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Analysis of drought conditions and their effects on Lake Trasimeno (Central Italy) levels

Analisi delle siccità ed effetti sui livelli del lago Trasimeno (Italia centrale)

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Riassunto: In questo lavoro è stata eseguita un'analisi dei periodi di siccità nell'area del lago Trasimeno (Umbria, Italia centrale) studiandone l'influenza sui livelli del lago. Il lago Trasimeno è uno dei più estesi laghi italiani ed è molto importante sia dal punto di vista economico che ambientale. L'analisi dei trend di temperatura (1963-2014) mostra che la temperatura annuale è in aumento – in accordo con quello che si riscontra in Italia centrale e nell'area mediterranea – con un gradiente significativo di circa 0.023°C/anno. Non si osservano trend annuali e stagionali delle precipitazioni ragguagliate sul bacino del lago Trasimeno. L'analisi spettrale delle precipitazioni e delle variazioni dei livelli mensili del lago mostra che in entrambi i periodogrammi, i cicli annuali e semestrali hanno livelli elevati di significatività (>99%). I cicli annuali nel periodogramma delle variazioni dei livelli del lago mostrano un livello di significatività superiore a quello dei cicli semestrali. Livelli di significatività inferiori a quello dei cicli annuali e semestrali sono stati evidenziati per altre oscillazioni, come l'oscillazione El-Niño e North Atlantic, e l'attività solare. Gli indici standardized precipitation index - SPI e standardized reconnaissance drought, a diverse scale temporali, mostrano che la frequenza e la durata delle siccità estreme e severe sono aumentate negli ultimi 25 anni. È stata inoltre ricavata una relazione significativa tra l'indice SPI e le variazioni dei livelli del lago standardizzati a 12 mesi per il periodo 1989-2014: l'analisi indica che SPI_{12} può essere utile come indicatore per rappresentare le siccità di sistemi come il lago Trasimeno prendendo come riferimento le fluttuazioni del livello standardizzate piuttosto che i livelli del lago.

Parole chiave: Lago Trasimeno, livelli del lago, indici climatici, siccità, analisi spettrale.

Keywords: *Lake Trasimeno, lake levels, climate indices, drought, power spectral analysis.*

Abstract: *An analysis of drought conditions on the Lake Trasimeno area (Umbria, Central Italy) and of their influence on the lake levels is presented. Lake Trasimeno is one of the largest Italian lakes, and its economic and environmental importance is very high. The analysis of temperature data (1963-2014) shows that annual temperature is increasing – in accordance with what is known for Central Italy and the Mediterranean area – with a significant gradient of about 0.023°C/year. No significant annual and seasonal rainfall trends were observed over the Lake Trasimeno catchment. The power spectrum analysis of rainfall and lake level fluctuations shows that both periodograms have high statistical confidence levels (>99%) for annual and semi-annual cycles. The annual cycles of the periodogram of lake level fluctuations show a higher statistical confidence level than semi-annual cycles. Some other cycles such as the El-Niño Southern oscillation, North Atlantic oscillation, and solar activity are highlighted, with significance levels lower than that of annual and semi-annual cycles. The standardized precipitation (SPI) and standardized reconnaissance drought indices, at different time scales, show that frequency and duration of extreme and severe droughts have increased in the last 25 years. A significant relationship between 12-month SPI and 12-month standardized lake levels fluctuations was obtained for the 1989-2014 period, indicating that* SPI_{12} *can be a useful indicator to represent drought severity for systems such as the Lake Trasimeno by considering lake level fluctuations rather than lake levels.*

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Introduction

In Southern Europe and Mediterranean basin, an increase in the atmospheric temperature in the last hundred years is associated with a significant general decrease in precipitation (IPCC 2013). In particular, in Central and Southern Italy, in the last fifty-sixty years there have been significant decreases in mean annual and seasonal precipitation in the wet seasons (autumn and winter) that – coupled with the increases of withdrawals – influence spring discharges, lake levels, river flows, soil moisture, etc. (Dragoni and Sukhija 2008; Ducci and Tranfaglia 2008; Vergni and Todisco 2011; Brunetti et al. 2004; Fiorillo and Guadagno 2010; Di Matteo et al. 2013; IPCC 2013; Romano and Preziosi 2013; Maccioni et al. 2014; Dragoni et al. 2015; Fiorillo et al. 2015). The effects of climatic variations on some lakes and springs located in Central Italy, such as Lake Trasimeno, Lake Bolsena, and Bagnara spring (Umbria-Marche Apennines) have been already quantified by adapting rainfall-runoff models at a monthly scale, previously implemented for other systems (Dragoni et al. 2006, 2015; Di Matteo et al. 2010). The frequency of extreme droughts is increasing, the effects of climatic variations on water resources are evident and storms with high intensity are increasing (Trenberth 2011; IPCC 2012, 2013). Some studies on precipitation time series of Central and Southern Italy have indicated the presence of periodicity superimposed, in some cases, to a general decreasing trend (De Vita and Fabbrocino 2007; Romano and Preziosi 2013). The present study takes as reference Lake Trasimeno, which is an important ecosystem with high economic and touristic value. Being a shallow lake (maximum depth of 5 m), lake levels are very sensitive to climatic variations such as: prolonged drought periods and withdrawals for agricultural purposes. Withdrawals have been reduced thanks to the construction of a water pipe line from the Montedoglio dam that has been in operation since 2013 (Di Matteo et al. 2016). In this framework, after the analysis of climate data at a monthly/yearly time scale by applying well-known drought indices [standardized precipitation index (SPI) and reconnaissance drought index (RDI), both lake level and rainfall data series (1963-2014 period) were analyzed by the spectral analysis. This allowed the investigation of the climatic cycles and their statistical significance.

In this work the influence of the El-Niño Southern oscillation (ENSO), North Atlantic oscillation (NAO), and solar activity on inter-annual variability of rainfall data series was also studied. The ENSO is defined as the difference between normalized monthly mean sea level pressures at Tahiti and Darwin (Allan et al. 1991). The NAO is defined as the difference of sea-level pressure between Iceland and the Azores barometric stations (Hurrell 1995; Hurrell and van Loon 1997). In general, if positive NAO values occur, Southern Europe is characterized by warm and dry winters; on the contrary, negative NAO winter values are linked to wet winters. In the last decades many studies on the relationship between NAO and temperature/precipitation time series of Italy have been carried out to study hydrologic regime in spring discharges in Central-Southern Italy (Brandimarte et al. 2011; Caloiero et al. 2011; De Vita et al. 2012; Romano and Preziosi 2013; Fiorillo et al. 2015). Sun activity, quasi-biennial oscillation (QBO) and sunspot cycles are also correlated with precipitation data series (Lamb 1977; Labitzke and van Loon 1990; Rind et al. 2008).

Geological and hydrogeological framework

Lake Trasimeno is located in the inner portion of the Northern Apennines, a NE verging arcshaped thrust belt, formed by the Oligocene-Early Miocene eastward convergence between the Alpine orogen and the Adriatic promontory. Lake Trasimeno is located in an extensional basin related to the opening of the Northern Tyrrhenian Sea that occurred in Western Umbria in Early-Middle Pliocene (Gasperini et al. 2010). The catchment is characterized by marls, calcareous marls, calcarenites and silico-clastic turbidites belonging to the Tuscan Domain (Scaglia Toscana and Macigno, Eocene-Miocene), which, in turn, lay over the easternmost Tuscan-Umbria turbidites. In the western part, rocks of Tuscan Domain are overlaid by marine and fluvio-lacustrine plio-pleistocene sediments. Olocenic alluvial deposits outcrop around the lake and along the main streams (Barchi and Marroni 2007). The permeability of rocks of the 4 Tuscan Domain is generally from low to very low. On the contrary, due to the low to medium-high permeability, the Plio-Pleistocene sediments host local aquifers, which are delimited at the bottom by the Tuscan Domain aquiclude. These aquifers drain toward the lake, so the hydrogeological basin can be virtually considered the same as the surface basin (Dragoni et al. 2015).

Materials and Methods

Data collection

Temperature and rainfall data

In order to define the climatic tendencies of Lake Trasimeno area and their effects on lake levels, monthly air temperature and precipitation time series recorded between 1963 and 2014 in six rainfall stations and one temperature station, were analyzed (Fig.1). Climatic data were retrieved from the Italian National Hydrographic and Mareographic Service as well as from the Umbria and Toscana Regional Hydrographic Services. The location of stations is shown in Fig.1. Records of four out of six rainfall stations were almost continuous, and the missing data were reconstructed by multiple regression. For the stations of Monte del lago and S. Savino, both located east of the lake, about 14% of monthly data were missing but in these periods at least one of the two stations was working. The temperature station (Monte del lago) has been running almost continuously. A few data missing have been reconstructed by means of multiple regression using data from stations located in the same area (Dragoni et al. 2015).

The monthly rainfall over Lake Trasimeno catchment (R) was calculated by means of Thiessen polygons, according to the stations shown in Fig. 1. The mean monthly rainfall of the 1963-2014 period is very similar in all stations, as the elevation and the morphology of the basin are fairly uniform (Fig. 2). The annual mean rainfall has a range between about 700 and 800 mm/year.

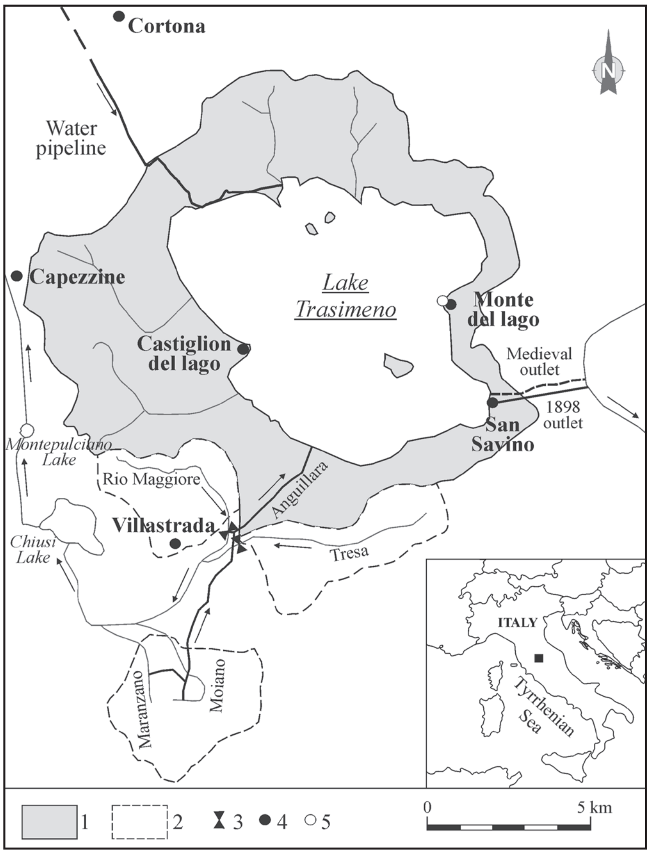

Fig. 1 - Map of study area with location of the outlet and weather stations. 1 - Natural catchment; 2 - artificially joined basins; 3 - location of sluice-gates of artificially joined channels; 4 - rain gauges; 5 - temperature station.

Fig. 1 - Schema dell'area di studio con la localizzazione dell'emissario. 1 - Bacino naturale del lago; 2 - bacini allacciati; 3 - localizzazione delle paratoie dei bacini allacciati; 4 - stazioni pluviometriche; 5 - stazione termometrica.

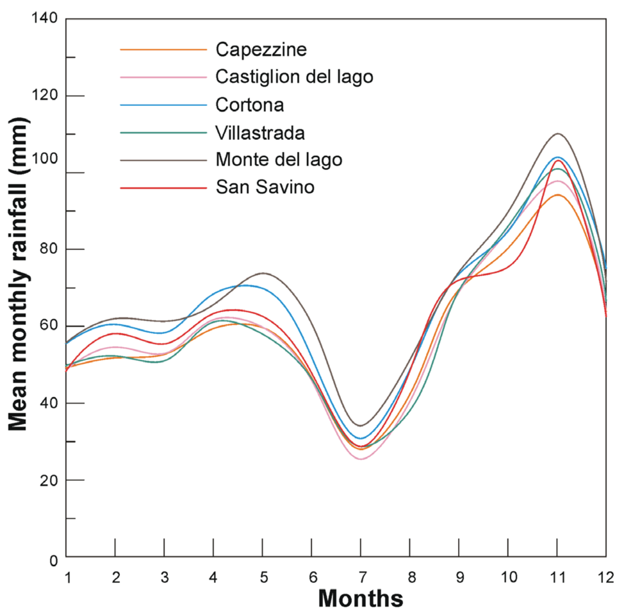

Fig. 2 - Monthly average rainfall for rain gauges located in the Lake Trasimeno area (1963- 2014 period).

Fig. 2 - Precipitazioni medie mensili nei pluviometri ubicati nell'area del lago Trasimeno nel periodo 1963-2014.

Lake levels

Levels of Lake Trasimeno have been recorded since January 1921 in a gauging station in the outlet (Fig. 1). During the 1959-1962 period, the lake catchment area was enlarged from about 309 to 383.4 km^2, by connecting the catchments of four creeks. In this work lake levels recorded from January 1963 were studied. Fig. 3 shows the monthly lake levels from 1963 to 2014. A strong seasonal and annual variability can be observed, with the lowest values generally occurring in October and highest values recorded in May and June. The elevations of the lake outlet (threshold) changed from 257.33 to 257.50 m above sea level in May 1983. During 1989- 2014, lake levels have been lower than the lake outlet threshold: the lowest lake levels were reached in 2002-2003 as a consequence of a prolonged drought period (OPCM 2002). In October-November 2003, the lake depth was as low as 4 m. After 2003, the lake levels decreased again during the drought periods, which occurred in 2007-2008 and 2012. After 2012, lake levels gradually recovered and in February 2015 the outlet bulkheads were opened after having been closed since May 1988.

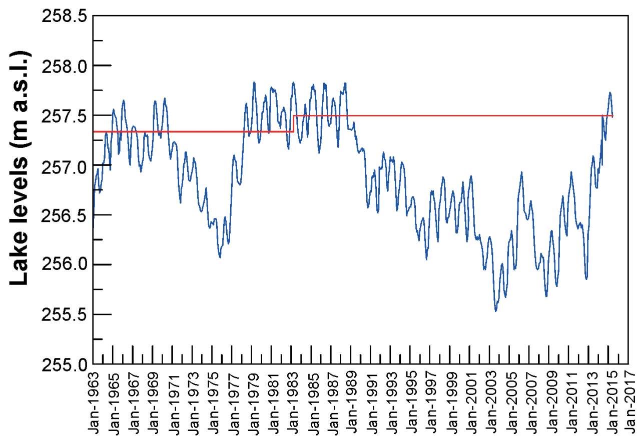

Fig. 3 - Monthly levels of Lake Trasimeno for the 1963-2014 period. The elevation of the outlet threshold is shown in red.

Fig. 3 - Livelli mensili del lago Trasimeno nel periodo 1963-2014. La linea rossa rappresenta la quota della soglia dell'emissario.

Methods

Spectral analysis

Spectral analysis was used to investigate the presence of climatic cycles in long time series of rainfall and lake levels as well as their statistical significance (Blackman-Tukey 1958; Jenkins and Watts 1968; Pardo-Igúzquiza and Rodríguez-Tovar 2012). The signal component represents the structured part of the time series, made up of a small number of cycles repeated over a long time. When one cyclic component contains any other cyclic component of a period longer than the length of the time series, it will give an apparent trend. This, together with possible real trends and other factors, gives rise to noise in the low frequencies, which is known as red noise.

Analysis of climatic trends and drought periods

The Mann-Kendall test (MK) was applied in order to check the presence of significant annual and seasonal trends of temperature and rainfall. The MK test is a non-parametric test (Mann 1945; Kendall 1975) according to which the null hypothesis H_0 assumes there is no trend (the data is independent and randomly ordered) and this is tested against the alternative hypothesis H_1, which assumes that there is a trend. The null hypothesis is tested at 95% confidence level.

In order to investigate the magnitude and number of droughts occurring over the last 5 decades and their effects on the lake, the SPI and RDI were used.

The SPI (McKee et al. 1993, 1995) is the number of standard deviations that the observed value would deviate from the long-term mean, for a normally distributed random variable. In the SPI computation cumulated rainfalls over different time scale (3, 6, 9, 12, 24, 48 months) are fitted to a gamma probability distribution and then transformed into a normal distribution. For a given data time series of precipitation X_i as X_1; X_2 ….. X_n, the SPI is defined by eq. (1):

$$SPI = \frac{x_i - \overline{x}}{\sigma_x} \tag{1}$$

Where: $\overline{x}$ is the arithmetic mean of rainfall and σ_x is the standard deviation. For a defined timescale, SPI equal to 0 implies that there is no deviation from the mean. Positive values of SPI indicate wet periods, while negative values indicate dry periods compared with the normal conditions of the area analyzed. The severity of drought events increases when SPI values are highly negative.

The RDI (Tsakiris and Vangelis 2005; Tsakiris et al. 2007) is another meteorological index used to analyze drought severity. The value (α_k) of RDI is calculated for the i-th year for a reference period of k months according to eq. (2):

$$\alpha_k^i = \frac{\sum_{j=1}^{k} P_{ij}}{PET_{ij}}; \quad with\ i = 1,2,.....;\ N\ and\ j = 1,2,.....k \tag{2}$$

Where P_{ij} and PET_{ij} are precipitation and potential evapotranspiration of month j of year i, respectively, and N is the total number of years of the available data. By assuming that the lognormal distribution is applied, eq. (3) can be used for the calculation of the standardized RDI (*i.e.* RDI_{st}):

$$RDI_{st}^{(i)} = \frac{y^{(i)} - \overline{y}}{\hat{\sigma}_y} \tag{3}$$

where $y^{(i)} = \ln(\alpha_k^{(i)})$; $\overline{y}$ is the arithmetic mean of $y^{(i)}$; $\hat{\sigma}_y$ is the standard deviation of $y^{(i)}$. In the case that the gamma distribution is applied, RDI_{st} can be calculated by fitting the gamma probability density function (pdf) to the given frequency distribution of α_k. Like the SPI index, positive values of RDI_{st} indicate wet periods, and negative values indicate dry periods compared to the normal conditions of the area. Tab. 1 shows the classification of drought conditions based on the SPI and RDI_{st} values.

Tab. 1 - Classification of drought conditions based on the standardized precipitation index and standardized reconnaissance drought index range values.

Tab. 1 - Classificazione delle condizioni di siccità basata sui range di valori di standardized precipitation index e standardized reconnaissance drought index.

Condition	Range
Extremely wet	(SPI, RDI_{st}) ≥2.0
Very wet	1.5≤(SPI, RDI_{st})<2.0
Moderately wet	1.0≤(SPI, RDI_{st})<1.5
Near normal	-1.0<(SPI, RDI_{st})<1.0
Moderately dry	-1.5<(SPI, RDI_{st}) ≤-1.0
Severely dry	-2.0<(SPI, RDI_{st}) ≤-1.5
Extremely dry	(SPI, RDI_{st}) ≤-2.0

Results and Discussion

Spectral analysis

Previous studies in Central Italy showed periodic signals with periods of 3, 4, 8 and 15 years (Romano and Preziosi 2013). In other places of the Mediterranean area, like Spain, similar climatic cycles have been shown in hydrologic time series (e.g., Lopez-Bustins et al. 2007; Luque-Espinar et al. 2008; Merino et al. 2015).

The power spectrum analysis of rainfall of the Lake Trasimeno catchment and lake levels showed some cycles. Figs. 4 and 5 show the periodograms obtained analyzing monthly rainfall and Lake Trasimeno level fluctuations, respectively. In both figures, eight different cycles having different significance level (s.l.) were highlighted: i) semi-annual (SAN), ii) annual (A), iii) quasi biennial oscillation (QBO), iv) El Niño South oscillation (ENSO), v) North Atlantic oscillation (NAO), vi) sun activity (SA), vii) sunspot cycle (SUNSPOT), viii) 15.5 year (15.5y).

Tab. 2 shows, in percentage, the statistical confidence levels of periodicities (or cycles repeated over a long time) of rainfall and lake level fluctuations. Both periodograms (Figs. 4 and 5) show high significance levels (>99%) for annual and semi-annual cycles. The annual cycles in the periodogram of lake level fluctuations show a higher statistical confidence level than those of semi-annual cycles (Fig. 5). QBO and 15.5y cycles for the rainfall data show an s.l.>90%. ENSO and cycles related with sun activity (SA and SUNSPOT) show an appreciable statistical significance (for both periodograms) but lower than or equal to 90%. Moreover, in the study area the NAO cycle is weakly represented in rainfall and lake level fluctuations time series.

Climatic trends and drought periods

The trend analysis of temperature and rainfall data sets in the 1963-2014 period using the MK test indicated that the annual temperature has increased 0.023°C/year (Fig. 6). Regarding the analysis of rainfall time series, no significant trends were observed.

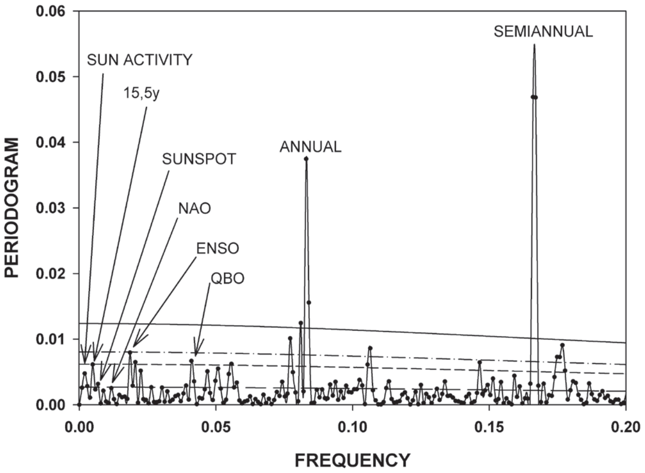

Fig. 4 - Periodogram of the precipitations in Lake Trasimeno basin in the 1963-2014 period. Long-dash line: mean power spectrum; short-dash line: 90% significance level (s.l.); dash-dot line: 95% s.l.; solid line: 99% s.l.

Fig. 4 - Periodogramma della pioggia ragguagliata sul bacino del lago Trasimeno nel periodo 1963-2014. Linea a trattini lunghi: power spectrum medio; linea a trattini corti: livello di significatività (s.l.) del 90%; linea a trattino-punto: s.l. del 95%; linea continua: s.l. del 99%.

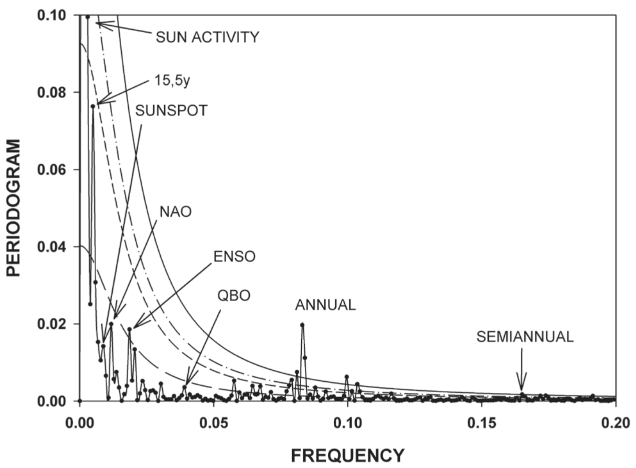

Fig. 5 - Periodogram of the fluctuations of Lake Trasimeno levels in the 1963-2014 period. Long-dash line: mean power spectrum; short-dash line: 90% significance level (s.l.); dash-dot line: 95% s.l.; solid line: 99% s.l..

Fig. 5 - Periodogramma delle variazioni dei livelli del lago Trasimeno nel periodo 1963-2014. Linea a trattini lunghi: power sprectrum medio; linea a trattini corti: livello di significatività (s.l.) del 90%; linea a trattino-punto: s.l. del 95%; linea continua: s.l. del 99%.

Although no significant rainfall trends are observed in this area, the use of two climate indices (SPI and RDI_{st}) allowed the investigation of drought periods during the last 5

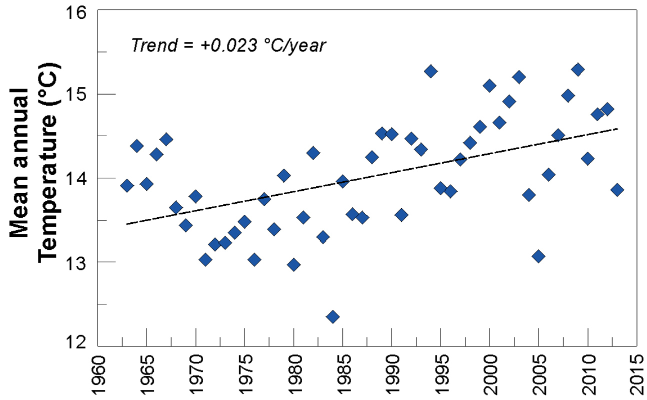

Fig. 6 - Mean annual temperature trend of Monte del lago station in 1963-2014 period (+0.023°C/year).

Fig. 6 - Trend di temperatura media annua della stazione di Monte del lago nel periodo 1963-2014 (+0.023°C/anno).

decades. Fig. 7 shows the 12-month SPI (SPI_{12}) and 12-month RDI_{st} (RDI_{12}) values calculated over the 1963- 2014 period. During the last 25 years (1989-2014) at least four prolonged droughts were recognized (1989-1990, 2002-2003, 2007-2008, and 2012), the frequency and magnitude of which have increased in the last 10 years (Fig. 7). During the first half

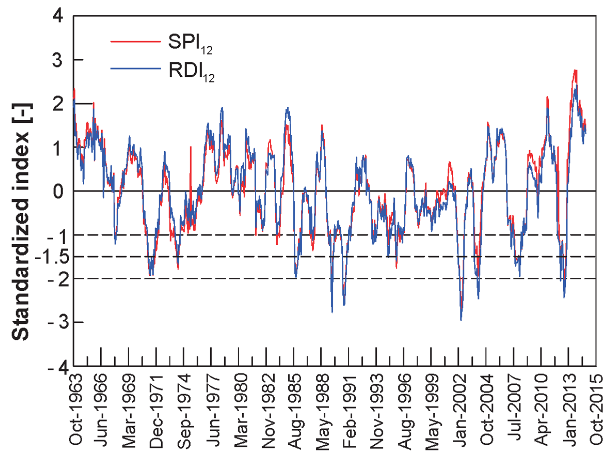

Fig. 7 - 12-month standardized precipitation and reconnaissance drought indices values during the 1963-2014 period.

Fig. 7 - Valori degli indici standardized precipitation e reconnaissance drought su dodici mesi nel periodo 1963-2014.

Tab. 2 - Statistical confidence level values (%). R: rainfall over the catchment; WLF: water level fluctuations; SAN: semi-annual. A: annual; QBO: quasi biennial oscillation; ENSO: El Niño South oscillation; NAO: North Atlantic oscillation; 15.5y: 15.5 years; SA: sun activity.

Tab. 2 - Valori dei livelli di confidenza (%). R: pioggia ragguagliata sul bacino; WLF: livelli del lago; SAN: semi-annuale; A: annuale; QBO: quasi biennial oscillation; ENSO: El Niño South oscillation; NAO: North Atlantic oscillation; 15.5y: 15,5 anni; SA: attività solare.

	SAN	A	QBO	ENSO	NAO	SUNSPOT	15.5y	SA
R	>99	>99	>90	90	90	90	>90	90
WLF	>99	>99	90	<90	<90	<90	90	90

of the rainfall series (1963-1988), two severe drought periods were observed (1971 and 1985). The RDI_{12} values show in general a high agreement with SPI_{12} values, supported by the high value of the coefficient of determination (R^2=0.95) and a significance level >99% with *t*-test (Fig. 7). As shown in Fig. 8, the number of months with SPI values≤-2.0 (extremely dry periods) passed from 0 (1963-1988 period) to 11 (1989-2014 period) with an increase of cases having consecutive values of SPI≤-2.0 especially during the drought periods in 1990 and 2002.

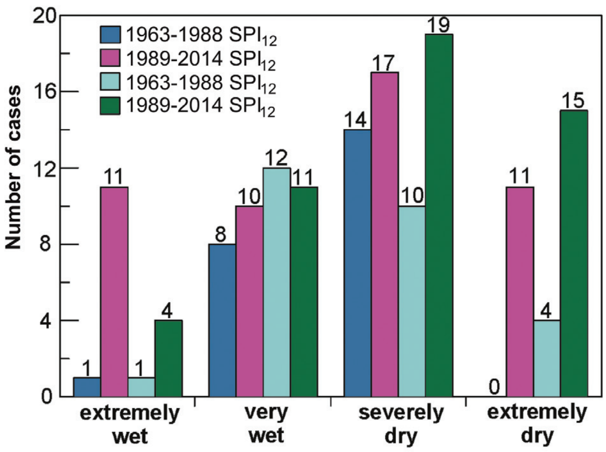

Fig. 8 - Comparison of the number of cases characterized by 12-month standardized precipitation and 12-month standardized reconnaissance drought indices values during the 1963-1988 and 1989-2014 periods according to categories reported in Tab. 1.

Fig. 8 - Confronto tra il numero di episodi con valori degli indici standardized precipitation e standardized reconnaissance drought su dodici mesi ≤-1.5 e ≥1.5 nei periodi 1963-1988 e 1989-2014 suddivisi per categorie (Tab. 1).

Referring to Fig. 3, lake levels experienced periods with very low values during 1989-2014, which recovered only during the last 2 years of the time period where SPI_{12} values higher than 2 and 1.5<SPI_{12}<2 occurred for prolonged periods (Fig. 7).

The relationships between lake levels and climatic indices (SPI and RDI) show weak correlation with a maximum R^2 of 0.3 reached for a 48-month time scale (1989-2014 period). This period has been chosen because lake levels are not affected by flows from the outlet. A further analysis was carried out on standardized lake level fluctuations (ΔH_{st}) calculated by eq. 4:

$$\Delta H_{st} = \frac{\Delta H_i - \overline{\Delta H}}{\sigma_{\Delta H}} \quad (4)$$

Where: ΔH_i= lake level fluctuation on monthly basis for a moving window of n months, where *n* indicates the lake level fluctuation of 3, 6, 9, 12, 24 or 48 months.

$\overline{\Delta H}$ = mean lake level fluctuations referred to the selected time scale for the 1989-2014 period;

$\sigma_{\Delta H}$= standard deviation lake level fluctuations referred to the selected time scale for the 1989-2014 period.

It is interesting to point out that by using ΔH_{st12} (n=12) for the same observation period, the correlation with climatic indices increases. Maximum R^2 values of about 0.9 are reached for both SPI_{12} and RDI_{12} (significance level by t-test higher than 99%) (Figs. 9 and 10).

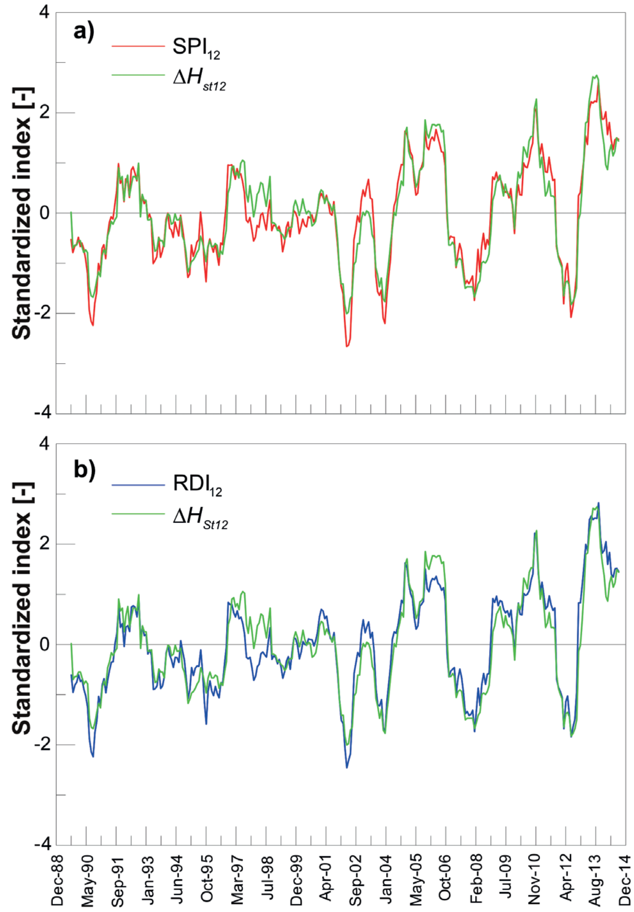

Fig. 9 - Comparison between SPI_{12} and ΔH_{st12} (a) and RDI_{12} and ΔH_{st12}(b) 1989-2014 period.

Fig. 9 - Confronto tra SPI_{12} and ΔH_{st12} (a) e RDI_{12} and ΔH_{st12} (b) nel periodo 1989-2014.

Conclusions

A study concerning the analysis of climatic tendencies in the Lake Trasimeno area was carried out in order to investigate their influence on the lake system. Unlike other places in Central and Southern Italy, in the Lake Trasimeno catchment no significant annual or seasonal rainfall trends were observed. This agrees with the findings of Di Matteo et al. (2006, 2016), Vergni and Todisco (2011), Ludovisi et al. (2013), and Dragoni et al. (2015), who obtained similar results for the Northern-Western part of the Umbria Region. The use of two well-known climatic indices (SPI and RDI) indicates that – at different time scales – they both show an increase of the frequency of droughts during the last 25 years (1989-2014) with respect to the 1963-1988 period. These drought periods – except that occurred in 2012 – were recognized also in the Central Apennines by Di Matteo et

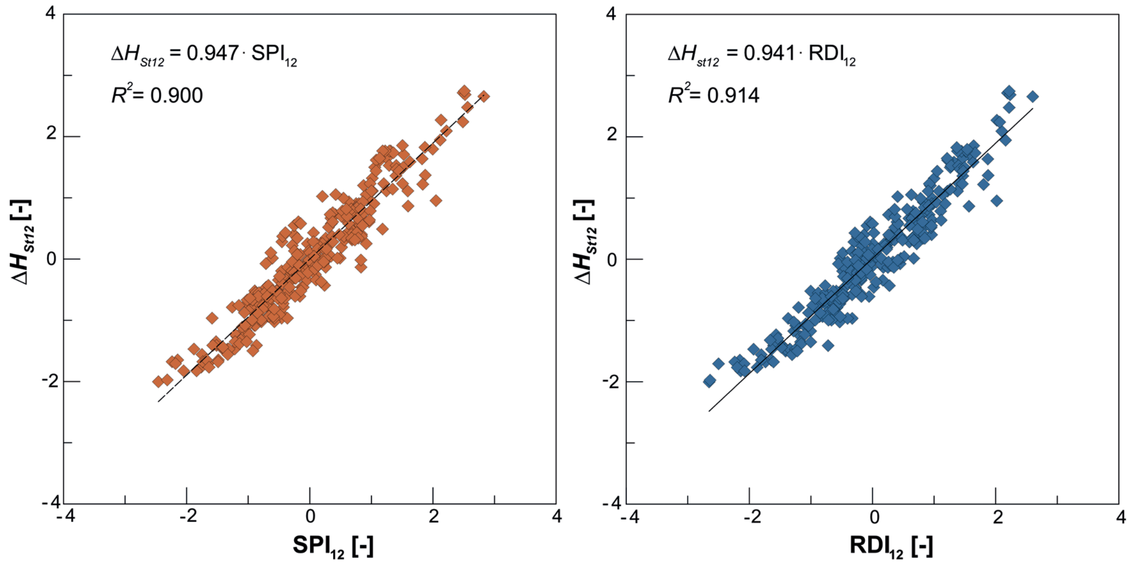

Fig. 10 - Relationship between SPI_{12} and ΔH_{st12} (a) and RDI_{12} and ΔH_{st12}(b) 1989-2014 period.

Fig. 10 - Relazione tra SPI_{12} and ΔH_{st12} (a) e RDI_{12} and ΔH_{st12} (b) nel periodo 1989-2014.

al. (2013), and in the Upper Tiber River basin by Maccioni et al. (2014), who investigated the 1963-2008 and 1953-2011 periods respectively. As reported by Fiorillo and Guadagno (2010) the SPI_{12} is a good indicator to represent drought severity for limestone aquifers. Maccioni et al. (2014) stated that SPI_{12} is a weak indicator to represent the levels of the Lake Trasimeno, which respond to the drought events with a longer lag time (analysis on period 1917-2011). The present analysis considered a period when the lake outlet was not working (1989-2014), obtaining similar results. On the contrary, a good relationship between SPI_{12} and 12-month standardized lake levels fluctuations (ΔH_{st12}) was obtained for the 1989-2014 period (R^2=0.90, significance by *t*-test >99%). The analysis also showed that very similar results are obtained by using the RDI_{12} index, which takes into account the monthly potential evapotranspiration. The power spectrum analysis of rainfall and lake level fluctuations shows that both periodograms (Figs. 4 and 5) have high significance levels (>99%) for annual and semi-annual cycles. The annual cycles in the periodogram of lake level fluctuations show a statistical confidence level higher than semi-annual cycles (Fig. 5).

According to Dragoni (2004), about 62% of the water feeding the lake in the 1963-1997 period was directly supplied by rainfall on the lake surface. Moreover, part of the rainfall on the catchment is subject to evapotranspiration. It is well known that much of the meteorological inflow feeding the lake consists of rainfall on the lake surface. It should be considered that the lake levels are also influenced by other components of the water budget, such as the evaporation from the lake surface and withdrawals. These latter represent the 5% of the mean annual evaporation, a small contribution if compared to the water losses due to the evaporation from the lake and to the evapotranspiration from the basin (Dragoni 2004; Dragoni et al. 2012). The problem of withdrawals was further mitigated by the construction, in 2008-2010, of a pipeline adducting water from the Montedoglio reservoir, on the Tiber River (Di Matteo et al. 2016).

In summary, the lake levels of Lake Trasimeno are very sensitive to the amount of annual rainfall. According to the modelling by Dragoni et al. (2015), even assuming the temperature to remain constant and the rainfall decrease to be as small as -5%, the water stored in the lake and the average lake depth would decrease significantly in the next decades, producing dramatic effects on the lake and its ecosystem (Ludovisi et al. 2013). In this context, SPI_{12} and RDI_{12} indices can be useful indicators to represent drought severity for systems such as Lake Trasimeno by considering lake level fluctuations rather than lake levels.

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