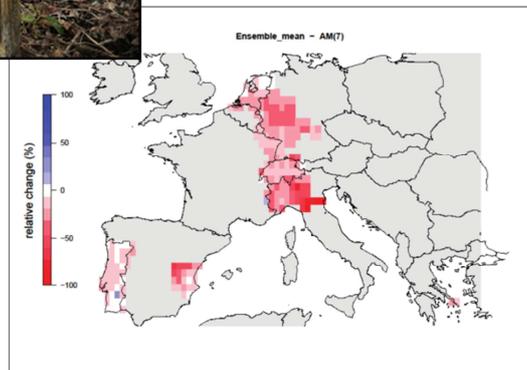


## Technical Report No. 8

# QUANTITATIVE ANALYSIS OF HISTORIC DROUGHTS IN SELECTED EUROPEAN CASE STUDY AREAS



Henny A.J. van Lanen, Marcel A.A. Alderlieste, Vanda Acacio, Joaquín Andreu, Emmanuel Garnier, Lukas Gudmundsson, David Haro Monteagudo, Demetris Lekkas, Javier Paredes, Abel Solera, Dionysis Assimacopoulos, Francisco Rego, Sonia Seneviratne, Kerstin Stahl and Lena M. Tallaksen

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<b>Authors:</b>	Henny A.J. van Lanen, Marcel A.A. Alderlieste, Vanda Acacio, Joaquín Andreu, Emmanuel Garnier, Lukas Gudmundsson, David Haro Monteagudo, Demetris Lekkas, Javier Paredes, Abel Solera, Dionysis Assimacopoulos, Francisco Rego, Sonia Seneviratne, Kerstin Stahl and Lena M. Tallaksen
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<b>Deliverable</b>	This report contributes DROUGHT-R&SPI deliverable D2.1 Historic drought analysis - case study scale.

Photos: Dry UK river, February 2012  
 Map of Europe with trend in the minimum 7-day flow taken from a multi-model set of nine large-scale models for the period 1963-2001



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The report is complementary to DROUGHT-R&SPI Technical Report No. 1<sup>1</sup>. It summarises the previous report, which is based upon the WATCH data, and it adds through the analysis of local hydrometeorological data. Furthermore it compares the trends obtained with the local with those derived from the WATCH data. We appreciate very much the guidance provided by Kerstin Stahl (Institute of Hydrology, University of Freiburg, Freiburg, Germany) on how to implement the Mann-Kendall test and the Sen slope method, which were applied to the WATCH data (Technical Report No. 1) and to the local data in Portugal and Syros.

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Wageningen, 30 September 2012

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<sup>1</sup> Alderlieste, M.A.A., and Van Lanen, H.A.J. (2012): Trends in low flow and drought in selected European areas derived from WATCH forcing data and simulated multi-model mean runoff. DROUGHT-R&SPI Technical Report No. 1, 110 pg.



## **Abstract**

This study summarizes trends in historic drought in the selected DROUGHT-R&SPI Case Study areas (Júcar River basin, The Netherlands, Po River basin, Portugal, Switzerland and Syros). The indicators that have used to investigate study the droughts are explained as well as the approach to quantify the trends. The first part of the reports describes information on droughts (trends, severe events) that has been collected on the basis of studies using local hydrometeorological data. The first part concludes with information on drought that has been collected from archives since 1500, so far beyond the instrumental record. The second part of the report provides outcome from a systematic analysis on trends in temperature, precipitation, low flows, droughts and drought ranked according their severity. The systematic analysis uses weather data (1963-2000) from one large-scale database (reanalysis data) and mean multi-model runoff of the same set of large-scale hydrological models that used the weather data from the reanalysis dataset as input. The results on drought from the second part of the study are more consistent (same weather data, same analysis tools) but coarser than from the first part that uses locally collected information and targeted methods. In the last part of the report the information on drought collected from the local studies (part 1) and from the more systematic investigation (part 2) are intercompared. The more systematic study shows that in general annual flow in northern Europe has increased and in southern Europe has decreased, whereas the annual minimum flow has decreased in most of Europe (except, for instance, North Scandinavia). The locally- collected data (part 1) do not always point in this direction, or are insufficient to support this observation. The last part of the report illustrated that the reported information on historic drought depends on the drought type (e.g. meteorological, hydrological), indicator used and how the indicator is calculated. If these differences are not considered, it seems that contradicting information exist for a certain Case Study area.



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# 1. Introduction

Drought is a natural hazard that occurs in both high and low rainfall areas of Europe and can develop over short periods (weeks or months) or longer periods (seasons, years or even decades). Over the last decades, Europe was regularly hit hard by drought. Droughts are complex large-scale phenomena involving numerous interacting climate processes and various land-atmosphere feedbacks. Different stores (persistence) in river basins lead to a complicated propagation of the climate signal into the water system (e.g. Peters et al., 2003; Tallaksen et al., 2009; Van Loon and Van Lanen, 2012). Although progress is made, the phenomena are still not well understood, which makes it difficult to adequately characterize, monitor and forecast drought. Droughts do not directly cause fatalities in Europe, but they have large socio-economic and environmental impacts affecting many sectors. These multi-faceted impacts happen both in water-stressed areas of Southern EU Member States, but also in countries where water availability has never before been a major concern. Climate change projections for Europe indicate that drought is likely to become more frequent and more severe due to the increased likelihood of warmer Northern winters and hotter Mediterranean summers, together with decreases in precipitation and increases in evaporation demand (e.g. Bates et al., 2008, Dai 2010; Seneviratne et al., 2012). Hence, there is an urgent need to improve drought preparedness through measures that reduce vulnerability to drought and the risks they pose for Europe, in particular considering the uncertain future.

The DROUGHT-R&SPI project considers future impacts and vulnerability on different scales. Case studies are being carried out at the national scale (Portugal, Switzerland, The Netherlands) and more detailed per river basin (Júcar, Po) and even on the local scale (Syros). Policies responses on drought are identified and risk mitigation options are defined per case study area. Assessment of impacts, vulnerabilities, policy responses and risk mitigations options can only be performed after the future drought hazard is known, and this requires a good understanding of the historic drought hazard.

The objective of this part of the DROUGHT-R&SPI study is to investigate severity and duration of historic drought events, and explore possible trends in the case study areas.

Two types of data were used to study the historic drought. The first type are the so-called local data, e.g. time series of precipitation or river flow, that were obtained from the meteorological agencies and river basin authorities that are responsible for the at-site collection of these local data. Local data differ per case study area. For example, in some study areas no flow data are available. In other areas either precipitation or temperature data could be obtained. Moreover, length of time series deviates per variable and per case study area. This called for an additional consistent analysis of historic drought that uses the same type of data and length of time series. This study decided to use time series of precipitation, temperature and runoff data from the EU-FP6 WATCH project (WATER and global CHange<sup>2</sup>, Harding et al, 2011a; 2011b). The outcome from this study is reported by Alderlieste and Van Lanen (2012).

The following research questions are addressed:

- are there trends in forcing data (e.g. precipitation, temperature) in the second part of the 20<sup>th</sup> century when local data from the case study areas, if available, are used;
- are there trends in observed river flow data in the second part of the 20<sup>th</sup> century when local data from the case study areas, if available, are used;
- are there trends in forcing data (precipitation, temperature) in the second part of the 20<sup>th</sup> century in the case study areas when WATCH data are used;

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<sup>2</sup> <http://www.eu-watch.org/>

- are there trends in simulated annual and monthly flow data in the second part of the 20<sup>th</sup> century in the case study areas when WATCH data are used;
- are there trends in low flow characteristics (e.g. n-day annual minimum flow, timing) in the second part of the 20<sup>th</sup> century in the case study areas when WATCH data are used;
- are there trends in drought characteristics (e.g. drought duration, severity) in the second part of the 20<sup>th</sup> century in the case study areas when WATCH data are used;
- are there differences in trends in forcing data in the case study areas when using WATCH data instead of local data;
- are there differences in trends in flow or drought characteristics in the case study areas when using WATCH data instead of local data;
- are there differences in trends in flow or drought characteristics in the case study areas when using WATCH data for the whole 20<sup>th</sup> century instead of data only for the second part of the century;
- is the ranking of the historic droughts derived from the WATCH confirmed by the local data;
- how large is the impact of the drought identification methods.

Hydrometeorological data in this study come from: (i) observations on the local scale, and (ii) reanalysis data from the WATCH project. A variety of approaches have been used in the current study. The Standardized Precipitation has been applied to local data in some case study areas to characterize meteorological drought. Most analyses in this report have been done with flow data. Incl. low flow indices and with drought characteristics (e.g. duration, deficit volume) to describe hydrological drought. A statistical test has been applied to all data to investigate trends. Proxy data coming from archives have been used to explore long series of historical drought.

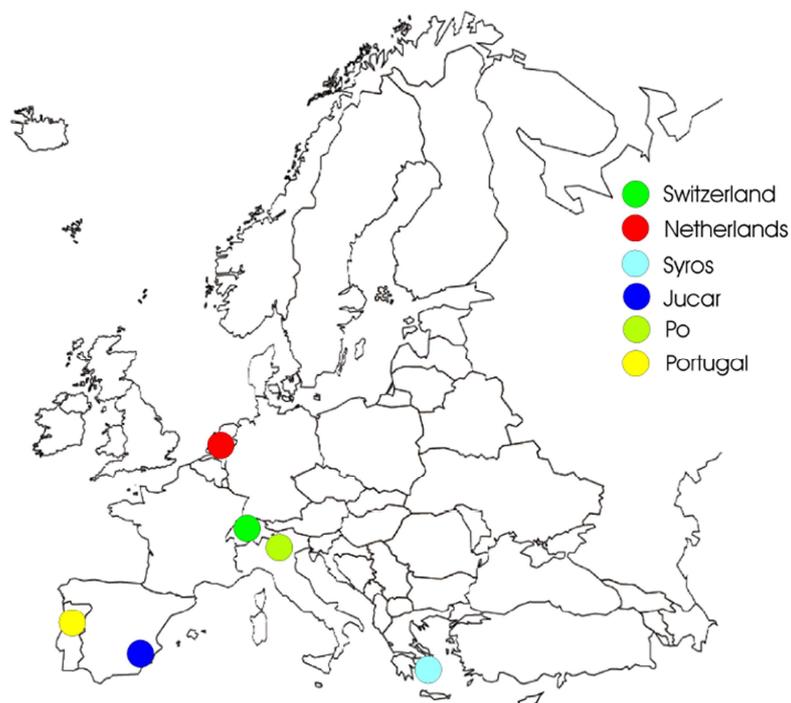
The report starts with a brief description of the DROUGHT-R&SPI case studies, and the data and the methods we employed (Chapter 2). Trends in historic drought obtained from local observed hydrometeorological data are described in Chapter 3. The report proceeds with a trend analysis of historic low flows and drought using WATCH data (Chapter 4). Next differences in trends between droughts derived from local data and WATCH data are discussed, and eventually the impact of low flow and drought identification methods is evaluated (Chapter 5). In Chapter 6 the report describes the main conclusions and recommendations.

## 2. Data and methodology to identify low flows and drought

This chapter briefly describes the DROUGHT-R&SPI Case Study areas (Sect. 2.1), the WATCH data (Sect. 2.2) that will be used for the consistent analysis (Chapter 4), which is followed by the different methods that we applied to describe drought (Sect. 2.3). The chapter concludes with the trend analysis methods that we employed (Sect. 2.4).

### 2.1. DROUGHT-R&SPI Case Study areas

Case Study areas have been selected in different geo-climatic regions. The Case Study areas have different scales (local, river basin and national) (Fig. 2.1). Each of the selected Case Study areas is described in the DROUGHT-R&SPI project description (Van Lanen, 2011).



**Figure 2.1** Location of the DROUGHT-R&SPI Case Study areas.

- The Júcar river basin in Spain, one of the most vulnerable areas of the western Mediterranean due to the high water exploitation, and environmental and water quality issues. Due to the prioritization of water uses, past drought episodes have primarily affected agriculture and hydroelectricity, but had significant economic impacts across all water use sectors.
- The Netherlands, where vulnerability to drought primarily concerns agriculture, navigation and sensitive ecosystems. Vulnerability is strongly linked to the very controlled water management and the country's dependence on transboundary river water.
- The Po river basin in Italy, where past drought episodes have resulted to extreme pressures on the river basin system, affecting downstream demands, energy production and agriculture and incurring economic damage that exceeded 1.3 billion Euros.
- Portugal, where the 2004-05 drought episode had a pronounced impact on all economic sectors and the environment, and resulted in the second worst wave of wildfires in the country's history, destroying more than 325,000 hectares.
- Switzerland, where the impacts of the 2003 episode motivated authorities to seriously consider the country's vulnerability to drought events, which are expected to become more severe as a result of

climate change. Sectors affected by the 2003 drought concerned agriculture, navigation, energy production, and ecosystems.

- Syros Island of the Cyclades complex in Greece, where drought impacts primarily concern local ecosystems, environmental quality and agriculture. The latter is a vital ingredient of the local economy and an important pillar in achieving a more balanced and sustainable economic development.

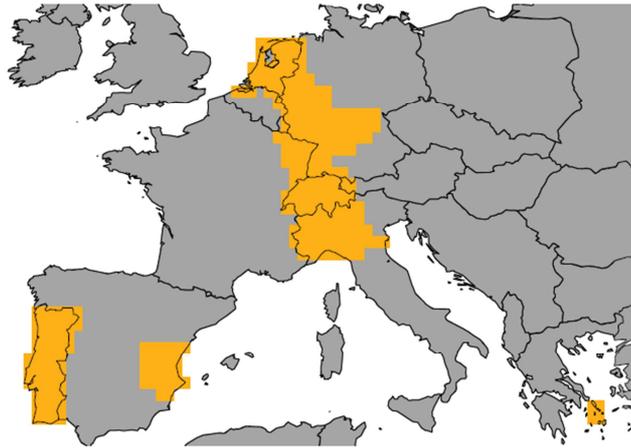
## 2.2. WATCH data

In this study we used the following data from the WATCH project: (i) time series of gridded daily meteorological data stored WATCH Forcing Data (WFD) (Weedon et al., 2011), and (ii) time series of gridded runoff that were simulated with a suite of large-scale models (Haddeland et al (2011).

The Watch Forcing Data (WFD) is a gridded global meteorological data set covering the period 1901-2001. For this study we only used the second part of the dataset covering the period 1958-2001. The dataset covers the land surface (minus Antarctica) of the Earth. The globe was divided in grid cells of 0.5 by 0.5 degree, resulting in a total of 67240 cells. For these cells several variables are available on daily and sub-daily time scales. For the trend study we used time series of gridded daily precipitation and temperature. The dataset has a 0.5 by 0.5 degree grid.. The data have been generated (i.e. re-analysis data) by combining the Climatic Research Unit's (CRU) monthly observations of temperature, wet days and cloud cover, plus the GPCCv4 monthly precipitation observations, and the ERA-40 reanalysis products (Uppala et al., 2005). The ERA-40 dataset is available for the period 1958-2002 (Uppala et al., 2005). For more details the readers are referred to (Weedon et al., 2011).

Gridded runoff on a global scale simulated with several large scale models (Global Hydrological Models, GHMs, and offline Land Surface Models, LSMs) on a 0.5° grid was available to assess low flows and drought characteristics in the Case Study areas. All models used a similar setup, which included the use of WFD as forcing (Haddeland et al., 2011). Simulated runoff data were available for the period 1963-2001, allowing a warming-up period for the models of 5 years. The total amount of water discharged per cell was considered, i.e. the simulated daily total runoff  $Q_{tot}$  was calculated by adding the surface  $Q_s$  and sub-surface  $Q_{sb}$  runoff. We calculated the multi-model ensemble mean runoff to reduce the effects of the different model' structures. The ensemble model mean composed of the following large-scale models: H08, HTESSSEL, JULES, LPJ, MPI-HM, Matsiro, Mac-PDM, Orchidee and WaterGAP. For more details the readers are referred to Haddeland et al. (2011) and Alderlieste and Van Lanen (2012).

Gridded time series of meteorological and runoff data for the Case Study areas were retrieved from the WATCH global dataset. The data for the cells covering the Case Study areas have been selected based on their coordinates. The bounding box coordinates (latitude, longitude) are given by Alderlieste and Van Lanen (2012). In total data from 244 unique cells were retrieved (some cells occur in two Case Study areas, i.e. overlapping areas in Switzerland and the Po basin). The Júcar basin, The Netherlands, Po basin, Portugal, Switzerland and Syros consist of 24, 30, 45, 49, 27 and 4 cells, respectively. In addition 108 cells were selected for the Rhine basin (Fig. 2.2). The Rhine basin was selected in addition to the DROUGHT-R&SPI Case Study areas to obtain a north-south cross section over Europe, which complements the west-cross section over Europe (Portugal-Júcar-Po-Syros).



**Figure 2.2** Selected grid cells of the Case Study areas and the Rhine river basin from the WATCH dataset.

### 2.3. Meteorological and hydrological drought identification methods

This section introduces the meteorological and hydrological drought indicators that were used in the DROUGHT-R&SPI Case Study areas to investigate the trends in historic droughts. It starts with the Standard Precipitation Index and then it continues with hydrological indices (low flow and drought characteristics). For a comprehensive overview of the drought-associated indices, incl. an intercomparison across the world, readers are referred to Wanders et al. (2010).

#### 2.3.1. Standard Precipitation Index

The Standardized Precipitation Index (SPI) was developed by McKee et al. (1993). The SPI calculation is done with precipitation data, which is fitted to a two parameter gamma probability distribution. This distribution is then transformed into a normal distribution. The SPI is designed to quantify the precipitation deficits for multiple timescales. McKee et al. (1993) suggest calculating the SPI for 3-, 6-, 12-, 24-, and 48 month time scales. The longer timescale are sometimes used as a proxy for streamflow and groundwater droughts (Hayes, 1999). Because of the normalized distribution, wetter and drier climates can be represented and intercompared. A disadvantage of the SPI is the need for a long time series of observed data, and the possibility of trends in precipitation during this period (Hayes, 1999). SPI has gained importance over recent years as a potential drought indicator and is being used more frequently for assessment of drought intensity in many countries. The World Meteorological Organization (2009) has adopted the SPI as the best suitable indicator for meteorological drought.

The SPI has been used in the Júcar River basin, Portugal and the Island of Syros to define meteorological drought.

#### 2.3.2. Low flow characteristics

Runoff obtained from local observations and the large-scale models (Sect. 2.2) was directly analysed on trends. The flow analysis focussed on the evolution of mean annual and mean monthly flow characteristics. The following (low) flow characteristics were calculated, based on the original time-series of total runoff:

- May-November AM(7) and AM(30)  
The 7-day/30-day minimum runoff per year, over the period May to November.

- May–November AM(7) and AM(30) timing  
The calendar day on which the minimum 7-day/30-day runoff occurred each year, over the period May to November.
- mean annual flow  
The annual average runoff value.
- mean monthly flow  
The monthly average runoff value (January, February, ..., December).

The reason for choosing the May–November period for calculating low flow indices is to ensure that only summer low flows (driven by low rainfall/high evapotranspiration) were considered, and not winter low flows caused by storage in ice and snow. Mixing processes in this way would hamper the interpretation of the results (Stahl et al., 2010; Stahl et al., 2012).

### 2.3.3. Drought: threshold method

In addition to the analysis of runoff data directly (Sect. 2.3.2) on trends, an analysis of drought was performed by identifying anomalies in the gridded time series of total runoff. One approach to define drought is by determining the degree of departure from normal for a given variable of interest such as precipitation, soil moisture, groundwater level or discharge (Tallaksen and Van Lanen, 2004). In this study, anomalies in simulated total runoff (sum of surface and sub-surface runoff) were used to determine hydrological drought. The method chosen to identify drought events was the threshold level method (TLM) (Yevjevich, 1967; Hisdal et al., 2004).

With the threshold method, drought occurs when the variable of interest (e.g. runoff, streamflow, precipitation) is below a predefined threshold level. A drought starts when the runoff falls below this thresholds, and it continues until it exceeds the threshold again (Hisdal et al., 2004). As the simulated runoff often shows a seasonal behaviour, a variable threshold was introduced i.e. monthly thresholds were calculated in this study by calculating the mean monthly flows. Based on these monthly flow values, a flow duration curve was calculated for each month to define the threshold levels. To avoid sudden "jumps" in the threshold, these monthly threshold values were smoothed using a 31-day sliding window (15 days post and 15 days prior) to get a smoothed threshold as proposed by Van Loon et al. (2010). In this study we used the 20<sup>th</sup> percentile (Q20) as threshold value to be consistent with the many other large scale studies. The Q20 is defined as the flow which is exceeded 80% of the time. The result of this approach is that droughts are identified in each grid cell, regardless of the hydrological regime. In Section 5.2 we discuss the impact of using another threshold on the trends in historic drought. The simulated daily runoff with the large-scale models was also smoothed to reduce peaky behaviour. As the output of the models can show strong daily fluctuations, the runoff was smoothed with a 15-day moving window (7 days post and 7 days prior) for the drought analysis. With the smoothed daily runoff and the thresholds calculated, droughts were identified. Short/minor droughts were excluded by only considering droughts with a duration of at least three days.

Drought characteristics commonly derived with this method are: beginning, end, duration, deficit volume, minimum flow during an event and the intensity (Hisdal et al., 2004; Fleig et al., 2006). As this study focussed on possible trends, the following annual drought characteristics were calculated:

- number of drought events per year (year<sup>-1</sup>)
- average drought duration, i.e. average duration for all events occurring in a year (day)
- average deficit volume, i.e. average of deficit volume of all events occurring in a year (mm)
- average intensity, i.e. average intensity of all events occurring in a year (mm/day)

### 2.3.4. Other methods

Some other methods than those earlier-mentioned (Sect. 2.3.1 – 2.3.3) have been applied to identify drought from the local, observed local hydrometeorological data.

#### Meteorological indicators

The following indicators associated with meteorological drought have been used in the Case Study areas:

- Júcar basin: the Accumulated Deviation of the annual Precipitation relative to the long term annual average precipitation has been used to identify drying and wetting phases over the period 1940-2009.
- Syros: the Rainfall Deciles have been applied to the Cyclades to which Syros belongs. The Rainfall Deciles is a simple meteorological drought index, in which the precipitation totals for the preceding three months are ranked against climatologic records. If the sum falls within the lowest decile of the historical distribution of 3-month totals, then the region is considered to be under drought conditions. The drought ends when: (i) the precipitation measured during the past month already places the 3-month total in or above the fourth decile, or (ii) the precipitation total for the past three months is in or above the eighth decile.
- Syros: the Reconnaissance Drought Index (RDI) has been used in the Cyclades. The Reconnaissance Drought Index (RDI) and more precisely through its standardised form (RDIst) was developed to approach the water deficit in a more accurate way, as a sort of balance between input and output in a water system (Tsakiris and Vangelis, 2005). The RDI is based both on cumulative precipitation and potential evapotranspiration.

#### Hydrological indicators

The following indicators associated with hydrological drought have been used in the Case Study areas:

- Júcar basin: the Standardised Reservoir Inflow Index was introduced. The calculation process is identical to that used for calculating the SPI (Sect. 2.3.1).

### 2.4. Trend detection

The Mann-Kendall test is often used for trend analysis of environmental time series, because it is nonparametric and therefore the data does not have to be normally distributed. The strength of this test is that it can also identify non-linear trends. An assumption of Mann-Kendall is that the data has no seasonality and is not auto correlated (Kendall, 1955). Mann and Kendall showed that even for a low number of observations the approach can be applied. The Mann-Kendall test gives no information about the magnitude of the trend. For this purpose the non-parametric Sen's slope estimator often is used (Sen, 1968).

To facilitate a relative comparison among the DROUGHT-R&SPI Case Study areas, the trend for each time series was expressed as the percent change over the period of record years relative to the mean for the period. This relative trend has the benefit that it allows for easy comparison.

Trends in observed and re-analysis meteorological data, and trends in observed river flow and simulated multi-model ensemble mean total runoff values were estimated with the Mann-Kendall test and the Sen slope.

For more details readers are referred to Stahl et al. (2010; 2012) and Alderlieste and Van Lanen (2012). The latter authors provide a flowchart describing all the steps taken for the trend analysis study using the data from the WATCH dataset.

### **3. Analysis of historic drought using local hydrometeorological and historic data**

This chapter that addresses past drought, includes two different approaches: (i) trend analyses of observed hydrometeorological (i.e. instrumental records), and (ii) use of historic archives.

#### **3.1. Instrumental records**

Trends in observed hydrometeorological (i.e. instrumental records) are dealt with for each DROUGHT-R&SPI Case Study area in this section. Which observed variables were considered varied per Case Study area and it was dependent on nature of the catchment and the availability of the data. Hence a consistent analysis was carried out in parallel using the same trend analysis approach everywhere (Sect. 3.4) and the same data source (WATCH dataset) (Chapter 4),

##### **3.1.1. Júcar River basin<sup>3</sup>**

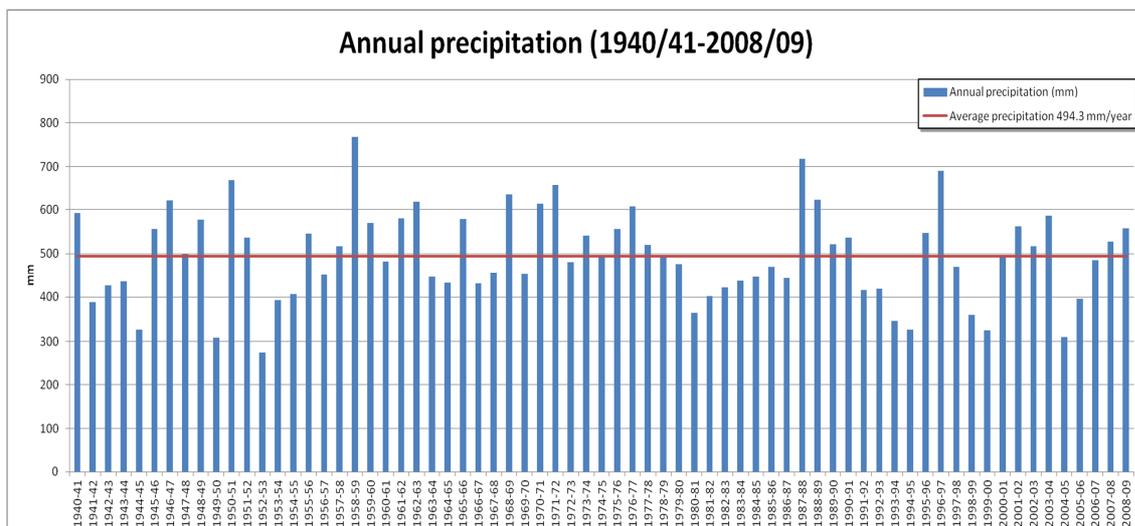
The characterization of drought events in the Júcar River Basin was done from both, meteorological and hydrological, perspectives. The meteorological approach studied the evolution of precipitation, and the hydrological approach takes into account the river flow and the stored volume in reservoirs. The Júcar river basin territory spans over three different climatic regions (climatic index, UNESCO), i.e. humid, sub-humid and semi-arid. The upper part of the basin corresponds to humid and sub humid regions, the mid part traverses a semi-arid region and the lower crosses a sub-humid region again. Due to the climatic characteristics of the Júcar River Basin, and the high intra-annual variability, drought were analysed on an annual basis since a lower temporal scale would result into a high frequency of droughts. Another reason for an annual study of drought occurrence is the capacity of the reservoirs existing in the basin, since they can store water for several years and release it during dryer periods. Moreover, the main concern at the Júcar River Basin Authority is operative droughts, those situations when water demands cannot be fully supplied due to the lack of available water, either in reservoirs or streams. The characterization of the historical droughts in the Júcar River is done with time series of annual values for the period covering the hydrological years from 1940/1941 to 2008/2009.

#### **Meteorological drought characterization**

The characterization of meteorological droughts has been done with regard to the precipitation over the whole territory of the Júcar River Basin Authority, from which the Júcar River Basin itself represents about the 50% of the total surface (22 000 km<sup>2</sup>). Figure 3.1 shows the evolution of the annual precipitation in the territory of the Júcar River Basin Authority. The average annual precipitation is 493 mm, with a standard deviation of 104 mm and a variation coefficient of 21%. Annual precipitation was below average in 36 occasions (52%). It should also be stressed that there is a high probability of having two or more years in a row with precipitation below average. For instance, since the 1970s, four of these periods have occurred with a period lasting 8 years in the 1980s.

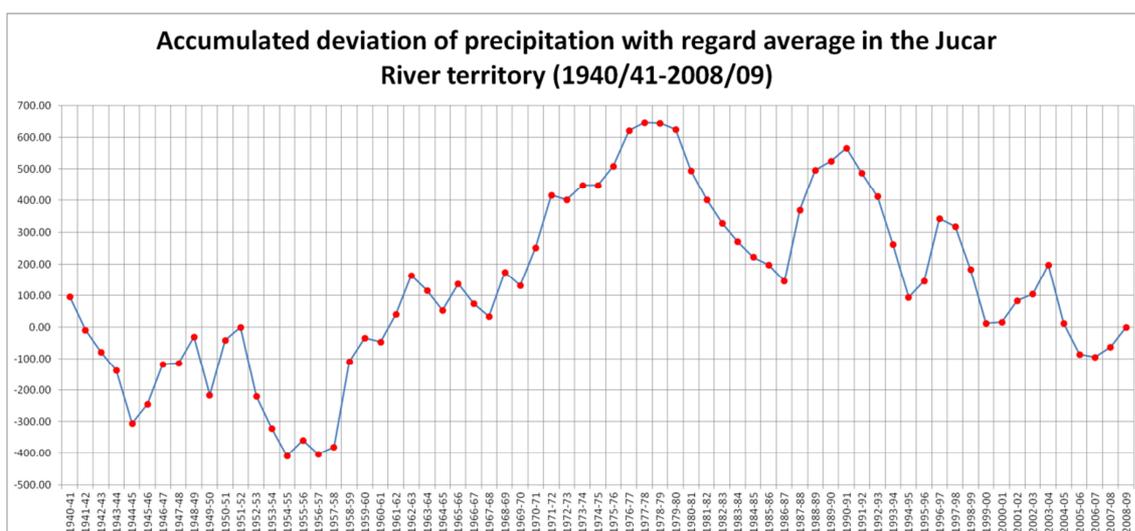
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<sup>3</sup> This section is based upon a technical note by: Andreu, J., Haro, D., Paredes, J. and Solera, A. (2012): Analysis of historical drought using local hydrometeorological data, characterization of droughts for the Júcar River Basin (Spain), Universidad Polytechnica de Valencia, Spain.



**Figure 3.1** Annual precipitation over the territory of the Júcar River Basin Authority.

For identifying dry and wet cycles it is useful to analyse the curve of the accumulated deviations from the mean annual precipitation representing the alternation between wet cycles (ascending parts) and dry cycles (descending parts). Figure 3.2 shows this curve, and Table 3.1. summarizes the cycles.



**Figure 3.1** Accumulated deviation of precipitation with regard the average in the territory of the Júcar River Basin Authority.

From the analysis presented in Table 3.1 it is important to emphasize that in the hydrologic years from 1940/41 to 2008/2009 there have been 7 periods with precipitation above average (wet) and 7 periods with precipitation below (dry). However, there is no a specific temporal duration pattern.

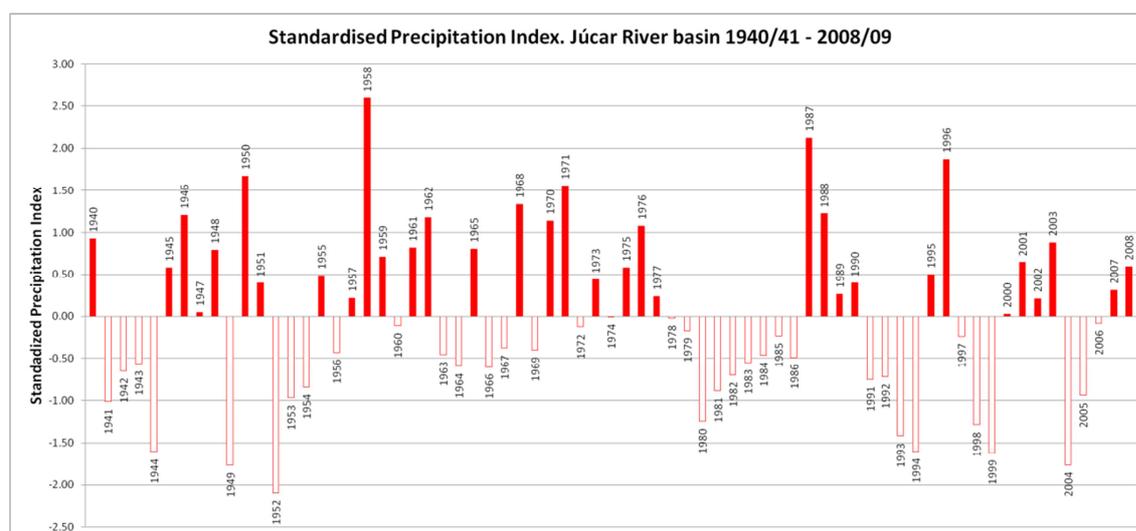
**Table 3.1.** Wet/Dry cycles distribution in the territory of the Júcar River Basin Authority (1940/41-2008/09)

Period	Length (years)	Type of cycle	Average precipitation (mm)
1940/41-44/45	5	Dry	433
1945/46-51/52	7	Wet	538
1952/53-54/55	3	Dry	358
1955/56-62/63	8	Wet	566
1963/64-67/68	5	Dry	468
1968/69-77/78	10	Wet	555
1978/79-86/87	9	Dry	439
1987/88-90/91	4	Wet	599
1991/92-94/95	4	Dry	376
1995/96-96/97	2	Wet	618
1997/98-99/00	3	Dry	384
2000/01-03/04	4	Wet	540
2004/05-06/07	3	Dry	397
2007/08-08/09	2	Wet	542

The length and intensity of dry periods has been quantified through the Standardized Precipitation Index (Sect. 2.3.1). The severity of the meteorological drought was defined by the magnitude of the SPI. Additionally, for defining the dry periods and their magnitude, the following criteria were followed:

- the dry period starts when the SPI value, or the accumulated of several years is negative and lower than -0.84 and ends when SPI reaches positive values.
- severity of a dry period corresponds to the sum of the SPI value of each of the years in the dry period.

Figure 3.3 shows the evolution of SPI in the period 1940/41 – 2008/09, and Table 3.2 groups the drought periods of more than three years in a row.



**Figure 3.2** Evolution of the Standardized Precipitation Index (SPI) in the territory of the Júcar River Basin Authority.

**Table 3.1** Intensity of meteorological droughts in territory of the Júcar River Basin Authority (1940/741-2008/09)

Period	Length (years)	Period Average SPI	Average classification	Accumulated SPI	Accumulated classification
1941/42-44/45	4	-0.96	Moderate	-3.84	Extreme
1952/53-54/55	3	-1.30	Severe	-3.91	Extreme
1978/79-86/87	9	-0.53	Minor	-4.76	Extreme
1991/92-94/95	4	-1.12	Moderate	-4.49	Extreme
1997/98-99/00	3	-1.05	Moderate	-3.15	Extreme
2004/05-06/07	3	-0.93	Moderate	-2.79	Extreme

Even though the most important recent drought period in the Júcar River basin was the period from 2004/05 to 2007/08, this cannot be observed in the meteorological characterisation of droughts. The reason is that the data used correspond to the precipitation over the whole territory of Basin Authority, which comprises almost 44,000 km<sup>2</sup>. The spatial variability of the precipitation partly hides the severity of the different drought periods. However, for operational purposes, it is more important to analyse the hydrological drought (to be characterised next), specifically the inflows to reservoirs which will in the end determine the amount of water availability.

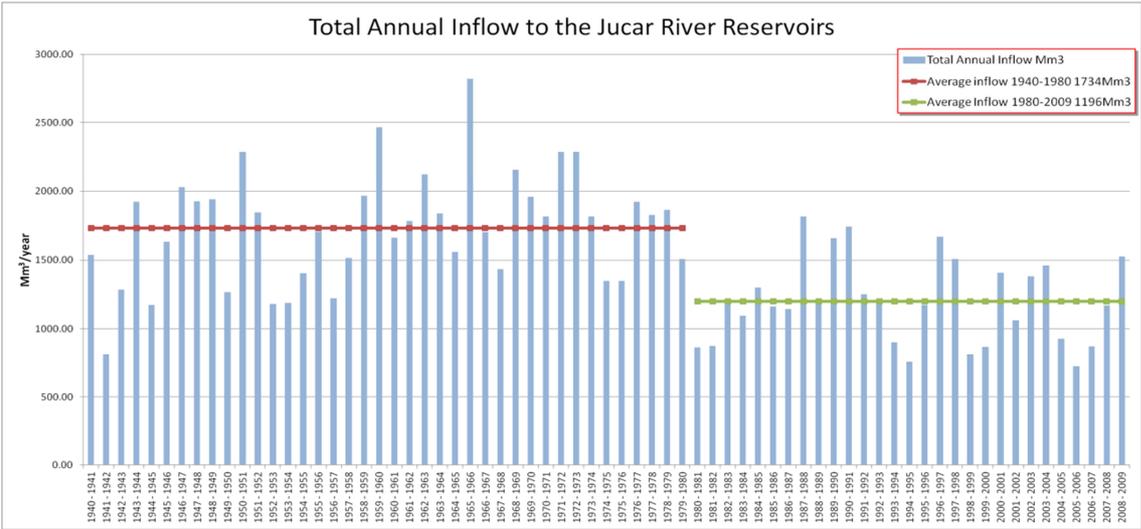
**Hydrologic drought characterization**

For the hydrologic characterization of droughts, the following data were used:

- inflows into the reservoirs existing in the river in natural regime generated by the SIMPA model for the period 1940/41 – 2008/09.
- average annual volume stored in the main regulation infrastructures (reservoirs of Alarcón, Contreras and Tous).

Inflows in the reservoirs

Figure 3.4 shows the total annual inflows to the Júcar River reservoirs for the period 1940/01 – 2008/09.



**Figure 3.3** Total annual inflow to the reservoirs of the Júcar River.

The analysis of the temporary distribution of inflows stresses the following facts:

- from 1980 a strong sudden decrease in the annual inflow can be observed. The average annual inflow before 1980 is 1734 Mm<sup>3</sup>/year and after is 1196 Mm<sup>3</sup>/year. At present, the decrease in the average inflows from 1980 is accepted as a permanent fact and calculations regarding drought are done considering two separate periods.
- from the 69 years period analysed, 33 years had an inflow higher than their corresponding period average value and 36 had it lower. Until 1979/80, 19 years had inflows lower than the first period average and from 1980/81 onwards there were 17 years lower than the second period average.

To determine the severity and duration of the cycles of minimum inflow, and comparing them with the cycles of minimum precipitation and mean annual stored volume in reservoirs, a "Standardised Inflow Index" was used. The calculation process is identical to that used for calculating the SPI, but using the higher average for the period 1940/41-79/80 and the lower for the period 1980/81-08/09. The results for the Júcar River basin are shown in Figure 3.5. Furthermore the cycles of two or more years with negative standardized inflow index are grouped in the Table 3.3.

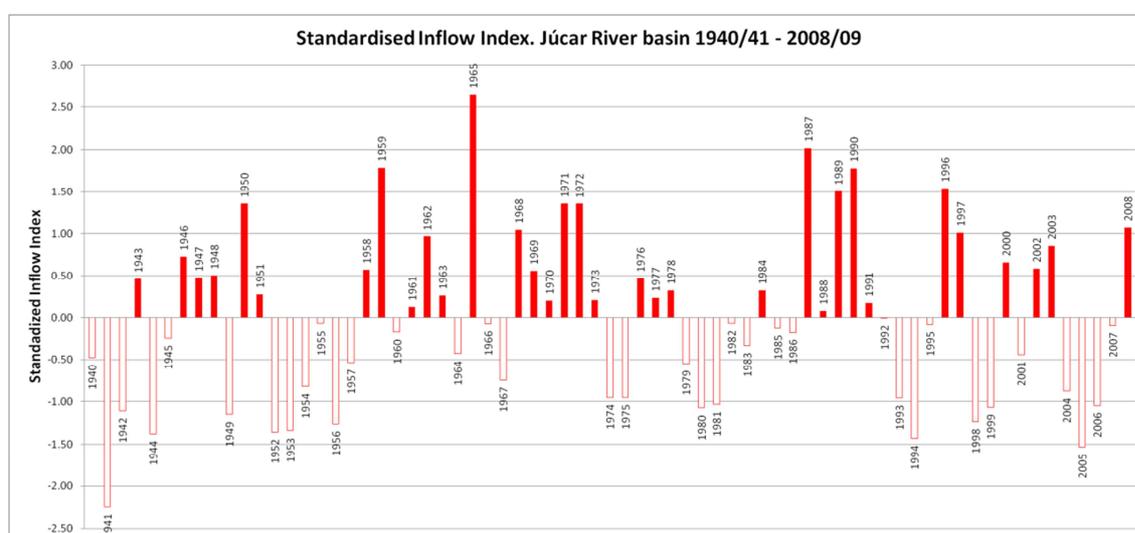


Figure 3.4 Standardised Inflows Index for the Júcar River Basin.

Table 3.2 Characteristics of dry cycles longer or equal than two years

Period	Length (Years)	Mean Annual Inflow (Mm <sup>3</sup> /year)	Deviation respect period average (%)	Mean Annual Standardised Index
1940/41-1942/43	3	1211	30	-1.28
1944/45-1945/46	2	1402	19	-0.81
1952/53-1957/58	6	1366	21	-0.90
1966/67-1967/68	2	1566	10	-0.41
1974/75-1975/76	2	1344	22	-0.95
1979/80-1983/84	5	1104	8	-0.61
1985/86-1986/87	2	1150	4	-0.15
1992/93-1995/96	4	1006	16	-0.62
1998/99-1999/00	2	841	30	-1.15
2004/05-2007/08	4	923	23	-0.88

The most intense cycle with a rather short length is 1998/99-1999/00. The period 1952/53-1957/58 has longer duration but was less intense. The last drought started in 2004/05 and lasted for 4 years being the second most intense drought on the record.

### Stored volumes in the main regulation infrastructures

The main regulation infrastructures in the Júcar River basin are the reservoirs of Alarcón (since 1959), Contreras (since 1972) and Tous (since 1994). The first two are located at the upper part of the Júcar River and the Cabriel River, the main tributary of the former, and stored all the inflows generated at the most humid area of the basin. They have the highest storage capacities of all the basin reservoirs. The Tous reservoir is located before the river enters the Plain of Valencia, downstream, the river crosses the plain before reaching its mouth. Although there are more reservoirs located on the river, the three mentioned are the ones which regulate the flows in the system. The rest of reservoirs are of less importance or for hydropower production and, therefore, their influence is lower.

**Table 3.3** Cycles of dry inflows in the Júcar River basin (Negative Standardised Index). Negative values are in red for the Júcar, and in green for the other reservoirs

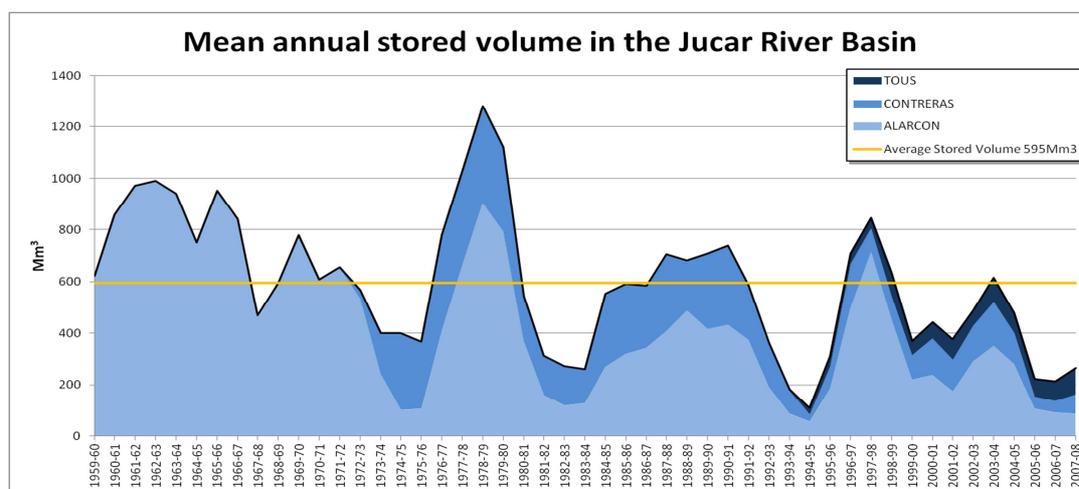
	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	
Jucar River	Red	Red	Red	Red	Red	Red			Red				Red	Red	Red	Red	Red	Red	Red		Red				Red		Red	Red								Red
Alarcón		Green	Green	Green	Green	Green			Green	Green			Green	Green	Green	Green	Green	Green							Green		Green	Green								Green
Contreras		Green	Green	Green	Green	Green			Green	Green			Green	Green	Green	Green	Green	Green							Green		Green	Green								Green
Tous		Green	Green	Green	Green	Green			Green	Green			Green	Green	Green	Green	Green	Green							Green		Green	Green								Green

	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	
Jucar River	Red				Red			Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red																	
Alarcón	Green				Green			Green	Green	Green	Green								Green																	
Contreras	Green				Green			Green	Green	Green	Green								Green																	
Tous		Green			Green	Green	Green	Green								Green																				

The Standardised Inflow Index also was computed for the separate inflows to each of the main regulation infrastructures in the Júcar River basin. Table 3.4 shows the cycles where the Standardised Inflow Index was negative.

Figure 3.6 shows the temporal evolution of the mean annual volume stored in the three reservoirs for the period 1959/60 – 2007/08.



**Figure 3.5** Mean annual stored volume in the three main reservoirs of the Júcar River Basin.

The capacity of regulation in the Júcar River basin is approximately 2586 Mm<sup>3</sup> (Tous was not operative until 1994). During the investigation period the average stored volume was 595 Mm<sup>3</sup>, 23% of the total capacity. The temporal distribution of the stored volume is logically similar to total annual precipitation and inflows with predominance of years below average and an irregular temporal distribution.

The cycles of minimum stored volume were determined by elaborating a standardized index for the mean annual stored volume identical to the calculation of SPI. Table 3.5 shows the periods of minimum mean annual storage (with negative index value), for the whole basin and the three studied reservoirs separately.

**Table 3.4.** Cycles of minimum mean annual storage in the main reservoirs of the Júcar River basin (period 1959/60-2007/08). Negative values are in red for the Júcar, and in green for the other reservoirs

	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09		
Total																																								
Alarcón																																								
Contreras																																								
Tous																																								

## Conclusions

Drought cycles (meteorological and hydrological) in the Júcar River basin were identified as those series of years which start with an accumulated SPI lower than -1.28 and a Standardised Inflow Index that is negative. The cycle ends when the Standardized Inflow Index is positive again.

**Table 3.5** Characteristics of drought periods identified for the Júcar River basin

Period	Length (year)	MP (mm)	mP (mm)	%DMP	MI (Mm <sup>3</sup> )	ml (Mm <sup>3</sup> )	%DMI	MV (Mm <sup>3</sup> )	mV (Mm <sup>3</sup> )	%DMV
1940/41-42/43	3	468.32	387.82	-8.16	1210.60	813.40	-30.19	ND	ND	ND
1952/53-58/59	6	478.75	274.40	-6.12	1451.60	1177.47	-16.29	ND	ND	ND
1980/81-84/85	4	413.66	363.57	-12.50	1061.23	864.82	-11.29	389.22	259.90	-17.30
1992/93-95/96	4	409.24	326.35	-13.43	1005.87	754.38	-15.92	241.81	110.10	-48.62
1998/99-99/00	2	341.70	814.77	-27.72	841.35	814.77	-29.67	501.55	369.10	6.57
2004/2005-07/08	4	429.22	723.81	-9.20	923.13	723.81	-22.84	295.33	213.10	-37.25

**MP:** Mean annual precipitation of the period in mm; **mP:** Precipitation in the driest year of the period; **%DMP:** Deviation percentage of MP from average; **MI:** Mean annual inflow of the period; **ml:** Inflow in the driest year of the period; **%DMI:** Deviation percentage of MI from average; **MV:** Mean annual stored volume in the period; **mV:** Lowest annual stored volume in the period; **%DMV:** Deviation percentage of MV from average; **ND:** No data

A negative value of the index of mean annual stored volume is not a drought indicator. Usually meteorological and hydrological drought cycles coincide with, and are the cause of, periods of minimum storage. However, there are humid periods which also register mean annual storage values below average. The reason to this is that the stored volume in reservoirs responds to other conditions, other than drought as a natural hazard, namely, to human-controlled operation rules (including the controlled storage during the first years of operation for security reasons), the volume and type of demands supplied, and the requirement of emptying reservoirs for flood protection (very relevant for the in Tous Reservoir).

Under the established conditions 6 drought cycles can be identified for the Júcar River basin with characteristics shown in Table 3.6.

### 3.1.2. The Netherlands

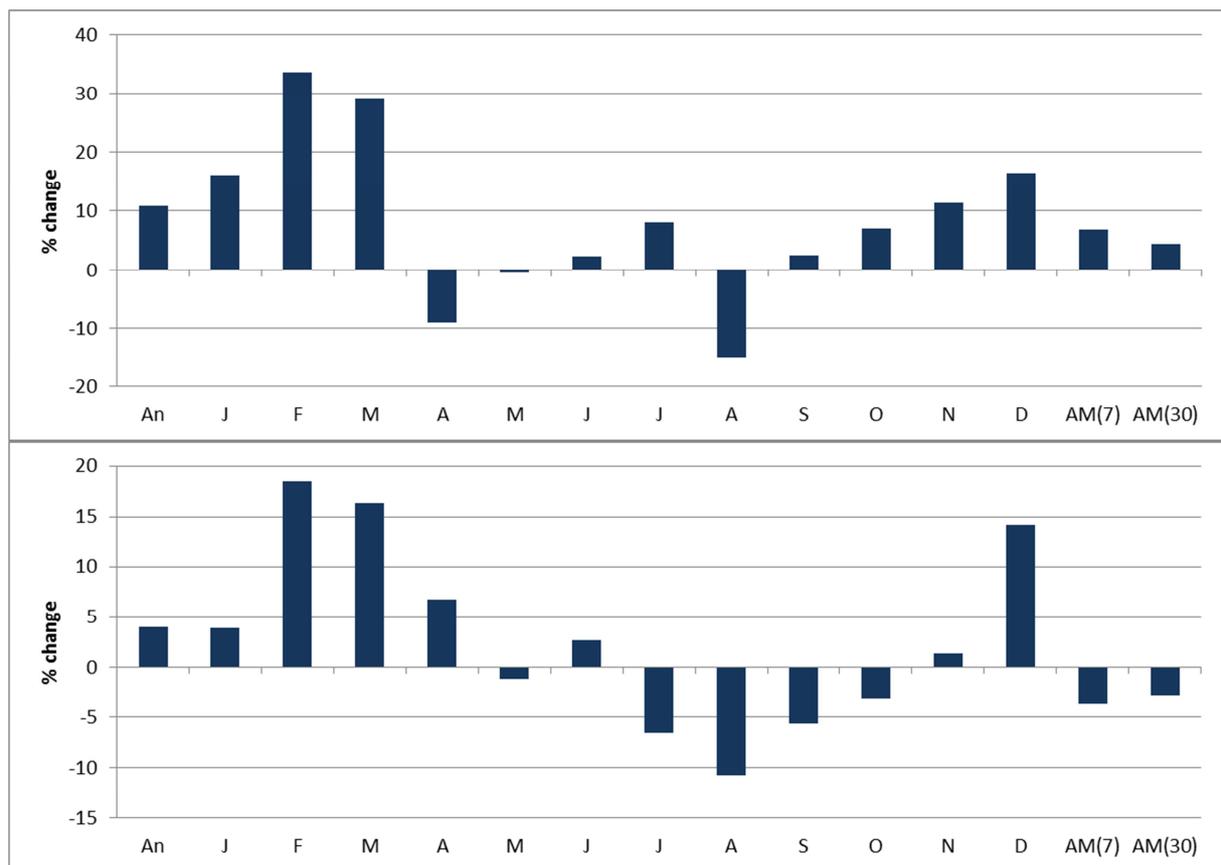
#### Meteorological drought characterization

Based on the measurement network of the Netherlands Royal Meteorological Institute (KNMI), trends in temperature were estimated. It appeared that the temperature trend in The Netherlands (for periods > 10 years) was in line with the trend in average global temperature.

Precipitation trends were determined for two periods, i.e. 1910-2009 and 1951-2009 using at least over 100 precipitation series. The study shows an increase in annual precipitation of 172 mm (25%) over the period of 1910 to 2009. This increase is for almost all stations (97%) significant. Both in the period 1951-2009 and the period 1910-2009 the trends are positive. The increase in annual precipitation and summer precipitation is strongest in the north-western part of The Netherlands. For more information, readers are referred to Alderlieste and Van Lanen (2012).

#### Hydrological drought characterization

Alderlieste and Van Lanen (2012) determined trends in observed river flow for the River Berkel (east Netherlands) and River Rhine (Lobith, where it enters the Netherlands) (Fig. 3.7).



**Figure 3.7** Trend in annual (An) and monthly discharge (A, F, ....D) and 7-day and 30-day annual minimum flow (AM(7), AM(30)) (all in % change) obtained from the observed river flow, upper: River Berkel (1958-2000) and lower: River Berkel (1901-2010).

Trends were determined using the methods that are described in Sections 2.3.2 and 2.3.3. Trends in observed annual river flow are positive. The increase is about 5% for the River Rhine and slightly over 10% for the River Berkel (Fig. 7, most left bar). The trend in increasing flow mainly occurs in the winter season. For the River Rhine this holds for the months November to April (Fig. 7, lower graph) and for the River Berkel is about the same period (September to March). The largest positive trends occur in February and March, i.e. about 15% for the River Rhine and around 30% for the River Berkel. For the summer months the trends are less clear. Not all months point in the same direction. In the River Rhine decreasing trends (up to -10%) were observed for the period July to October. In the River Berkel 3 out of 6 summer months have weak trends ( $< \pm 5\%$ ). The remaining months show both upward trends and downwards trends. August stands out with a decreasing trend from about -15%.

Trends in 7-day and 30-day minimum flow are negative for the River Rhine, implying that the low flows have decreased by about -3% (Fig. 3.7, two right bars). In the River Berkel positive trends occur (4-7%).

Trends in drought characteristics (e.g. average annual duration, average annual deficit volume, average annual drought intensity) is mostly negative, which points at less severe droughts. For example, the trend in annual drought intensity is about -20 and -30% for the River Berkel and River Rhine, respectively.

### **3.1.3. Po River basin**

#### **Meteorological drought characterization**

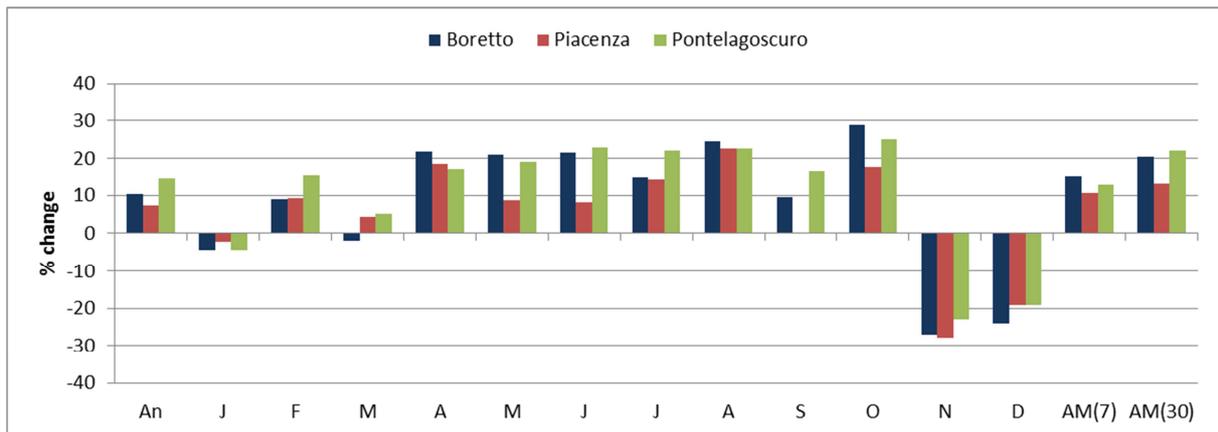
Alderlieste and Van Lanen (2012) determined trends in observed temperature and precipitation for the Po River basin, according to the method described in Section 2.4. Over the period 1987-2006 daily temperature of three meteorological stations was available, and over the period 1951-2008 monthly precipitation totals from nine meteorological stations were available for this study. Locations are given by Alderlieste and Van Lanen (2012).

Two temperature stations (Parma and Santo Stefano D'aveto) show the expected increasing trend in annual temperature (about 0.7°C), whereas for the third station (Santa Maria del Taro) a decreasing trend was found (-0.3°C). In the two stations with increasing trends all months have increasing trends (March in Parma is an exception). The strongest trend was found in the June temperature (about 1.5°C). In the station Santa Maria del Taro the months in the period August-March have no or negative trends. In the summer period (April-July) the expected increasing trends occur. The largest increase (0.9°C) was reported for June.

The annual precipitation has decreased in all nine stations. The negative trends vary from -0.1% (Ponte Becca Po) to -10.1% (Pontelagoscuro). Direction of trends in precipitation is very similar for all nine stations, but varies among the months. For example, all stations show strong negative trends in February (about -40%), March (-45 to -50%), June (-35 to -45%), and July (-25 to -45%). In April, August and November declining trends are smaller (about 0 to -15%). However, increasing trends in precipitation were also reported. In all stations increasing trends were found for May, September, October and December. In January seven stations reveal increasing trends.

#### **Hydrological drought characterization**

Alderlieste and Van Lanen (2012) determined trends in observed river flow for the River Po. Three gauging stations (Boretto, Piacenza and Pontelagoscuro) have daily discharge measurements in a common period (1947-1990) that was sufficiently long for trend analysis. Figure 3.8 gives the trends for the three gauging stations.



**Figure 3.8** Trend in annual (An) and monthly discharge (A, F, ...,D) and 7-day and 30-day annual minimum flow (AM(7), AM(30)) (all in % change) obtained from the observed river flow at three location in the River Po (1947-1990).

The decrease in observed annual precipitation and increase in observed annual temperature (likely leading to a higher potential evapotranspiration) in two out of three stations is not reflected in the annual river flow. A decreasing trend was expected, but in all three gauging stations an increase was found (Fig. 3.8, most left cluster of three bars). The increase varies from 7 to 15%. Trends in monthly flow show a clear flow increase (usually over 10%) in the summer period (April-August), whereas a strong decrease was found for November (over -20%) and for two stations also in December. The flow increase during the summer months is also reflected in the k-day annual minimum flow (Fig. 3.8, two most right clusters of three bars). The increase is at least more than 10%. Trends in monthly flow over the period 1947-1990 are certainly affected by reservoir operation (distribution over water storage and release over the year).

The threshold method (Sect. 2.3.3) was applied to calculate trends (Sect. 2.4) in drought characteristics using the observed river flow as input. The analysis showed that the number of drought events per year clearly declined (about -25 to -40%). The remaining droughts increased in length (about 10 to 30%), but the deficit volume decreased in two gauging stations (3 to 22%). In Pontelagoscuro the deficit volume increased by about 10%.

### 3.1.4. Portugal<sup>4</sup>

#### Meteorological drought characterization

Mainland Portugal is located on south-western Europe, on the Iberian Peninsula, between latitudes 37° and 42° N, in the transitional region between the sub-tropical anticyclone and the sub-polar depression zones. The geographic location of mainland Portugal and its associated climate variability is favourable to the occurrence of regular drought episodes, especially in the south. Analysis of events that occurred during the last century shows an increase in drought frequency and intensity since the 1980s, particularly from February to April (Do Ó, 2005). A regional study (49 weather stations for southern Portugal) using SPI analysis also shows that drought occurrence and respective severity seem to be

<sup>4</sup> This section is based upon a technical note by: Acacio, V., Rego, F., Dias, S. (2012): Quantitative analysis of historic drought, based on instrumental records - Case study analysis (Portugal). Centro de Ecologia Aplicada Prof. Baeta Neves, Instituto Superior de Agronomia (ISA-CEABN), Universidade Técnica de Lisboa.

higher during the second half of the period 1931-1999, particularly during spring, which highly influences the productivity of rain fed agriculture (Paulo et al. 2003).



**Figure 3.9** Location of the meteorological and gauging stations selected for case study analysis in mainland Portugal.

An analysis of droughts in mainland Portugal based on monthly precipitation data (SPI) from 1910 to 2004 presents three regions with different behaviours (the north, the centre and the south of Portugal), which are consistent with the precipitation spatial distribution in mainland Portugal, which generally decreases from north to south. The same analysis also shows an occurrence of more frequent cycles of dry events in the south than in the north (Santos et al. 2010).

**Table 3.6** Number of years registered with moderate to severe drought ( $SPI_{12} < -1$ ) and with weak/moderate to severe drought ( $SPI_{12} < -0,5$ ) in mainland Portugal for different periods from 1864 to 2011

Meteorological Station	Number of years below $SPI_{12} < -1$ and below $SPI_{12} < -0.5$ (between brackets)				
	1864-1900	1901-1940	1941-1970	1971-2000	2001-2011
Bragança	- (-)	- (-)	4 (7)**	1 (8)	4 (7)
Porto	6 (11)	7 (11)	4 (12)	2 (8)	4 (5)
Coimbra	8 (13)*	6 (8)	5 (11)	3 (9)	4 (5)
Lisboa	4 (9)	9 (20)	4 (8)	5 (13)	3 (3)
Beja	- (-)	- (-)	2 (4)	1 (8)	6 (10)

\* (for the period 1866-1900)

\*\* (for the period 1945-1970)

In the framework of the DROUGHT&SPI project, precipitation data was collected from the National Meteorological Service (Institute of Meteorology). Meteorological stations with the longest datasets of monthly precipitation were selected. Six stations were chosen that were distributed across a north-south gradient (Fig. 3.9). Main outcome is reported by Rego et al. (2013).

SPI12 (Sect. 2.3.1) was calculated for each of the 5 meteorological stations (Bragança, Porto, Coimbra, Lisboa and Beja) from 1864 to 2011 and then number years with a SPI12 below a certain magnitude ( $SPI12 < -1$  and  $SPI12 < -0.5$ ) were counted. Specific trends seem to take place for moderate to severe drought ( $SPI < -1$ ) for the last data period (2001 to 2011), with an increasing frequency after 2000 for all stations, except for Lisbon. For weak/moderate to severe drought ( $SPI12 < -0.5$ ) an increasing frequency is observed since 1941 for all stations, except again for Lisbon. Results also show an alarming trend for Beja, where in an 11 year-period (2001-2011), 6 years were moderate to severe drought years (more than half of the period).

### **Hydrological drought characterization**

Streamflow data was collected from the National Information System on Hydric Resources (SNIRH), a public national dataset provided by the National Water Authority (INAG). Gauging stations with monthly and daily streamflow data were selected based on 3 simultaneous criteria:

- near-natural streamflow (as least disturbed as possible), i.e., that did not include reservoirs, agricultural water withdrawals and groundwater abstractions;
- longest time series of recorded daily/monthly streamflow (minimum 30 years);
- small catchment area ( $< 1000 \text{ km}^2$ ) of the gauging station.

A large number of catchments were tested against the above-mentioned criteria. across mainland Portugal were visualized using GIS the criteria above. Finally, 11 gauging stations were selected for analysis, which are distributed across a north-south gradient in mainland Portugal (Fig. 1), covering the regional climatic gradient of the case study.

Trends in streamflow were estimated from the slope of the Kendall-Theil robust line (Sect. 2.3.3) and from the Regression slope for mean annual streamflow and mean monthly streamflow, for the selected gauging stations. Statistical significance of trends was tested with Spearman test (non-parametric).

Results show that significant trends are predominantly decreasing (i.e. reduced flow). Vascão in the south is the only gauging station with significant decreasing trends for annual streamflow, with an alarming value of about 5 mm decrease per year over a period of 51 years. March is the month with a higher number of stations (6 out of 11 gauging stations) that have a significant decreasing streamflow.

A recent study of 187 river basins shows an overall decrease in annual, winter and spring flows between 1945 and 2005 for most parts of the Iberian Peninsula, which could be associated with reduced rainfall and increased temperature observed in recent decades (Lorenzo-Lacruz et al. 2012). These authors also show that the highest decline rate is observed for some parts of the Guadiana basin, which is in accordance with the case study results.

#### **3.1.5. Switzerland<sup>5</sup>**

This section reports on two recent extreme droughts (i.e. 2003 and 2011) in Switzerland. No trend studies using observed data were described.

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<sup>5</sup> This section is based upon a technical note by: Gudmundsson, L. and Seneviratne, S. (2012): Characterisation of 2003 and 2011 Droughts in Switzerland - Natural Water Bodies, ETH-Zurich, Switzerland.

## Meteorological drought characterization

The 2003 drought in Switzerland was part of the pan European episode of exceptionally warm temperatures occurring that summer [Luterbacher et al., 2004]. In the Alpine region, this summer has been reported to be the warmest in the past millennium [Büntgen et al., 2006]. The summer of 2003 was also likely to be the driest in the past 500 years, characterised by a pronounced precipitation anomaly [Casty et al., 2005].

Due to their recent occurrence the dry episodes of 2011 are not yet covered by scientific literature or official reports. However, the Federal office for the Environment <sup>1 2 3</sup> and the Federal office for Meteorology and Climatology <sup>4</sup> have compiled a series of reliable online publications, characterising the 2011 drought. Overall, the 2011 drought was defined by two dry episodes. The first half of the year was characterised by abnormally low precipitation rates. The dry episode in spring was then finally interrupted by a comparably wet July. The second dry episode in 2011 was characterised by below average August precipitation.

<sup>1</sup> <http://www.bafu.admin.ch/dokumentation/fokus/11095/11332/index.html>, latest access: 26. July 2012

<sup>2</sup> <http://www.bafu.admin.ch/hydrologie/01834/02041/11404/index.html>, latest access: 26. July 2012

<sup>3</sup> <http://www.bafu.admin.ch/dokumentation/fokus/11095/11850/index.html>, latest access: 26. July 2012

<sup>4</sup> <http://www.meteoschweiz.admin.ch/web/de/wetter/wetterereignisse/herbsttrockenheit.html>, latest access: 26. July 2012

## Hydrological drought characterization

### 2003 Drought

The response of surface water bodies to the extremely warm and dry conditions in 2003 was reportedly complex. The discharge of some mesoscale rivers on the Swiss plateau was extremely low, especially in August and September. This was contrasted by above average discharges from highly glaciated headwater basins where melting ice caps released abnormally large amounts of water. The water levels of lakes have also been influenced by the extreme meteorological conditions. Even large lakes, where storage effects can buffer anomalies in the water input, have had exceptionally low water levels. Examples include the Lago Maggiore and Lake Constance, the latter of which had the lowest August and September water levels since the beginning of continuous observations in 1866.

Soil moisture observations at a research catchment in north-eastern Switzerland exhibited extreme anomalies in August 2003, corresponding to 2.8 standard deviations from the climatological mean, which triggered a reduced evaporative fraction (evapotranspiration/radiation) in August [Seneviratne et al., 2012].

In spring 2003 groundwater levels were exceptionally high, owing to intense precipitation in winter 2002/2003. These starting conditions did buffer some of the most adverse effect of the dry summer. Overall the response of ground water to the strong precipitation and temperature anomalies was highly influenced by the type and size of the aquifers as well as the source of recharge. The groundwater levels of precipitation fed catchments with shallow and highly conductive aquifers in southern Switzerland did drop below the long-term mean. This was contrasted by the fact that the majority of observed ground water levels on the Swiss plateau were larger than average. The groundwater levels in the valleys of larger Alpine rivers were above average due to large amounts of water released by melting snow and glaciers.

The extreme weather conditions in 2003 did substantially impact different aspects of water resources in Switzerland. Many of the effects on surface water bodies and ground water are documented in

comprehensive reports compiled for the Federal office for the Environment [BUWAL, 2004] and the Swiss Academy of Sciences [ProClim, 2005].

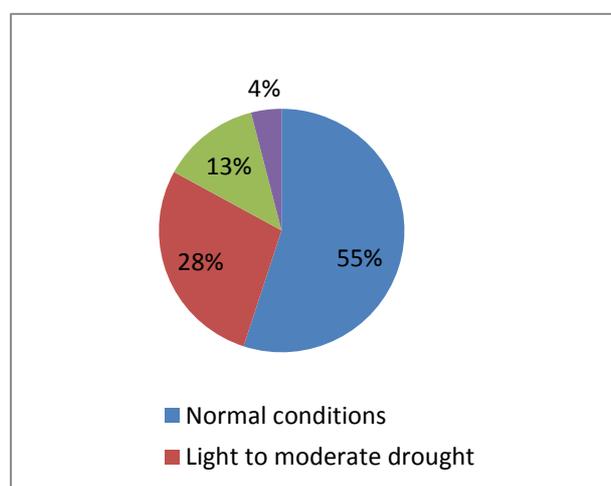
### 2011 Drought

The first half of the year was characterised by abnormally low precipitation rates. As a consequence, the spring water level of many rivers was well below the climatological mean. Also snow melt did not cause substantial relief, due to the small amount of snowfall in winter. Similarly, many lakes had below average spring water levels and groundwater levels were mostly reported to be below average. The wet July did cause some relief but the amount of precipitation was likely not sufficient to recharge all relevant terrestrial water storages such as groundwater or soil moisture [Mittelbach and Seneviratne, 2012]. The below average August precipitation combined with depleted storages due to the spring drought did lead to below average river flows in northern Switzerland throughout the following months. Similarly many (groundwater fed) lakes north of the Alps were reported to have water levels close to previously recorded minima.

### 3.1.6. Syros<sup>6</sup>

#### Meteorological drought characterization

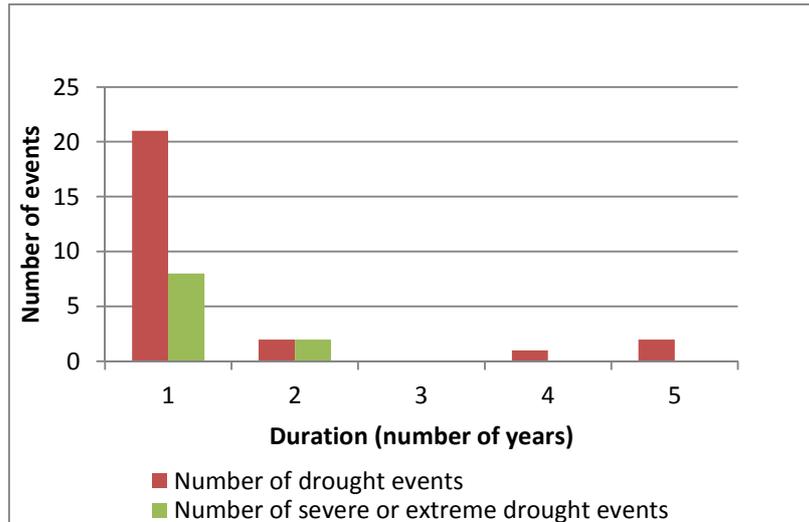
Several studies and papers described the drought hazard either for Greece or the Cyclades complex, where Syros belongs to. However, no drought study has been undertaken particularly for Syros Island. Tigkas (2008) analysed the drought hazard in the Cyclades for the period 1955-2002 using the Reconnaissance Drought Index (RDI, Tsakiris and Vangelis, 2005) for characterizing drought conditions. The main results are illustrated in Figures 3.10 and 3.11. Severe and extreme drought events account for 17% of drought episodes, whereas there were drought events that lasted up to 5 years and severe or extreme events with duration up to 2 years.



**Figure 3.10** Frequency of drought events for the period 1955-2002 (Tigkas, 2008).

Kanellou et al. (2008) assessed past drought conditions (meteorological drought for the hydrological years 1956 to 2001) in Naxos Island using three indices: Deciles, RDI and Palmer Z-index. Mild drought conditions have been estimated for the hydrological years 1959-1960, 1966-1967, 1982-1983 and 1985-1986. Severe droughts are estimated for the years 1957-1959, 1965-1966, 2000-2001, whereas extreme are characterized the years 1989-1990, 1999-2000.

<sup>6</sup> This section is based upon a technical note by NTUA (2012): Historic drought analysis based on instrumental records (Task 2.1): Syros Case Study. Preliminary results.



**Figure 3.11** Duration of consecutive drought years the period 1955-2002 (Tigkas, 2008).

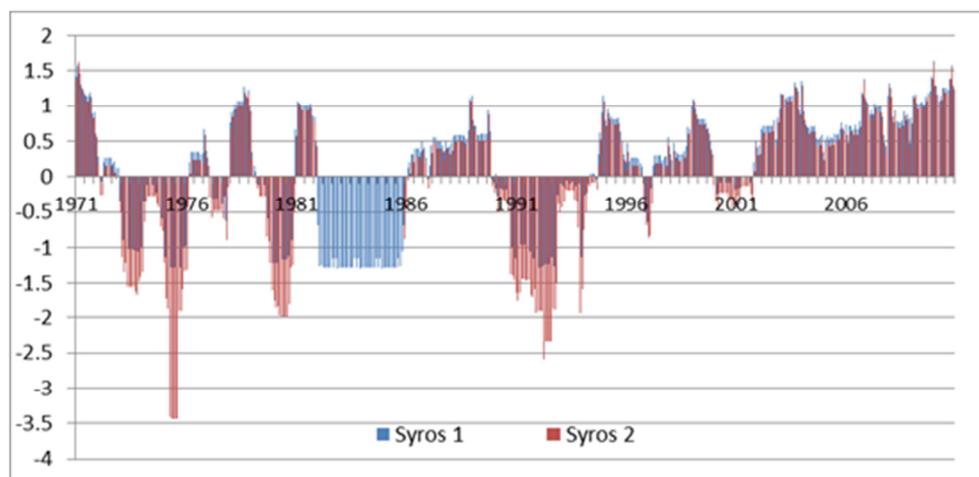
In the framework of the DROUGHTR&SPI project the following meteorological data were used:

- monthly precipitation data for the period 1970-2010;
- monthly temperature: data for the period 1970-2010 for Syros, and 1970-2003 for Naxos and Milos islands (island next to Syros).

The following methods were applied:

- Standard Precipitation Index (SPI);
- threshold analysis;
- trend analysis, using: (i) the Mann-Kendal Test, (ii) Sen's slope, and (ii) the percentage change relative to the mean.

The SPI index has been calculated for five different time scales (1, 3, 6, 9 and 12 months). The SPI12 is plotted (Fig. 3.12). Missing data are treated in two different ways.



**Figure 3.12** The Standard Precipitation Index for 12 months for Syros Island (1970-2010). Syros 1: missing data in 1982-1984 are included in the analysis as zero precipitation, and Syros 2 as missing data.

SPI12 for the Syros2 analysis (Fig. 3.12) shows that meteorological droughts ( $SPI_{12} < -1.5$ ) occurred in the first part of the 1970s (1971, 1973, 1975), late 1970s and early 1980s (1979, 1980), and first half of the 1990s (1991, 1992, 1994).

Trend analysis indicates a significant increasing trend in annual precipitation. In particular for the period August-December significant increasing trends were found. The annual temperature in Syros has slightly decreased, but trend is not significant. Significant trends in temperature occurred in April and August. Trends are opposite, i.e. -9% and +4%, respectively. The trend analysis for Naxos and Milos Islands indicate that there is no trend in precipitation and an increasing trend in temperature for spring and summer time.

## Hydrological drought characterization

Hydrological droughts have not been described because there is observable runoff in the Island of Syros.

### 3.2. The droughts of the historian

Instrumental records on hydrometeorological variables to investigate droughts in a reasonable spatial coverage are only available for the last one or two centuries. However, droughts left multiple milestones in the archives of the last 500 years because of their impacts on societies, they (Garnier, 2010).

Historic material includes;

- diaries: drafted by private persons (priests, middle-class persons, blue bloods);
- municipal chronicles: besides the private, economic and political events, they are often very sensitive to the extreme events;
- catholic church: *ex voto*, small naive paintings hung on in churches in France, in Spain, in Portugal and in Italy, are iconographic testimonies which tell very frequently the meteorological abnormality. Religious ceremonies allow the reconstruction of historic series. The Roman Catholic Church or the municipal authorities ordered these qualified ceremonies of rogations (*rogativas*) in Spain or processions in Portugal and in France to remove a situation putting in danger the established order or the socioeconomic balance. In the case of the droughts, they organized processions *pro pluvia*, literally ' for the rain '.
- precious municipal archives in war-spared cities. They contain the registers of the municipal deliberations and the accounts. These documents contain an inexhaustible deposit of climatic data.

#### 3.2.1. Evaluation of drought severity

The above-mentioned historic material offers two methodological approaches to estimate these natural drought events.

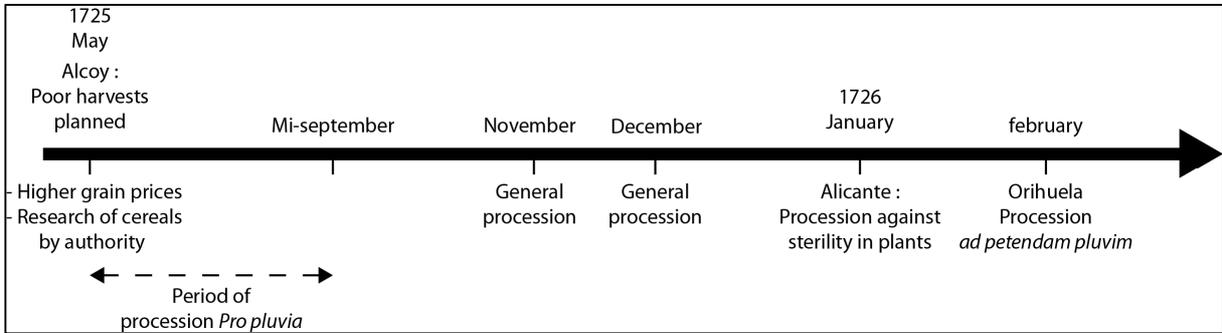
The first approach uses all the chronological mentions of a drought appearing in archives. Concretely, it is a question of noting, for example, the first mention of procession religious *pro pluvia*, then the municipal acts which evoke the drying up of the public fountains, the ban to draw some water from certain places, the layoff of weatmills and, in the most extreme cases, the problems of supply in wheat and wooden by the waterway. Naturally, this list is not exhaustive. However, the location of these milestones in archives allows proposing duration in days for the very great majority of past droughts. The drought duration defined by the historian does not correspond to a total absence of rain. but rather to its chronological perception by societies. Thereof, the drought of the historian indicates rather a very

dry and long episode with very important economic and human impacts to appear in the archives of the men.

The second methodological approach, which can complete the evaluation of the duration (approach 1), consists of creating an indexed scale of severity directly built according to the descriptive contents of the drought. Naturally, it results from a systematic inventory of the impacts engendered by the extreme event on societies. The list below lists the types of damage mostly evoked by archives about the droughts:

- rogation *pro pluvia*
- early Grape harvest dates
- plants dry and die
- no harvest of hay
- low water
- 'no rain' during the period
- drying up of springs
- ground is cracked
- we can ford a river
- layoff of weatmills
- forest fires
- cattle dies of thirst
- riots around the springs
- shortage of food or/and famine

Thus, the historian can observe the chronology of an event informed well in archives. Here, it is about a particularly grave drought which had affected the region of Valencia in 1725 and 1726.



**Figure 3.13** Assessment of drought duration and severity of the Júcar drought of 1725-1726.

These kinds of inventories are used to compile a severity scale (low to severe impacts, 1 - 5, respectively) as shows in Table 3.7. An index of -1 was been introduced for conditions that insufficient information was available.

Index 1 represents conditions that absence of precipitation (atmospheric or meteorological drought) begins to be felt. If these conditions continue, crops are affected and a fall in prices of water is observed in the records (index 2). Indices 3 and 4, characterize conditions that lack of resources become important. The situation deteriorates as the absence of precipitation affects societies with a high price of farm products, a layoff of weatmills and a degradation of the ecosystems (index 4). The paroxysm of the social crisis is reached with the conditions classified as index 5 when the drought turns in a severe

hydrological drought with a very clear living conditions worsening and an increase of the social tensions for the access to the water.

**Table 3.6** Indexed method drought severity (16-19<sup>th</sup> centuries)

Index	Descriptions	Types of drought
5	exceptional drought: no possible supply, shortage, sanitary problem, very high prices (prizes) of the wheat, the forest fires).	hydrological drought
4	severe low-water mark: impossible navigation, layoff of weatmills, research for new Springs, forest fires, died from the cattle	hydrological drought
3	general low-waters ( difficulties for navigation) and water reserves	phreatic drought
2	local low-waters of rivers, first effects on the vegetation	edaphical drought
1	absence of rainfalls: rogations, evidences in texts	atmospheric drought
-1	insufficient qualitative and quantitative information but the event is kept in the chronological reconstruction	

Drought types are not independent. The absence of rainfall results from an atmospheric drought. The ground dries out more quickly because of the wind and of the heat. Slower or quicker, the water resources decrease, the drought becomes first phreatic then hydrologic. Drought propagates through the hydrological system (e.g. Van Loon and Van Lanen, 2012).

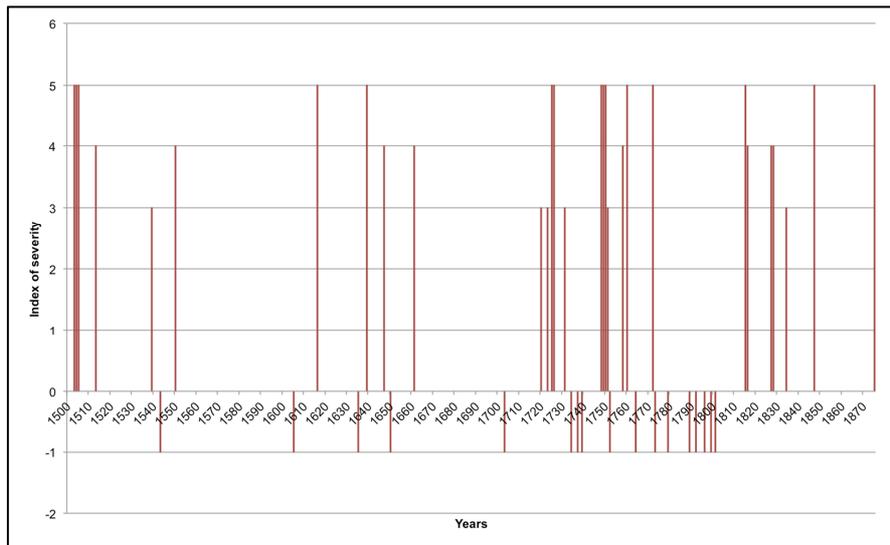
Finally, a database is built. Part of such a database for the Júcar Basin is given in Table 3.7.

**Table 3.6** Extract from the historical database for the Júcar Basin

Location	River	Year	Date	Comments	Relative duration	Severity index
Valencia	Júcar Basin	1412		<i>Que com per esguard de la seccada e sterilitat el any present, que per nostras paccats era estada en aquestra ciutat</i>	1 year	5
Orihuela	Segura	1726	Februar	<i>Rogativas ad petendam pluviam</i>	30 days	2
Valencia	Júcar Basin	1815-1816		<i>Las sequais extraordinarias de 1815 y 1816, las que dieron margen a abusos tan considerables y a tanta indigencia que à cado paso se veia uno asaltado, robado, espuesto a mil insultos y usurpaciones</i>	2 years	4

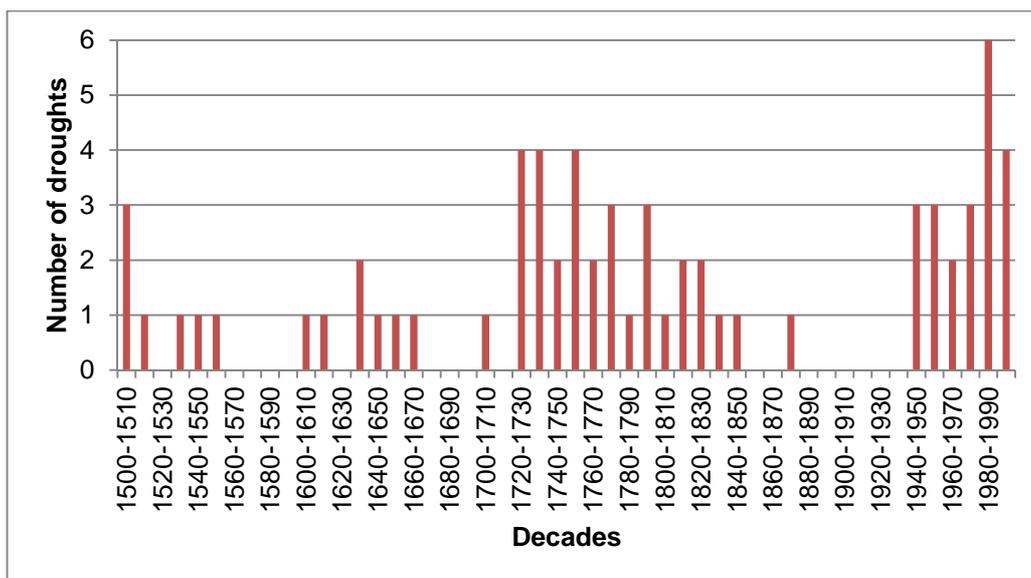
### 3.2.2. The case of the Júcar droughts (1500-2000)

Information about historic droughts in the region of Valencia collected in archives between the 16<sup>th</sup> century and the beginning of the 20<sup>th</sup> century has been classified using the scales proposed in Table 3.6. Figure 3.14 provides the temporal distribution of the drought index for the period 1500-1880.



**Figure 3.14** Evolution of the drought severity for the Júcar River basin (1500-1880).

Number of droughts in the Júcar River basin was interfered from drought severity (Fig. 3.14). Recent information on droughts in the 20<sup>th</sup> century has been added. The distribution of the droughts by decade is given in Figure 3.15.



**Figure 3.15** Number of the drought in the Júcar River basin (1500-2000).

In the 20<sup>th</sup> century, the Valencia region unmistakably has faced an outbreak of droughts since the 1940s with acceleration in the years 1980-1990. However, this interpretation can be better put in perspective if the droughts are investigated over a longer period. The relative mildness of period 16<sup>th</sup>-17<sup>th</sup> centuries can be possibly explained by insufficient document retrievals. However, the 18<sup>th</sup> century and first half of the 19<sup>th</sup> century faced an outbreak of the droughts widely superior to those of the 20<sup>th</sup> century.



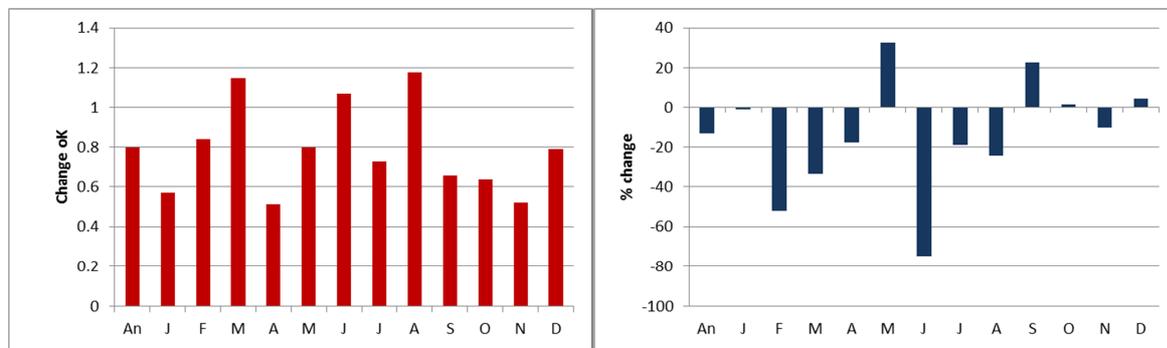
## 4. Analysis of historic drought using WATCH data

This chapter summarizes the outcome from the analyses of the trends in: (i) temperature and precipitation, (ii) low flow characteristics, and (iii) drought characteristics using the WATCH data for the DROUGHT-R&SPI Case Study areas. In the report compiled by Alderlieste and Van Lanen (2012) the trends mainly were presented in maps covering all Case Study areas. In this report we focus on the outcome for the individual Case Study areas. Furthermore we present the ranking of the drought in terms of severity. The trends and the ranking is the basis for the intercomparison with the results obtained from the local observed hydrometeorological data.

### 4.1. Júcar River basin

#### Trends in Temperature and Precipitation

The WATCH Forcing data (WFD, Sect. 2.2) were used to calculate trends (Sect. 2.4) in temperature and precipitation for the Júcar River basin, Spain (Fig. 4.1).



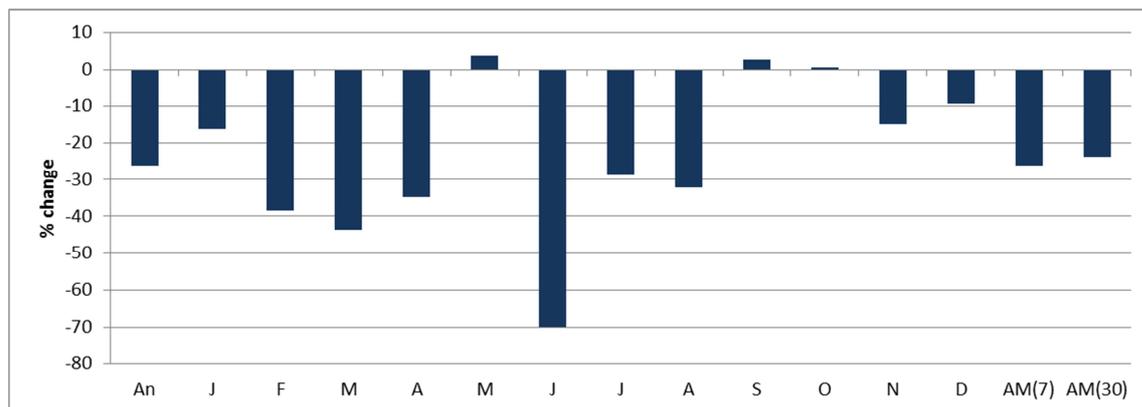
**Figure 4.1** Trend in annual (An) and monthly historic temperature (A, F, ....D) (°K)(left) and annual (An) and monthly historic precipitation (A, F, ....D) (% change) (right) obtained from the WATCH Forcing Data for the Júcar River basin, 1963-2001.

According to the WFD the average annual temperature has increased by 0.8°K (Fig. 4.1, left). The trends in the monthly temperature are mono-directional implying that in all months throughout the year the temperature has increased. The increase varies between 0.5 and 1.2°K. No clear seasonal pattern can be observed.

The annual average precipitation in the Júcar River basin has decreased by slightly more than 10% (Fig. 4.1, right). The trend in the monthly precipitation is not mono-directional. In 8 months the precipitation has decreased, whereas in 4 months it has increased. The decrease varies from almost nothing to about -75% (June). In 2 months the increase is almost zero, but in the other 2 month the increase is over 20%.

#### Trends in Low Flows

Trends in the multi-model mean annual and monthly runoff (Sect. 2.3.2 and 2.4) are presented in Figure 4.2. In the figure also the trends in the 7-day and 30-day annual minimum flow are given (two right bars). The multi-model mean runoff shows that the mean annual flow in the Júcar River basin has declined by about 25% as a response to the increased temperature and the general decrease of precipitation in the second part of the 20<sup>th</sup> century (Fig. 4.2, most left bar). In general, monthly flows also show declining trends (75% of months), although trends considerably vary (-10 to -70%). In the early summer season (May) and late summer and early autumn (September and October) some small increasing trends are observed (max. 4%).



**Figure 4.2** Trend in annual (An) and monthly historic multi-model mean runoff (A, F, ....D)(left) and 7-day and 30-day annual minimum flow (AM(7), AM(30)) (all in % change) obtained from the WATCH Forcing Data for the Júcar River basin, 1963-2001.

### Trends in Droughts

The drought analysis (Sect. 2.3.3 and Sect. 2.4) using the WATCH multi-model mean runoff reveals that the number of drought event per year has increased by about 10% Júcar River basin. The duration and the deficit volume of the drought events have also increased, i.e. about 25 and 35%, respectively. The increased duration and deficit volume also imply a positive trend in drought intensity (increase by about 20%).

### Most severe drought years

The years in the period 1963-2001 in the Júcar River basin have been ranked according drought characteristics (i.e. duration, deficit volume and intensity, all averaged per year<sup>7</sup>) using the simulated WATCH data (Table 4.1).

**Table 4.1** Most extreme drought years for the Júcar River basin, 1963-2001, ranked with regard to different drought characteristics

No.	Average drought duration		Average drought deficit volume		Average drought Intensity	
	year	day	year	mm	year	(mm/day)
1	<b>1994<sup>1)</sup></b>	61.78	<b>1994</b>	1.54	1982	0.02
2	<b>1978</b>	54.28	<b>1978</b>	1.42	1983	0.02
3	<b>2001</b>	53.02	<b>1985</b>	1.38	1981	0.02
4	1984	49.68	2000	1.27	1995	0.02
5	<b>1985</b>	48.30	<b>2001</b>	1.12	2000	0.02

<sup>1)</sup> The three most severe drought years in terms of duration and deficit volume are marked in bold. The years 1985 and 2001 have the same total rank.

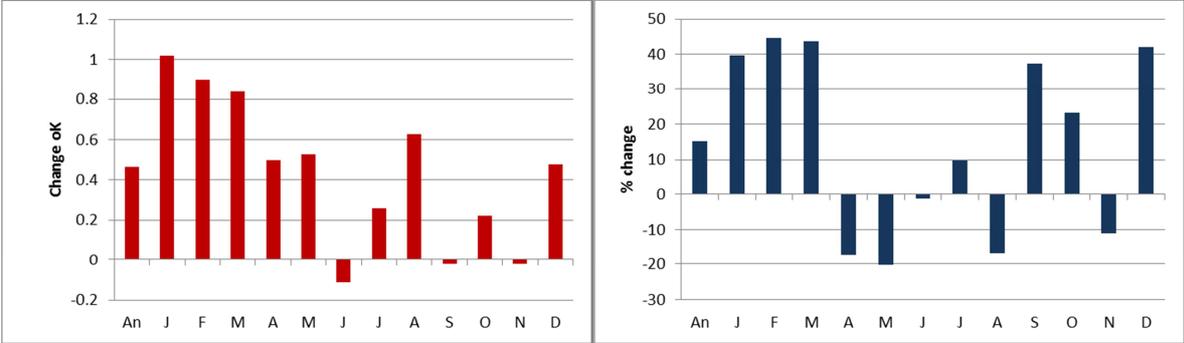
According to the WATCH multi-model mean runoff, the single years 1994 and 1978 are the most severe on the record in terms of duration and deficit volume. Third on the record are both 1985 and 2001.

<sup>7</sup> No multiple year drought analysis was carried out in this study.

## 4.2. The Netherlands

### Trends in Temperature and Precipitation

The WATCH Forcing data (WFD, Sect. 2.2) were used to calculate trends (Sect. 2.4) in temperature and precipitation for The Netherlands (Fig. 4.3).



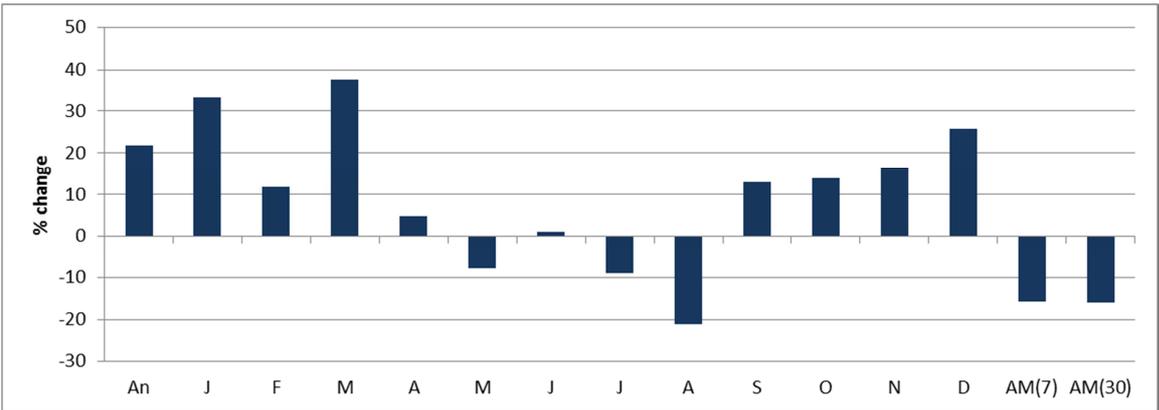
**Figure 4.3** Trend in annual (An) and monthly historic temperature (A, F, ....D) (°K) (left) and annual (An) and monthly historic precipitation (A, F, ....D) (% change) (right) obtained from the WATCH Forcing Data for The Netherlands, 1963-2001.

The trends study using the re-analysis data shows that the annual temperature has increased by slightly more than 0.4° C (Fig. 4.3, left). A consistent increase occurred in the period December-May (about 0.4-1.0° C). In the period June-November the monthly trends were not mono-directional, i.e. decreases occurred in half of the months (largest decrease was about -0.1° C) and in the remaining months the increase varied between about 0.2-0.6° C.

The annual precipitation increased by 15% (Fig. 4.3, right). In most winter months (December-March) a positive trend was observed that was about 40%. In the remaining 7 months both negative and positive trends were observed. In 4 months a decrease was reported, i.e. from -1% (June) to -20% (May).

### Trends in Low Flows

Trends in the multi-model mean annual and monthly runoff (Sect. 2.3.2 and 2.4) are presented in



**Figure 4.4** Trend in annual (An) and monthly historic multi-model mean runoff (A, F, ....D)(left) and 7-day and 30-day annual minimum flow (AM(7), AM(30)) (all in % change) obtained from the WATCH Forcing Data for The Netherlands, 1963-2001.

Figure 4.4. In the figure also the trends in the 7-day and 30-day annual minimum flow are given (two right bars). The multi-model mean runoff shows that the mean annual flow in The Netherlands basin has increased by slightly more than 20% as a response to the increased precipitation in most of the months in the second part of the 20<sup>th</sup> century (Fig. 4.4, most left bar). Positive trends in monthly flow were reported for the months in the period September to March (12-38%). In the summer months (April-August) weak positive trends (maximum of 5% in April) to rather strong negative trends (-21%, August) occurred. Both the 7-day and 30-day annual minimum showed declined magnitude (about -25%). It seems that the low flows have gone down in The Netherlands.

### Trends in Droughts

The drought analysis (Sect. 2.3.3 and Sect. 2.4) using the WATCH multi-model mean runoff for The Netherlands reveals that the number of drought event per year has not increased. However, all the other drought characteristics show increasing trends. Over the period 1963-2001, the average drought duration has increased by about 15%. The deficit volume and the drought intensity have increased by slightly more than 20 and 35%.

### Most severe drought years

The years in the period 1963-2001 in The Netherlands have been ranked according drought characteristics (i.e. duration, deficit volume and intensity, all averaged per year<sup>8</sup>) using the simulated WATCH data (Table 4.2).

**Table 4.2** *Most extreme drought years for The Netherlands, 1963-2001, ranked with regard to different drought characteristics*

No.	Average drought duration		Average drought deficit volume		Average drought Intensity	
	year	day	year	mm	year	(mm/day)
1	<b>1976</b> <sup>1)</sup>	141	<b>1976</b>	26.95	1976	0.15
2	<b>1989</b>	59	<b>1996</b>	7.79	1999	0.12
3	1982	52	<b>1989</b>	7.79	1986	0.11
4	<b>1996</b>	52	1982	7.59	1995	0.11
5	1986	48	1986	6.73	1996	0.11

<sup>1)</sup> The three most severe drought years in terms of duration and deficit volume are marked in bold.

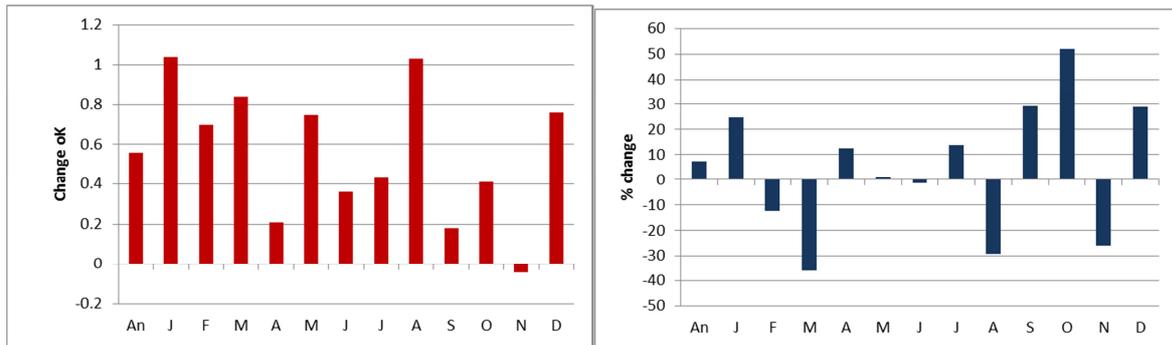
According to the WATCH multi-model mean runoff, the single years 1976 and 1989 are the most severe on the record in terms of duration and deficit volume. Third on the record is 1996. The year 1982 has the same duration (52 days), but a slightly smaller deficit volume than 1996.

## **4.3. Po River basin**

### Trends in Temperature and Precipitation

The WATCH Forcing data (WFD, Sect. 2.2) were used to calculate trends (Sect. 2.4) in temperature and precipitation for the Po River basin, Italy (Fig. 4.5). The annual temperature in the basin increased by about 0.6°C (Fig 4.5, left figure, most left column). A temperature increase was found for almost all months. The increase varied from 0.2 to 1.0 °C. November is the only month with a decreasing temperature trend, but the trend is weak.

<sup>8</sup> No multiple year drought analysis was carried out in this study.

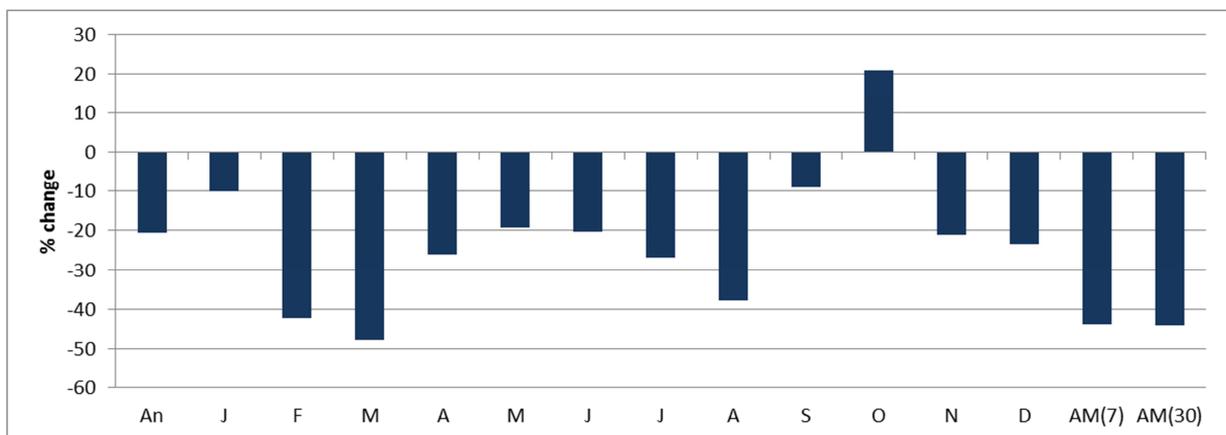


**Figure 4.5** Trend in annual (An) and monthly historic temperature (A, F, ....D) (°K)(left) and annual (An) and monthly historic precipitation (A, F, ....D) (% change) (right) obtained from the WATCH Forcing Data for the Po River basin, 1963-2001.

According to the WATCH data, annual precipitation has increased over the period 1963-2001 (Fig 4.5, left figure, most left column) by 7%. Trends in monthly precipitation are very different. In five months the increase of precipitation is more than 10%, whereas in four months the decrease is more than -10%. Months with either increasing or decreasing trends are not clustered.

### Trends in Low Flows

Trends in the multi-model mean annual and monthly runoff (Sect. 2.3.2 and 2.4) are presented in Figure 4.6. In the figure also the trends in the 7-day and 30-day annual minimum flow are given (two right bars).



**Figure 4.6** Trend in annual (An) and monthly historic multi-model mean runoff (A, F, ....D)(left) and 7-day and 30-day annual minimum flow (AM(7), AM(30)) (all in % change) obtained from the WATCH Forcing Data for the Po River basin, 1963-2001.

According to the WATCH data, the general higher temperature and higher annual precipitation, has led to a decreasing trend in runoff (slightly more than -20%, Fig. 4.6, most left bar). The figure also shows that in almost all months (October is an exception) decreasing trends in monthly runoff were found. Trends in k-day annual minimum flow are strongly negative. The 7-day and 30-day AM declines with more than -40% (Fig. 4.6, most two right bars).

### Trends in Droughts

The drought analysis (Sect. 2.3.3 and Sect. 2.4) using the WATCH multi-model mean runoff reveals that all drought characteristics show an increasing trend in the Po River basin. The number of drought events per year has increased by 26%, the average drought duration by 20%, the deficit volume by 33% and the drought intensity by 24%.

### Most severe drought years

The years in the period 1963-2001 in the Po River basin have been ranked according drought characteristics (i.e. duration, deficit volume and intensity, all averaged per year<sup>9</sup>) using the simulated WATCH data (Table 4.3).

**Table 4.3** Most extreme drought years for the Po River basin, 1963-2001, ranked with regard to different drought characteristics

No.	Average drought duration		Average drought deficit volume		Average drought intensity	
	year	day	year	mm	year	(mm/day)
1	<b>1983</b> <sup>1)</sup>	46	<b>1983</b>	8.68	1987	0.20
2	<b>1991</b>	42	<b>1985</b>	8.34	1983	0.17
3	<b>1985</b>	42	1987	8.27	1989	0.17
4	1971	38	<b>1991</b>	8.12	1978	0.16
5	1988	37	1989	7.82	1997	0.16

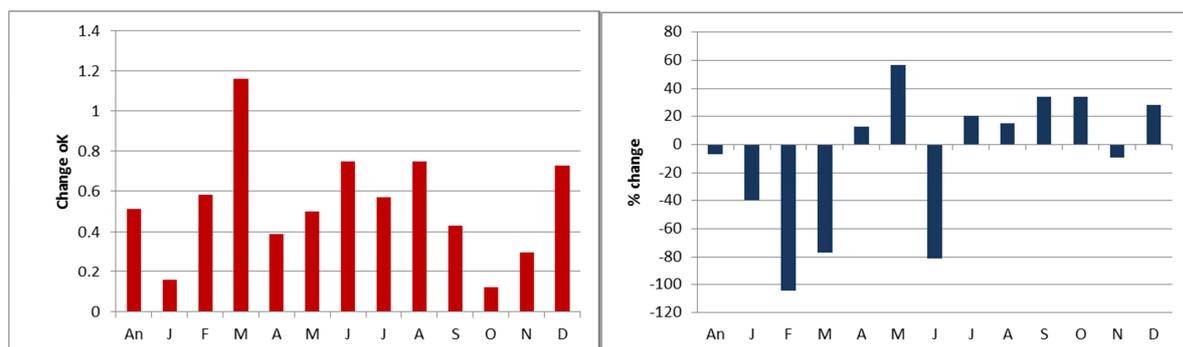
<sup>1)</sup> The three most severe drought years in terms of duration and deficit volume are marked in bold.

According to the WATCH multi-model mean runoff, the year 1983 is most severe on the record in terms of duration and deficit volume. Second and third on the record are the single years 1991 and 1985. The years 1991 and 1985 have the same duration (42 days), but 1991 has a slightly smaller deficit volume than 1985.

## 4.4. Portugal

### Trends in Temperature and Precipitation

The WATCH Forcing data (WFD, Sect. 2.2) were used to calculate trends (Sect. 2.4) in



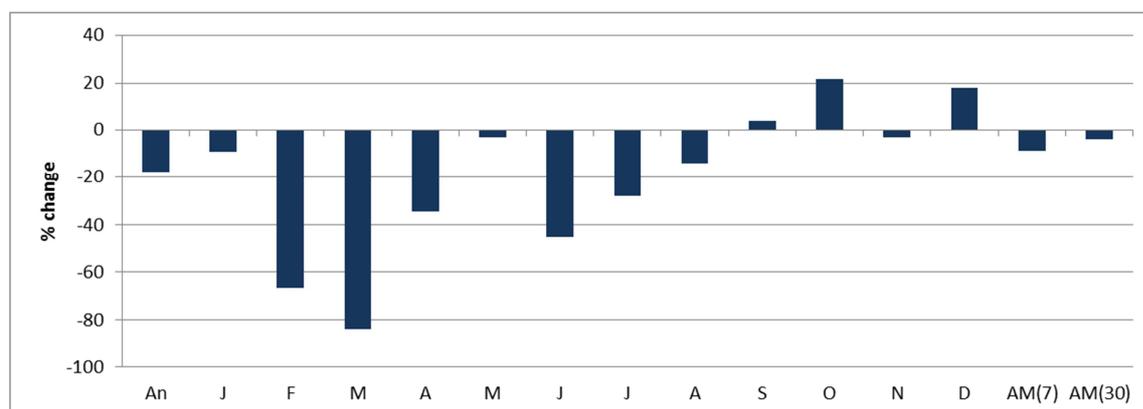
**Figure 4.7** Trend in annual (An) and monthly historic temperature (A, F, ....D) (°K) (left) and annual (An) and monthly historic precipitation (A, F, ....D) (% change) (right) obtained from the WATCH Forcing Data for Portugal, 1963-2001.

<sup>9</sup> No multiple year drought analysis was carried out in this study.

temperature and precipitation for Portugal (Fig. 4.7). An increase of about 0.5°C was found for the mean annual temperature over the period 1963-2001. In March the temperature increase is more than 1.0°C. The annual precipitation has decreased by about 6% (Fig. 4.7). Five months show a decrease with a cluster of 3 months (Jan-March) with reduced precipitation at the start of the year. The largest decrease has been found for March.

### Trends in Low Flows

Trends in the multi-model mean annual and monthly runoff (Sect. 2.3.2 and 2.4) are presented in Figure 4.8. In the figure also the trends in the 7-day and 30-day annual minimum flow are given (two right bars). The AM(7) decreased by about 9% over the period 1963-2001. The decrease of the AM(30) is slightly smaller (about 5%).



**Figure 4.8** Trend in annual (An) and monthly historic multi-model mean runoff (A, F, ...,D) and 7-day and 30-day annual minimum flow (AM(7), AM(30)) (all in % change) obtained from the WATCH Forcing Data for Portugal, 1963-2001.

Annual runoff over the whole of Portugal has decreased by slightly less than 20% (Fig. 4.8). Decreasing trends were found for most months. Like for the precipitation, March is the month with the largest decrease (about 80%).

### Trends in Droughts

The drought analysis (Sect. 2.3.3 and Sect. 2.4) using the WATCH multi-model mean runoff reveals that trends are rather small (<10%). The number of droughts increased by about 2.5%, whereas the average duration and the average deficit volume decreased by about 8 and 2%, respectively.

**Table 4.4** Most extreme drought years for Portugal, 1963-2001, ranked with regard to different drought characteristics.

No.	Average drought duration		Average drought deficit volume		Average drought intensity	
	year	day	year	mm	year	(mm/day)
1	<b>1985</b> <sup>1, 2)</sup>	94	<b>1985</b>	5.78	<b>1965</b>	0.06
2	<b>1965</b>	86	<b>1965</b>	5.20	1976	0.06
3	<b>1970</b>	85	<b>1970</b>	5.00	<b>1985</b>	0.06
4	1990	81	1990	4.93	1989	0.05
5	1995	74	1989	4.79	1995	0.05

<sup>1)</sup> The three most severe drought years in terms of duration and deficit volume are marked in bold.

<sup>2)</sup> The drought years 1965 and 1985 have the same total sum of ranks.

### Most severe drought years

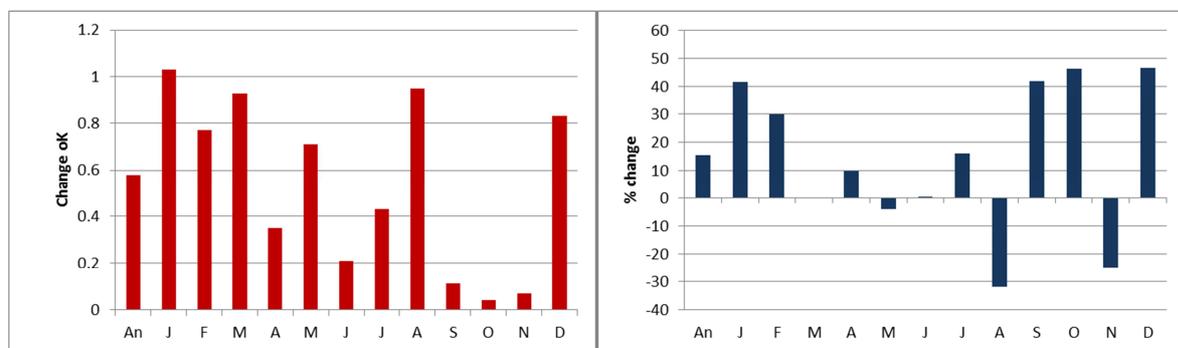
The years in the period 1963-2001 in Portugal basin have been ranked according drought characteristics (i.e. duration, deficit volume and intensity, all averaged per year<sup>10</sup>) using the simulated WATCH data (Table 4.4).

The most severe drought happened in 1985 according the WATCH multi-model mean runoff when we consider average drought duration and deficit volume, but also the 1965 drought must have been severe. The 1970 drought has the third rank.

## **4.5. Switzerland**

### Trends in Temperature and Precipitation

The WATCH Forcing data (WFD, Sect. 2.2) were used to calculate trends (Sect. 2.4) in temperature and precipitation for Switzerland (Fig. 4.9). The mean annual temperature has increased by about 0.6°C as an average over the whole of Switzerland. All months show a positive trend with a maximum change in January (about 1°C) and the lowest trends in autumn (0.05-0.1°C).



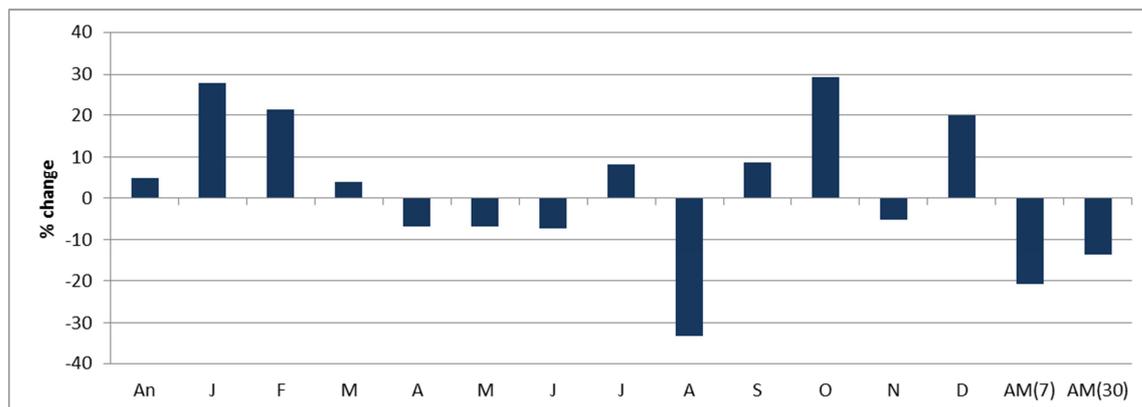
**Figure 4.9** Trend in annual (An) and monthly historic temperature (A, F, ....D) (°K) (left) and annual (An) and monthly historic precipitation (A, F, ....D) (% change) (right) obtained from the WATCH Forcing Data for Switzerland, 1963-2001.

In Switzerland as a whole, the annual precipitation shows a positive trend, i.e. an increase of about 15%. Trends over the months are irregular, both positive and negative trends occur. The longest periods with positive trends (increase by about 30-45%) is the winter (December-February). In four months negative trends were found with larger ones in August and November (about -25-30%).

### Trends in Low Flows

Trends in the multi-model mean annual and monthly runoff (Sect. 2.3.2 and 2.4) are presented in Figure 4.10. In the figure also the trends in the 7-day and 30-day annual minimum flow are given (two right bars). The annual runoff shows a small positive trend (increase by about 5%) as a response to the increased temperature and precipitation. The largest positive trends were found for the winter months (December-February), i.e. an increase by 20-30%, which reflects the larger snow melt induced by the higher temperature in addition the increased precipitation. Four out of six summer months (April-September) have negative trends. According to the WATCH data the monthly runoff has decreased by slightly more than -6% in the period April-June and August stands out with a decrease of about -30%.

<sup>10</sup> No multiple year drought analysis was carried out in this study.



**Figure 4.10** Trend in annual (An) and monthly historic multi-model mean runoff (A, F, ....D) and 7-day and 30-day annual minimum flow (AM(7), AM(30)) (all in % change) obtained from the WATCH Forcing Data for Switzerland, 1963-2001.

The annual minimum low flows (AM(7) and AM(30)) show clear negative trends implying that these have decreased (Fig. 4.10). The decrease is about -20 and -15%, respectively.

### Trends in Droughts

The drought analysis (Sect. 2.3.3 and Sect. 2.4) using the WATCH multi-model mean runoff reveals that the number of droughts over the period 1963-2001 has hardly changed. The average drought duration and severity (deficit volume) show a clear negative trend (about -20%), which means that these became less severe.

### Most severe drought years

The years in the period 1963-2001 in Switzerland have been ranked according drought characteristics (i.e. duration, deficit volume and intensity, all averaged per year<sup>11</sup>) using the simulated WATCH data (Table 4.5).

**Table 4.5** Most extreme drought years for Switzerland, 1963-2001, ranked with regard to different drought characteristics.

No.	Average drought duration		Average drought deficit volume		Average drought intensity	
	year	day	year	mm	year	(mm/day)
1	<b>1984</b>	53	<b>1976</b> <sup>1)</sup>	21.33	1989	0.32
2	<b>1976</b>	52	<b>1984</b>	19.44	<b>1976</b>	0.30
3	<b>1985</b>	43	1963	16.23	1985	0.30
4	1963	43	<b>1985</b>	15.94	1983	0.30
5	1973	38	1972	15.33	1986	0.29

<sup>1)</sup> The three most severe drought years in terms of duration and deficit volume are marked in bold.

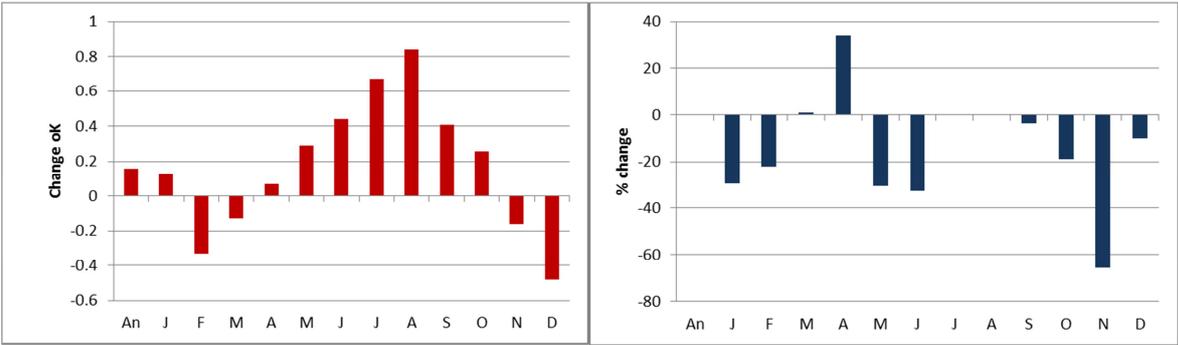
The most severe drought year in the period 1963-2001 was 1976. It was followed by 1984, which had a similar drought duration and deficit volume. Third in the row of severe historic drought is 1985.

<sup>11</sup> No multiple year drought analysis was carried out in this study.

### 4.6. Syros

#### Trends in Temperature and Precipitation

The WATCH Forcing data (WFD, Sect. 2.2) were used to calculate trends (Sect. 2.4) in temperature and precipitation for the island of Syros, Greece Spain (Fig. 4.11). The annual temperature shows a minor upward trend (about 0.2°C). There is a clear pattern over the year with decreasing temperatures in the winter period (November – March, January is an exception) and increasing temperatures in the summer period (April – October). The maximum decrease is in December (-0.5°C) and the maximum increase is in August (0.8°C).

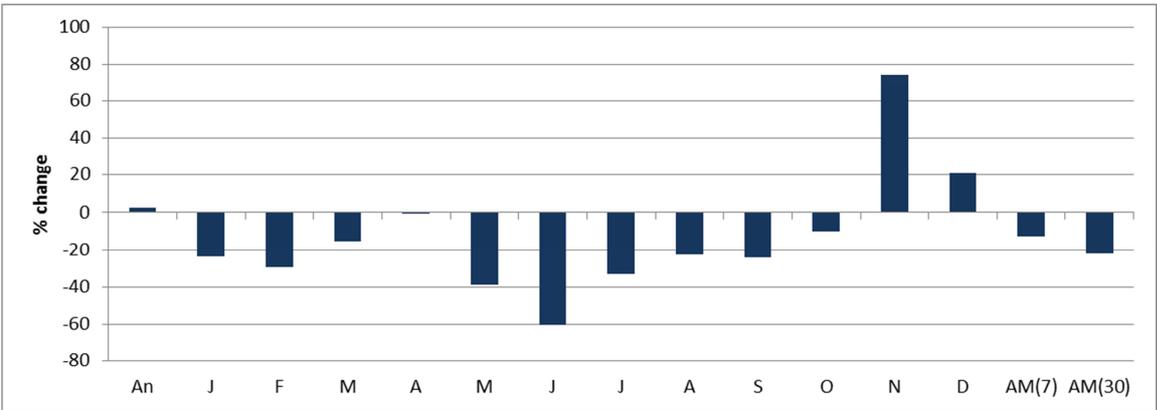


**Figure 4.11** Trend in annual (An) and monthly historic temperature (A, F, ....D) (°K) (left) and annual (An) and monthly historic precipitation (A, F, ....D) (% change) (right) obtained from the WATCH Forcing Data for Syros, 1963-2001

The annual precipitation hardly shows a trend. Trends in monthly precipitation are weak (4 months) or negative, i.e, reduced precipitation (up to about -60%). April is an exception with trend of more precipitation (about 30%).

#### Trends in Low Flows

Under current conditions no runoff is reported in the island of Syros (Sect. 3.1.6). The multi-model mean runoff represents natural conditions. The models simulate for the period 1963-2001 a median annual runoff of 0.37 mm/d, whereas the 25% quantile is 0.28 mm/d. In most of the summer months the flow is almost zero.



**Figure 4.12** Trend in annual (An) and monthly historic multi-model mean runoff (A, F, ....D) and 7-day and 30-day annual minimum flow (AM(7), AM(30)) (all in % change) obtained from the WATCH Forcing Data for Syros, 1963-2001.

Trends in the multi-model mean annual and monthly runoff (Sect. 2.3.2 and 2.4) are presented in Figure 4.12. In the figure also the trends in the 7-day and 30-day annual minimum flow are given (two right bars). A minor increase in annual runoff (about 3%) has been found. According the WATCH the November flow has increased by about 75%. The months January – October show weak trends or decreasing flow. The 7-day Annual Minimum flow also decreased (about -10%). This also applies to the 30-day Annual Minimum flow (about -20%). However, the magnitude of the flow is low.

### Trends in Droughts

The drought analysis (Sect. 2.3.3 and Sect. 2.4) using the WATCH multi-model mean runoff reveals that the number of droughts over the period 1963-2001 has not changed. However the average drought duration and severity (deficit volume) has increased, i.e. by about 10 and 30%, respectively.

### Most severe drought years

The years in the period 1963-2001 in the island of Syros have been ranked according drought characteristics (i.e. duration, deficit volume and intensity, all averaged per year<sup>12</sup>) using the simulated WATCH data (Table 4.6).

**Table 4.6** *Most extreme drought years for Syros, 1963-2001, ranked with regard to different drought characteristics.*

No.	Average drought duration		Average drought deficit volume		Average drought Intensity	
	year	day	year	mm	year	(mm/day)
1	<b>1987</b>	130	<b>1987</b>	2.16	1987	0.02
2	<b>1979</b>	121	<b>1979</b>	1.52	1992	0.01
3	<b>1993</b>	84	<b>1993</b>	1.42	1990	0.01
4	1981	79	1990	1.05	1993	0.01
5	1967	76	1967	1.02	1986	0.01

<sup>1)</sup> The three most severe drought years in terms of duration and deficit volume are marked in bold.

According to the WATCH data the 1987 drought is the most extreme on the record of the period 1963-2001. The 1979 and 1993 droughts are on the second and third rank, respectively.

<sup>12</sup> No multiple year drought analysis was carried out in this study.



## 5. Discussion

This chapter discusses in the first part (Sect. 5.1) differences in trends between droughts derived from local data (Chapter 3) and WATCH data (Chapter 4). In the second part (Sect. 5.2) impact of low flow and drought identification methods is evaluated.

### 5.1. Differences between local data and WATCH data

#### Júcar River basin

No trends in observed critical drought indicators (precipitation, reservoir inflow) at the local scale were reported (Sect. 3.1.1). Extreme drought events were determined that combined observed precipitation and reservoir inflow. In the basin 6 drought cycles were identified (Table 3.6), which can be intercompared with the ranked events derived from the simulated WATCH runoff (Table 4.1). The most severe drought year (1994) obtained from the WATCH data is part of a multiple year drought (1992/93-95/96). The same applies to the drought year 1985, which is part of the 4 year lasting drought (1980/81-84/85). The single drought years 1978 and 2001 that were obtained from the WATCH data did not show up in the multiple-year drying cycles derived from the local observed data.

#### The Netherlands

Increasing trends in annual temperature occur both in the observed and re-analysis data. The reanalysis data show that in particular in the winter months positive trends were observed. In the second part of the summer and autumn both months with increasing and decreasing trends occurred. The annual precipitation showed increasing trends both in the observed data (25%) and in the reanalysis data (15%). In the period April-November (re-analysis data) both positive as negative trends in monthly precipitation were reported.

The trends in flow characteristics derived from observed and simulated flow are more or less similar in direction. Both show increasing trends in annual flow and flow in winter months. In the summer months also decreasing trends occur in both series. August appears to be the month with the strongest decreasing trends. Trends are -15 and -11% in the observed August flow, whereas the WATCH data give a slightly stronger trend (-21%). Trends in mean annual k-day minimum flow (AM(7) and AM(30)) are negative both in observed and simulated flow for the River Rhine. The trends in AM(7) and AM(30) for the River Berkel derived from observed data and simulated contradict. Drought characteristics derived from observed and simulated flow also contradict, but now both for River Rhine and River Berkel.

#### Po River basin

Two of out of three of the selected meteorological stations show an increasing trend in the observed annual temperature (0.7°C) over the period 1987-2006. In all three stations an increasing trend occurred in the summer months (April-July). The strongest increase in the observed temperature was found for the month June (0.9-1.5°C). The WATCH data show increasing trends in annual temperature (0.6°C) and in almost all months.

Observed annual precipitation shows a declining trend in all nine selected stations over the period 1951-2008. The negative trends vary from almost zero (-0.1%) to about -10%. The direction of the trends in the observed monthly precipitation series of all stations is similar, but substantially varies among months. Months with strong decreasing trends are: February-March and June and July, whereas May, September-October and December show increasing trends.

The expected decreasing trend in observed annual river flow could not be found. On the contrary, trends in the selected three gauging stations show an increase (7-15%). The summer months

## Portugal

An SPI analysis using observed precipitation data shows an occurrence of more frequent cycles of dry events in the south than in the north. SPI12 data from 1864 to 2011 reveal specific trends towards more moderate to severe drought (SPI<-1) for the last data period (2001 to 2011). Significant trends in observed streamflow are predominantly decreasing (i.e. reduced flow). March is the month with the highest number of stations (6 out of 11 gauging stations) that have a significant decreasing streamflow. The WATCH data show that for Portugal as a whole, the annual temperature has increased in the second part of the 20<sup>th</sup> century, whereas precipitation has decreased. March is the month with the largest changes both for temperature and precipitation. Annual runoff has decreased and again March is the month with the largest changes. The annual minimum flow (7-day and 30-day) show a relatively small decrease (about 5-10%). This pattern is not reflected in the drought characteristics. Both the average drought duration and the severity (deficit volume) are slightly reduced.

## Switzerland

No trends in observed drought indicators (precipitation, groundwater, river flow) at the local scale were reported (Sect. 3.1.5). Extreme drought events were determined on the basis of lack of precipitation and its hydrological impacts. Two recent severe droughts, i.e. 2003 and 2011, were described, which unfortunately cannot be intercompared with the ranked events derived from the simulated WATCH runoff (Table 4.5) because the periods do not overlap.

The WATCH data show that the mean annual temperature has increased by about 0.6°C as an average over the whole of Switzerland. All months show a positive trend with the lowest trends in autumn. The annual precipitation shows a positive trend. The longest period with positive trends is the winter (December-February) and larger negative trends were found in August and November. The annual runoff shows a small positive trend, but most summer months have negative trends, with the largest decrease in August. The annual minimum low flows (AM(7) and AM(30)) show clear negative trends implying that these have decreased. The decrease in summer flows is not supported by the drought analysis, i.e. average drought duration and severity (deficit volume) have decreased, whereas the opposite was expected.

## Syros

The annual observed temperature in Syros has slightly decreased, but trend is not significant. Significant trends in temperature occurred in April and August, but with opposite directions. Observed annual precipitation has increased in Syros. In particular for the period August-December significant increasing trends were found. However, trends are opposite, i.e. -9% and +4%, respectively. The trend analysis for Naxos and Milos Islands indicate that there is no trend in precipitation and an increasing trend in temperature for spring and summer time. An analysis of meteorological droughts (SPI12 < -1.5) reveals that severe events have occurred in the first part of the 1970s (1971, 1973, 1975), late 1970s and early 1980s (1979, 1980), and first half of the 1990s (1991, 1992, 1994). In Naxos Island (island next to Syros) severe meteorological droughts were found for the years 1957-1959, 1965-1966, 2000-2001, whereas extreme are characterized the years 1989-1990, 1999-2000.

According to the WATCH data the annual temperature shows a minor upward trend. There is a clear pattern over the year with decreasing temperatures in the winter period and increasing temperatures in the summer period. The latter agrees with the trend analysis for Naxos and Milos Islands. The annual precipitation hardly shows a trend. For most months, trends in monthly precipitation are weak or negative, i.e. reduced precipitation. Extreme droughts (in runoff) retrieved from the WATCH data partly agree with the meteorological droughts identified with the SPI (i.e. 1979 and 1993). The 1987 drought does not clearly show up

There is no observable runoff in the Island of Syros under current conditions, which implies hydrological droughts could not be assessed. The WATCH models, which are representative for natural conditions,

simulate some runoff, show a minor increase in annual runoff, but for spring and summer months weak trends or decreasing flow was observed. The 7-day and 30-day Annual Minimum flow also decreased. The average drought duration and severity show upward trends.

## **5.2. Impact of low flow and drought identification methods**

Droughts are identified using a wide set of types and associated indicators. This might lead to different conclusions. A recent example, is the discussion whether the soil moisture drought on a global scale has become more severe over the second part of 20<sup>th</sup> century. Dai (2012) claimed that the global area in drought has increased over the second part of the last century. He used the Palmer Drought Severity Index (PDSI), which is a soil moisture drought indicator, to illustrate this. On the contrary, Sheffield et al. (2012) show that the global area in drought has not increased. They also use the PDSI to demonstrate this, but with a more comprehensive approach to calculate the potential evapotranspiration.

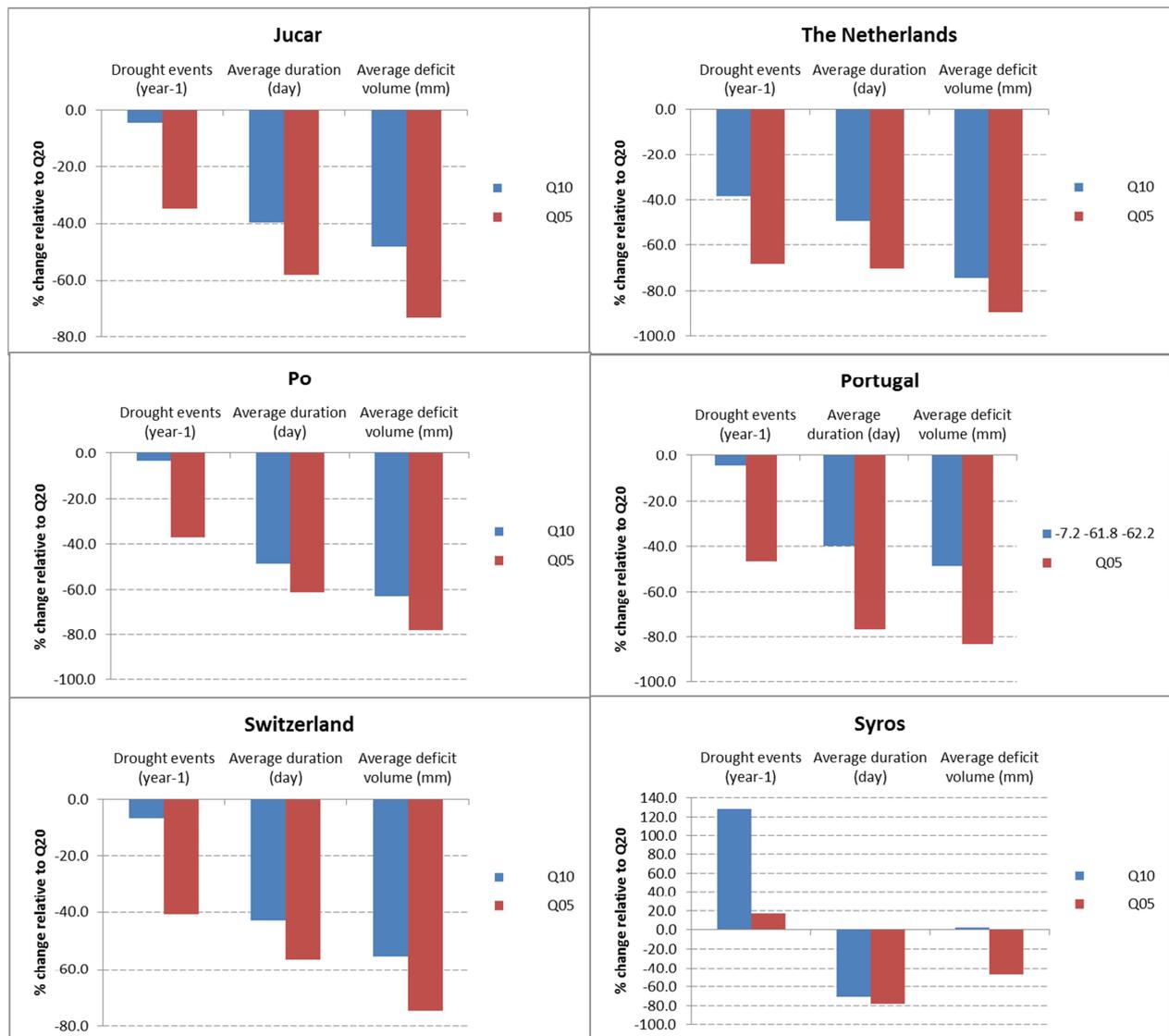
### Difference between SPI and threshold

Both the Standard Precipitation Index (SPI, Sect. 2.3.1) and the threshold method (Sect. 2.3.3) are often used to identify drought. Wanders et al (2010) intercompares these two approaches for various climates across the globe. They show that the correlation of the SPI and the Moving Average Precipitation with a Variable Threshold (MAPVT) is highest in Brazil, but still rather low (0.43). For other areas (Papua New Guinea, Australia, Germany, Russia, Canada) there is no correlation. This intercomparison applies to two indicators of the same drought type, i.e. meteorological drought. We know that drought propagation (i.e. lagging, pooling, attenuation, lengthening) leads to drought types that deviate, e.g. hydrological drought differs from meteorological. The difference between these two drought types is determined by both climate and catchment characteristics (e.g. Van Loon and Van Lanen, 2012; Van Lanen et al., 2013). So, if we would apply the threshold method to identify meteorological drought (MAPVT) and hydrological drought (i.e. Discharge with a Variable Threshold, QVT) this will lead to different conclusions about the drought. Correlations between MAPVT and QVT are low (i.e. Brazil: 0.3, Papua New Guinea: 0.47, Australia: 0.06, Germany: 0.19, Russia: 0.12 and Canada: 0.24) confirm this (Wanders et al., 2010).

### Impact of threshold selection

In this study (Sect. 3.1.2, 3.1.3 and 3.1.4, and Chapter 4) we used the 20<sup>th</sup> percentile (X20) of a hydrometeorological variable as threshold (Sect. 2.3.3.) to be consistent with other large scale studies. The Q20 is a rather high threshold value. Alderlieste and Van Lanen (2012) have repeated the drought analysis done using the X10 and X5 as threshold to investigate the drought characteristics of more extreme droughts. Figure 5.1 shows the change in drought characteristics by using the Q10 and Q5 instead of the Q20 for the six DROUGHT-R&SPI Case Study areas. For this analysis they used the multi-model mean runoff from the period 1906-2000. The percent change is given relative to the magnitude of the characteristics. When we take lower thresholds (Q10 and Q5) then the number of drought events decreases; only the more extreme droughts are identified. When the Q10 was used the decrease in number droughts is rather small (< -10%), except for The Netherlands (about -40%). Surprisingly, in Syros the number increases (more than 100%) due to the very low and irregular runoff. Using the Q5 instead of the Q20 results in substantial decreases of the number of droughts (except Syros). The decrease varies between -35% and -70%. Selection of a lower threshold leads to shorter average drought durations and lower deficit volumes. Average drought duration decreases by -40% and -70% in case the Q10 was used instead of the Q20. These percentages are between -60% and -80% when the Q5 was chosen. The percent change in deficit volume is slightly higher than for the duration. The average drought deficit volume decreases -50% and -75% when the Q10 was used instead of the Q20). These percentages are between -70% and -90% when the Q5 was chosen. Syros again is an exception.

In this study no trends in drought characteristics were determined for the cases that the Q10 and Q5 were used instead of the Q20. It is assumed that the effect on the trends is lower than on the average drought duration and the deficit volume.



**Figure 5.1** Effect of using another threshold, i.e. Q10 and Q5 instead of Q20 expressed as change in drought characteristics (number of events, average drought duration, average drought deficit volume) relative to Q20 for the DROUGHT-R&SPI Case Study areas. Data are from the multi-model mean runoff for the period 1906-2000 (Alderlieste and Van Lanen, 2012).

In the island of Syros (Sect. 3.1.6) the 20<sup>th</sup> percentile (P20) could not be used to identify drought in precipitation. There were too many zeros. So, P20 was too low. The median (P50) was used instead of the P20.

### Time window

The selected time window can also have impact on observations whether the drought has increased or decreased. The number of years and the selected years that are included in the trend analysis is the first aspect. For example, Hisdal et al. (2001) and Hannaford et al. (2013) show that the length of the record and the timing in history have a substantial impact on the trends. Opposite directions in drought trends can even be found dependent on the selected period and the number of years. Garnier (2010,

Sect. 3.2) demonstrates the importance of the selected period beyond the instrumental record. He used various archives to describe that the droughts in the 18<sup>th</sup> and first part of the 19<sup>th</sup> century were likely more severe than the recent ones, which show an upward trend.

Furthermore, it is relevant whether single drought years are included in the drought trend analysis, as has been done by Alderlieste and Van Lanen (2012), or that sets of consecutive years are investigated (multiple year drought, second aspect). Particularly, in the Mediterranean region multiple year droughts are relevant for management of groundwater and surface water resources. The outcome of the trend analysis for the Jucar River basin demonstrates that no every single drought year has been reported as a severe event, because it is not part of set of consecutive dry years (Sect. 5.1).



## 6. Concluding remarks

The quantitative analysis of historic droughts in selected European case study areas leads to the following concluding remarks:

- No trends in observed hydrometeorological data were available for the Júcar River basin. Low flow and drought characteristics derived from simulated runoff shows declining trends.
- In The Netherlands temperature is increasing. In general precipitation has increased, although some summer months show a decreasing trend. Trends in low flow characteristics and drought characteristics are contradicting.
- Most observed temperatures in the Po River basin, but not all, show upward trends, which is supported by the WATCH data. Annual precipitation has decreased in all selected stations.
- In Portugal often a north-south gradient in drought characteristics is found. A spatial averaging over the whole country as has been done with the WATCH data hides this gradient. The same applies to Switzerland, where the Alpine region has not separately been investigated.
- Portugal faced reduced precipitation with March as the month with the largest decrease. This is reflected in the streamflow in March, which also decreased most of all months.
- Over the whole of Switzerland both the mean annual temperature and annual precipitation have increased (about 0.6°C and 15%, respectively) according the WATCH Forcing data. However, for some summer months (e.g. August) negative trends were observed.
- In Switzerland the annual runoff shows a small positive trend (about 5%), but most summer months have negative trends, with the largest decrease in August. The annual minimum low flows (AM(7) and AM(30)) show clear negative trends implying that these have decreased.
- In the Cyclades complex to which Syros belongs, severe and extreme meteorological drought events account for 17% of drought episodes (1955-2002). There were drought events that lasted up to 5 years and severe or extreme events with duration up to 2 years. In Naxos Island (island next to Syros) severe meteorological droughts were found for the years 1957-1959, 1965-1966, 2000-2001, whereas extreme are characterized the years 1989-1990, 1999-2000.
- The annual observed temperature in Syros has slightly decreased and annual precipitation has increased. Trends in temperature among the months have opposite directions. This also applies to precipitation. The trend analysis for Naxos and Milos Islands indicate that there is no trend in precipitation and an increasing trend in temperature for spring and summer time. The WATCH model data are more in line with the outcome for Naxos and Milos Islands than for Syros.
- In the Island of Syros no hydrological droughts have been described because there is no observable runoff under current conditions. WATCH data, which are representative for natural conditions, show weak to decreasing trends for spring and summer flows, although the trend in annual flow is positive (i.e. increased flow).
- In heavily-exploited and managed river basins as the Júcar River basin (Spain) reservoir inflow was identified as the critical drought indicator in combination with precipitation rather than runoff as such.
- Drought analysis in the Mediterranean region should consider the multiple-year time scale and not only rely on the drought severity of a single year.
- WATCH Forcing Data give insight in the monthly trends in temperature and precipitation, which were not available for the local observations in most of the Case Study areas.
- Trends found in observed and simulated data (WATCH) are hard to compare, because usually periods are different (number of years, period covered).
- Reported information on historic drought depends on the drought type (e.g. meteorological, hydrological), indicator used and how the indicator is calculated (e.g. selected threshold level). If these differences are not considered, it seems that contradicting information has been provided. Hence, for the assessment of impact and management and policy options it should be clearly

stated which drought information is required. For example, for the assessment and planning of water resources, information on hydrological drought usually is more relevant than only information on meteorological drought (e.g. SPI).

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