Bio-climatic Evaluation of Drought Severity: a Computational Approach using Dry Spells[#]

Luca Salvati[1], Angelo Libertà[2] & Antonio Brunetti[1]

[1]Consiglio per la Ricerca e la Sperimentazione in Agricoltura - Ufficio Centrale di Ecologia Agraria
Via del Caravita 7a, I-00186 Rome

[2] AgriSian s.p.a. - Unità Territorio e Ambiente, Via L. Rizzo, I-00136 Rome

Key words: Drought, DSI, dry spell, index, water deficit, plant/animal communities.

Corresponding author:

Dr. Luca Salvati

Consiglio per la Ricerca e la Sperimentazione in Agricoltura (CRA)

Ufficio Centrale di Ecologia Agraria (UCEA)

Via del Caravita 7a

I-00186 Rome (Italy)

Fax: +39 6 69531214

E-mail: lsalvati@ucea.it

[#]Climagri - Publication no. 37

BIOTA – Journal of Ecology and Biology

In press 2005

Abstract

Drought is defined as a significant, temporary reduction in water availability below the expected amount for a specified period and for a defined climatic zone. Drought episodes may be described by means of drought duration and intensity. Among the several methods proposed for describing drought, the run method appears as the most suitable to provide an objective identification and characterisation of drought events. In the bio-climatology approach, a simple drought index, obtained from few input variables and able to describe the two dimensions of drought is meaningful. Such index should recognise 'normal' conditions, not only in term of statistical average, but especially from an ecological point of view, in order to highlight anomalies in dryness conditions. Our interest is therefore to develop a climatic index, called drought severity index (DSI) able to produce such information on a detailed geographic and time scale.

The procedure to derive DSI calculates for each day, classified as dry or wet according to the amount of rainfall measured, the length of the current dry spell, as well as rainfall, evapotranspiration and water deficit during the dry spell. Furthermore, for each day we associated the agro-climatological variables measured to the corresponding percentile value obtained from the climatology. Finally, the length of dry spell was expressed as consecutive number of dry days (LHS), and daily mean water deficit during dry spell (DFS) was computed as the maximum value between LH and LH6 percentiles and between DF and DF6, respectively. LHS describes drought duration, whereas DFS represents an indicator of drought intensity. DSI was developed by calculating the geometric mean of the variables LHS and DFS.

Duration, intensity and severity of drought were estimated on a day time scale for the test period 1988-2003 based on climatological figures. At the national level, the most arid spell along the test period was recorded during spring-summer 2003, with especially dry conditions occurred in northern and central Italy. DS index correctly indicates a consistent increase in dryness from March to July 2003 in all the Italian meteorological stations. We further selected a sample station (Rome) in order to evaluate the behaviour of the drought index in the whole test period. In such station, the period May-August 2003 was characterized by an exceptionally long dry spell with extremely hot conditions. This spell was correctly classified as very anomalous, with both LHS and DFS indexes rapidly increasing from the normal (40° percentile and 60° percentile for LHS and DFS, respectively) at the beginning of May to the 99° and 90° percentiles, respectively, at the end of August 2003, and the same pattern was measured for DSI.

DSI may therefore be used in order to assess the general drought conditions occurred at a certain location. Such features make this index suitable to study the relationships between plant phenology/animal ecology and climate changes.

Introduction

Increasing interest on drought and its impact on natural and man-made ecosystems in the framework of climate change is demonstrated by consistent growth of research activities in such field (e.g. Heim 2002). Drought generally affects animal and plant communities in the widest sense; the occurrence of severe drought episodes, coupled with high temperature conditions, is correlated to different ecological phenomena, among which anticipated spring flowering of many plant species and lowered animal breeding rate or survival represent only simplified examples (e.g. Schwartz 2003).

Drought is usually defined as a significant, temporary reduction in water availability below the expected amount for a specified period and for a defined climatic zone (e.g. Kenneth Hare 1993). Among the several methods proposed to describe drought, the run method (Bonaccorso et al. 2003) appears as the most suitable to provide an objective identification and characterisation of drought events (Ochola & Kerkides 2003). Accordingly, droughts are identified as consecutive intervals where the investigated hydrological variable is continuously below a fixed threshold. In recent publications (Brunetti et al. 2001, Bonaccorso et al. 2003), some problems concerning this methods are explored by introducing relative rainfall thresholds to identify dry periods, as well as by stochastic modelling the return period of drought based on rainfall data. Therefore, drought episodes may be described by means of different characteristics, namely drought duration and intensity, considered as the two dimensions of this climatic phenomenon (e.g. Kenneth Hare 1993). In particular, drought duration refers to the length of dry spells, whereas drought intensity refers to the amount of water deficit, taking into account a simplified water balance with rainfall and potential evapotranspiration respectively as input and output variables.

In the last years a large amount of meteorological data were available on digital sources by national and regional technical services, and the use of indexes to describe drought conditions at different geographic scales was consequently developed. Unfortunately, for many meteorological stations, data are generally restricted to rainfall measures (Brunetti et al. 2003). Therefore some drought indexes include only such input variable and provide output referring to general climatic conditions (e.g., Standardized Precipitation Index, McKee et al. 1993). When other measures are recorded (i.e., temperature, wind and umidity records), indexes able to provide a deeper evaluation of drought conditions were obtained by filling agro-meteorological information (Incerti et al. in press) with soil pedology and crop need (e.g., Palmer’s index, see Kenneth Hare 1993), but such information is generally available in a restricted number of stations. When researchers are interested in detecting the response of animals or plants (in terms of ecological determinants) to climate variations (e.g., increasing occurrence of drought episodes through time), the direct correlation between ecological variables (e.g., spatial distribution, breeding success, survival, phenology) and precipitation/temperature measured in a defined time-scale is generally the most widely used procedure. Simple or complex indexes, intended to synthetically describe climatic conditions in a certain time scale, are less used with the exception of some aridity indexes (e.g., Mitrakos, Bagnouls-Gaussen). In the bio-climatology approach, a simple drought index, obtained from only rainfall and temperature as input variables, able to describe the two dimensions of drought (i.e., duration and intensity) and to recognise 'normal' conditions, not only in term of statistical average, but especially from an ecological point of view, is meaningful. The aim of this paper is to develop a drought index able to produce such information on a detailed geographic and time scale (e.g. daily measures).

Materials and methods

Climatic data. The data set containing precipitation and temperature time series used in this study was extracted from the database of the National Agriculture Information System (SIAN). All the series here analysed are from the Italian Air Force (AM) meteorological network and cover the whole Italy. We selected the meteorological stations with a percentage of readable daily rainfall data > 97% and daily temperature (maximum and mininum figures) data > 95% across the whole period considered (1/1/1951 – 31/12/2003). We obtained 32 meteorological stations fitting such criteria (Fig. 1). $ET_{0,}$ daily estimated evapotranspiration (mm•day^{-1}), was computed using Hargreaves-Samani approach (Hargreaves & Samani 1985), through computation on minimum and maximum daily temperature:

$$ET_0 = \frac{0.549H[(T_x - T_n)^{1/2}](T_{med} + 17.8)}{23.88(595 - 0.51T_{med})}$$

where H is the daily radiation (cal • cm^{-2} • day^{-1}), T_{med} is mean daily temperature, T_n is minimum daily temperature, and T_x is maximum daily temperature. Daily H values were computed according to the day of the year and to the latitude of each station. Daily values of T_{med} were calculated as the average of daily minimum and maximum temperature (Hargreaves & Samani 1985, Cahoon *et al.* 1991). Water deficit was obtained as the difference between precipitation and ET_0 along a fixed time period. Lacking ET_0 values were obtained by linear interpolation.

Drought severity index (DSI). The computational method applied to derive DSI (Fig. 2) consists of three steps: (i) identification of dry days and characterisation of dry spells; (ii) computation of dry spell climatology; (iii) assessment of drought severity through dry spell climatology.

(i) Definition of dry spell. Dry spells were considered as enough long periods during which rainfall is consistently below a fixed threshold (Brunetti et al. 2001, Bonaccorso et al. 2003). Each day considered was classify as dry if the daily precipitation was < 10 mm. This threshold was obtained by dividing the average annual precipitation in Italy (ca. 840 mm, Brunetti et. al. 2002) by the mean number of rainy days in Italy (ca. 90 days, Brunetti et al. 2001). The use of an absolute threshold allows an easier comparison of the results from different climatic regions, that is a purpose of this study. A period along the time series was classified as dry if more than 10 consecutive dry days occurred. The distribution of dry spell length was truncated to 10 day-length in order to avoid considering too short periods to identify dry spells. Moreover, dry periods shortest than 10 days

showed more evident trends during the last fifty years in Italy (Brunetti, *et al.* 2002), and this contrasts with the stationarity condition generally required by the statistical analysis of climatic time series.

(ii) Climatology of dry spells. Climatology of dry spells was computed for the period 1/1/1951 – 31/12/1985 to avoid considering anomalous drought episodes starting in the late ’80 decade in Italy (Brunetti et al. 1994) and also occurred in more recent years. More generally, Brunetti et al. (2002) identify in the ’80 decade significant changes in precipitation regimes and temperature distribution, which were continuously recorded across the ’90 decade. For each period 8 variables were calculated: (i) length of dry spell expressed as number of consecutive dry days (LH), (ii) rainfall cumulated during dry spell, (iii) cumulative potential evapotranspiration during dry spell, and (iv) water deficit computed as the difference between cumulated rainfalls and ET_0. From cumulate rainfall and potential evapotranspiration we obtained mean daily rainfall (PR), mean daily ET_0 (ET_0) and mean daily water deficit (DF) by dividing the cumulate values by LH. We computed additional variables measured in the 180 days preceding the start date of each dry spell, including: (v) proportion of dry days (LH6), (vi) cumulated daily rainfall (PR6), (vii) cumulated daily ET_0 ($ET_0$6), and (viii) cumulated daily water deficit computed as the difference between cumulated rainfalls and ET_0 measured along the 180 days preceding the dry period (DF6). A period of 6 months preceding the beginning of each dry spell was considered adequate to depict the climatic conditions of the season. Consequently, we obtained an intermediate dataset containing each dry spell described by the variables LH, PR, ET_0, DF, LH6, PR6, $ET_0$6, and DF6. Each spell was further classified as started in spring-summer (March-August) or in autumn-winter (September-February), irrespective of the ending month. Such classification allows to consider the effect of seasonality, typical of the Mediterranean climate and which appears as important from an ecological point of view. The final dataset contained 5,892 dry spells with a mean number of periods per station of 183 spells in autumn-winter and 185 spells in spring-summer. From the final dataset, we described the frequency distribution conditioned to the season of the variables LH, PR, ET_0, DF, LH6, PR6, $ET_0$6, and DF6 by percentiles.

(iii) *Assessment of drought severity.* To assess the conditions of drought during the last years through a synthetic index, we identified a test period (1/1/1988 – 31/12/2003) during which drought episodes increased throughout Italy (e.g., Brunetti et al. 2002). In such period, the drought severity was evaluated according to the following procedure (see Fig. 2). Each day of the year was classified as dry or wet and, if dry, the length of the current dry spell (expressed as the number of consecutive dry days before the *i*-th day), was associated to the *i*-th day as well as the mean daily rainfall, ET_0, and water deficit. To the same variables, the corresponding percentile figure obtained from climatological statistics of dry spells was associated on a day basis. If the *i*-th day is classified as wet, the associated percentile for each variable considered is undetermined, as the climatology considered only the dry periods. To obtain a complete classification of the whole days (i.e., including wet days) we considered the climatic situation occurred during the 180 days before by calculating the variables LH6, PR6, $ET_0$6, and DF6. The corresponding percentile was daily associated to the value of the variables LH, PR, and DF. We therefore obtained, for each dry day, the percentile of the eight variables considered in terms of both current dry spell (LH, PR, ET_0, DF) and climatic conditions in the 6 months-past (LH6, PR6, $ET_0$6, DF6) and, for each wet day, the percentile of the four variables LH6, PR6, $ET_0$6, and DF6. Finally, to obtain a synthesis of the whole information gathered, two indexes of drought conditions, namely drought duration and intensity indexes, were calculated. Drought duration index (LHS) refers to the length of dry spells, and was evaluated for each wet day as the percentile associated to the variable LH6 and for each dry day as the maximum between LH and LH6 percentiles. Drought intensity index (DFS) refers to the water deficit during dry spells, and was calculated for each wet day as the percentile associated to the variable DF6 and for each dry day as DF6 percentile under the condition that LH percentile is less than LH6 percentile. Under the condition that LH percentile is greater than LH6 percentile, the percentile associated to water deficit variable was DF percentile. Finally, the drought duration and intensity indexes were aggregated into DSI index by calculating the geometric mean of the two indexes.

LHS and DFS time series were graphically analysed in order to detect trends during the test period. Pairwise correlations between LH, PR and DF variables and elevation, latitude, and longitude of each station were explored by Spearman rank test.

Results and discussions

Climatology of dry spells. Climatological analysis of the dry spells occurred over 32 meteorological stations during 1951-1985 is reported in Table 1. Dry spells were described by length (LH), average rainfall (PR), and water deficit (DF). The influence of the location of each station on LH, PR, and DF was explored by non parametric tests (Table 2). On average, LH was consistently different between northern and southern Italy in spring-summer, with a range encompassing 17 - 85 dry days; even higher differences were detected considering LH 95° percentile. Correlation between median LH and the altitude of each station was significant, as well as with latitude, whereas was not significant with longitude. Median LH in autumn-winter was similar throughout Italy, ranging between 19 and 33 days. Slight differences were detected considering LH 95° percentile. Correlations between median LH and the geographical coordinates of each station were not significant.

Median PR was consistently higher in northern than in southern Italy in spring-summer, ranging between 0.1 and 1.1 mm/day; higher differences were detected considering PR 95° percentile. Correlation between median PR and the altitude of each station was significant, as well as with latitude, whereas is not significant with longitude. Median PR in autumn-winter was comparable in southern Italy and in the north. Slight differences were detected considering PR 95° percentile. Correlations between median PR and the location of each station were not significant.

Median DF is higher in northern than in southern Italy, ranging between –5.2 and –3.2 mm/day in spring-summer. Higher differences were detected considering DF 95° percentile.

Correlation between median DF and the altitude of each station was significant, as well as with latitude, whereas was not significant with longitude. Median DF in autumn-winter was higher in southern Italy than in the north. Slight differences were detected considering DF 95° percentile. Correlations between median DF and the location of each station were not significant.

Assessment of drought severity: a case study. Duration, intensity and severity of drought on a day time scale were estimated for the test period 1988-2003 based on climatological figures. At the national level, the most arid spell along the period considered was recorded during spring-summer 2003, with especially dry conditions occurred in northern and central Italy. This year was considered one of the most hot and dry even recorded in the whole Europe (IPSC 2004). DSI correctly indicates a consistent increase in dryness from March to July 2003 in all the Italian meteorological stations. In March, drought severity reaches the 99° percentile in nine on 32 stations rapidly increasing to 20 on 32 stations in July, all concentrated in the Po plain, Appennines and coastal areas of central Italy. DSI was interpolated by inverse distance weighting procedure throughout Italy to obtain a simple estimation of dryness conditions during the most extreme drought event (Fig. 2), depicting the regions where drought was more severe.

We further selected a sample meteorological station (Rome) in order to daily evaluate the behaviour of the drought index. In such station, the period May-August 2003 was characterized by an exceptionally long dry spell with extremely hot conditions (Mangianti et al. 2004): mean temperatures were always higher than the climatological figures, and extremely low precipitation were recorded (see Table 3). Considering also the climatic conditions in the 6 months preceding the dry spell, drought duration and intensity (Fig. 3), show a high concordance ($r_s = 0.8$, $p < 0.001$). The exceptionally dry spell encompassing the beginning of May till the end of August 2003 was correctly classified as a very anomalous period, with both LHS and DFS indexes rapidly increasing from the normal (40° percentile and 60° percentile for LHS and DFS, respectively) at the beginning of May to the 99° and 90° percentiles, respectively, at the end of August 2003, and the same pattern was measured for DSI.

To verify the influence on drought estimate of reduced precipitation and ET_0 increase, we plotted in a scatterplot (Fig. 4) the ten-day values of LHS and DFS percentiles from 10 May 2003 to 30 August 2003, as compared to the line [$y = x$] indicating a comparable progression of drought severity both in terms of drought duration and intensity. In fact, drought intensity rapidly increased during May and June 2003, due to exceptionally high values of temperature (and thus of ET_0) that enhanced the water deficit (see Table 3). During July and August, both indexes comparably increased, indicating a contribution of both ET_0 and rainfall. A scatterplot comparing LHS and DFS may therefore allows to describe the critical drought episode considering together the two dimensions of drought severity (duration, mainly linked to the consecutive number of dry days occurred, and intensity, mainly linked to the fashion of water deficit). When DFS is higher than LHS, ET_0 contribution to water balance is consistently high, whereas the reverse pattern may indicate that a long period with reduced precipitation rate, but with low ET_0 contribution to water deficit, is occurring. These two situations may represent two extreme drought episodes from an ecological point of view. The first episode may produce a harsh condition potentially dangerous for the development of crop and natural vegetation if occurred during the growth season. The second episode produces a limited drought damage to the vegetation, especially if occurred during the resting season but may provoke a potential reduction of water availability in reservoirs especially in Mediterranean areas, where the resting season corresponds to the wet season.

Drought severity index was used in order to assess the general climatic conditions occurred in a certain location. It allows a synthetic description of drought episodes in terms of both length of dry spells and water balance. Such features make this index suitable to study the relationships between plant phenology/animal ecology and climate changes.

Acknowledgments

This work was carried out in the framework of the national research project 'Climagri – Cambiamenti climatici e agricoltura' coordinated by CRA-UCEA and funded by the Italian Ministry for Agriculture and Forestry Policies (MIPAF). Thanks are due to L. Perini and C. Epifani for fruitful discussion and to S. Giambalvo and C. Todisco for continuous technical assistance. We are grateful to T. Ceccarelli, G. Dal Monte, and E. Di Giuseppe for a critical review of the manuscript.

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Table 1. Length of dry spells (LH), as well as rainfall (PR), and water deficit (DF) during dry spells in Italy (1951-1985, average values).

Variable	*Season*	Percentile	Northern Italy	Central Italy	Southern Italy
Dry spell length [days]	*Spring-Summer*	50°	20.5	30.2	41.8
		95°	54.6	96.5	140.9
	Autumn-Winter	50°	23.6	20.5	23.4
		95°	76.1	57.3	74.3
Rainfall [mm/day]	*Spring-Summer*	50°	0.7	0.4	0.3
		95°	0.1	0.0	0.0
	Autumn-Winter	50°	0.6	0.7	0.7
		95°	0.1	0.1	0.1
Water deficit [mm/day]	*Spring-Summer*	50°	-3.2	-3.7	-3.2
		95°	-4.7	-5.2	-4.6
	Autumn-Winter	50°	-0.3	-0.5	-0.6
		95°	-2.2	-2.6	-2.6

Table 2 – Spearman rank correlation tests between climatological variables [Length (LH, days), daily rainfall (PR, mm/day) and daily water deficit (DF, mm/day) of dry spells] and the geographic location of the 32 meteorological stations here considered (1951-1985); P-values corrected by Bonferroni's multiple comparison correction (testing for significance at $\alpha = 0.0042$).

Variable	**Season**	**Percentile**	**Altitude**	**Latitude**	**Longitude**
LH	*Spring-Summer*	*50°*	$r = -0.11$, $p = 0.56$	$r = -0.96$, $p < 0.001$*	$r = 0.56$, $p = 0.001$*
		95°	$r = -0.10$, $p = 0.58$	$r = -0.96$, $p < 0.001$*	$r = 0.55$, $p = 0.001$*
	Autumn-Winter	*50°*	$r = -0.30$, $p = 0.09$	$r = -0.05$, $p = 0.78$	$r = -0.11$, $p = 0.56$
		95°	$r = -0.40$, $p = 0.02$	$r = -0.10$, $p < 0.59$	$r = -0.18$, $p = 0.32$
PR	*Spring-Summer*	*50°*	$r = 0.25$, $p = 0.16$	$r = 0.90$, $p < 0.001$*	$r = -0.55$, $p < 0.001$*
		95°	$r = 0.42$, $p = 0.02$	$r = 0.57$, $p < 0.001$*	$r = -0.46$, $p = 0.007$
	Autumn-Winter	*50°*	$r = 0.01$, $p = 0.97$	$r = -0.39$, $p = 0.02$	$r = 0.48$, $p = 0.005$
		95°	$r = 0.15$, $p = 0.42$	$r = -0.41$, $p = 0.02$	$r = 0.34$, $p = 0.05$
DF	*Spring-Summer*	*50°*	$r = 0.48$, $p = 0.005$	$r = 0.48$, $p = 0.005$	$r = 0.14$, $p = 0.45$
		95°	$r = 0.41$, $p = 0.02$	$r = 0.41$, $p = 0.02$	$r = 0.21$, $p = 0.24$
	Autumn-Winter	*50°*	$r = 0.35$, $p = 0.05$	$r = 0.35$, $p = 0.05$	$r = -0.14$, $p = 0.44$
		95°	$r = 0.47$, $p = 0.006$	$r = 0.29$, $p = 0.10$	$r = -0.20$, $p = 0.26$

Table 3 – Temperature and precipitation in Rome from May 2003 to August 2003 as compared to the climatological figures.

	Mean Temperature (°C)				*Precipitation (mm)*			
	May	June	July	August	May	June	July	August
2003	21.4	27.3	27.9	29.3	2.6	0.0	2.8	2.4
Average (1960-1990)	18.3	22.2	25.5	24.8	51.0	34.0	16.0	24.0
2003 – Average	+3.1	+5.1	+2.4	+4.5	-48.4	-34.0	-13.2	-21.6

Figure 1 – The meteorological stations included in this study.

Figure 4 – Daily estimates of drought duration (LHS) and drought intensity (DFS) (Rome, October 2002 - August 2003 [date is reported in the format year/month/day]).

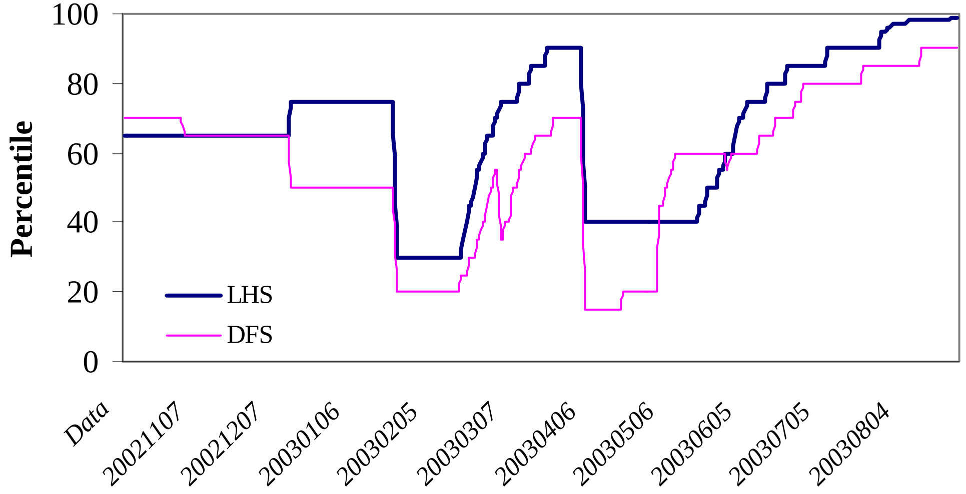
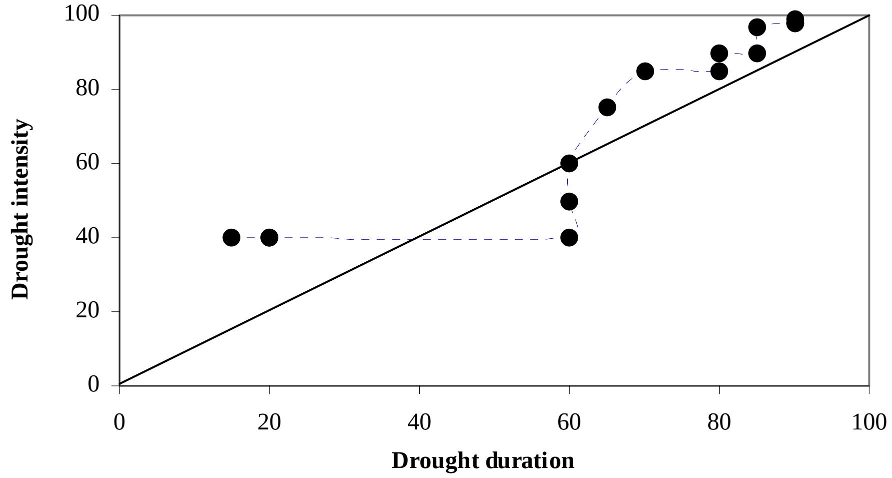


Figure 5 – Ten-days comparison between LHS and DFS: Rome (filled line indicates the values measured consecutively from 10 May 2003 to 30 August 2003; straight line indicates the equation [y = x]).



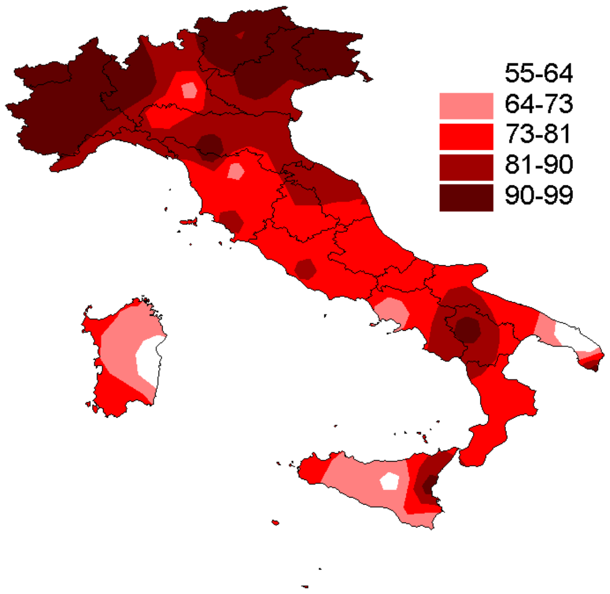


Figure 3 – Drought severity index (DSI) in Italy (30 July 2003).

Figure 2 – Computational flow chart describing the evaluation of drought severity through DSI index.