Drought events were defined according to the zero SPI threshold from the filtered SPI series (upstream and downstream, Portuguese tributaries, and release from the Alcántara reservoir). Two main components from each drought event were chosen for further analysis: drought magnitude (accumulated deficit below a certain threshold, which is the sum of negative SPI anomalies belonging to the same drought event) and drought duration (number of months or years below a certain threshold).

OVERALL EFFECT OF ALCÁNTARA DAM

Under average conditions, the inflows to Alcántara reservoir exceed the outflows from October to May, in particular from October to February. During summer the opposite occurs: the outflows exceed the inflows due to the release of water for the maintenance of the ecological discharge, industrial and irrigation use, and urban supply in the Portuguese part of the basin (López-Moreno *et al.,* 2009). As a result of the 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 part 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. In fact, during dry years, the water release during winter and early spring is reduced dramatically.

Figure 1 shows the time series of the hydrological drought index upstream and downstream of the dam, and of the SPI for the precipitation series in the entire Tagus River basin.

Comparison of the hydrological series suggests that they are generally similar (r = 0.71) despite the runoff contribution of the several important Portuguese tributaries. For both Spain and Portugal, the most severe droughts were recorded in the 1940s, 1980s, and 1990s, while the wettest period occurred in the 1960s and 1970s, with the 1950s showing an average behaviour.

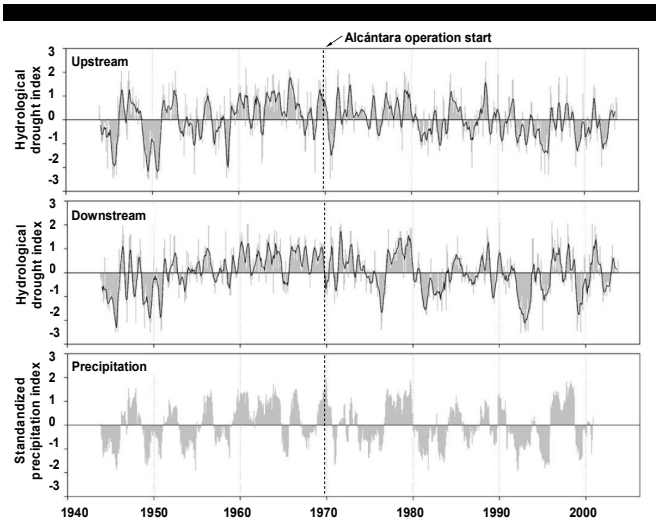

Figure 1. Time series of the drought index for the flows upstream of Alcántara reservoir and downstream at Santarém and for the precipitation in the entire basin. Solid lines represent the 5-months moving average of the hydrological drought index (adapted from López-Moreno *et al.*, 2009).

There is generally a high correspondence between periods with anomalous precipitation and those with anomalous runoff. This finding indicates the modest role, in the middle and lower sectors of Tagus River basin, of upstream regulation in the hydrological response to climatic signals. 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.

Moreover, Figure 1 shows that drought occurrences in the Tagus, as well as in the regional precipitation, do not show clear trends during the analyzed period: an equivalent number of drought events occurred during the predam and postdam periods and the highest drought duration and magnitude were found at the beginning and the end of the time series (1940–1950s and 1980–1990s decades).

DROUGHT DURATION AND MAGNITUDE BEFORE AND AFTER THE CONSTRUCTION OF THE ALCÁNTARA DAM

Figure 2 shows the duration of drought events recorded in Tagus River upstream of Alcántara reservoir (''Tagus upstream''), downstream at Santarém gauging station (''Tagus downstream''), in the Portuguese tributaries (''Portuguese tributaries''), and immediately downstream of Alcántara dam (''foot of the dam''). When the period (1943–2003) is considered, 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 2 (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, under the Atlantic influence which smoothes the temporal pattern of 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 Santarém, 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 Santarém). Since 1970 the duration of droughts has been markedly longer at the foot of the dam than upstream the reservoir, indicating that the management of Alcántara reservoir has led to an increase in the duration of droughts downstream. The effects of the dam are not compensated downstream by the contribution of the incoming Portuguese tributaries.

Figure 3 shows equivalent data to that of Figure 2, although for the magnitude of drought events. As for the

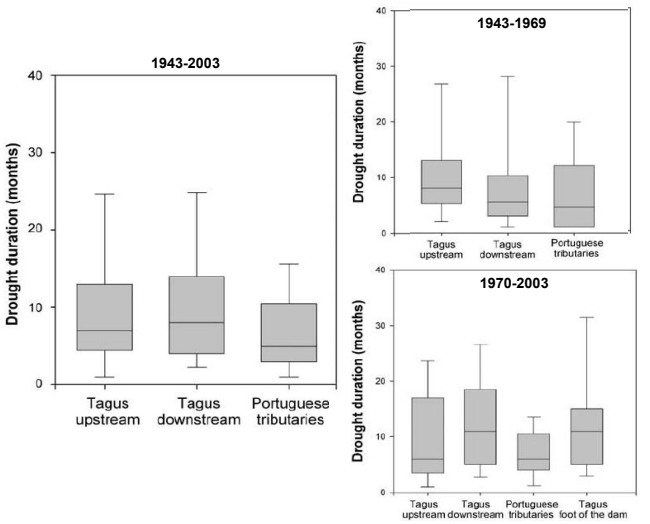

Figure 2. Boxplots of the duration of drought events in the Tagus River at Alcántara reservoir (upstream), at Santarém gauging station (downstream), in the Portuguese tributaries, and at the foot of Alcántara dam. The upper and lower parts of the boxes are the 75th and 25th percentiles, respectively; the whiskers indicate the 90th and 10th percentiles and the lines within the boxes the median values (adapted from López-Moreno *et al.*, 2009).

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,

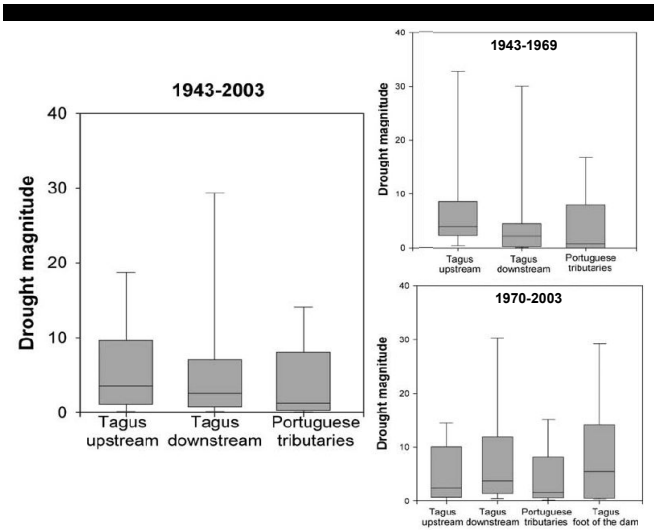

Figure 3. Boxplots of the magnitude of drought events (accumulated negative anomalies per event) recorded along the Tagus River, at Alcántara reservoir (upstream), at Santarém gauging station (downstream), in the Portuguese tributaries, and at the foot of Alcántara dam. The upper and lower parts of the boxes are the 75th and 25th percentiles, respectively; the whiskers indicate the 90th and 10th percentiles and the lines within the boxes the median values (adapted from López-Moreno *et al.*, 2009).

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 the 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 accentuated the magnitude of droughts.

An additional analysis of the results (López-Moreno *et al.*, 2009) showed 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 number of months with slight negative SPI values (-1.0<SPI<-0.5) similar to the upstream sector (40/44 downstream/ upstream, respectively), a higher occurrence of months with anomalies in the range -1.5<SPI<-1.0, and a lower occurrence of months with large negative anomalies (SPI<-1.5). However, since the reservoir has come into operation, the number of months with large negative anomalies (downstream/upstream of 14/3 for -2.0<SPI<-1.5 and of 11/6 for SPI<-2.0) is noticeably higher in the Portuguese stretch of the Tagus.

By listing the statistics (duration, total magnitude, mean monthly magnitude, and maximum magnitude) of drought events upstream and downstream of Alcántara dam, as well as the sign of change in upstream-downstream drought characteristics, a marked shift in the upstream-downstream drought characteristics since the Alcántara reservoir was first exploited was detected. 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.

Finally, Figure 4 shows examples (for four different periods) of how the exploitation of Alcántara reservoir can explain observed differences in the duration and magnitude of droughts upstream and downstream of the dam. Figures 4A and 4B 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, the 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 4C 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 (Figure 4D), under conditions of severe water scarcity in the upstream areas, the exploitation practices of the Alcántara reservoir led to increased water storage, causing several peaks of high drought intensity in the downstream areas.

DISCUSSION AND CONCLUSIONS

The analysis carried out showed that:

i) Despite an apparent similar evolution of the hydrological drought series for areas upstream (Spain) and downstream (Portugal) of the Alcántara reservoir, noticeable differences emerged as a consequence of the management of the Alcántara reservoir.

ii) 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 discharges during the dry summer season. As a result of the reservoir exploitation, releases during winter and spring are severely reduced under periods of water scarcity, while summer low flows may exhibit a slight increase.

iii) Characteristics of the 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 (Santarém, 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 own droughts.

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 the analysis of hydrological droughts has demonstrated that it also 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 the analysis of drought magnitude and duration.

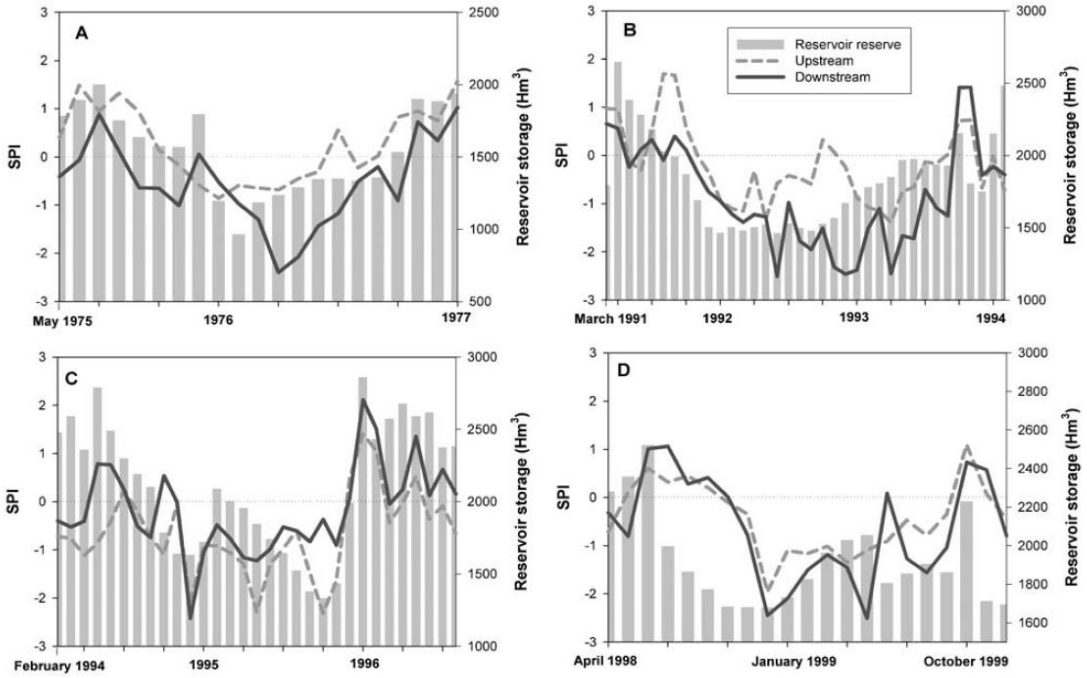

Figure 4. Evolution of the standardized upstream and downstream river flows (SPI) in relation to water storage levels in Alcántara reservoir for four drought events (reproduced from López-Moreno *et al.*, 2009).

The results achieved 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.

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. Such results indicate that exploitation of 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. The adverse role of the Alcántara reservoir in accentuating droughts is somehow minimized by the inflow of the 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. Probably, the reduction in drought severity may be related to increasing regulation of some tributaries (i.e., in the Zêzere 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. However, 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 at Santarém compared to the duration and magnitude of droughts recorded at the foot of the dam.

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