Presentació de l'estudi *El Niño The Southern Oscillation and climate trends impact reservoir water quality*

(El Niño i les tendències climàtiques afecten la qualitat de l'aigua als embassaments)

Roda de premsa

Barcelona, 28 d'abril 2010

Dossier de premsa

Índex

L'estudi

L'estudi ***El Niño i les tendències climàtiques afecten la qualitat de l'aigua als embassaments*** analitza dades sobre la quantitat i la qualitat de l'aigua recollides des que es va omplir per primer cop l'embassament al 1964 fins el 2007. Amb aquestes s'ha pogut detectar l'efecte del Niño i de canvis climàtics recents.

La quantitat d'aigua que entra al pantà de Sau des del riu Ter ha disminuït un 44% en els darrers 44 anys. Així doncs, mentre que a la dècada dels 60 entrava prou aigua per omplir l'embassament 4 cops l'any, actualment el riu Ter només el pot omplir 2.2 cops l'any. Això representa aproximadament el volum d'aigua potable urbana consumida a tot Catalunya durant 4 mesos.

Els resultats de l'estudi indiquen que la principal causa de la reducció dels cabals al Ter és el canvi en el clima de la conca, principalment l'augment de les temperatures que hauria provocat un augment significatiu de la transpiració dels boscos. Cal destacar que la relació d'aquesta tendència climàtica al Ter amb el fenomen de l'escalfament global, tot i que és plausible, no es demostra en aquest estudi.

La baixa quantitat d'aigua que entra al pantà de Sau ha repercutit negativament en la qualitat de l'aigua. Així doncs, a l'estudi podem comprovar que les situacions de dèficit d'oxigen dissolt a l'aigua de l'embassament -paràmetre indicador de baixa qualitat de l'aigua- han augmentat un 23% de mitjana degut al descens dels cabals provocats pel canvi en el clima a la conca. Tanmateix, aquest efecte és més intens durant anys secs, quan l'embassament presenta un augment del 30% de les situacions d'anòxia provocada per la tendència climàtica.

D'altra banda, la disminució de cabals provocada pel canvi climàtic a la conca ha contrarestat parcialment els beneficis provocats per la implantació del Pla de Sanejament a la conca del Ter durant els anys 80-90. La construcció de depuradores als principals nuclis urbans aigües amunt de l'embassament va provocar-hi una millora ostensible de la qualitat de l'aigua al mateix, amb un descens del 30% de les situacions de dèficit d'oxigen dissolt. L'estudi, però, estima que sense la presència del canvi climàtic el descens de les situacions d'anòxia hauria arribat al 48%.

Finalment, **l'estudi demostra que tant els cabals a la conca del Ter com la qualitat de l'aigua al pantà de Sau es veuen afectats pel fenomen climàtic El Niño**. Aquest es reflecteix a la conca del Ter en oscil·lacions del seu cabal i en la quantitat d'oxigen dissolt a l'aigua del pantà de Sau en períodes entre 2 i 5 anys, coincidint amb els cicles del Niño.

Tot això suggereix que els recursos aquàtics al nostre país estan afectats per fenòmens climàtics globals com els canvis climàtics o les oscil·lacions climàtiques com El Niño. **Si les prediccions climàtiques per a la nostra regió es compleixen, això implicarà una reducció important de la qualitat de l'aigua als nostres embassaments, que només podria ser contrarestada amb l'afinament dels processos de depuració de les aigües residuals**.

Tanmateix, aquest estudi no només té implicacions locals ja que moltes regions basen l'abastament d'aigua potable en els embassaments, com poden ser Europa, Austràlia, Sud-àfrica, Xile i Estats Units, com a reginons de clima mediterrani, i Estats Units, Amèrica Central, el Nord de Brasil i l'Orient Mitjà, com a regions àrides. Aquests resultats suposen un avís als gestors de l'aigua en aquests països en el sentit que el canvi climàtic pot ser un risc futur pel que fa no només a la quantitat d'aigua, sinó també a la seva qualitat i els costos de tractament de l'aigua.

[Veure l'estudi. Annex 1]

Punts clau de l'estudi

1. Aquest estudi és **el primer a escala internacional** a demostrar els efectes del canvi climàtic i del Niño en la qualitat de l'aigua als embassaments.

2. La singularitat de l'estudi fa que aquest es converteixi en **una referència per als gestors de l'aigua arreu del món**, especialment en els països on els embassaments són nombrosos.

3. L'estudi demostra que **els efectes del canvi climàtic es poden detectar a regions de l'Estat** no només com un augment de temperatures, sinó també **com una disminució dels cabals als rius i de la qualitat de l'aigua als embassaments.**

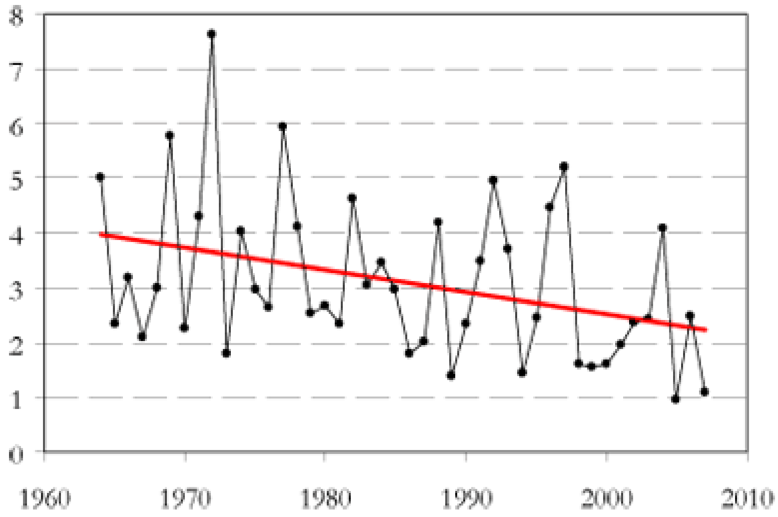
4. L'estudi aporta dades rellevants pel que fa a la gestió dels recursos hídrics a Catalunya i deixa clar que **les tendències climàtiques poden provocar descensos en la quantitat de recursos a mitjà termini**.

5. L'estudi demostra que **un canvi climàtic recent a Catalunya ha contrarestat parcialment mesures ambientals destinades a millorar la qualitat dels ecosistemes aquàtics.**

6. Si les prediccions climàtiques sobre escalfament global es compleixen, **les conseqüències dels previsibles descensos de cabals als rius sobre la qualitat de l'aigua als embassaments només es podran contrarestar amb una actuació decidida de les administracions** pel que fa al refinament dels processos de depuració de les aigües residuals.

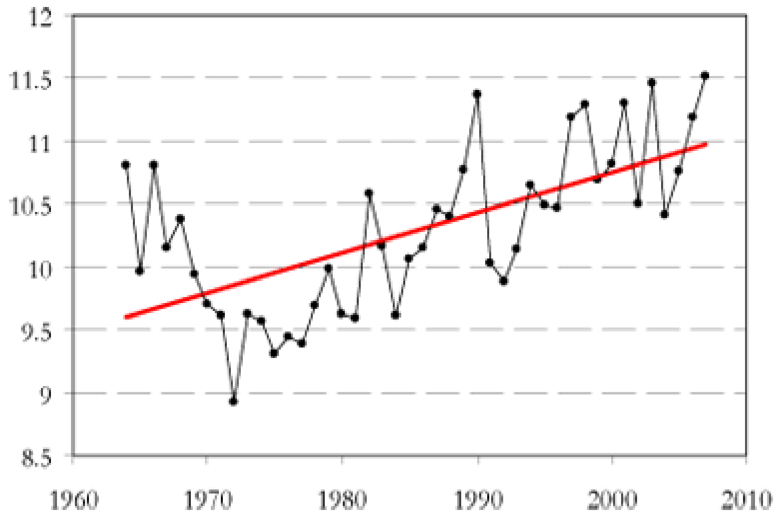
L'estudi en xifres

Aportacions d'aigua al pantà de Sau des del riu Ter



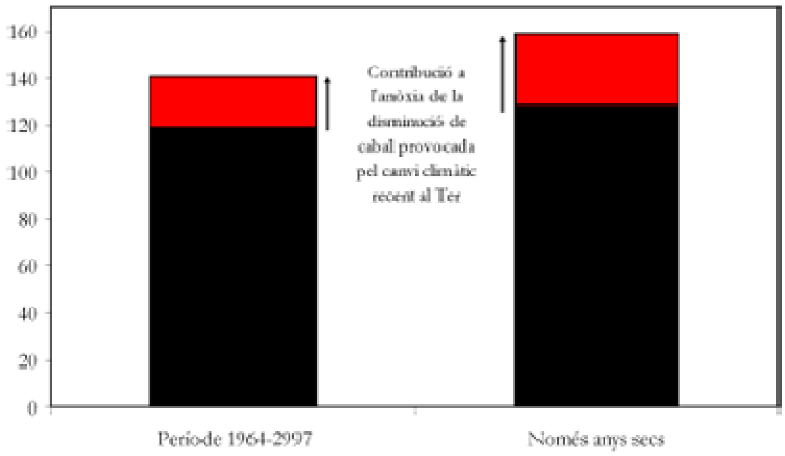
Evolució de les aportacions al pantà de Sau des del riu Ter, expressades com el nombre de cops que es podria omplir l'embassament amb l'aigua aportada pel riu Ter cada any. La línia vermella és la tendència estadística d'aquestes aportacions.

Temperatura mitjana a la conca del riu Ter



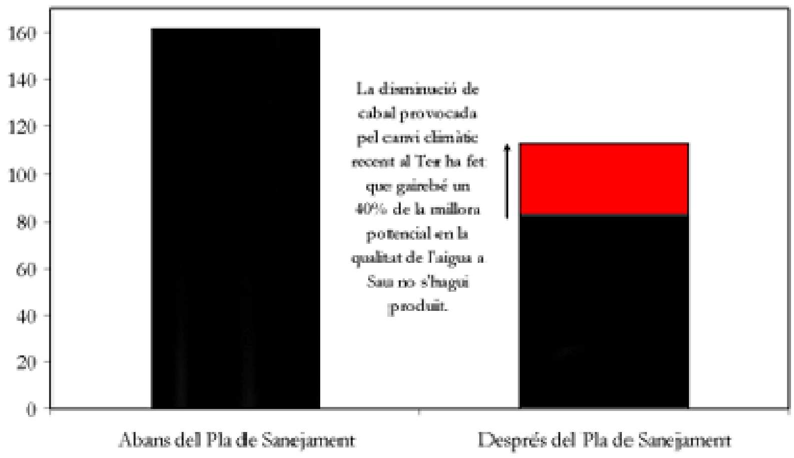
Evolució de la temperatura mitjana a la conca del riu Ter. La línia vermella és la tendència estadística d'aquesta evolució.

Efecte del canvi climàtic recent en la qualitat de l'aigua al pantà de Sau (durada dels episodis d'anòxia en dies/any)



Contribució de la disminució de cabals provocada pel canvi climàtic recent a la conca del Ter a l'empobriment de la qualitat de l'aigua a Sau. Es donen les dades per a tot el període estudiat i per als anys considerats secs. Es veu que en anys de sequera l'efecte del canvi climàtic sobre la qualitat de l'aigua és més acusat. L'anòxia és una situació de manca d'oxigen dissolt a l'aigua que repercuteix molt negativament en la qualitat de l'aigua i els processos de potabilització.

Efecte del canvi climàtic contrarestant les millores en la qualitat de l'aigua al pantà de Sau degudes a l'aplicació del Pla de Sanejament al Ter (durada dels episodis en dies/any)



La disminució de cabals provocada pel canvi climàtic recent al Ter ha tingut conseqüències negatives pel que fa al resultat de l'aplicació de mesures ambientals. Aquí es veu com la millora esperada a l'embassament de Sau per l'aplicació del Pla de Sanejament a la conca del Ter només s'ha complert parcialment, ja que el canvi climàtic ha contrarestat parcialment la millora. L'anòxia és una situació de manca d'oxigen dissolt a l'aigua que repercuteix molt negativament en la qualitat de l'aigua i els processos de potabilització.

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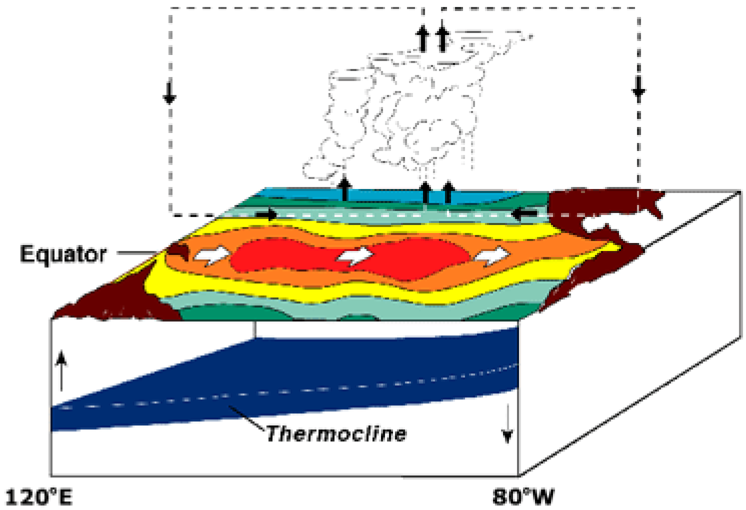
El Niño



Condicions del Niño

El Niño és una anomalia climàtica de més d'onze mil·lennis d'història que es produeix al Pacífic i que consisteix en un canvi en els patrons de moviments de masses d'aire fet que provoca un retard en la cinètica dels corrents marins, la qual cosa desencadena l'escalfament de les aigües sud-americanes; i provoca estralls a escala mundial, afectant primordialment les zones d'Amèrica del Sud, Indonèsia i Austràlia.

Aquesta anomalia climàtica comença a l'oceà Pacífic Tropical alterant la pressió atmosfèrica de zones molt distants entre elles, fet que causa canvis en la direcció i la velocitat dels vents que es desplacen a las zones de pluja de les regions tropicals.

Durant el Niño els vents alisis es debiliten i deixen de bufar, la màxima temperatura marina es desplaça fins al sistema de corrents Xilenoperuà, que és relativament fred, i la mínima de la temperatura marítima es desplaça cap al sud-est asiàtic. Això provoca un augment de la pressió atmosfèrica del sud-est asiàtic i la disminució a Amèrica del Sud. Tot aquest canvi passa en un interval de 6 mesos que, aproximadament, van des de juny fins a novembre.

El Niño també afecta la resta de continents, on provoca un canvi a la circulació atmosfèrica i un canvi a la temperatura oceànica.

Fitxa tècnica

La recerca presentada es basa en dades recollides al pantà de Sau i a la conca del Ter des de 1964 fins a 2007 per l'equip de recerca FLUMEN i l'empresa Aigües Ter Llobregat. Els autors han estat analitzant les dades durant dos anys (2008-2009).

El treball es publicarà pròximament a la prestigiosa revista *Global Change Biology*. Es tracta de la revista de referència internacional en el tema de l'efecte del canvis globals als ecosistemes, només per sota de les revistes generalistes *Science*, *Nature* i *PNAS*. Actualment, el podem veure a la versió electrònica de la revista, secció *Early View*, amb data de 5 de gener del 2010.

ANNEX 1:

El Niño Southern Oscillation and Climate Trends impact reservoir water quality

Global Change Biology

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El Niño Southern Oscillation and climate trends impact reservoir water quality

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Abstract

Low dissolved oxygen concentration in bottom layers of lakes and reservoirs usually indicates low water quality. In lakes, empirical models predicting anoxia are almost entirely based on the decay of plankton biomass, while in reservoirs recent findings suggest a prominent role of streamflow and load of organic carbon. This suggests a potential link between water quality in reservoirs and climate processes affecting streamflow. Here we support this hypothesis presenting evidence that both interannual climate variability and recent climate change, mainly consisting in a significant increase in potential evapotranspiration in the upstream basin, affected the oxygen content in a Mediterranean reservoir (Sau Reservoir, Spain). Using a 44-year monthly record, we found strong and consistent signatures of El Niño Southern Oscillation in the inflow and reservoir oxygen content. Spectral and wavelet techniques showed that the El Niño, streamflow, and reservoir oxygen content series oscillated in common periods, which coincided with the main El Niño variability modes. An empirical model explaining the annual oxygen content in the reservoir suggested that a decreasing streamflow trend reduced the oxygen content of the reservoir by about 20%, counteracting remediation measures implemented at the basin upstream the reservoir. Our results provide the first quantitative evidence of climate change effects on reservoir water quality using long-term instrumental data, and indicate that streamflow should be considered as a key variable in assessing climate change impact on reservoir water quality. These results are especially relevant in regions of the world where reservoirs are abundant and most climate models predict a decrease in runoff during the next decades. Both the expected trends and the sensitivity of reservoir water quality to global interannual climate variability should be considered for a correct management of water resources in the present and to design adaptation policies in the future.

Keywords: anoxia, Anoxic Factor, climate change impacts, ENSO, streamflow

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Introduction

There is a general consensus that water quality in lakes and reservoirs will change as climate changes (Carpenter *et al*., 2006; Gleick *et al*., 2008; Williamson *et al*., 2008, 2009a, b). Field data on lakes have demonstrated climate effects on water quality variables, including modifications in stratification (Verburg *et al*., 2003; Jankowski *et al*., 2006), water transparency (Verburg *et al*., 2003; Hampton *et al*., 2008), oxygen content (O'Reilly *et al*., 2003; Jankowski *et al*., 2006), primary production and algal biomass (O'Reilly *et al*., 2003; Hampton *et al*., 2008), phenological patterns (Magnuson *et al*., 2000; Winder & Schindler, 2004), and occurrence of harmful algal blooms (Paerl & Huisman, 2008). Most of these studies relate those changes to increasing air temperatures that drive alterations through modifications in the heat balance and the mixing dynamics of water bodies.

In contrast, despite the ecological and socio-economic relevance of man-made reservoirs (Downing *et al*., 2006) and the idiosyncrasy of their ecological behaviour (Wetzel, 1990), only a few modelling exercises have tried to discuss climate change effects on water quality in these systems (Fang *et al*., 1999; Meyer *et al*., 1999; Hurd *et al*., 2004). This is due to the fact that reservoirs

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are relatively young systems where paleolimnological approximations are difficult to apply, and historically long-term monitoring programs are usually restricted to large lakes (Great Lakes, Tanganyika, Baikal, etc.) and to water bodies located in the Northern hemisphere temperate region, where concerns about water quality in reservoirs are smaller compared with arid and semi-arid regions. In addition, the relationship between warming and limnological processes in reservoirs is fuzzy, because in these systems water management can modify heat balances and stratification patterns (Moreno-Ostos *et al*., 2008), hence masking any climatic influence. In summary, our knowledge about the impact of climate change on reservoirs is still sparse, and a robust quantitative evidence of recent climate change effects on reservoir water quality using instrumental data is still missing. The goal of this study is to cover this gap.

The starting point of our study is the recent finding that the inflow largely controls anoxia extent in reservoirs (Marcé *et al*., 2008). Although the allochthonous inputs of organic carbon are a significant driver of anoxia in reservoirs located in highly humanized watersheds, the dependence of anoxia on streamflow is applicable to a wide range of reservoirs from different climatic regions and showing varying trophic states (Marcé *et al*., 2008). Because streamflow essentially is a function of rain and evapotranspiration in watersheds, the dependence of anoxia on streamflow opens the possibility of finding climate signals in a variable closely related to water quality issues. Climate processes like the El Niño Southern Oscillation (ENSO) (Maity & Kumar, 2009) and climate trends can drive interannual variations in water budgets in catchments, and in this work we look for the signature of such climate drivers in reservoir anoxia. This would support the existence of a link between climate and water quality in reservoirs suggested by some authors (Nürnberg, 2002), but would also add streamflow to the list of climate-related processes driving water quality changes in lacustrine systems, where increasing air temperatures have focused most studies on climate change impact studies (Adrian *et al*., 2009; Tranvik *et al*., 2009; Williamson *et al*., 2009a, b). Considering the overlap between the global distribution of reservoirs and the arid and semi-arid areas of the world that will most probably suffer increasing frequency of water shortage episodes (Milly *et al*., 2005), understanding the link between long- and short-term streamflow variability and water quality in reservoirs may be fundamental to develop sustainable water management plans in those regions, and to design adaptation strategies.

For this purpose, we analyzed a 44-year record (1964–2007) of monthly oxygen profiles and streamflow from Sau Reservoir (Spain) in order to detect effects of both global climate cyclic phenomena and recent local climate trends in these variables. Our results provide the first quantitative evidence of recent climate change effects on reservoir water quality using long-term instrumental data, and strongly support that anoxia in reservoirs may be closely related to both climate cycles and trends.

Materials and methods

Experimental approach

We divided our study in two parts:

(1) In the first one, we tested whether streamflow and water quality in the reservoir were sensitive to ENSO (Niño 3.4 index of SST anomalies in the Equatorial Pacific Ocean), the dominant oscillation pattern in global interannual climate variability. For this we analyzed ENSO, streamflow, and reservoir anoxia series using state-of-the-art time-series and spectral analyses, in order to detect whether the series oscillated in common frequencies.

(2) In the second part, we quantified the effect of a decreasing trend observed in the streamflow entering the reservoir on the anoxia development. First, we showed that climate was the main driver of the streamflow trend using a watershed-scale water budget approach. Then, we tested the effect of the streamflow trend on reservoir anoxia using the empirical modelling framework proposed by Marcé *et al*. (2008).

Study site

Sau Reservoir (Spain, 41°58′ N, 2°22′E) is a recreational and water supply system for Barcelona metropolitan area (ca. 3 million people), and it is located in a highly humanized catchment. Reservoir capacity is 165 hm^3, and the mean inflow is 10 $m^3 s^{-1}$, although these figures show huge seasonal variation due to the typical Mediterranean climatology. The reservoir experienced an acute process of water quality deterioration from first filling until wastewater treatment plants were built upstream the dam during the early 1990s (Vidal & Om, 1993). During the last decade, unusual recurrent drought episodes posed in threat the water supply for lasting periods due to the scarce volume available and the deterioration of water quality.

Field data collection

Sampling started with the first filling of the reservoir in 1964 and consisted in a detailed characterization of water column chemistry and physics, including 1 m resolution dissolved oxygen profiles measured with calibrated field probes at a single sampling site. Sampling was performed on a fortnightly to monthly basis, depending on the year. We expressed the monthly oxygen content of the reservoir using the Anoxic Factor (AF), which is an areal-standardized measure of the anoxia extent in a water body (Nürnberg, 1995). AF was calculated on a daily basis following Nürnberg (1995):

$$\mathrm{AF}\,(\mathrm{days}) = \frac{t \times a}{A_0}, \quad (1)$$

where t is the period of time (1 day in our case), a_i is the anoxic area (m^2), i.e., area overlain by water with $<1\,\mathrm{mg\,O_2\,L^{-1}}$, and A_0 is the surface reservoir area (m^2) during the sampling day. To calculate the anoxic area, the depth of the $1\,\mathrm{mg\,O_2\,L^{-1}}$ isopleth was determined from the oxygen profile, and then the anoxic area calculated using a hypsometric curve. The same hypsometric curve was used to estimate A_0. To calculate AF for monthly periods, daily AF values between sampling dates were linearly interpolated, and monthly AF values (days month^{-1}) calculated summing daily AF values corresponding to a given month (Fig. 1, bottom). Note that this procedure is numerically equivalent to the one detailed in Nürnberg (1995). We did not apply Eqn (1) using monthly averages because this procedure is equivalent to our calculation only in case of a perfect even sampling, but number of days between samplings was not constant in our study. Two gaps present in 1971 and 1976 were filled with Singular Spectrum Analysis (SSA) reconstruction techniques (Ghil *et al.*, 2002) after calculating the monthly AF. Most of the analyses involving the AF series were divided in two periods because the long-term monitoring program in Sau was halted during 4 years in the early 1990s. The main tributary of the reservoir (Ter River) was sampled with the same periodicity, and among other analyses water samples were processed for chloride by liquid chromatography (Konik KNK 500-A, Konik group, Miami, FL, USA). Before 1995, chloride was analyzed with silver nitrate. The Catalan Water Agency (ACA) daily recorded streamflow to Sau Reservoir, and the monthly Niño 3.4 index was obtained from the webpage of the Climate & Global Dynamics Division of the University Corporation for Atmospheric Research (http://www.cgd.ucar.edu).

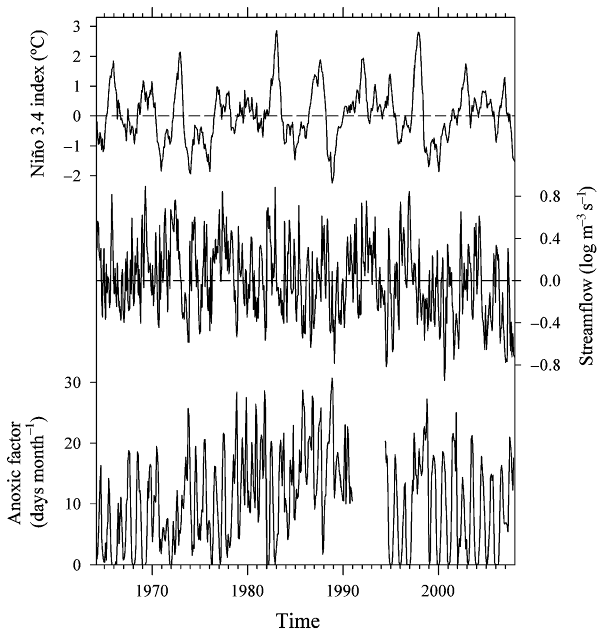

Fig. 1 Monthly time-series of El Niño 3.4 index, inflow to Sau Reservoir, and the Anoxic Factor measured in the reservoir. Note the gap in the last series.

Detection of the impact of ENSO on streamflow and reservoir anoxia

As a first approach to the link between ENSO, streamflow, and reservoir anoxia, we calculated the frequency spectra of the series to assess whether they shared common periodic oscillations. Previous to spectral analyses, we enhanced the signal-to-noise ratio of the series (AF, streamflow, and Niño 3.4) using SSA (Ghil *et al.*, 2002). SSA is a variability decomposition technique in the frequency domain that isolates the main oscillatory patterns in a time-series, and then allows reconstructing the same time-series by merging only the most prominent oscillatory signals and discarding noise (denoising) and trends (detrending). SSA reconstructions have proven to be crucial to extract information from short and noisy time-series, and to detect periodic signals in this kind of natural series (Pascual *et al.*, 2000; Ghil *et al.*, 2002). SSA analyses were performed using the SSA-MTM Toolkit by the SSA-MTM Group at UCLA (http://www.atmos.ucla.edu/tcd/ssa/).

After SSA filtering, we calculated the frequency spectra of the series using the Maximum Entropy Method (MEM) (Ghil *et al.*, 2002) using the same toolkit. The method was chosen because its robustness in analyzing very short time-series, as the ones in this study.

Next, we determined whether the coupling between the time-series was stationary or intermittent using the continuous wavelet transform (CWT), cross-wavelet transform (XWT), and wavelet coherence (WTC) (Grinsted *et al.*, 2004; Cazelles *et al.*, 2008). A CWT is a time-frequency spectral decomposition of the variability in a time-series. In a CWT plot, the intensity of any oscillatory component detected after the decomposition (wavelet power) is depicted in time (x-axis) and period (y-axis) coordinates: when a series is oscillating in a given frequency, a colour dot is placed in the corresponding time-period coordinates, being intensity of the colour proportional to the power of the oscillation. XWT exposes the common power of two CWT decompositions, i.e., it shows when two series oscillate in a common frequency for some time. Therefore, XWT can detect intermittent couplings between time-series. Finally, WTC uncovers the local phase-locking between two CWTs, clearly distinguishing when two series are in phase (e.g., crests of the oscillations happen at the same time), or in antiphase (e.g., crests and valleys happen simultaneously). CWT, XWT, and WTC analyses on SSA filtered series were performed using software provided by Aslak Grinsted (http://www.pol.ac.uk/home/research/waveletcoherence/). Significant areas in the time-period wavelet plots were identified using Monte Carlo techniques. See the supporting information for further details on SSA, MEM, and wavelet analysis.

Relationship between climate and the streamflow trend

In the second part of our study, we assessed the repercussion of a climate-related decreasing streamflow trend observed in

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the basin on AF development in the reservoir. Annual inflow to Sau Reservoir from the tributary (Ter River) during the last 44 years showed a significant decreasing trend ($-0.22 \pm 0.09\,m^3\,s^{-1}\,yr^{-1}$). To discriminate the role of climate variability (precipitation and potential evapotranspiration) from that of land use and cover changes (e.g., reforestation) on the generation of this trend, we calculated the water budget of the Ter River watershed using three different rainfall-runoff models that were solved considering only climate variability: the Dooge's annual water balance model (Dooge *et al.*, 1999), the regression between annual streamflow vs. the difference between precipitation and potential evapotranspiration, and the monthly Thornthwaite–Mather procedure (Steenhuis & van der Molen, 1986). All models were calibrated using precipitation, potential evapotranspiration, and streamflow data from 1941 to 1963, and then applied to the period 1964–2007. As snow accumulates in some areas of the watershed, the annual time step corresponds to hydrologic years and not to calendar years. With this shift, we avoided including snow precipitation in the wrong time-step. See the references above and the supporting information for a detailed description of the rainfall-runoff models.

Annual mean precipitation and potential evapotranspiration values for the Ter River watershed were computed from monthly figures supplied by ACA. The raw data consist of daily precipitation and air temperature observations collected by 17 meteorological stations ($\sim 100\,km^2$ per station) since 1941. Gaps in individual stations were filled at the monthly scale using the MOSS-IV procedure developed by the Hydrologic Engineering Center of the US Army Corps of Engineers. To calculate average values for the entire watershed, stations were weighted according to their area of influence, which were drawn considering topography. Monthly potential evapotranspiration values were calculated from monthly air temperature after calibrating the Blaney–Criddle equation with a set of 7 years long monthly series of Penman evapotranspiration ($r^2 = 0.98$, $n = 79$, $P < 0.0001$, slope $= 0.99 \pm 0.01$). The Penman series was calculated using hourly meteorological records from 12 stations in the watershed.

Effect of the streamflow trend on AF development

In order to quantify the effect of the streamflow trend on reservoir AF, we first built an empirical linear model to explain annual AF variability using two independent variables: mean annual river chloride concentration as a proxy of the labile organic matter entering the system, and mean annual water residence time in the reservoir as a proxy of its hydrological behaviour (Marcé *et al.*, 2008). The annual AF values used in the empirical model were calculated as the sum of all AF daily values for a given year (units being days per year). The model included a categorical covariate in order to differentiate the periods 1964–1991 and 1995–2007. The rationale of this procedure was that the remediation measures applied in the basin since 1991 strongly modified the relationship between the dependent and independent variables. Only 29 years were used to build the model, because during the 1960s and some of the 1970s river chloride data was missing. Confidence intervals (95% CI) were calculated assuming the linear approximation.

After calibrating this model, and taking advantage of the fact that mean annual water residence time shows a significant negative power relationship with annual streamflow ($r^2 = 0.66$, $P < 0.0001$), we re-evaluated the model results (without recalibration) using a synthetic residence time-series derived from the streamflow that would have been expected in the absence of the observed trend. The detrended streamflow was calculated by adding the linear trend extracted from the observed streamflow series by least squares regression. The difference between results obtained with the original model and the model solved with the synthetic residence time can be considered as the effect of the decreasing streamflow trend on the AF. For the model solved with the synthetic residence time-series, the error of the regression between residence time and streamflow was propagated to the AF model in order to calculate 95% confidence intervals.

Results

ENSO and AF

The spectral analysis on SSA filtered series showed that streamflow, AF, and ENSO oscillated in two common frequencies between 0.016 and 0.035 cycles month^{-1} (5.2 and 2.4 years) during the period 1964–1991 (Fig. 2),

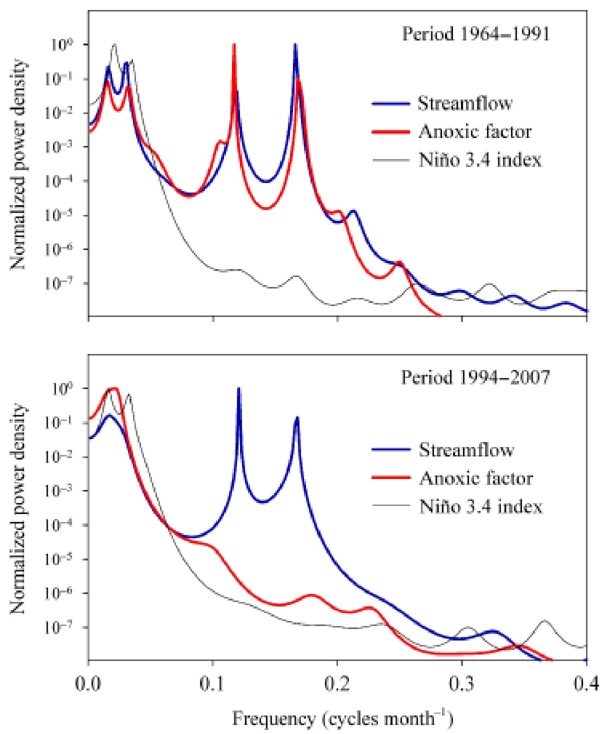

Fig. 2 Spectral analysis of SSA filtered time-series of streamflow, Anoxic Factor, and Niño 3.4 index. Upper panel: spectral analysis for the period 1964–1991. Bottom panel: spectrums for the period 1994–2007. Power density was normalized to facilitate comparisons.

corresponding with the two main variability modes of ENSO (the quasi-biennial and quasi-quadrennial periods) (Fedorov & Philander, 2000). The same low frequency oscillation was apparent in the streamflow and AF series during the period 1994–2007 (Fig. 2), although the short length of the series in this period did not permit consistent separation of the two peaks (see the supporting information for details). Spectral analysis also showed strong intra-annual oscillations in the streamflow record (0.12 and 0.17 cycles $month^{-1}$, corresponding to periods of 8.3 and 5.9 months), attributed to the variable timing of the climatic spring and autumn rains of this region. AF perfectly matched these high frequency oscillations, but only during the period 1964–1991 (Fig. 2).

Wavelet analysis for streamflow and AF series showed significant common wavelet power in the low and high frequency regions (Fig. 3d), but with sharp discontinuities. The common longer period switched several times between ~30 and ~65 months, while the shorter period (~6 to ~8 months) was present only from 1964 to 1991. It is remarkable that around the same wavelet period the oscillations of the series were phase-locked during the whole time-span (e.g., negative coherence at lag 0 for low frequency bands, see arrows and WTC significant regions in Fig. 3d), strongly suggesting that series are physically coupled (Grinsted *et al*., 2004). After the gap in the AF series, there was no common variance in the higher frequencies, but in the low frequency band was still present. This suggests that the anoxia in the reservoir was very sensitive to the high streamflow peaks during spring and autumn when the human impact on the reservoir was the highest (see AF values in Fig. 1). After the remediation measures, the reservoir lost its sensitivity to this local forcing.

Wavelet analysis for streamflow and ENSO index indicated a persistent common wavelet power for oscillations with periods between ~30 and ~65 months (Fig. 3e), which varied accordingly with the intensification and weakening of the quasibiennial and quasiquadrennial band of ENSO (see for instance ENSO CWT in Fig. 3a). Furthermore, oscillations at ~65 months were persistently in-phase and WTC was significant in large portions of this frequency band, suggesting that the remote forcing by ENSO was the driver of streamflow low frequency oscillations. The high human impact during the 1980s (see AF values in Fig. 1) may mask the climate signal on local variables during this period, as the gap in the significant WTC region suggests. More interestingly, wavelet analysis for AF and ENSO index showed an identical coincidence in the low frequency band (Fig. 3g), which basically was a mirror image of the XWT between streamflow and ENSO. All in all, wavelet analyses strongly support the hypothesis that ENSO oscillations affect water quality in the reservoir via modifications of the streamflow.

Climate trends and AF

Results from rainfall-runoff models driven only by climate variables hardly differed from observed streamflow (Fig. 4, bottom), suggesting that climate variability is the main explanation for the decreasing streamflow trend. Although some of the rainfall-runoff models showed a significant different trend compared with the observed one, climate variability explained between 70% and 80% of the negative tendency (see supporting information). Thus, changes in land cover and other factors seemed to play a minor role in the generation of the decreasing trend.

The empirical AF model explained 85% of annual AF variance (Fig. 5), and both independent variables (water residence time and river chloride concentration) and categorical covariate were significant ($n = 29$, $P < 0.0001$). We did not include any interaction term in the model because none was significant. Independent variables had similar explanatory power, with F-ratio = 50 for water residence time and F-ratio = 59 for river chloride.

Applying the above model (without recalibration) with the synthetic water residence time-series (i.e., the residence time-series built on the basis of the detrended streamflow record), resulted in a mean AF increase by 23% (Table 1), although differences greatly varied from year to year (Fig. 5). Remarkably, differences did not depend on the magnitude of the observed AF value, but on climate. If we correlate the differences between models with a simple climatic index [aridity index (AI), the result of annual potential evapotranspiration divided by annual precipitation in the watershed], the outcome is a significant positive relationship (Pearson's $r = +0.70$, $P < 0.0001$). That is, the effect of the decreasing streamflow trend on AF was more pronounced during dry years than during wet years (Table 1). Also interesting, we can compare the mean AF for the period 1972–1991 obtained with the original model with the mean AF for the period 1994–2007 (i.e., after the implementation of remediation measures in the watershed), using the original model and the results from the model solved without the streamflow trend (Table 1). From these figures we can state that the streamflow trend prevented a ~40% of the potential improvement in oxygen levels due to remediation measures.

Discussion

The detection of the ENSO influence over the Mediterranean climate has a long tradition in diagnostic

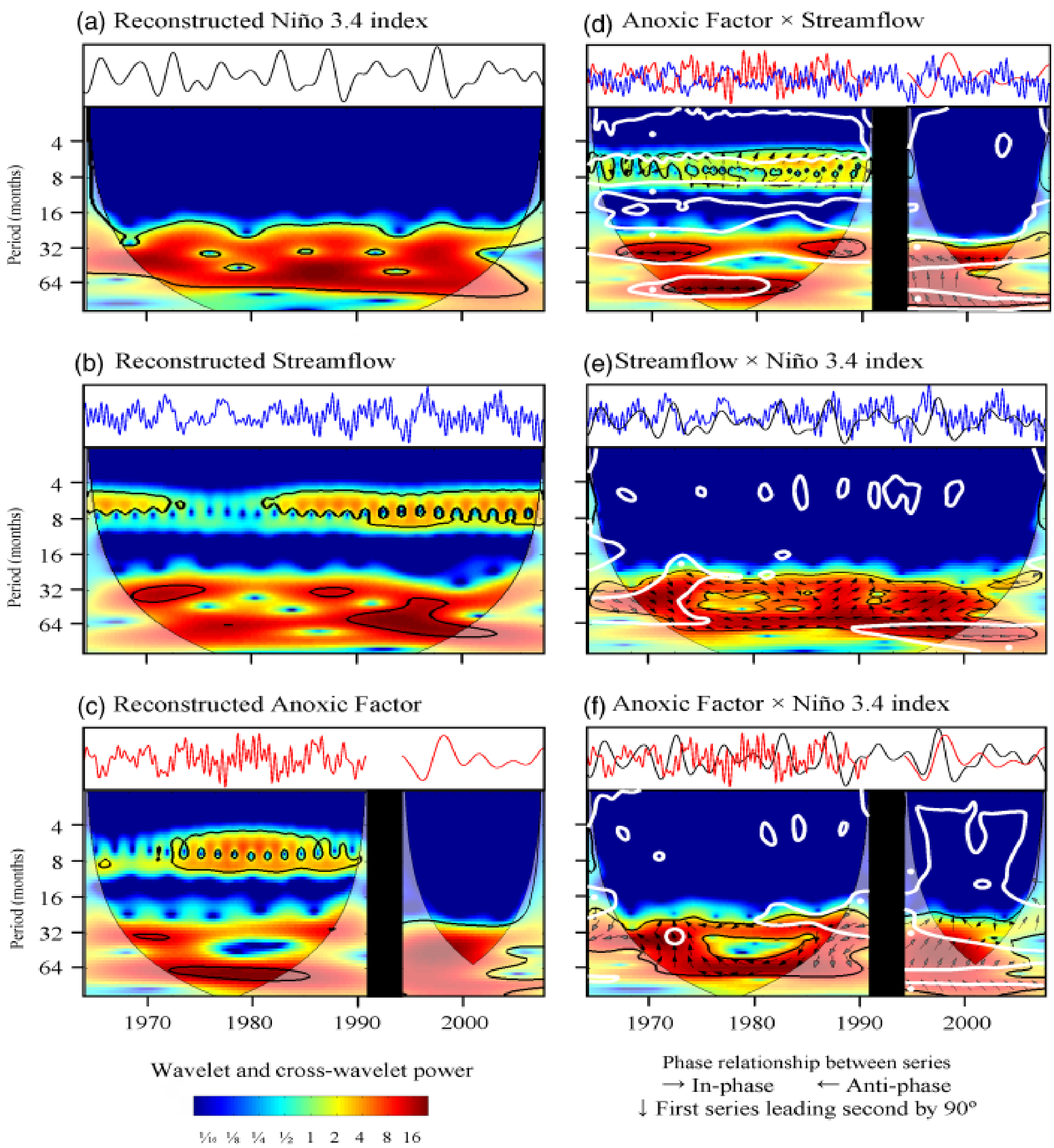

Fig. 3 Continuous wavelet and cross-wavelet power spectra for Singular Spectrum Analysis (SSA) filtered series. Left panels are continuous wavelet transforms for (a) Niño 3.4 index, (b) streamflow, and (c) Anoxic Factor. Right panels are cross-wavelet power spectra for (d) Anoxic Factor and streamflow, (e) streamflow and Niño 3.4 index, and (f) Anoxic Factor and Niño 3.4 index. The thick black contour designates the 5% significance level against red noise. Overlapped to cross-wavelet power spectra is the 5% significance level for wavelet coherence (WTC), delimited by a white line (for the sake of clarity, we did not include all the WTC information in the figure). Small white circles inside some significant regions were added to facilitate reading. Arrows indicate the relative phase relationship between series in a portion of the period-time domain. Inside each panel, the upper frame contains the SSA filtered time-series involved in the analysis below. Shaded areas represent the cone of influence, where interpretations should be cautious. Phase arrows should be interpreted with care: a lead of 90° can also be interpreted as a lag of 270° or a lag of 90° relative to the antiphase.

studies. Considering only rainfall, most studies shown negative precipitation anomalies in the spring following an ENSO event (Kiladis & Diaz, 1989; Rodó *et al.*, 1997; Mariotti *et al.*, 2002), but also in the next winter (Rodriguez-Fonseca & de Castro, 2002). Several mechanisms have been proposed to explain this large distance relationship (Merkel & Latif, 2002; Nigam, 2003) but none of them has been sorted out as the dominant model of propagation. The extratropical influence of each ENSO event is highly variable and

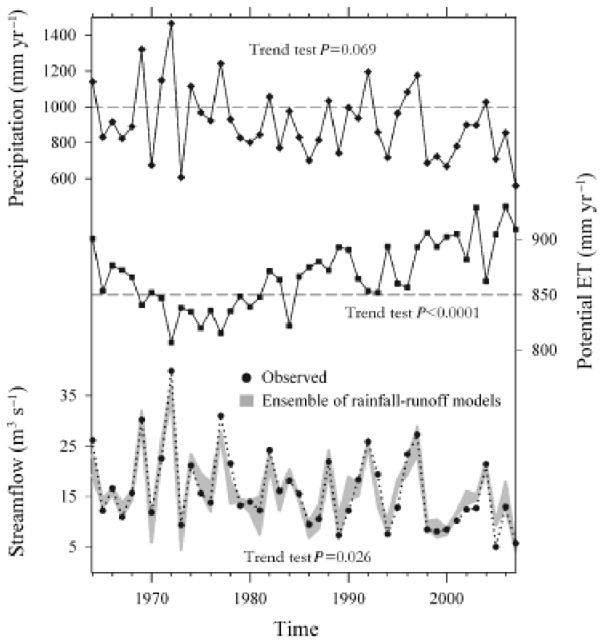

Fig. 4 Long-term series of annual precipitation, potential evapotranspiration, and runoff generation in the Ter River watershed upstream Sau Reservoir. The *P*-value is the significance of a nonparametric Kendall's test for presence of monotonic trends. The grey area following the observed streamflow series is the ensemble of results obtained with three rainfall-runoff models that consider only climate variability.

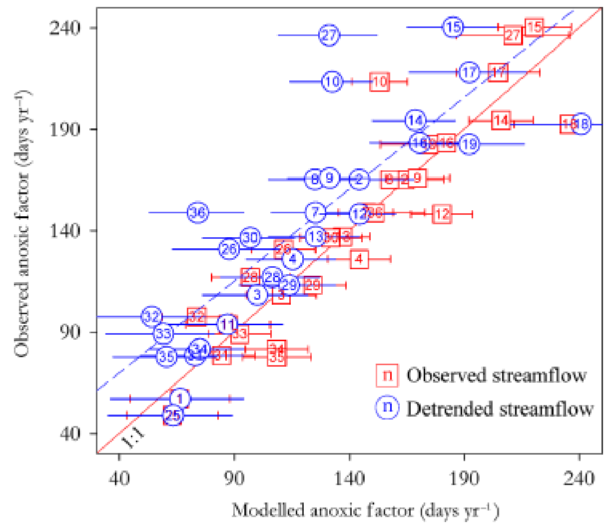

Fig. 5 Comparison between observed annual Anoxic Factor (AF) in Sau Reservoir and the results of an empirical linear model using river chloride concentration and water residence time as independent variables. Red squares are results for the model calibrated with observed residence time data. Blue circles are the results for the same model solved (without recalibration) using a synthetic residence time-series built on the basis of a detrended streamflow series. Numbers represent the year since 1971. Lateral whiskers represent model 95% confidence intervals, and caps were added only to red squares to help comparing paired years. Red and dashed blue diagonal lines represent the fit between modeled and observed AF, and were added for reference.

depends on both the particularities of the episode and the state of the ocean and the atmosphere in distant basins (Kumar & Hoerling, 1997). This may explain the intermittency and varying phase of the relationships between ENSO and the local variables (streamflow and AF) measured in this and other studies. The varying trophic status of the reservoir may also explain some of these transients. During late 1970s and most of the 1980s the oxygen content in the reservoir was so low that even during mixing periods anoxic conditions prevailed (Fig. 1). In this situation the reservoir was very sensitive to high streamflow peaks during spring and autumn, but the system was hardly sensitive to the remote forcing by ENSO. When the oxygen content of the reservoir improved due to the treatment of wastewater in the basin, the reservoir lost the sensitivity to intra-annual streamflow peaks during mixing conditions, and full sensitivity to remote forcing was recovered. That is, the sensitivity to remote and local forcings depended on the intensity of the human impact on the reservoir.

Although the causal link between streamflow and anoxia development in reservoirs still needs to be fully understood, our results strongly support that the oxygen content in reservoirs is directly linked to climate modes and trends affecting streamflow, a hypothesis suggested by Nürnberg (2002). Considering that the dependence of AF on streamflow is a global phenomena in reservoirs (Marcé *et al.*, 2008), this single system study constitutes a powerful, paradigmatic example of how streamflow alterations may modify reservoir anoxia, establishing a framework for studies dealing with climate change effects on water quality in reservoirs. In lakes, increasing water temperatures and associated hydraulic and community-level consequences have focused climate change impact studies. Depletion of hypolimnetic oxygen levels have been frequently related to increasing surface water temperature and strengthening of thermal stability, which reduces mixing resulting in a longer confinement of hypolimnetic waters. We consider that causal mechanisms explaining the dependence of the AF on climate detected in reservoirs may differ from causal mechanisms explaining anoxia increase in lakes, because climate is not necessarily governing mixing in reservoirs subject to water management. The injection of oxygen from tributaries directly into intermediate and deep layers may play a prominent role in reservoirs, where density currents are a common feature (Rueda, 2006).

Table 1 Analysis of the role of the streamflow trend on the Anoxic Factor development in Sau Reservoir

Period	Anoxic factor (days yr^{-1})	Anoxic factor (% variation)
All years (n = 29)		
Observed	141 ± 53	
Original model	141 ± 48	
Model using detrended streamflow	119 ± 48	
Difference between models	23 ± 22	23 ± 26
Wet years (AI < 1, n = 12)		
Original model	116 ± 42	
Model using detrended streamflow	105 ± 49	
Mean difference during wet years	11 ± 14	12 ± 14
Dry years (AI > 1, n = 17)		
Original model	159 ± 45	
Model using detrended streamflow	128 ± 43	
Mean difference during dry years	31 ± 24	31 ± 30
Before remediation measures (1972–1991, n = 17)		
Original model	161 ± 45	
After remediation measures (1994–2007, n = 12)		
Original model	113 ± 40	
Model using detrended streamflow	83 ± 25	
Mean variation between periods (original model)	−48	−30
Mean variation in absence of streamflow trend	−78	−48

Uncertainties are standard deviations.

Although not directly addressed in this study, the influence of riverine labile organic matter on reservoir anoxia deserves special attention. Our results on the impact of a decreasing streamflow trend on Sau Reservoir anoxia should be considered a conservative estimate, because changes in labile organic matter river concentration (in our model this would be reflected in changes in river chloride concentration) were not considered. Those changes are probable because a decrease in streamflow would curtail the dilution capacity of rivers, enhancing the effect of human-related, organic rich spills. Taking into account that both dissolved organic matter concentration and hydrology have strong influence on AF prediction in reservoirs (Marcé *et al.*, 2008, this study), and that reservoirs are frequently located in human populated watersheds, the role of labile organic matter and its interactions with streamflow on anoxia development should be scrutinized.

In any case, this work provides a paradigmatic example of the importance of maintaining long-term monitoring programs (Lindenmayer & Likens, 2009), and constitutes a warning on the urgency of developing an ad hoc framework for climate change impact studies in reservoirs. This is especially relevant in arid and semiarid areas, where many countries rely on reservoirs for water supply. A correct management of water resources in the present and appropriate mitigation actions for future threats needs a deeper knowledge of water quality drivers in reservoirs and its connections with climate and human intervention. Considering the coupling between climate, ecological processes, and socioeconomic interests present in reservoir dynamics, researchers should consider the probable presence of nonlinearity and abrupt responses when forecasting reservoir behaviour under climate change (see Higgins *et al.*, 2002). All these considerations are even more important taking into account that resurgence in dam construction will be almost unavoidable in developing countries during next decades (World Commission on Dams, 2000).

All in all, our findings put streamflow in the centre of the scene in reservoirs, where climate-driven water temperature trends are difficult to detect because water management may mask the tendencies (Moreno-Ostos *et al.*, 2008). This work opens the question of how streamflow modulates the metabolic balance of reservoirs, a basic trait to understand the role of reservoirs as sentinels of global environmental changes (Williamson *et al.*, 2008, 2009a, b). Finally, these results constitute a warning for the management of water supply systems based on reservoirs. Water scarcity should be viewed as a threat not only for the quantity of resource, but also for its quality and the cost of treatments and remediation measures. The link between global climate interannual patterns like ENSO and water quality in reservoirs may be a relevant water management issue, especially if local droughts associated to ENSO events can be predicted some months in advance. Furthermore, sensitivity to interannual variability implies that low water quality episodes associated to extreme events of low water availability must be important way before long-term decreasing streamflow trends reach those conditions.

All these considerations are especially relevant in Mediterranean climatic regions in Europe, Australia, South Africa, Chile, and USA, but also in other arid regions in USA, Central America, Northern Brazil, Australia, and the Middle East, where many water supply systems rely on reservoirs, and where most climatic models predict a decrease in streamflow and increasing droughts frequency during this century (Milly *et al.*, 2005).

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. El Niño Southern Oscillation and climate trends impact reservoir water quality.

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ANNEX 2:

Currículums

Rafael Marcé

Nascut a Barcelona el 1974, es va doctorar en Ecologia el 2007. Actualment és investigador júnior a l'ICRA i professor associat al departament d'Ecologia de la UB, on forma part del grup FLUMEN.

Des del 2000 fins a l'actualitat ha participat en 9 projectes d'investigació, com ara *Evaluación y predicción de los efectos del cambio global en la cantidad y la calidad del agua en ríos ibéricos (SCARCE)*; *Criterios limnolóicos para la gestión sostenible de embalses. Casos de Ribarroja (río Ebro) y Sau (rio Ter)*; *Gestión hidráulica y técnicas de detección remota aplicada al control de poblaciones de mejillón cebra: el caso del embalse de Ribarroja y el tramo inferior del Ebro;* entre d'altres.

Al llarg de la seva trajectòria professional ha participat en 24 articles com poden ser: *El Niño Southern Oscillation and climate trends impact reservoir water quality; Modeling nutrient in-stream processes at the watershed scale using Nutrient Spiralling metrics*; *Sedimentary phosphorus in a chain of five reservoirs (Lozoya River, central Spain)*; entre d'altres.

Ha participat en 25 contractes d'interès especial per a empreses privades i/o serveis públics, com poden ser: *Estudi limnològic de l'embassament de SAU; Anàlisi de l'impacte de l'arribada d'aigua potable des del sistema cat a l'embassament de Riudecanyes; Estudi limnològic de l'embassament de Sau: composició química aigua, variacions en la càrrega de nutrients i canvis en el seu estat tròfic*; entre d'altres.

Ha realitzat un total de 5 investigacions a l'estranger, com: *Reservoir biogeochemical models; Metabolic balances in reservoirs; Biogeochemical models at the watershed scale*; entre d'altres.

Finalment, ha assistit com a ponent a 32 congressos, com per exemple *Estructura física del sedimento de Ribaroja: resultados preliminares; Simulating the phytoplankton dynamics in a mesotrophic reservoir; El ciclo del oxígeno en el embalse de Sau: patrones de variación estacional y su modelizado mediante DYRESM-CAEDYM*.

Joan Armengol

Es va doctorar en Biologia per la Universitat de Barcelona (UB) l'any 1972, és catedràtic d'Ecologia de la UB des de 1982, va ser director del departament d'Ecologia de la UB del 2003 al 2007. També ha estat professor i investigador a la Universitat de Washington, Estats Units, UQAM, Canada, Lisboa, Portugal, Luján, Argentina.

Actualment és director del Centre Especial d'Investigació en Ecologia i Gestió de l'Aigua (CEREGA) de la UB i codirector del Grup d'Excel·lència de la Generalitat de Catalunya: Dinàmica Fluvial "FLUMEN".

Les seves àrees d'interès són l'estudi de cicles biogeoquímics amb èmfasi en nutrients i processos d'eutrofització, d'ecologia de rius i embassaments, i d'interaccions entre processos físics i ecològics en embassaments.

Ha realitzats 5 tesis de mestria i 6 tesis doctorals

Ha donat a conèixer més de 100 publicacions a revistes nacionals i internacionals, com per exemple *Tailoring dam structures to water quality predictions in new reservoir projects: Assiting decision-making using numerical modeling; Driving factors of the phytoplankton functional groups in a deep Mediterranean reservoir; El Niño Southern Oscillation and climate trenes impact reservoir water quality*.

Ha treballat i en els següents projectes d'investigació: projecte de l'Agència Catalana de l'Aigua (2003-2008), projectes d'investigació o assessorament en la gestió dels embassaments de l'ATLL (1995-actualitat), i projectes d'investigació i assessorament al Canal d'Isabel II, Madrid, (2001-actualitat)

Ha estat membre del Comitè editorial de les següents revistes: *Limnetica* (1998-2009), *Oecologia aquatica, Revue des Sciènces de l'eau* (1986-1988), *Ingeniería del Agua,* i *Revista Brasileira de Biologia.*

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Format com a ecòleg marí en el Departament d'Ecologia de la Universitat de Barcelona, durant la darrera dècada la seva carrera en el món de la recerca ha evolucionat cap a tasques de gestió i organització institucional. A l'Institut Català de Ciències del Clima (IC3) desenvolupa tasques d'adjunt del director i lidera l'àrea de gestió de projectes en la que té experiència des del 4rt Programa Marc de la Unió Europea. Últimament també s'està involucrant en la disseminació de la recerca i fruit d'això ha estat el seu recent nomenament com a cap del Laboratori d'Educació, Divulgació i Comunicació (LEDIC) de l'IC3. Ha publicat quatre articles científics i ha fet més d'una trentena de contribucions en revistes de viatges, de divulgació científica, i en mitjans de comunicació.