THE HYDROLOGIC REGIME OF THE TAGUS BASIN IN THE LAST 60 YEARS

Francisco J. FLORES-MONTOYA[1], Luis M. GARROTE[2], Francisco J. MARTIN-CARRASCO[2]

[1]Confederación Hidrográfica del Tajo. Av. Portugal, 81. 28011 Madrid (Spain)

[2]Universidad Politécnica de Madrid. ETS Ingenieros de Caminos. Ciudad Universitaria s/n 28040 Madrid (Spain)

ABSTRACT

An analysis of the hydrologic regime of the Tagus basin in the last 60 years is presented in this paper. A detailed study was made of the hydrologic characteristics of time series of precipitation and streamflow in the basin. The study focused on drought occurrence. Fourteen hydrologic regions were analyzed, obtaining basic statistics (duration and intensity of departures below the mean and other quantiles) to identify recent tendencies in mean values and variability. The study showed an apparent increase of the frequency and magnitude of droughts in the basin during the 80's and 90's, although the length of the series is short to discriminate between natural long-term variability and man-induced climate change. To conclude, some implications for water planning under non-stationary hydrologic conditions are presented in the paper.

1. INTRODUCTION

The objective of this paper is the analysis of the hydrologic regime of the Tagus basin during the last 60 years, with emphasis on drought occurrence. The Tagus basin is located in the central part of the Iberian peninsula, with the main river running on east-west direction, and covering an area of 83,678 km^2, of which 55,870 km^2 are located in Spain and the rest Portugal. Drought occurrence in the Tagus basin is relevant because water resources usage is close to sustainability levels in several important regions, like, for instance, the urban water supply for the city of Madrid.

The study presented here covers only the Spanish part of the basin, corresponding to the area under control of the Confederación Hidrográfica del Tajo, which is the Spanish basin authority. For planning purposes, the basin is divided in 14 hydrological homogenous zones, which are in turn divided in 216 sub-basins. Figure 1 shows the location and denomination of the 14 hydrological zones. Several analyses were made on hydrologic records available for these basins, identifying drought occurrence from different points of view: meteorological, hydrological and operational.

2. DATA

Analysis were performed on data collected for the elaboration of the Tagus Water Plan. Daily and monthly rainfall data were collected at 296 stations across the Spanish Tagus basin with an average record length of 60 years, although the analysis was restricted to monthly data. Monthly average precipitation was also computed for the 216 sub-basins for the period 1940-41 to 2000-01. Streamflow data came from 119 gauging stations, distributed over the basin. These records could not be directly used in most cases because the natural regime was strongly altered due to reservoirs, diversions and consumptive uses. Synthetic series for the natural regime were therefore computed with the Sacramento model. The Sacramento model was calibrated in unaltered basins, and used to generate runoff series for the 216 sub-basins for the period 1940-

41 to 2000-01. It is estimated that the synthetic series contain the same hydrologic information as original records do and can therefore be used in drought analysis

Figure 1: Hydrological zones defined for the study

Historical information of stored water in basin reservoirs was compiled for 46 major reservoirs in the basin. These data were processed and recomputed with the aid of water resources system simulation models to generate the synthetic series of stored volume assuming that all water demands were active and all reservoirs were in operation since the beginning of the study period.

3. STATISTICS OF CROSSING PROPERTIES

The first group of analyses consists on a application of the theory of runs to study departures below the mean and the corresponding statistics of crossing properties. When applied to droughts, runs theory describes how a hydrologic process crosses above and below a critical threshold value. The analyses were performed on the cumulative runoff series (considering the cumulative values of runoff for each hydrologic year), using the percent of normal values, which were taken as the long term mean. The analysis of the percent of normal runoff is a simple calculation well suited for descriptive purposes. However, it should be noted that, since the distribution of runoff values is highly skewed (the median value is 78.4% of the mean), the probability of having values below the mean on any given month is 0.61. The distribution of runoff values is shown on Figure 2.

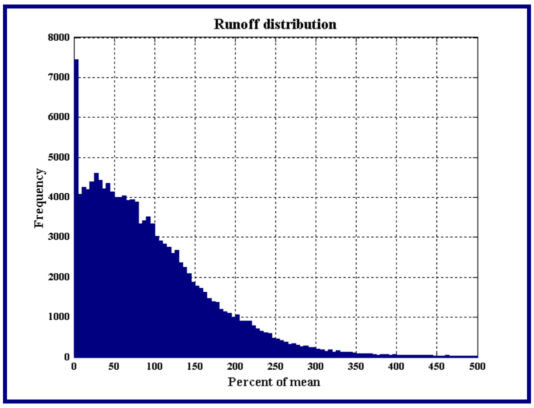

Figure 2. Distribution of runoff values

Threshold values of 75%, 50% and 25% of the mean were chosen as critical values, and statistics of crossing properties were computed for each of them. Main properties computed were: drought duration (number of consecutive months below the threshold), drought intensity (maximum departure below the threshold, expressed as percentage of mean) and drought magnitude (cumulative deficit during the departure below the threshold, expressed as percentage of mean times number of months). Mean values for the three threshold values analyzed are shown on table 1. Figures 3 and 4 show the distribution of the duration and maximum intensity of departures below 50% of the mean. Durations show secondary peaks for 12, 24 and 36 months, corresponding to droughts spanning over more than one hydrologic year. The distribution of intensities shows that, once the drought situation is started, there is high probability of reaching considerable deficits.

Table 1: Main statistics of crossing properties for threshold values of 75%, 50% and 25 % of mean

Threshold	***75%***	***50%***	***25%***
Duration (months)	11.70	8.36	5.49
Intensity (% of mean below threshold)	55.78	36.65	18.01
Magnitude (% of mean times months)	467.93	223.50	77.69

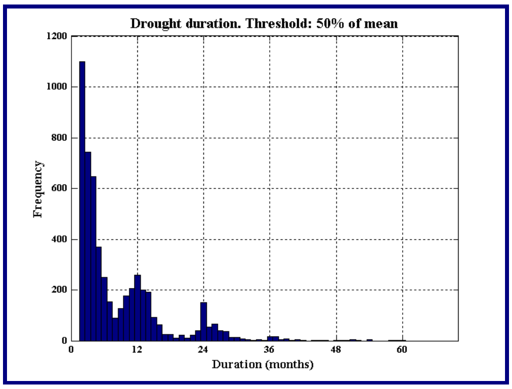

Figure 3 Histogram of drought duration for threshold value of 50% of mean

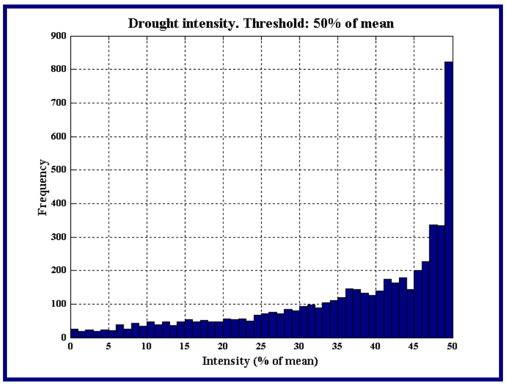

Figure 4 Histogram of drought intensity for threshold value of 50% of mean

A departure of more than 6 consecutive months below a pre-specified threshold was considered a drought. Figures 5 and 6 show the streamflow deficit below the threshold (in % of the mean) for the 216 sub-basins, grouped by hydrologic zones. Two different thresholds: 50% (Figure 4) and 25% (Figure 5) of the long-term mean value for the corresponding month were considered. Both figures show distinct behavior in different hydrologic zones. Hydrologic zones 8, 12, 13 and 14, located on the left bank and in the mid and lower courses of the river, show more extreme behavior than zones 1 through 7 and 9 through 11, where the intensity of departures is less. Analysis of figure 5 hints an intensification of drought occurrence in the last years of the series, although the quantification of the effect is difficult in statistical terms (Douglas et al., 2000)

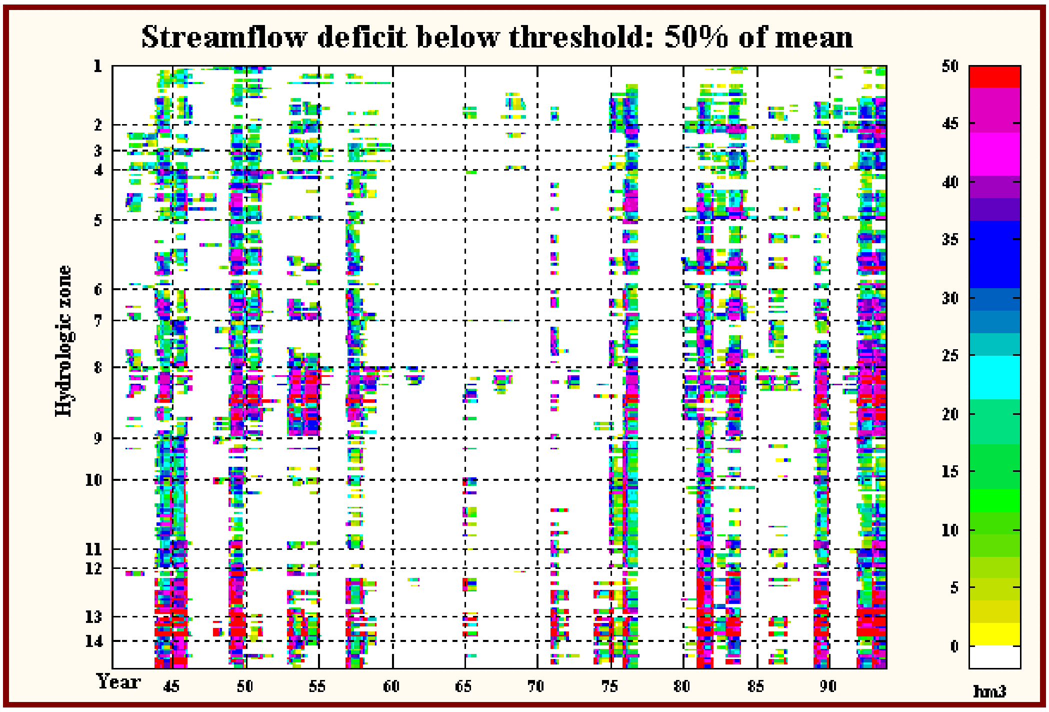

Figure 5 Streamflow deficit below a threshold value of 50% of the long-time mean

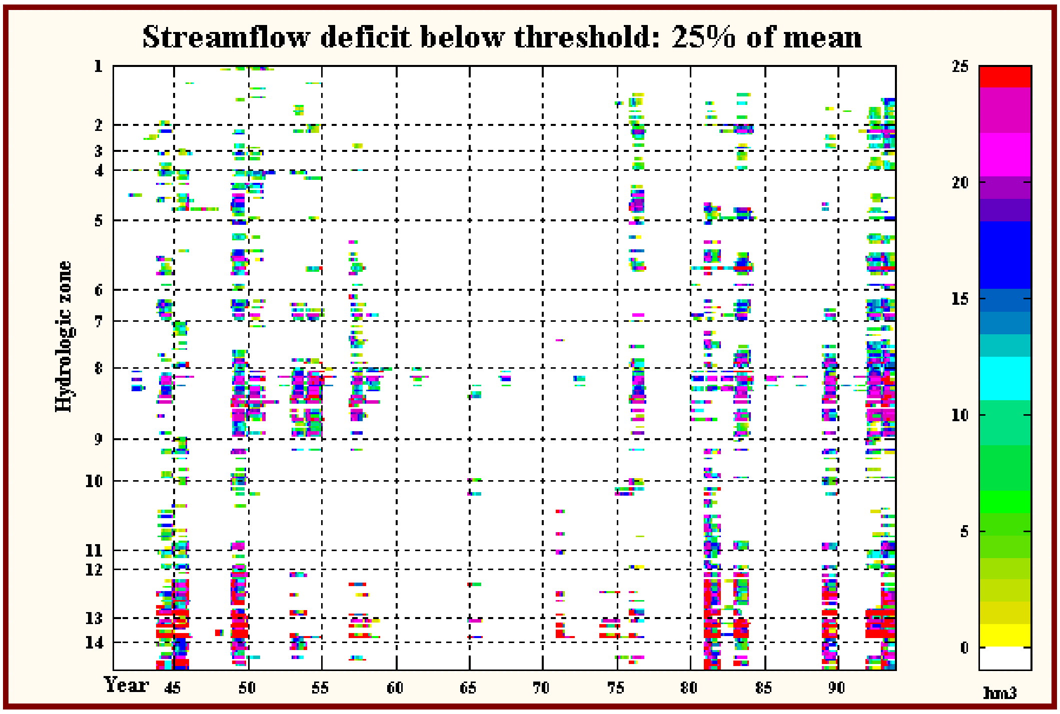

Figure 6 Streamflow deficit below a threshold value of 25% of the long-time mean

The spatial distribution of droughts was analyzed considering the percentage of the basin under drought conditions as a function of threshold value. The time evolution of the basin coverage under drought conditions for different threshold values is shown on Figure 7. Even for threshold values as low as 25% of the mean, there are several episodes with spatial coverage above 50% of the basin area

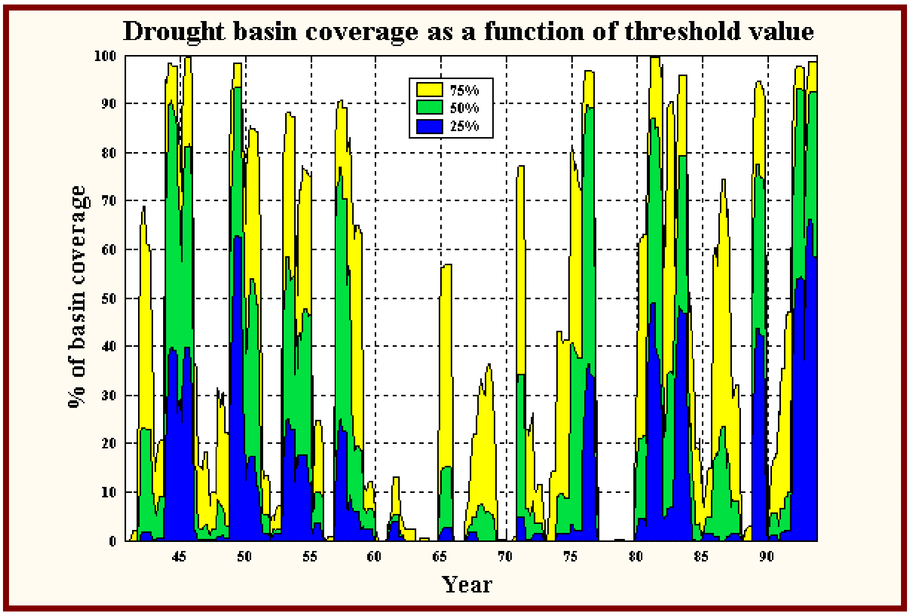

Figure 7 Spatial extent of drought conditions as a function of threshold value

4. ANALYSIS OF DROUGHT INDICES

A drought index is a single value that summarizes the relative situation of a basin with respect to normal use of water resources. Drought indices are defined for decision-making purposes from the meteorological, hydrological or operational perspective. Usefulness of drought indices is based on their ability to establish comparisons between basins of different hydrological conditions. Two well-known indices were computed for the Tagus basin in this study: the Standardized Precipitation Index and the Surface Water Supply Index.

Standardized Precipitation Index. The Standardized Precipitation Index (SPI) is a an index based on the probability of precipitation at a given time scale (McKee et al., 1993; Guttman, 1999). It is computed by fitting the long-term record of precipitation to a normal probability distribution by an adequate variable transformation, so that the mean SPI for the period of analysis is zero and the variability is symmetrical around the mean. A drought period is an event when the SPI is continuously negative and reaches an intensity value of –1.0 or less. The event ends when the SPI becomes positive (Hayes, 2002). Because the SPI is standardized, index values can be compared across a wide range of climates.

Analysis of the SPI was performed on the 296 raingauges in the basin. Skewness in the original rainfall distribution was corrected by taking the square root of precipitation. The SPI is computed by subtracting the mean and dividing by the standard deviation of the transformed variable. SPI values of -1.5 or less are considered severe droughts, and SPI values of –2.0 or less, extreme droughts. Figure 7 shows drought periods where SPI reaches the value of –1.5 or less. Drought periods where the SPI is continuously negative and reaches a value of –2.0 or less are shown in Figure 8.

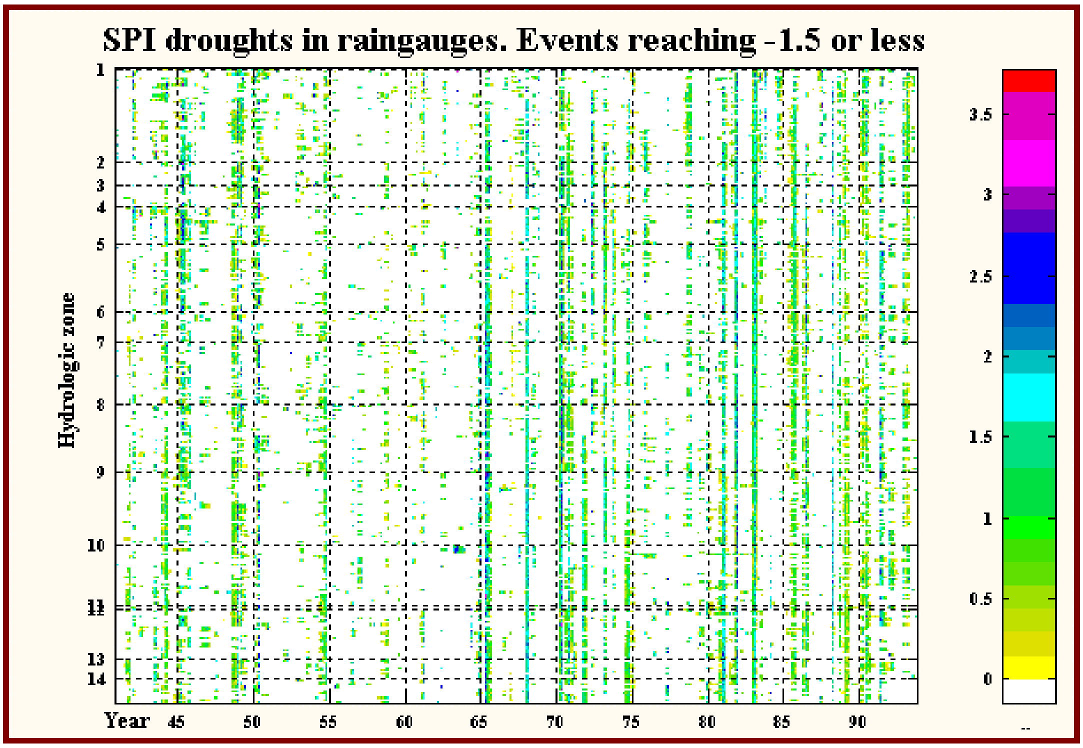

Figure 8 Droughts when SPI index reaches a value of –1.5 or less

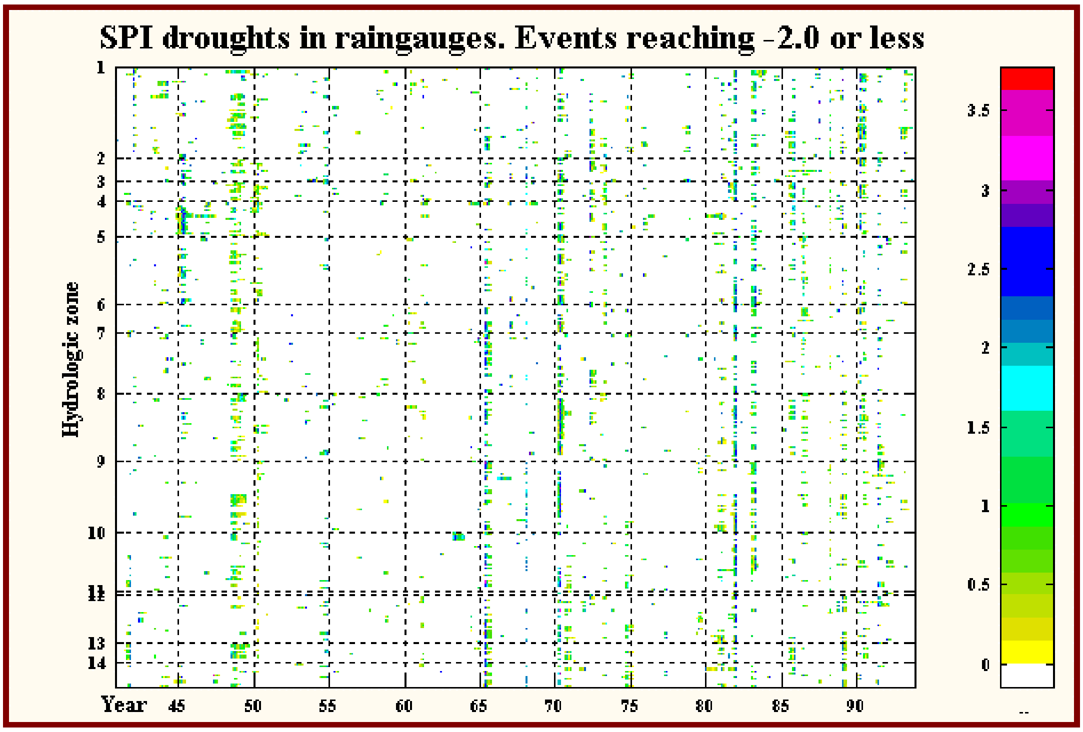

Figure 9 Droughts when SPI index reaches a value of –2.0 or less

Surface Water Supply Index. The Surface Water Supply Index (SWSI) has the advantage of combining hydrological and climatological features in a single index and allows for the consideration of reservoir storage, very important in the Tagus basin. SWSI is computed for a hydrographic basin or for a water resources system by obtaining the probability of non-exceedance for the values of precipitation, runoff and stored water in the basin (Garen, 1993).

Each component is assigned a weight depending on local conditions. These weighted components are summed to determine the global SWSI value for the entire basin.

SWSI was computed for the 14 hydrologic zones in the Tagus basin, assigning equal weight to all three components. Precipitation and runoff were computed as spatial averages over the basins. Stored water was estimated using the water resources system simulation model, since historical values of reservoir storage do not correspond to current basin conditions. The results are shown in Figures 10 and 11, where threshold values of -2 and –3 of SWSI have been chosen, corresponding to moderate and severe drought respectively.

Comparison of Figures 5, 8 and 10, or Figures 6, 9 and 11 show the difference between meteorological, hydrological and operational droughts. Meteorological droughts, based on precipitation alone, appear frequently and are uniformly distributed over the period of study. Hydrological droughts take into account the role of soil moisture, and are less frequent, but more intense, and cover a greater part of the basin. Operational droughts include information regarding the situation of water reserves in the basin, and usually appear at the end of hydrological droughts, after several months of streamflow deficits deplete reservoir stora

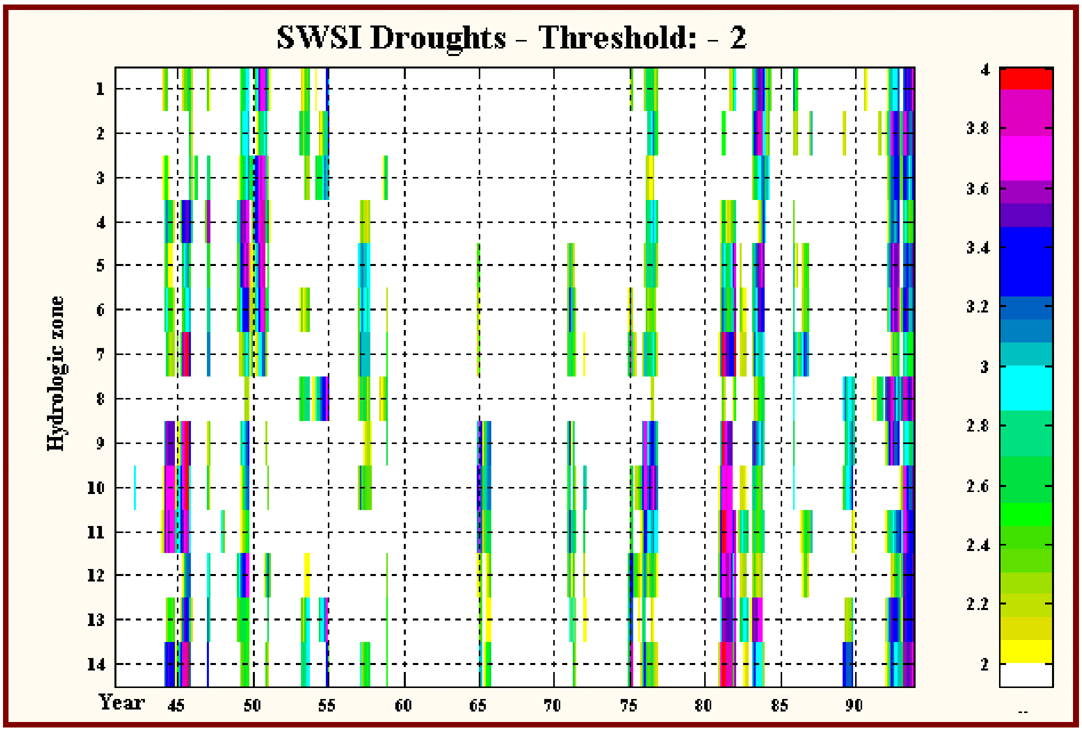

Figure 10 Droughts when SWSI has a value of -2 or less

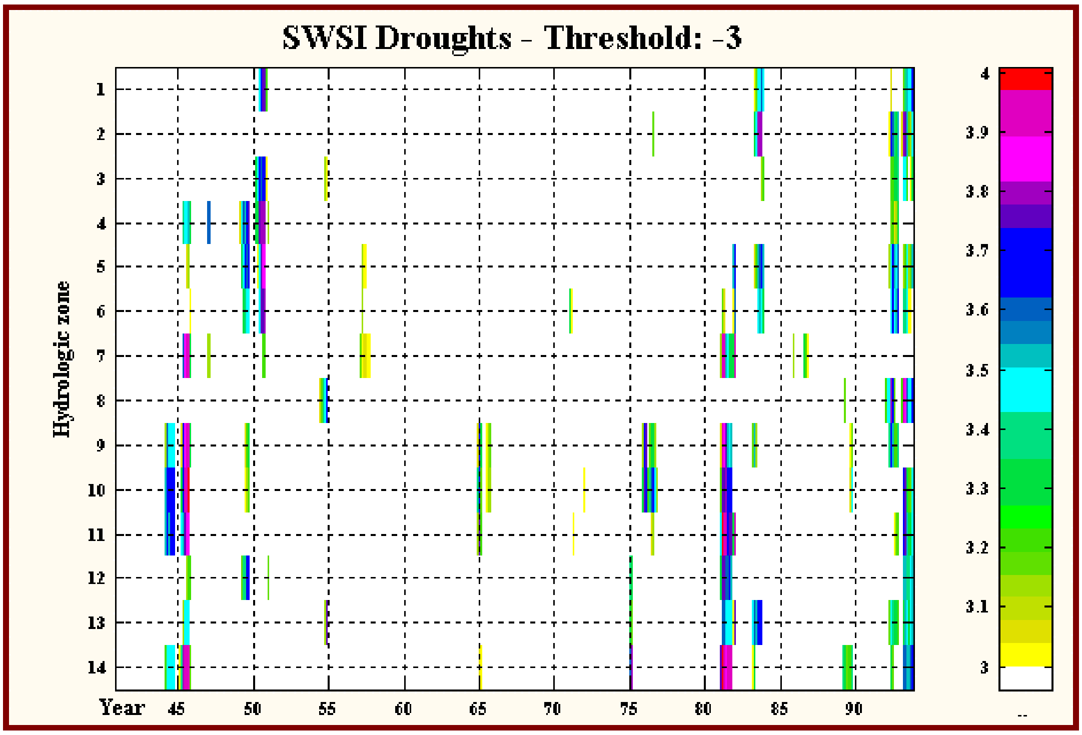

Figure 11 Droughts when SWSI has a value of -2 or less

5. TIME EVOLUTION AND RECENT TENDENCIES

The graphs shown hint a possible intensification of drought conditions in recent years, during the decades of 1980's and 1990's. However, since droughts were also important during the 1940's and 1950's, the question arises of whether recent droughts are a consequence of man-induced climate change or there is a multi-annual cycle of wet and dry conditions with a period of about 40 years. The series analyzed are too short to study this issue, but the situation can be clarified in a few local points with longer data sets.

For instance, the case of the headwaters is illustrative of the great variability of streamflow series in the basin. Figure 12 shows the series of annual flows from 1912 to 1998 in Bolarque, located just downstream the reservoirs of Entrepeñas and Buendia, with a contributing basin of 7,420 km^2. Mean annual flow in Bolarque is 1,260 Mm^3/yr, but the series shows great variability. For instance, the average annual flow in the last 20 years was 786 Mm^3/yr. If a linear trend is fitted to the data, the slope is clearly negative, with a decrease of more than 8 Mm^3/yr every year. The graph shows also the cumulative mean computed from the beginning and from the end of the series, which are separated more than 500 M^3/yr in several years. Overall, the behavior of this series appears to be non-stationary, or, at least, highly variable with a period between wet and dry spells clearly beyond the possibilities of regulation for water supply.

Variability of this data at Bolarque is relevant because there is a large facility for water transfer in Spain, the Tajo-Segura aqueduct, that diverts water from the Tagus river at Bolarque and transports its to South-East Spain. The aqueduct was planned during the wet period using data that, at that time, seemed to be reliable, but the subsequent evolution of streamflow showed a significant reduction of mean flows and forced a change in the planned exploitation of the infrastructure.

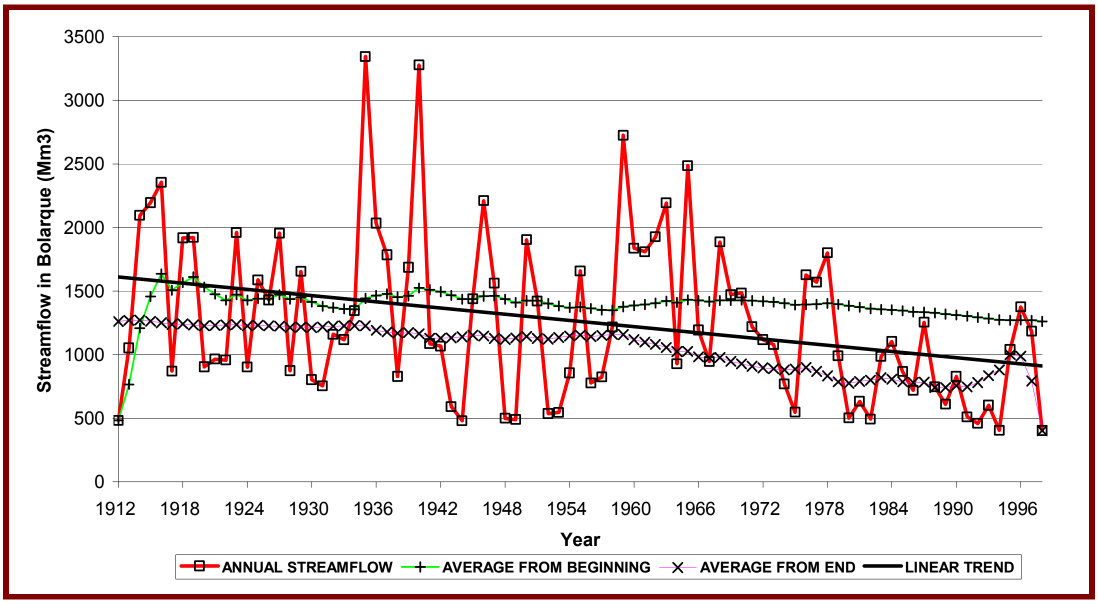

Figure 12 Streamflow series in Bolarque (1912-1998)

6. IMPLICATIONS FOR PLANNING UNDER UNCERTAINTY

The Tagus Water Plan has to deal with the problem of uncertainty in hydrologic series and mitigate the societal impacts of droughts. Although the apparent tendency to more frequent and intense droughts could not be assessed in rigorous terms, this possibility could not be ignored during the planning process, and therefore several scenarios were analyzed to take into account, among other eventualities, the possible non-stationarity of basin hydrology. Several measures were adopted to be put into practice in case a decrease in availability of water resources was detected. The planner should allow margin for adaptive feedback between the forecast scenarios and actual development of the basin situation.

Although the measures contemplated in the Water Plan in theory solve identified problems for all demands in the basin, the Water Plan includes the possibility of occurrence of a drought of duration, intensity or magnitude superior to registered historic events. One of the objectives of the Plan is to reduce the vulnerability of the basin to droughts of greater severity than historic ones through the adoption of special measures to mitigate their impacts, specifically in systems of strategic importance, like the urban water supply to Madrid, and to prepare the political and technical environment to respond in a timely and effective manner during periods of crisis. Consideration is given primarily to operational droughts, these being defined as situations in which water resources stored in reservoirs plus a conservative forecast of future flows based on current conditions do not allow the basin demands to be fully met.

An early warning system was established to identify possible drought situations. The system is in continuous revision, taking into consideration the availability of new information and the progress in knowledge of the hydrologic behavior of the basin. Variables used as early warning levels to predict droughts are as follows: significant departure from normal values in cumulative precipitation during the hydrologic year in representative rain gauges, reduction of water stored in strategic reservoirs below critical thresholds, abnormal thickness of snow pack during winter months and depletion of piezometric levels in aquifers exploited for consumption.

In the event of a drought situation, operating strategies have been defined to limit consumption (programs for public awareness, restrictions of nonessential uses, intensification of control of water consumption and implementation of penalties for violators) and to increase supply (implementation of planned structural and non structural measures: the use of dead reservoir storage or water of lower quality, transient overexploitation of the aquifers, modification of usage priorities and resort to high-cost sources of supply).

Given the extremely complex relationships between supply and demand in the basin, special consideration was given to the analysis of the relative situation of each demand. Demands having only a single source of supply were distinguished from those having various sources, and, in this group, demands having such sources available exclusively were distinguished from those sharing them with other demands. With respect to those demands for which a part of the resources consist of return flows from irrigation, their dependency on such flows was quantified.

In systems where demands are close to average flows, like, for instance, the urban water supply to Madrid, there is little margin for action. It is critical to evaluate the elasticity of water demand, and plan to act on it if it can be reduced. Most emergency measures find the difficulty of having to alter existing water rights, face the development of new transport or storage facilities under great social pressure or impose stronger rules and penalties and more strict control.

In summary, drought mitigation is an essential feature of the Tagus hydrologic Water Plan. The severity of droughts in the basin, both in terms of wide spatial coverage and intense water deficits, require that the planner take into account a possible increase of drought impacts and provide for emergency and long-term programs to react to drought situations.

7 REFERENCES

Douglas, E.M.; R.M. Vogel; C.N. Kroll: *Trends in floods and low flows in the United States: impact of spatial correlation*. Journal of Hydrology, Vol 240, pp 90-105, 2000.

Garen, David C.: *Revised Surface Water Supply Index (SWSI) for Western United States*. Journal of Water Resources Planning and Management Vol 119(4), pp 437-454. 1993

Guttman, Nathaniel B.: *Accepting the Standardized Precipitation Index: A calculation algorithm*. Journal of the American Water Resources Association, Vol 35(2) pp 311-22. 1999

Hayes, Michael: *Drought indices*. National Drought Mitigation Center (Available at http://www.drought.unl.edu/pubs/pubs.htm), 2002

McKee, T.B.; N.J. Doesken; J. Kleist: *The relationship of drought frequency and duration to time scales*. 8th Conference on Applied Climatology, Anaheim, CA. 1993.

Wilhite, Donald A.: *The enigma of drought*, part of "D.A. Wilhite (ed.). Drought Assessment, Management, and Planning: Theory and Case Studies ", Ch.1, pp 3-15. Kluwer Academic Publishers, 1993.