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That twenty years is nothing for gravel-pit limnology

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ABSTRACT

That twenty years is nothing for gravel-pit limnology

The past twenty years have witnessed a rise in the analysis of long-term limnological data given the need to know whether global warming is affecting freshwaters, and if so, how. Previous studies indicated that processes affecting ecosystem functioning may develop slowly, thus requiring long-term study, as in the case of the eutrophication-oligotrophication gradient.
Here we report annual averages and seasonal variability of meteorological data (air temperature, solar radiation, rainfall) and the main limnological variables (lake level, water temperature, euphotic depth, mixing depth, nitrogen and phosphorus compounds and phytoplankton biomass) for a gravel-pit, seepage lake close to Madrid (Central Spain), collected monthly from 1992 to 2018. Linear trends (both upward and downward), long-term constancy, regime shifts, piecewise patterns and mixed patterns (constant and piecewise) were found for the variables tested, but their variability did not increase over time. Water warming and decreased lake levels were related with atmospheric warming. In turn, these physical changes covaried with nitrate increase and decreases in total phosphorus and phytoplankton biomass. However, the weak relationships between climate- and limnological variables (for example, the lack of rainfall effects on lake level) would indicate that other factors, such as land use, were more influential. Broadly speaking, it would appear that the observed limnological patterns were greatly influenced by the local increase in novel lake basins through mining activities, which led to a decrease in lake level until the year 2000, and the ecological stabilization of a recently created ecosystem, which is an analogous process to that occurring after reservoir construction. The above processes might have partly offset global warming effects in this lake but twenty years is ALMOST nothing within the framework of this fascinating puzzle. Hence longer studies are necessary to gain an accurate picture of gravel-pit limnology, which is urgently needed.

Key words: long-term series, nutrients, phytoplankton biomass, temporal trend, seasonal variability, global warming, Mediterranean climate

RESUMEN

Que veinte años no es nada para la limnología de las graveras

El análisis de series largas de datos en Limnología ha aumentado en la última década debido a la necesidad de saber si el calentamiento global está afectando a nuestros ecosistemas de agua dulce y cómo. Antes, ya se había demostrado que los procesos relevantes para el funcionamiento del ecosistema podían ser lentos y requerían estudios a largo plazo, como ocurrió con el gradiente eutrofización-oligotrofización.
En este trabajo se presentan los promedios anuales y la variabilidad estacional de las principales variables meteorológicas (temperatura atmosférica, radiación solar, precipitación) y limnológicas (nivel del lago, temperatura del agua, capa fótica, capa de mezcla, concentraciones de nitrógeno y fósforo y biomasa fitoplanctónica) de una laguna de gravera próxima a Madrid (centro de España), alimentada por aguas subterráneas. Los datos se obtuvieron mensualmente desde 1992 hasta 2018. En esas variables, detectamos tendencias lineales (crecientes y decrecientes), constancia a largo plazo, cambios de régimen, pautas "en sierra" y pautas mixtas (constancia en un periodo y dinámica "en sierra" en otros); además, no parece que aumenten su variabilidad estacional con el tiempo. También se observó cómo el calentamiento del aire estaba vinculado con el calentamiento y la pérdida de nivel del agua. A su vez, esos cambios físicos en la laguna covariaban con un aumento del

nitrato y con la pérdida de fósforo y de biomasa fitoplanctónica. Sin embargo, la debilidad de las relaciones entre las variables ligadas al clima y las limnológicas (por ejemplo, la falta de efecto de las lluvias sobre el nivel del agua de la laguna) apunta a que otros factores, como el uso del territorio, tuvieran también relevancia. Grosso modo, parece que la creación local de nuevas cubetas lacustres por la actividad minera, que hizo descender notablemente el nivel lacustre hacia el año 2000, y la estabilización ecológica de un ecosistema de creación reciente, proceso análogo al que sucede tras la creación de un embalse, pudieron ser determinantes para las pautas limnológicas observadas. Dichos procesos probablemente hayan contrarrestado los previsibles efectos del calentamiento global. Por lo tanto, veinte años no parecen CASI nada para montar este interesante rompecabezas cuya imagen final nos urgiría conocer, aunque ello haría necesario prolongar los estudios.

Palabras clave: *series temporales largas, nutrientes, biomasa fitoplanctónica, tendencia temporal, variabilidad estacional, calentamiento global, clima mediterráneo*

Sentir
que veinte años no es nada[1]
Carlos Gardel & Alfredo Le Pera

INTRODUCTION

Reports of long-term data on lake limnology are increasingly common in temperate areas of the world since the first warnings about global warming thirty years ago (IPCC, 1990; Carpenter *et al.*, 1992). A search on the Web of Knowledge for the 1992-2018 period using the keywords "lakes" and "long-term" identifies over 11 000 items. The scientific interest and usefulness of long-term limnological studies have often been emphasized; to name a couple of reports there are those by Likens (1985) and Dodds *et al.* (2012). In the Iberian Peninsula some long-term studies (> 10 years) have been published on stagnant limnology, such as those by Sau- (Vidal & Om, 1993; Armengol *et al.*, 1994; 2005) and La Minilla reservoirs (Armengol *et al.*, 1994), Sanabria lake (Hernández *et al.*, 2015), Las Madres lake (Benavent, 2015; Hernández *et al.*, 2015; Alvarez-Cobelas *et al.*, 2019) and Las Tablas de Daimiel wetland (Alvarez-Cobelas *et al.*, 2010; Sánchez-Carrillo & Alvarez-Cobelas, 2010; Sánchez-Carrillo *et al.*, this issue).

Most long-term studies of limnosystems point to global warming and eutrophication (or reoligotrophication where public funding has enabled abatement measures) as the main causes for the trends and the vagaries observed in limnological variables (Adrian *et al.*, 1995; Bailey-Watts *et al.*, 1990; Hsie *et al.*, 2010; Köhler *et al.*, 2005; McIntire *et al.*, 2007; Zhang *et al.*, 2015). Less frequently other factors have been suggested, such as the intended (or not) introduction of species (Estepp & Revie, 2015) and the role of water renewal (Reynolds *et al.*, 2012).

However, other features that could be additional, complementary explanations and/or controlling factors for observed patterns in the long-term have seldom been explored. For example, changes in the socio-economical context affecting ecosystem management have been put in the limelight in Eastern Europe environments (Znachor *et al.*, 2018). In addition, the recent creation of limnosystems for different purposes (irrigation, water supply, cooling, hydropower or mineral exploitation) might be affecting ecosystem dynamics through biotic colonization-extinction processes and simultaneous biogeochemical changes, as often occurs in reservoirs (Atkinson, 1988; Holz *et al.*, 1997).

Gravel-pit lakes are artificial ecosystems arising from mineral exploitation for building materials. Since this exploitation is usually carried out in Quaternary valleys, the resulting basin fills with water, thus yielding a stagnant water body that gradually turns into a lake as viruses, bacteria, plants and animals colonize the novel environment. The number of gravel-pit lakes is high in those areas with large building industries, such as USA, Europe and, more recently, China. Gravel-pit limnology has become interesting because these environments are somewhat different from natural basins for several reasons: 1st) their geological setting (sand

[1] To feel/that twenty years is nothing

and gravel enabling faster exchanges with the underlying aquifer), 2nd) natural lakes having wider depth ranges than gravel-pits (Mollema & Antonellini, 2016), and 3rd) steeper littoral slopes that result in narrower littoral zones (Vadillo, 2001). There are few studies on gravel-pit limnology in the Iberian Peninsula. Besides our studies, summarized in Alvarez Cobelas & Sánchez Carrillo (2020), one early report is that by Gómez Martos & Buyo (1993), undertaken in the lower Jarama plain (Central Spain).

Our studies began in 1991 when the first author was awarded a permanent position in the Spanish administration. It was his view that any given limnosystem could be better understood through long-term in-depth study. Those were the days when the issue of climate change was awakening, and was one of the factors that encouraged him to take this initiative. The study has been ongoing, with monthly measurements, for 27 years now. Here we will report data of some meteorological and limnological variables, which have been averaged for the water column of Las Madres lake, close to Madrid (Central Spain) for the 1992-2018 period. The main goal of this study is to show the main long-term patterns of these series and their variability; data are pooled to report them on a yearly basis, the strength of

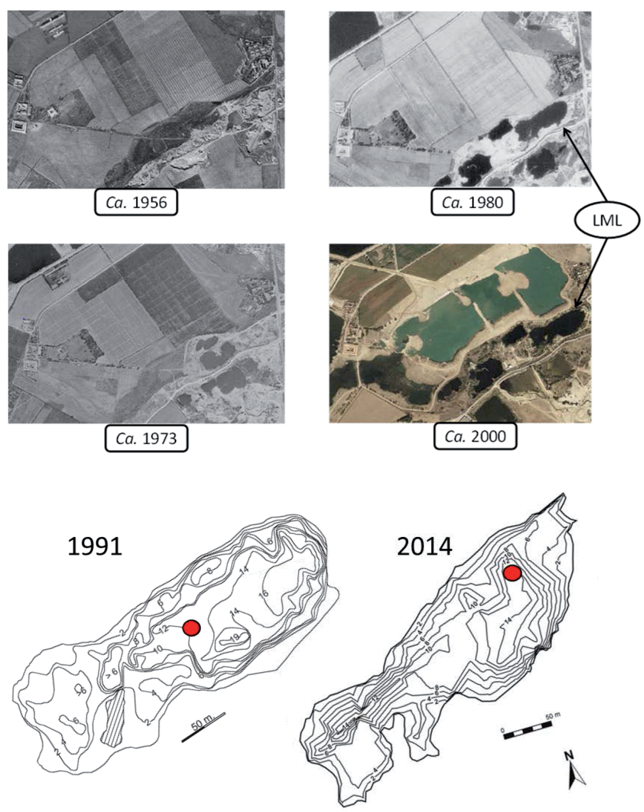

Figure 1. Upper and middle panels. Long-term land use changes in the surroundings of the gravel-pit area where Las Madres lake emerged as a result of mining. Images were taken from the photographic library of the Spanish National Geographical Institute. Photographs were taken in air surveys of the Iberian Peninsula, but the exact year of each one is unknown. Lower panel. Bathymetric maps of Las Madres lake, undertaken in 1991 and 2014. Red circles depict sampling stations during the years 1992-2013 and 2014-2018, respectively. LML: Las Madres lake. *Paneles superior e intermedio. Cambios a largo plazo del uso del suelo en los alrededores de la zona donde la laguna de Las Madres surgió posteriormente por la actividad minera. Las imágenes proceden de la fototeca del Instituto Geográfico Nacional y fueron obtenidas a partir de fotos aéreas de la Península Ibérica, pero el año exacto de cada una se desconoce. LML: laguna de Las Madres. Panel inferior. Mapas batimétricos de la laguna de Las Madres, realizados en 1991 y 2014. Los círculos rojos sitúan la estación de muestreo limnológico para 1992-2013 y 2014-2018, respectivamente.*

seasonality being shown by the CV of variables within each year under consideration. Moreover, we test whether climate warming and other factors have had any effect on certain limnological variables in this lake.

MATERIALS AND METHODS

Study site

Until the seventies, the alluvial plane of the lower Jarama River was exploited mostly for irrigated crops. However, the dramatic increase in building in Madrid during that decade promoted the digging of many croplands in the valley to collect sand and gravel, and that has led to the formation of more than one hundred new lakes since then (Roblas & García Avilés, 1997). The use of heavy machinery resulted in the creation of many aquatic basins inundated by groundwaters, but the number, form, bathymetry and average depth of such basins fluctuated greatly over the years. We lack accurate data on the creation of Las Madres lake, which did not exist in 1973 (Fig. 1 upper panel) and whose mineral exploitation was discontinued by 1984, thus enabling aquatic organismic colonization and biogeochemical processes to occur. Other newly formed, nearby basins appeared around the year 2000 to the north of Las Madres, whose water surfaces were no more than 100 m apart from this environment (Fig. 1 central panel). As a result, the water column slowly decreased due to water extraction from Las Madres to the other basin on a hydraulic head gradient of groundwaters (see below). By 2001 the former SW reed islet, which was plotted in our 1991 map (Fig. 1 lower panel), had disappeared because of decreasing lake depth. Mineral exploitation in the surrounding area ended around the period 2006-2010, coinciding with the end of Spanish building boom (http://www.aridos.org/estadisticas).

Las Madres Lake is a seepage environment close to Madrid (Central Spain, 40° 18’ N 3° 31’ W). In 1991 it had a surface area of 3.4 Ha and an average and maximum depth of 7.9 m and 19.0 m, respectively, but its volume diminished over time (see above). As a result, its average and maximum depths were 5.8 m and 15.5 m, respectively, in 2014. It is hard to envisage a catchment area for this lake because the alluvial terrain is so altered by mining that topographic isolines can hardly be traced. Therefore, we are not able to provide a value for the catchment area of Las Madres lake.

Las Madres is a closed environment, whose water inputs come from the underlying aquifer and rainfall. The lake is usually P-limited, being oligo-mesotrophic. Occasionally some variables reach high values due to a vernal upwelling of hypolimnetic water triggered by the entrance of warmer seepage water. A monimolimnion effect is frequently observed, arising from both the influx of groundwaters that differ thermally from the hypolimnion layers and the waters at the lake bed, which are higher in density due to decaying plant biomass, mixing with upper layers in some, but not all, autumns. Therefore, double diffusion processes have often been found in the bottom layers (Alvarez-Cobelas *et al.*, 2005).

Las Madres ionic content is mostly composed of sulphate and calcium. Conductivity ranges 1480-3890 µS/cm over time, always being much higher in the bottom layers. Alkalinity is 3.36-7.95 meq/L, whereas dissolved organic carbon contents range between 3.11-24.93 mg C/L, again being much higher in deep waters. Silicon concentrations are highly variable (0.09-13.11 mg Si/L). Suspended solids are generally low (0.5-10 mg/L), except in monimolimnion.

The lake becomes anoxic in summer in the bottom layers as a result of decaying littoral, emergent macrophytic biomass dating from the previous autumn. The lake does not freeze and its isothermal conditions rarely drop below 8 ºC since local climate is semi-arid Mediterranean continental with an annual mean temperature of 15.1 ºC and a mean annual rainfall of 383 ± 87 mm. Phytoplankton biomass is dominated by Diatoms, Cryptomonads and Dinoflagellates. Changes in zooplankton composition have been negligible in the long-term, its assemblage being dominated by the Copepods *Arctodiaptomus salinus* and *Tropocyclops prasinus* and the Cladoceran *Daphnia longispina*, with a few smaller Cladocerans and some 50 species of Ciliates and Rotifers, whose biomass is usually much lower than those of the former Crustaceans. Bacterioplankton density ranges between 500 000 and 10^6 cells/mL, covering most physiological groups of bacteria, including photosynthetic bacteria, albeit these with negligible densities. Fish assemblages are comprised by *Lepomis gibbosus*, *Micropterus salmoides*, *Cyprinus carpio*, *Luciobarbus bocagei* and *Gambusia holbrooki* and a rich macroinvertebrate fauna occurs within the littoral fringe, which is surrounded by cattail (*Typha domingensis*), reed (*Phragmites australis*) and occasionally *Scirpus lacustris*. Submerged macrophytes are rare, only *Najas marina* has been recorded. Chironomids are the dominant lake bed fauna, living in very fluidized, albeit anoxic, layers throughout the lake basin.

Further data on the lake can be found in Alvarez-Cobelas & Sánchez Carrillo (2020), Alvarez-Cobelas *et al.* (2019), Benavent (2015) and http://www.sanchezandalvarezlab.es.

Meteorology, lake sampling and analyses

The lake was sampled monthly from January 1992 to December 2018, between 10:00 and 12:00 (GMT hour). Lake level was recorded on each sampling event at an *in situ* meter until 2003; subsequently, after water levels decreased beyond that meter, it was measured using a portable sonar Hondex PS-7 at the sampling buoy. This was changed in 2014 (see Fig. 2) because lake volume reduction did not enable us to sample layers below 10 m at the older site. In 2014, samples were taken in the old and new sites and physical and chemical measurements were taken for all samples. There were not statistically significant differences between either site (Mann-Whitney tests, $p > 0.05$), which was clearly because the lake is too small to develop strong horizontal heterogeneity. The physical water-column variables recorded were temperature and PAR attenuation, the latter enabling estimation of the thickness of the euphotic layer. All these variables were measured with various YSI and LI-COR probes until 2005, and mounted on a SBE-19 Seabird rack from 2006 onwards. Local weather variables were recorded at 10 min intervals with a meteorological station 3 Km away from the lake, which gathered air temperature,

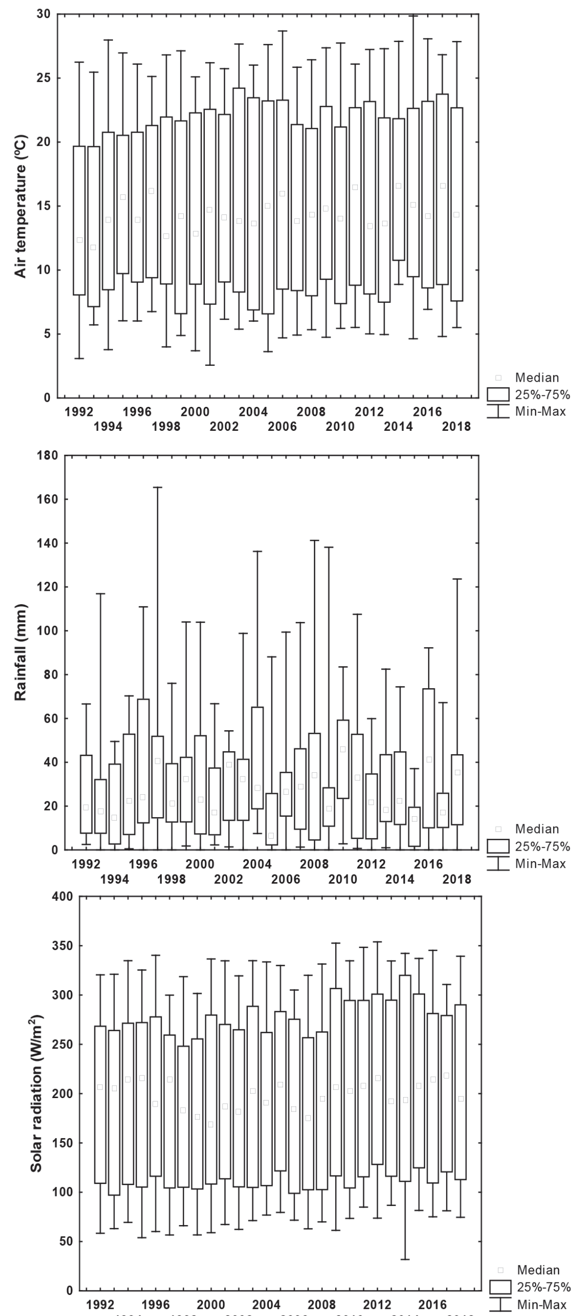

Figure 2. Long-term (1992-2018) box-whisker plots (showing the first quartile, the median or second quartile and the third quartile, and the maximal and minimal values of monthly air temperature, rainfall and solar radiation of Las Madres lake. They were measured 3 km away. *Diagramas de cajas y bigotes (indicando el primer cuartil, la mediana o segundo cuartil y el tercer cuartil, así como los valores mínimo y máximo alcanzados) para los registros mensuales de la temperatura del aire, la pluviosidad y la radiación solar sobre la laguna de Las Madres desde 1992 a 2018. Se midieron a 3 kms de la laguna.*

rainfall and incoming solar radiation. Daily averages and monthly averages of the latter were calculated for this study. The euphotic depth was estimated from underwater PAR profiles, assuming a negative exponential function. The only long-term data set of groundwater levels in the area belonged to the Tajo Water Authority (03.99.005 well, also called Arganda-Azucarera; http://sig.mapama.gob.es/redes-seguimiento), whose recording period started in 2011, data being available until late 2016.

Water for chemical analyses and plankton was collected with a 5L Niskin PVC bottle at representative depths of each of the main thermal layers (epi-, hypo-, monimolimnion and thermocline). Those layers were estimated to be anywhere that temperature gradients were lower than 0.4 ºC/m. The chemical variables measured were nitrate, ammonia, soluble reactive phosphorus (SRP hereafter) and total phosphorus. Chemical concentrations were measured within half an hour after sampling following standard procedures (APHA, 2005) and using a Seal-3 QuAAtro AQ2 auto-analyzer and a Shimadzu TOC-VCSH analyzer for measuring N and P contents after 2009, respectively. For statistical analyses, chemical factors were water-column averaged after weighting by the thickness of each layer, but also excluding monimolimnion because it did not always mix with the upper layers (see above). So a water-column average of a given chemical compound for a given date was estimated as

$$\text{Nutrient (mg N or P/L)} = (\sum n_i * t_i) / Z_t \quad (1)$$

Where n_i was the average nutrient content at layer i, t_i was the thickness of such a layer and Z_t was the overall depth of the three layers involved (epi-, hypolimnion and thermocline). The same procedure was followed for water temperature.

Phytoplankton samples were retrieved at each meter and immediately pooled for the whole water column (excluding monimolimnion), thus having a single sample for each monthly date. In the field this sample was fixed with iodine-lugol. Phytoplankton was counted in Utermöhl chambers with an inverted microscope (Zeiss or Olympus CK2) at 400 magnifications to obtain its

Table 1. Long-term statistics (1992-2018) of variables measured monthly in Las Madres lake. See the Materials and Methods' section to know how they have been measured and vertically-averaged or pooled. SD: standard deviation; CV: coefficient of variation; Min & Max: minimum and maximum values. *Descriptores estadísticos a largo plazo (1992-2018) de las variables medidas mensualmente en la laguna de Las Madres. SD: desviación típica; CV: coeficiente de variación; Min & Max: valores mínimo y máximo. Véase la sección de Material y Métodos para saber cómo se midieron y se promediaron o integraron verticalmente.*

Variable	Unit	Average	SD	CV	Min	Max	Median	Skewness	Kurtosis
Air temperature	(ºC)	15.23	7.47	49	2.57	29.85	14.38	0.21	-1.29
Rainfall	(mm)	31.0	29.1	94	0	165.4	22.4	1.5	2.6
Solar radiation	(W/m^2)	196	90	46	32	354	197	0.05	-1.36
Lake level	(m a.s.l)	528.9	0.8	15	527.2	530.4	528.8	0.03	-0.83
Euphotic depth	(m)	6.92	1.37	20	4.31	12.82	7.01	0.5	0.96
Water temperature	(ºC)	14.42	4.14	29	6.78	21.49	14.76	-0.14	-1.34
Mixing depth	(m)	4.59	3.16	69	0.50	12.00	3.00	0.67	-0.81
Nitrate	(mg N/L)	0.775	0.29	37	0.108	1.477	0.716	0.54	-0.42
Ammonia	(mg N/L)	0.203	0.140	69	0	0.670	0.170	0.83	0.23
Soluble reactive P	(mg P/L)	0.005	0.01	99	0	0.028	0.004	2.23	6.07
Total phosphorus	(mg P/L)	0.048	0.06	131	0	0.465	0.030	3.37	14.89
Phytoplankton biomass	(mm^3 FW/L)	1.01	1.45	143	0	11.04	0.42	2.99	11.81

population densities. At least 400 individuals of each population were counted, implying a 10 % error (Lund *et al.*, 1958). Taxonomic classification was carried out following standard taxonomic texts. Algal biomass (expressed as biovolume) was calculated using density and cell volume, measuring sizes of at least 20 individuals of each species and following Hillebrand *et al.* (1999).

Statistical treatment

Raw data can be found in http://www.sanchezandalvarezlab.es. We have decided to keep statistical processing as simple as possible due to the exploratory nature of this study. Long-term annual trends are depicted as box-whisker plots, and the trend of annual averages is studied using non-parametric tests. The CV of annual variables is employed as an index of seasonal variability within each year. The monthly variables used in statistical analyses are the following: air temperature, solar irradiance, rainfall, lake level, water-column averaged water temperature, euphotic depth, water-column averaged nitrate, ammonia, SRP, total phosphorus, and phytoplankton fresh biomass of water column (which was pooled in the field to represent a water-column composite sample; see above).

To test long-term, monotonic trends it is useful to apply a non-parametric test because data need not conform to any particular distribution (Gilbert, 1987). The Mann-Kendall test has been employed on the yearly average of each studied variable (Hirsch *et al.*, 1982), an approach that is usually undertaken in long-term hydrological studies with monthly sampling (e.g. Gocic & Trajkovic, 2013). In order to apply the Mann-Kendall test, observations must be independent (i.e. autocorrelation should not be statistically significant), which is not always the case and hence the variance of the statistic would be underestimated. Two methods are available to avoid such autocorrelation issues and have been used in our study: those by Hamed & Rao (1998) and Yue & Wang (2004). The former works well when the series does not show any trend, whereas the latter performs well when both a trend and an autocorrelation exist. Therefore, these methods have been applied prior to calculating the Mann-Kendall test to deal with likely autocorrelation and/or trend, using the XLSTAT package.

In any case, trends can be more complex than those represented by a linear function. Znachor *et al.* (2018) have suggested an approach that enables the characterization of such trends. They identify several types: constant, linear, piecewise and regime shift. The former are invariant over time. Linear trends can either increase or decrease monotonically over time. Piecewise trends experience several ups and downs throughout the study period whereas a regime shift depicts a sudden jump or depletion of the time course of the variable concerned for any given year (see the graphical abstract by Znachor *et al.*, 2018). Constant, linear and piecewise patterns were ascertained using least squares regressions (Pearson coefficient) of yearly-averaged variables against time, the breaking point in piecewise trends being detected visually. Regime shifts were established using the sequential regime shift detector software 6.2 (https://sites.google.com/site/climatelogic) which followed the method by Rodionov & Overland (2005); the settings for this test were the same as those used by Znachor *et al.* (2018).

Covariations among variables were ascertained using Spearman correlation (Siegel & Castellan, 1988); slope comparison was made by ANCOVA. While Statistica 7.0 was used to plot box-whisker items, the PAST package (Hammer *et al.*, 2001) was employed to test non-parametric statistics (Mann-Kendall test and Spearman correlation) and ANCOVA.

RESULTS

Long-term trends and seasonal variability

The statistics of all the variables considered in this study are shown in Table 1. Long-term CVs of rainfall, mixing depth, ammonia, SRP, total phosphorus and phytoplankton biomass, however, exceeded 50 % (Table 1). As judged by both the Mann-Kendall test and Spearman correlation, air temperature and solar radiation appeared to experience long-term increasing dynamics (Table 2; Fig. 2). Rainfall did not show any long-term trend for Las Madres lake (Table 2; Fig. 2). Water

Table 2. Results of the Mann-Kendall test as applied to long-term series of variables in Las Madres lake for 1992-2018. While S is an index of trend, which can be positive (increasing trend), negative (decreasing trend) or zero (no trend), Z is the test statistic and p is the associated probability. Spearman' correlation values between annually-averaged limnological variables and years are also shown. Statistically significant values at $p < 0.05$ are highlighted in bold. *Resultados del test de Mann-Kendall aplicado a las series de variables medidas a largo plazo en la laguna de Las Madres desde 1992 a 2018. S es un indicador de tendencia, que puede ser positivo (tendencia creciente), negativo (tendencia decreciente) o nulo, mientras que Z es el estadístico del "test" y "p", su probabilidad asociada. También se muestran las correlaciones de Spearman de los promedios anuales de dichas variables con el tiempo (medido en años). Los valores estadísticamente significativos a un nivel de probabilidad inferior a 0.05 se han recalcado en negrita.*

Variable	Mann-Kendall test			Spearman (year)	
	S	Z	*p*	rs	*p*
Air temperature	119	2.46	**0.0139**	0.49	**0.0089**
Solar radiation	141	2.92	**0.0035**	0.63	**0.0004**
Rainfall	13	0.25	0.8025	-0.06	0.7600
Lake level	-314	6.53	**<0.0001**	-0.76	**< 0.0001**
Euphotic depth	-37	0.75	0.4528	-0.09	0.6705
Water temperature	70	1.44	0.1502	0.33	0.0963
Mixing depth	-15	0.29	0.7703	0.01	0.9783
Nitrate	181	3.75	**0.0002**	0.66	**0.0002**
Ammonia	-32	0.65	0.5178	-0.06	0.7371
Soluble reactive phosphorus	28	0.58	0.5653	0.09	0.6501
Total phosphorus	-199	4.13	**<0.0001**	-0.73	**<0.0001**
Phytoplankton biomass	-221	4.59	**<0.0001**	-0.79	**< 0.0001**

temperature appeared to increase slightly (positive S of Mann-Kendall test), but the long-term trend was not significant (as judged by the Mann-Kendall Z and the Spearman correlation; Table 2; Fig. 3). It proceeded at a faster pace during mixing than during stratification (slopes of the temperature-year relationship = 0.041 *vs* 0.032, respectively; $p < 0.05$, ANCOVA test). Nitrate content increased over time (Table 2, Fig. 4), rising more in stratification than during mixing (slopes = 0.010 *vs* 0.021, respectively; $p < 0.05$, ANCOVA test). Total phosphorus, phytoplankton biomass and lake level experienced a long-term downward trend (Table 2, Figs. 4-6), the latter fluctuating in the earlier years, albeit diminishing after 1999 (Fig. 6 upper panel).

As expected, lake level partly depended upon groundwater level directly (Fig. 6 lower panel). The recorded groundwater level by the Tajo Water Authority from 2011 to 2016 was weakly dependent upon rainfall with a one-month lag ($R^2 = 0.20$, $p = 0.0001$), but lake level was unrelated to rainfall without any delay ($p > 0.05$). Mixing depth, ammonia and SRP did not show any long-term trend (Table 2, Figs. 3-4).

A deeper understanding of long-term patterns can be gained when using the Znachor *et al.* (2018) approach. In addition to a visual inspection of plots (Figs. 2-5), statistical analyses provided a good classification of such patterns (Table 3). While yearly air- and water temperatures and solar radiation appeared to depict an upward linear trend, phytoplankton biomass underwent a marked decrease for the whole study period, as mentioned above (Table 3). Lake level, euphotic depth and ammonia behaved in a piecewise manner; albeit with two different years of reversal because they undertook an up-down-upward- and an up-down-up-downward course, respectively (Table 3). Rainfall was roughly constant throughout the study period ($p > 0.1$), whereas regime shifts are depicted by mixing depth and nitrate

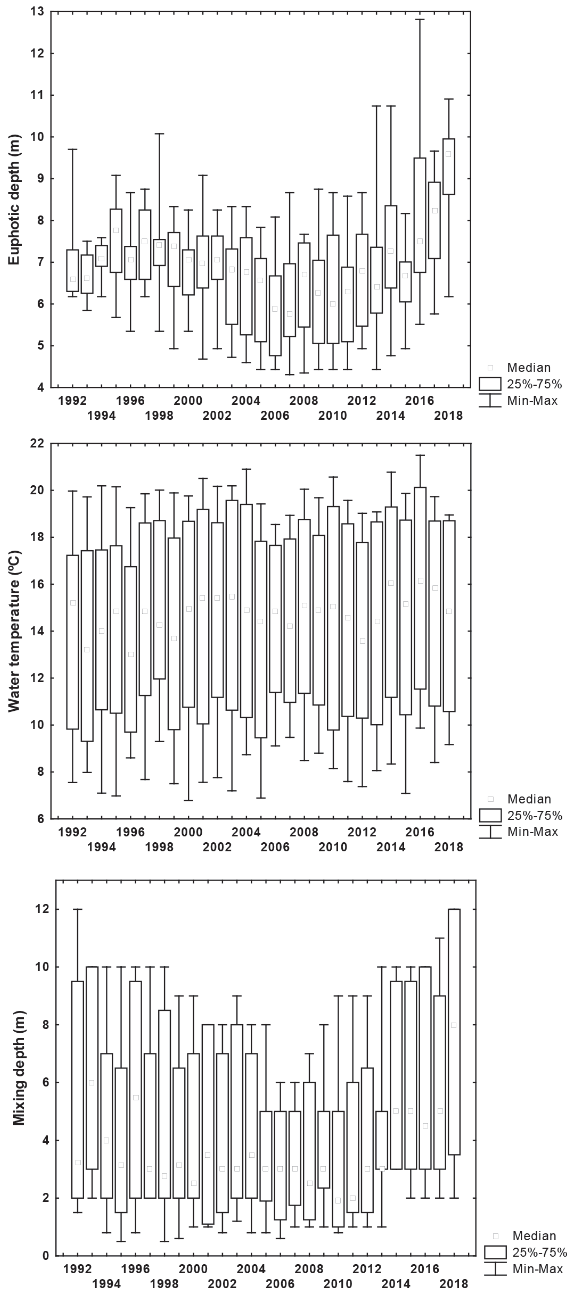

Figure 3. Long-term (1992-2018) box-whisker plots of physical factors in Las Madres lake. Water temperature is the weighted average for epi-, hypolimnion and thermocline. Further explanations can be found in Fig. 2. *Distribuciones anuales en cajas y bigotes (véase la Fig. 2) de las variables físicas registradas en la laguna de Las Madres desde 1992 a 2018. La temperatura del agua es el promedio ponderado de las temperaturas medidas en cada muestreo en epilimnion, termoclina e hipolimnion.*

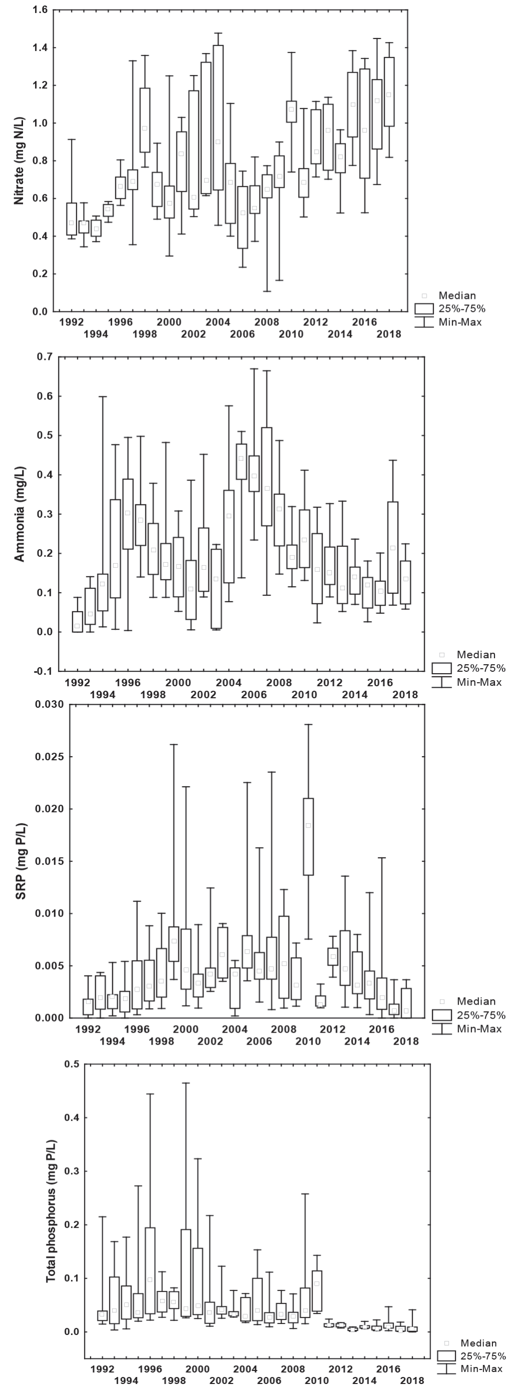

Figure 4. Long-term (1992-2018) box-whisker plots of chemical factors in Las Madres lake. All are weighted averages for for epi-, hypolimnion and thermocline. Further explanations can be found in Fig. 2. *Distribuciones anuales en cajas y bigotes (véase la Fig. 2) de las variables químicas registradas en la laguna de Las Madres desde 1992 a 2018. Todas son el promedio ponderado de las medidas para cada variable en cada muestreo en epilimnion, termoclina e hipolimnion.*

concentration, albeit having different years where shifts occurred (Table 3). Finally, mixed behaviour was demonstrated by phosphorus content because SRP increased earlier until 1999, later being constant until 2010 and finally decreasing, whereas total phosphorus was initially constant until 1999, later decreasing (Table 3).

The intra-annual range of ammonia, nitrate, SRP, total phosphorus and phytoplankton biomass was higher in the first half of the study (i.e. whiskers in Figs. 4-5). Therefore, seasonal fluctuations of those factors appeared to decrease over time, as opposed to the trends for euphotic depth (Fig. 3). However, when seasonal variability was judged by annual coefficients of variation, only two correlations with time (years) were significant: those relating to the euphotic zone (Spearman's rs: 0.63, $p < 0.001$) and ammonia concentration (Spearman's rs: -0.52, $p = 0.03$).

Covariations among series in the long-term

An increase in air temperature and solar radiation (i.e. climatic variables) impacted on some lake physics, thus raising water temperature and co-occurring with decreasing lake level (Table 4). However, no effect of air temperature on mixing- and euphotic depths, both of which co-occurred, was observed (Table 4). Furthermore, water temperature also positively covaried with nitrate, which correlated negatively with lake level. This variable and total phosphorus partly followed the same trend (Table 4). An increase in mixing depth was related with decreasing ammonia and SRP. Finally, both total phosphorus and nitrate concentrations were positively and negatively related with phytoplankton biomass, but the relationship (rs = 0.75) of the latter variable with lake level was stronger (Table 4).

The rise in air temperature did not increase in line with its annual variability ($p > 0.05$). Furthermore, water temperature, mixing- and euphotic depths were inversely related with their seasonal variability in the long term ($p < 0.05$). There were also inverse relationships between both solar radiation and euphotic depth and the seasonal variability of phytoplankton biomass. The long-term trend of such a biomass was positively related with NH_4 seasonal variability (Table 4). And last but not least, seasonality of phytoplankton biomass

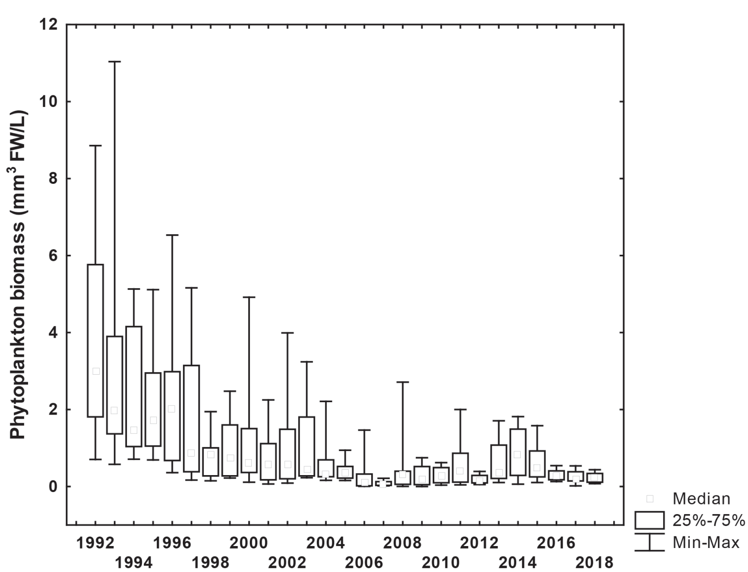

Figure 5. Long-term (1992-2018) box-whisker plots of fresh phytoplankton biomass in Las Madres lake. Phytoplankton samples were pooled in the field to yield a water column composite sample. Further explanations can be found in Fig. 2. *Distribuciones anuales en cajas y bigotes (véase la Fig. 2) de la biomasa fitoplanctónica registrada en la laguna de Las Madres desde 1992 a 2018. En el campo las muestras tomadas en la columna vertical en cada fecha concreta se mezclaron para generar una muestra compuesta.*

Table 3. The approach of Znachor *et al.* (2018) to characterize the main types of trends observed in limnological variables of Las Madres lake in the long-term. Years when trends change are shown, along with statistical probability of changing trends for a given period (*p* of Pearson's). *Uso de la metodología de Znachor* et al. *(2018) para caracterizar las principales tendencias que les suceden a las variables limnológicas de la laguna de Las Madres a largo plazo. Se muestran los años en los que cambia la tendencia, junto con la probabilidad estadística (la probabilidad proviene del coeficiente de correlación de Pearson) del cambio para un periodo determinado.*

Variable	Trend	Year(s) of changing	*p*
Air temperature	Upward linear		0.003
Solar radiation	Upward linear		0.001
Rainfall	Constant		0.931
Lake level	Mixed (constant & piecewise)	1999	< 0.00001 (2000-2018)
Euphotic depth	Mixed (constant & piecewise)	1999, 2007	>0.05 (1992-1998), 0.0003 (1999-2006), 0.0008 (2007-2018)
Water temperature	Upward linear		0.032
Mixing depth	Regime shift	2005, 2014	< 0.0006 (1992-2004) (2005-2013) (2014-2018)
Nitrate	Regime shift	2010	< 0.0003 (1992-2009) (2010-2018)
Ammonia	Piecewise	1997, 2002, 2007	0.002 (1992-1996), 0.08 (1997-2001), 0.07 (2002-2006), 0.04 (2007-2018)
Soluble Reactive Phosphorus	Mixed (constant & piecewise)	1999, 2010	0.003 (1992-1998), > 0.05 (1999-2009), 0.05 (2010-2018)
Total phosphorus	Mixed (constant & piecewise)	1999	> 0.05 (1992-1998), 0.0005 (1999-2018)
Phytoplankton biomass	Downward linear		0.021

positively covaried with seasonality of solar radiation and SRP concentration (Table 4).

DISCUSSION

Long-term annual patterns and their control

Here we have undertaken a preliminary long-term analysis of some important variables for the limnology of a very recent lake. While field data have been gathered on a monthly basis for 27 years, here we have attempted to depict trends, fluctuations and controlling factors by reducing the signals of interest to a tractable temporal form. One such scale is the annual scale. The main climatic and limnological variables of Las Madres lake can be calculated as annual averages in a first approximation to describe their long-term dynamics and to suggest factors controlling them. This approach has also been followed in other long-term studies (e.g. Hatvani *et al.*, 2011; Hsieh *et al.*, 2010). It is true that such an approach may overlook important processes taking place at other time scales (Hanson *et al.*, 2006; Benavent, 2015; Alvarez-Cobelas *et al.*, 2019), but it will suffice here as a picture of long-term trends, their vagaries and controlling factors at that temporal scale.

Long-term responses of Las Madres ecological variables depicted the trend patterns previously reported by Znachor *et al.* (2018) and Cloern (2019) in their recent long-term studies: constancy, linear trends, piecewise regressions and regime shifts (Figs. 2-6; Table 3). In some cases, mixed patterns were even observed in Las Madres, such as for lake level and phosphorus content, which displayed constant behaviour in the earlier period but piecewise behaviour after-

Table 4. Statistically significant ($p < 0.05$) Spearman correlations among all variables pooled annually in Las Madres lake for 1992-2018. The CV of annual measurements has been used as an index of seasonality. *Correlaciones de Spearman estadísticamente significativas (p < 0,05) entre las variables estimadas anualmente en la laguna de Las Madres durante el periodo 1992-2018. El coeficiente de variación de los datos anuales se ha usado como indicador de estacionalidad.*

	Variable	Average											CV					
		Air Temp.	Solar Rad.	Lake L.	Euphotic D.	Water Temp.	Mixing D.	NO_3	NH_4	SRP	Total P	Phyto. Bio.	Air Temp.	Solar Rad.	Lake L.	Water Temp.	NO_3	SRP
Average	Solar Rad.	0.52																
	Lake L.	-0.47	-0.67															
	Water Temp.	0.40																
	Mixing D.				0.71													
	NO_3		0.42	-0.54		0.49												
	NH_4						-0.60											
	SRP				-0.52		-0.63		0.40									
	Total P	-0.44	-0.42	0.73				-0.50										
	Phyto. Bio.			0.75				-0.44			0.46							
CV	Solar Rad.		-0.41															
	Rainfall							-0.47										
	Lake L.				0.53		0.53											
	Euphotic D.			-0.59	-0.44		-0.43								-0.60			
	Water Temp.					-0.42							0.46					
	Mixing D.						-0.43											
	NO_3					0.40									-0.47			
	NH_4								-0.54	-0.44		0.57				0.40		
	SRP				0.44											-0.41		
	Total P																	0.60
	Phyto. Bio.		-0.42		-0.53									0.61			0.47	

	Positive	Negative
[0.40-0.50[		
[0.50-0.60[		
≥0.60		

wards (Figs. 4 and 6, Table 3). Except for euphotic depth and P compounds, changing patterns did not occur in the same years for all aquatic variables, which also occurred in other environments studied for many years, such as the Czech Římov reservoir (Znachor *et al.*, 2018) and San Francisco bay (Cloern, 2019). The sudden decrease in lake level appeared to match changing patterns of euphotic depth and P compounds, whose turning point occurred between 1999 and 2000 when nearby mineral exploitation led to a sharp drop in lake level (Figs. 1 and 6).

Many studies on long-term dynamics in lakes (to name a few: Adrian *et al.*, 1995; Hsie *et al.*, 2010; McIntire *et al.*, 2007; Reynolds *et al.*, 2012) suggest that the main processes responsible for such dynamics are global warming and eutrophication (or its reversal). Often the weight of one effect prevails over the other, as occurs in the German Saidenbach reservoir (Horn *et al.*, 2015), but they may cancel each other out when oligotrophication takes place, as in the Swedish Krankesjön lake (Zhang *et al.*, 2015).

While long-term patterns at the yearly scale of the main climatic and limnological variables of Las Madres lake are clear (Figs. 2-6, Tables 2-3), their set of controlling factors appears to be more complex and differ somewhat from those reported in most other studies (see above). Correlation analyses (Table 4) have demonstrated that long-term trends in solar radiation and atmospheric forcing, the surrogate of the latter being the increasing air temperature above the lake (Fig. 2), have partly impacted on water temperature, which has also augmented (Fig. 3), and lake level, which has diminished (Fig. 6). However, two further facts have to be kept in mind: Firstly, water temperature averages are inversely related

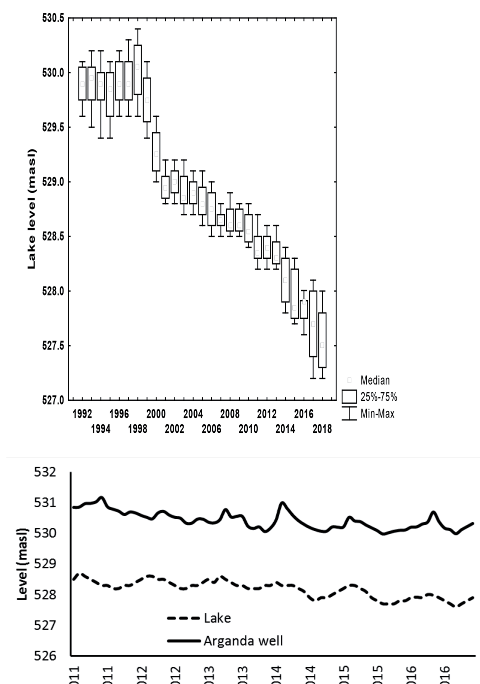

Figure 6. Upper panel. Long-term (1992-2018) box-whisker plots (see Fig. 2 for further explanations) of *in situ* Las Madres lake level (m a.s.l). Lower panel. Plot of monthly lake level vs groundwater level data recorded upgradient, 4 km away from Las Madres lake, for 2011-2016. There is a statistically significant relationship between both variables (R^2 = 0.51, p = 0.00001). *Panel superior. Diagramas de cajas y bigotes (véase la Fig. 2) del registro mensual del nivel lacustre en Las Madres. Panel inferior. Curso temporal del nivel lacustre en relación con el nivel piezométrico medido por la Confederación Hidrográfica del Tajo a unos 4 kms aguas arriba de la laguna de Las Madres para el periodo 2011-2016. La relación es estadísticamente significativa (R^2 = 0.51,* p *= 0.00001).*

to their yearly variation (Table 4), and secondly, no effect of air temperature could be seen on mixing depth. Both facts are opposite effects to those reported for global warming (Austin & Colman, 2007; Kirillin, 2010). In any event, the lake level was found to be inversely related with air temperature and solar radiation (Table 4), also emphasizing a partial effect of climate forcing on Las Madres lake because a temperature increase usually results in higher evaporation losses, thereby reducing the water column height. Since no statistically significant relationship has been recorded between rainfall and water level in Las Madres lake, it is unlikely that such recent decreases in water level can be attributed to changes in precipitation.

In addition, dynamics of total phosphorus, phytoplankton biomass and lake level have positively co-occurred (Table 4). Phytoplankton and its often usual controlling factor in lakes (i.e. total P; Vollenweider, 1968) experience a decrease over time (Figs. 4, 5), which is the opposite to that observed in other lakes experiencing global warming effects (George, 2010). Furthermore, the mere water column shrinkage should have resulted in higher total phosphorus concentrations and phytoplankton biomass in the long-term, but this has not been the case. It is hence clear that other mechanisms might have been operating on the limnological variables of this lake over time. Another study (Benavent, 2015) has highlighted the fact that periods of phytoplankton growth have lengthened over time in Las Madres lake, but this does not appear to yield higher phytoplankton biomasses in the long-term.

Two processes appear to be responsible for part of the unexplained variability in Las Madres lake: the opening of new basins in its surroundings in 1999-2000 and stabilization of the newly-formed lake, whose mineral exploitation had finished by 1984. As a seepage lake (McBride & Pfannkuch, 1975), Las Madres water level is partly dependent upon groundwater flux (Fig. 6, lower panel), but the closer mining industry was also responsible for lake level decrease (Fig. 1), the greatest of which took place by late nineties (Fig. 6, upper panel). This fact is supported by Himi's (2001) observations in a nearby (< 300 m) well, where water level decreased by 1.15 m between March 1999 and November 2000.

In addition, an ecological stabilization process is often depicted by newly-built freshwater environments, such as reservoirs (Atkinson, 1988; Holz *et al.*, 1997). Over the whole study period, this process decreases the amount and variability of both phytoplankton biomass and some chemical factors, such as total phosphorus, in Las Madres lake (Figs. 4-5, Table 3). Hence, the lake would have experienced ongoing oligotrophication, due to the slow settlement of suspended sediments originating from past mineral exploitation, which tend to form nutrient-mineral complexes. This process, i.e. ecosystem stabilization, strongly offsets other trends such as global warming, the most commonly reported in recent years (Adrian *et al.*, 2009). Annual phytoplankton biomass responds to this oligotrophication process, arising from ecosystem stabilization, and is directly related to total phosphorus content in the lake (Table 4).

On the other hand, the seasonality (annual variability) of most limnological variables in Las Madres lake, as judged by annual ranges, has decreased over time (Figs. 2-6), which is another feature contrary to what we would expect from global warming, whose index variable (air temperature, rainfall) variability increases over time (IPCC, 2001). Even water temperature averages are inversely related to the annual variability (Table 4), a fact that contradicts what one may expect in terms of global warming. These facts again provide evidence for other processes that might offset the importance of global warming on long-term dynamics of Las Madres lake.

Furthermore, nitrogen dynamics appears to fall outside the main long-term picture of Las Madres lake. Only a fraction of nitrate seasonality is explained by increasing water temperature variability (Table 4), thus suggesting the importance of nitrification in the long term, which is certainly enhanced by temperature increase. Ammonia seasonality, on the other hand, rises along with long-term phytoplankton biomass (Table 4). Finally, the seasonality of phytoplankton biomass is partly and positively related with both the averages of solar radiation and euphotic depth and the seasonality of SRP, which also makes the picture of phytoplankton dynamics

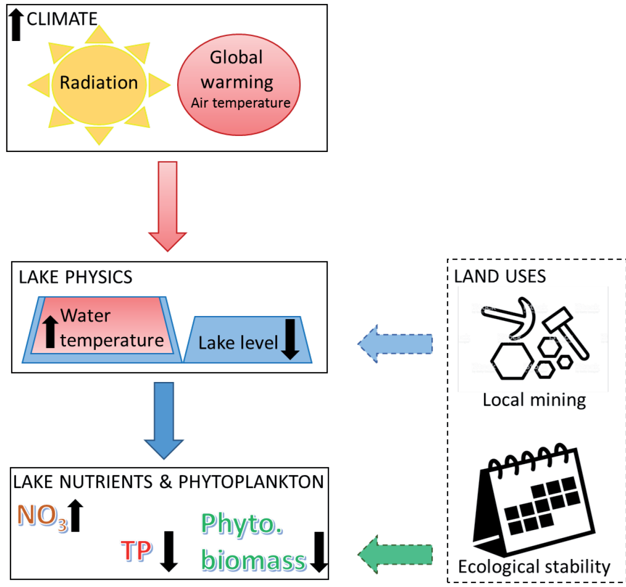

Figure 7. Sketch of the main controlling factors of limnology in Las Madres lake in the long-term (1992-2018) at the yearly scale. *Esquema de los probables factores de control limnológico a largo plazo (1992-2018) en la laguna de Las Madres a escala anual.*

more complex. These facts suggest that different controlling factors are related with the temporal scale involved (see Alvarez-Cobelas *et al.*, 2019). In any event, our preliminary calculations of annual variability imply that it has changed for most variables, emphasizing their long-term complexity in the aquatic realm. A similar conclusion has been reached by Cloern (2019) after his analysis of San Francisco Bay long-term series (1975-2016).

Therefore, regarding the outcome when several drivers (e.g. global warming and eutrophication) contest in lakes, as mentioned above, ecological stabilization has also played an important role in the limnological processes in Las Madres lake, thus counterbalancing effects of global warming and local mining (Fig. 7). A rich picture of long-term dynamics emerges for this lake, disclosed thanks to our yearly approach.

Such a complexity implies that a thorough, integrative picture of long-term dynamics in a given lake can only be acquired following a polyhedral approach, using a wide array of statistical techniques to detect changing control factors in different periods, as demonstrated by our study (Alvarez-Cobelas *et al.*, 2019) on Las Madres phytoplankton biomass. Trend reversals detected in some variables, such as euphotic depth and ammonia (Table 3), would also support this argument.

Prospects

Although this study, exploratory as it is, does not identify responses at various scales as done by our previous (Alvarez-Cobelas *et al.*, 2019) and other (e.g. Hanson *et al.*, 2006) studies, it does emphasize different controlling factors at each scale and study period. In fact, our preliminary correlation study also suggests the latter by showing different statistical relationships at the annual and the seasonal scales. Furthermore, long-term patterns can be very complex, when viewed at the annual scale, and are not the same for all variables involved.

In any event, multiscale ecology is only at the outset (Wheatley & Johnson, 2009), and long-term studies recorded at proper time scales will prove very important to detect distinct scales of operation and their controlling factors, but also their hierarchical responses (Wagner & Adrian, 2009). The multiple dynamics and scales that long-term limnological studies are now suggesting must lead to a renewed, interdisciplinary focus on the temporal variable, which would coalesce related concepts, help develop new theories and methods and guide further data collection, as advocated by Wolkovich *et al.* (2014). Our study on this gravel-pit lake has demonstrated that 20 years are enough to disentangle part of the complexity of patterns and processes involved in its long-term dynamics, but not sufficient to solve further co-occurring issues of interest. For example, it is likely that global warming effects might be detected more easily once the ecological stabilization of the site has terminated, but this will need the gathering of further data in the near future. Therefore, more and longer studies in Las Madres lake will provide a more accurate picture of its long-term dynamics, albeit surely more complex.

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