TEMPORAL AND SPATIAL VARIATIONS IN THE QUALITY OF WATER IN EL GERGAL RESERVOIR, SEVILLE, SPAIN

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Introduction

It is often difficult to define 'water quality' with any degree of precision. One approach is that suggested by Battarbee (1997) and is based on the extent to which individual lakes have changed compared with their natural 'baseline' status. Defining the base-line status of artificial lakes and reservoirs however, is, very difficult. In ecological terms, the definition of quality must include some consideration of their functional characteristics and the extent to which these characteristics are self-sustaining (Harper 1992; Moss 1999). The challenge of managing lakes in a sustainable way is particularly acute in semi-arid, Mediterranean countries. Here the quality of the water is strongly influenced by the unpredictability of the rainfall as well as year-to-year variations in the seasonal averages (Thornton & Rast 1993). Wise management requires profound knowledge of how these systems function. Thus a holistic approach must be adopted and the factors influencing the seasonal dynamics of the lakes quantified over a range of spatial and temporal scales.

In this article, we describe some of the ways in which both long-term and short-term changes in the weather have influenced the seasonal and spatial dynamics of phytoplankton in El Gergal, a water supply reservoir situated in the south of Spain. The quality of the water stored in this reservoir is typically very good but surface blooms of algae commonly appear during warm, calm periods when the water level is low.

El Gergal reservoir is managed by the Empresa Municipal de Abastecimiento y Saneamiento (EMASESA) and supplies water for domestic, commercial and industrial use to an area which includes the city

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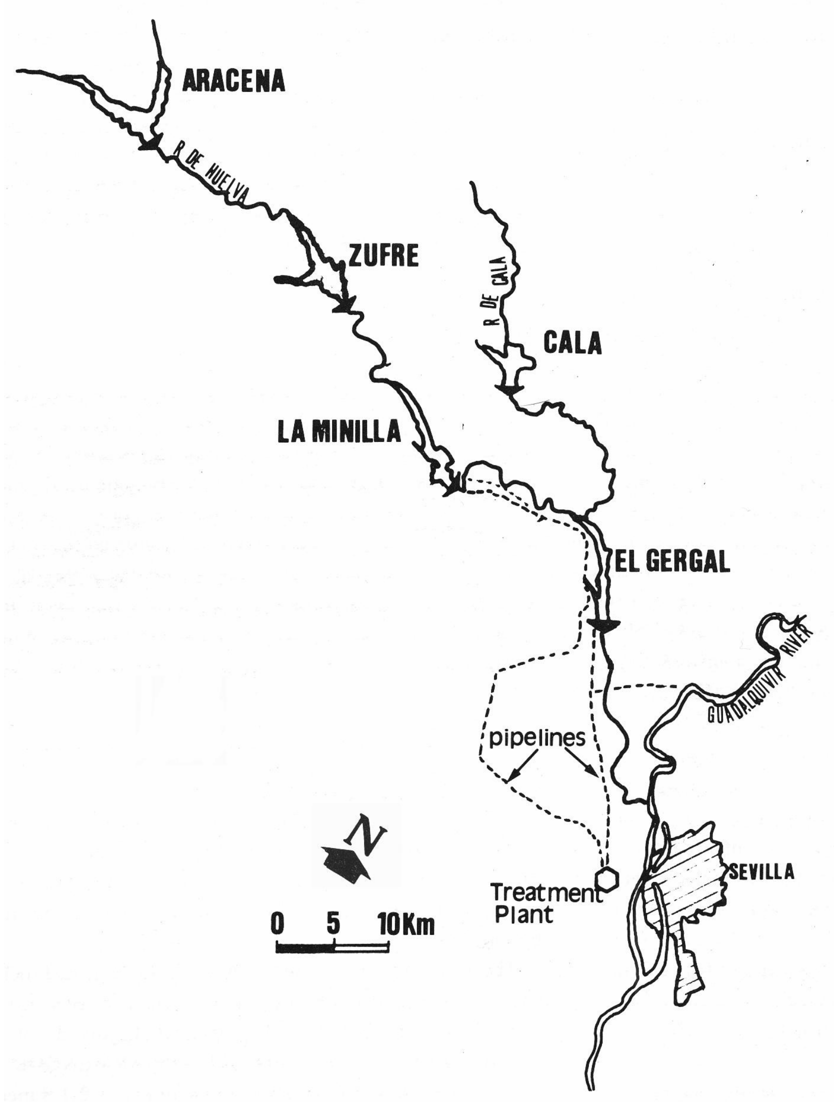

FIG. 1. The reservoir network and the water-transfer options within the El Gergal system (modified from Toja et al. 1992).

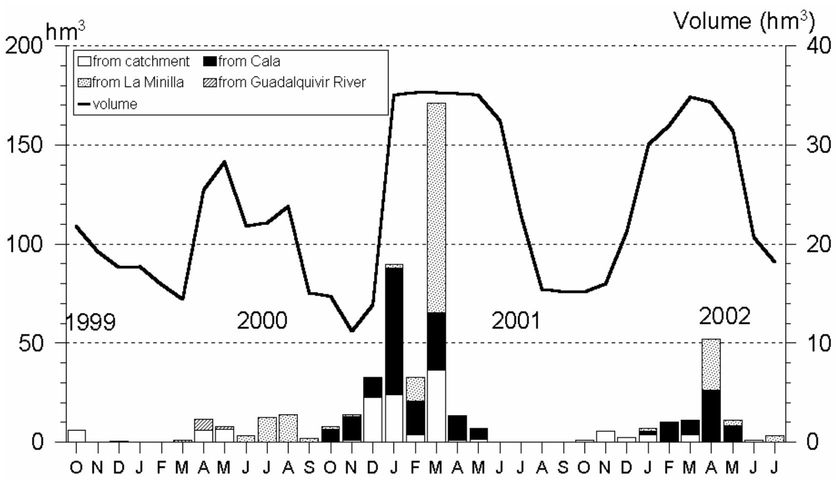

FIG. 2. The transfers of water into El Gergal reservoir between October 1999 and July 2002 (filled areas) in relation to the total volume in the reservoir (solid line). The vertical bars show the source of the different inflows.

of Seville and twelve of its surrounding towns (ca. 1.3 million inhabitants). El Gergal is the last of two reservoirs in a chain of four situated in the Rivera de Huelva basin, a tributary of the Guadalquivir river. It was commissioned by EMASESA in 1979 and since then the company has monitored its main limnological parameters on, at least, a monthly basis and used this information to improve the management of the reservoir. As a consequence of these intensive studies the physical, chemical and biological information acquired during this period makes the El Gergal database one of the most complete in Spain. Some of these data have already been published (Toja 1982, 1984; Toja et al. 1981, 1983, 1992; Sancho-Royo & Granado-Lorencio 1988; Galindo 1998; Moreno-Ostos 2004) and highlight the complex processes that influence the quality of the water. In this article we concentrate our attention on three 'weather-related' effects that have had a significant impact on the composition and distribution of phytoplankton in El Gergal: (i) the changes associated with severe droughts; (ii) the spatial variations produced by short-term changes in the weather; (iii) the impact of water transfers on the seasonal dynamics of the dinoflagellate *Ceratium*.

The operational characteristics of El Gergal

El Gergal is the last in a chain of reservoirs (Aracena, Zufre, La Minilla and El Gergal) situated in the basin of the Rivera de Huelva (Fig. 1). A

fifth reservoir (Cala), located on a tributary to the Huelva, completes the network and is primarily used to generate hydroelectric power. The complexity of the system and the location of El Gergal at the end of the network have profound consequences for the management of the reservoir (Toja et al. 1992; Galindo 1998). El Gergal is usually described as a medium-size reservoir (surface area 250 ha; volume 35 hm^3; maximum depth 37 m; mean depth 15.7 m) but both the area and the volume can be severely reduced during dry periods. Estimated retention times thus vary from a minimum of 20 days during very wet periods to a maximum of one year during severe droughts. Fig. 2 shows the variations in the hydraulic loading to El Gergal between October 1999 and July 2002. These measurements show the seasonal variation in the transfers of water within the El Gergal system as well as the changes in the total volume. During the course of this study, one of the most important limnological events was the transfer of water from Minilla in late May 2000. This water contained very high concentrations of the alga *Ceratium* which had a significant effect on the seasonal succession of phytoplankton in the main reservoir basin (see PROTECH simulation in Elliott et al. 2005, this volume).

El Gergal is a relatively deep reservoir and typically remains thermally stratified from the end of February to the end of October (Fig. 3a). During June and, especially in July and August, a well defined thermocline develops at depths between 5 and 10 m. The only period of complete mixing occurs at the end of autumn–early winter. As might be expected, the spatial and temporal variations in the concentration of dissolved oxygen are closely correlated with the timing and intensity of thermal stratification. An orthograde oxygen (uniform oxygen–depth profile) can only be observed during the autumn mixing, when the water column remains well oxygenated. In summer, when the reservoir is stably stratified, the oxygen content of the deep water is usually below 50 %. Table 1 shows values for some other variables related to water quality. These include the average concentration of chlorophyll in the reservoir, a measure of the transparency of the water column (Secchi depth) and a number of chemical measurements. Very high concentrations of chlorophyll are periodically recorded during the summer, when the water column is stably stratified and the low nitrogen to phosphorus ratio (Galindo 1998) stimulates the growth of nitrogen fixing Cyanobacteria, such as *Microcystis aeruginosa, Aphanizomenon flos aquae* and *Anabaena* spp. Fig. 3b shows the week-to-week variations in the vertical distribution of Cyanobacteria in El Gergal between October 2000 and December 2001. The most prolonged surface bloom was that recorded in August and September 2001 when the near-surface concentrations exceeded 2000 individuals ml^{-1} for four consecutive weeks.

Table 1. General water quality characteristics of El Gergal reservoir (January 1979–November 2002).

Variable	Mean	Minimum	Maximum
Temperature (ºC)	16.53	8	28.8
pH	7.51	6.22	9.91
Conductivity (μS cm^{-1}; 20 ºC)	282.55	114	1850
Dissolved Oxygen (mg l^{-1})	5.85	0.01	17.24
Turbidity (Nephelometric Turbidity Units)	11.35	0.4	290
Colour (mg Pt-Co l^{-1})	16.88	1	72
Nitrate (mg NO_3 l^{-1})	2.64	0.001	23.419
Dissolved Phosphorus (mg PO_4^{3-} l^{-1})	0.13	0.001	8.96
Chlorophyll *a* (mg m^{-3})	12.78	0.065	493
Secchi depth (m)	1.77	0.2	8

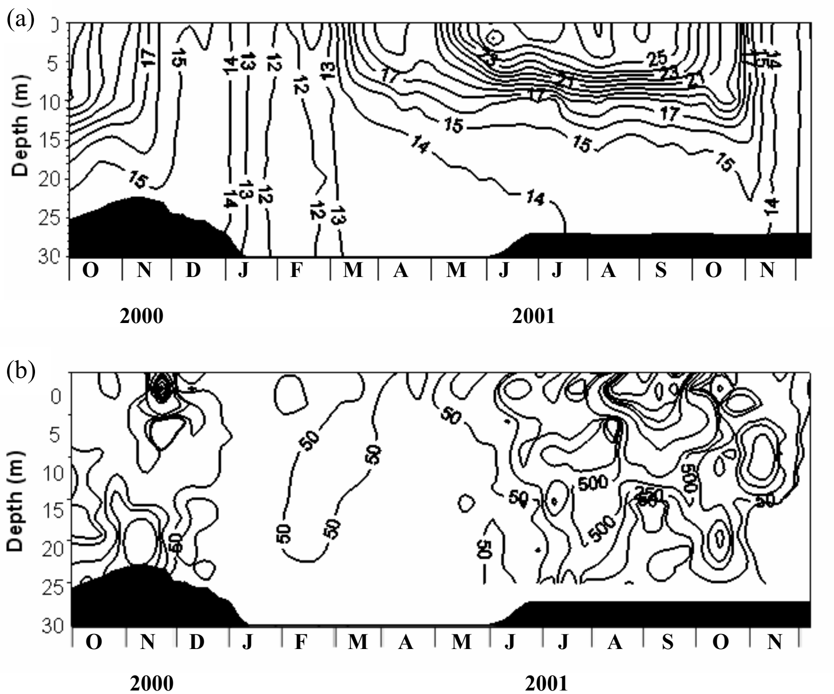

FIG. 3. The seasonal variation in (a) the thermal structure of El Gergal, (b) the vertical distribution of Cyanobacteria, between October 2000 and December 2001. Contours in (a) are in ºC; contours in (b) are individuals ml^{-1}.

The monitoring programme at El Gergal

In recent years, EMASESA has developed a very intensive sampling programme on El Gergal. Samples of water for chemical and biological analyses are collected from a range of depths at a station located near the deepest point of the main basin. Water column temperature is measured at fixed depths using a YSI Model 58 probe. Water samples from different depths are collected using a 5-litre Van Dorn sampler and then analysed for chlorophyll *a* content and nutrient composition. Temporal and spatial variations in the composition and density of the phytoplanktonic community are recorded by fixing sub-samples of water and counting the cells and colonies according to the Utermöhl method (1958).

A number of intensive synoptic surveys have also been organised to study the impact of wind-induced water movements on the spatial distribution of the phytoplankton. In these surveys, the trajectory of the surface and sub-surface currents is recorded using free-running, depth-specific current-crosses and the spatial variations in the wind field measured by a portable anemometer, a wind-vane and a compass. In these surveys, the concentration of chlorophyll and a number of related measurements is recorded at 20 stations distributed over the main part of the reservoir. At each station, the concentration of chlorophyll and the relative abundance of different functional groups of algae are monitored using a new instrument known as a Fluoroprobe (bbe Moldaenke). This instrument measures the total biomass of the phytoplankton and estimates the relative proportion of different broad functional groups (e.g. diatoms and Cyanobacteria). Spatial variations in the physical and chemical characteristics of the water are recorded at the same stations using a profiling system, the Windermere Profiler, developed at the Centre for Ecology and Hydrology (CEH) Windermere (Rouen 1989).

The impact of droughts on the quality of water in El Gergal

Analysis of the historical data acquired by EMASESA between 1989 and 2002 shows the extent to which long-term changes in the weather influence the quality of water stored in El Gergal. Fig. 4a shows monthly mean variations in the volume of inflows in relation to the total volume of water stored in the reservoir. Fig. 4b shows the corresponding variation in the annual development of the phytoplankton. Mean chlorophyll values for the upper 5 m of the water column are available for the whole period and species counts for the last nine years. In the 1980s, the concentration of chlorophyll in the reservoir was relatively low (data not shown) but this increased in the 1990s with the highest concentrations being recorded in 1993 and 2001. A key factor responsible for this increase was the severe drought experienced between 1992 and 1995. This dry period also had a

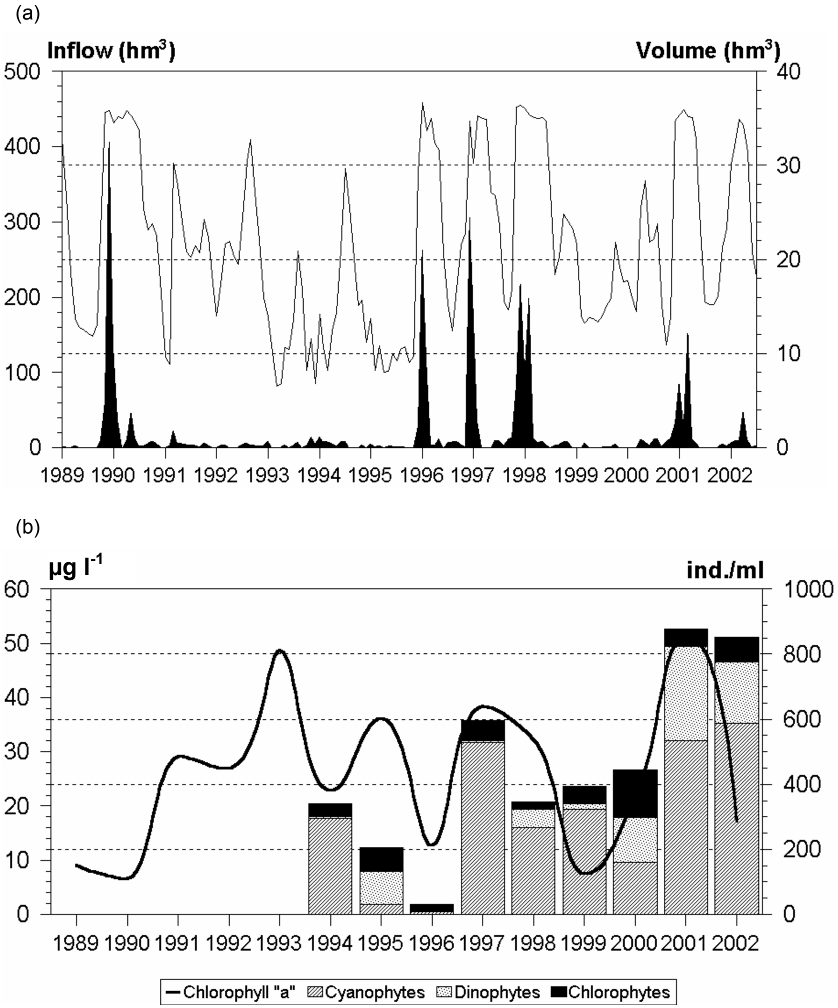

FIG. 4. (a) The change in the volume of water entering El Gergal between 1989 and 2002 (filled areas) in relation to the total volume (solid line). (b) The change in the abundance of four functional groups of phytoplankton in El Gergal between 1994 and 2002 (individuals ml^{-1}). The solid line shows the average biomass (expressed as chlorophyll *a*, μg^{-1}).

marked effect on the qualitative composition of the phytoplankton. No blooms of Cyanobacteria were reported in El Gergal in the 1970s and 1980s, but such blooms have become increasingly common in the 1990s. One of the densest blooms hitherto recorded occurred in October 1997 when one species accounted for 75 % of the measured biomass.

The impact of water transfers on the qualitative composition of the phytoplankton in El Gergal

One important factor influencing the floristic composition of phytoplankton in El Gergal is the concentration of cells present in the water transferred from other reservoirs in the system. A good example of this inoculum effect was reported in May and June 2000 when a mid-water maximum of the dinoflagellate *Ceratium* sp. was observed in La Minilla reservoir (Fig. 5a). This species is widespread in temperate lakes, where it develops mid-water maxima that periodically migrate towards the surface (Heaney & Talling 1980). In May 2000, a large amount of water was transfered from La Minilla to El Gergal and this inoculum subsequently gave rise to a summer maximum of *Ceratium* sp. in the main basin of El Gergal in July and August (Fig. 5b). A detailed analysis of the horizontal distribution of phytoplankton in El Gergal during this period (Fig. 6) showed a well defined north to south gradient of *Ceratium*. In most situations, such as those described by Heaney (1976), George & Heaney (1978) and Harris et al. (1979) such aggregations are the result of the organisms' response to wind-induced water movements. In this case, the spatial structure was directly related to the influx of *Ceratium* from La Minilla and the highest concentrations were observed in the upper riverine zone of El Gergal.

The impact of short-term changes in the weather on the development of phytoplankton patches in El Gergal

In El Gergal, some of the most serious water quality problems encountered are those experienced when surface blooms of Cyanobacteria accumulate downwind. A number of accounts of the impact of wind-induced water movements on the spatial distribution of Cyanobacteria have been published (George & Edwards 1976; George & Heaney 1978). In most situations the critical factor is the interaction between the vertical distribution of the organisms and the mixing effects of the wind. Such wind-induced patches are highly dynamic (Margalef 1974) and change their size and position as weather conditions change. In this study, we have used a combination of high-resolution monitoring at a fixed site and more extensive synoptic surveys to quantify the effects of day-to-day changes in the weather on the vertical and horizontal distribution of the phytoplankton.

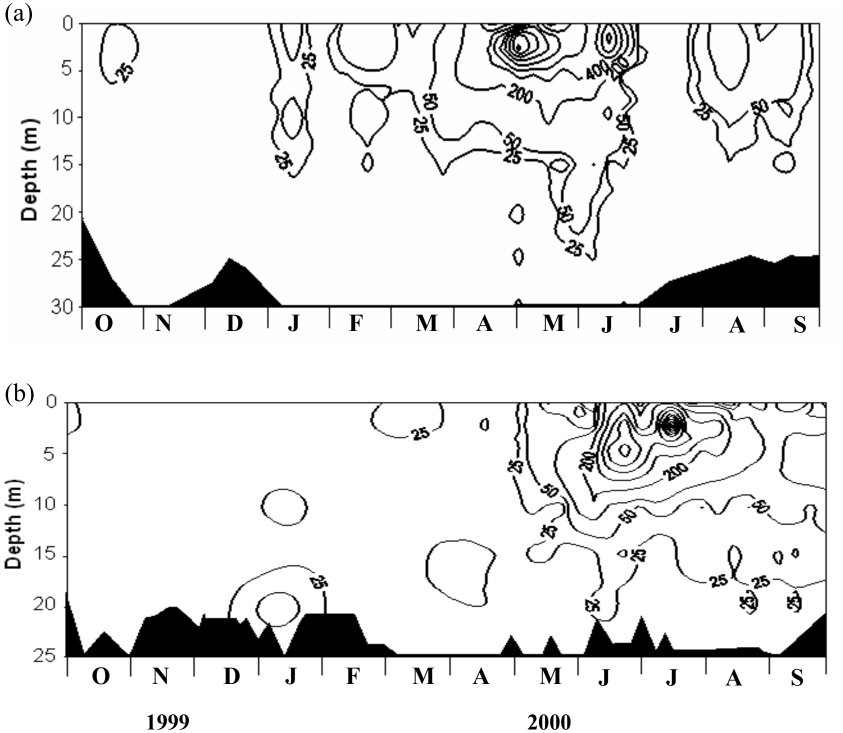

FIG. 5. The seasonal variation in the vertical distribution of *Ceratium* sp. in (a) La Minilla and (b) El Gergal between October 2000 and September 2001 (contours are individuals ml^{-1}).

Meterological parameters were monitored using the Automatic Water Quality Monitoring Station (AWQMS2) described in Rouen et. al. (2005, this volume).

The examples in Fig. 7 show the vertical distribution of two contrasting functional groups of phytoplankton in El Gergal in mid-summer. On the morning of 12th July 2002, the average wind speed recorded by the AWQMS2 was 1.2 m s^{-1} and a well defined secondary thermocline had formed at a depth of 5 m (Fig. 7a). Most of the Cyanobacteria present were concentrated in the top 5 m (Fig. 7b) but the Chlorophyta (Fig. 7c) were relatively homogeneously distributed in the water column. These differences in the vertical distribution of the two groups can be directly related to their form and function. Most species of Cyanobacteria can

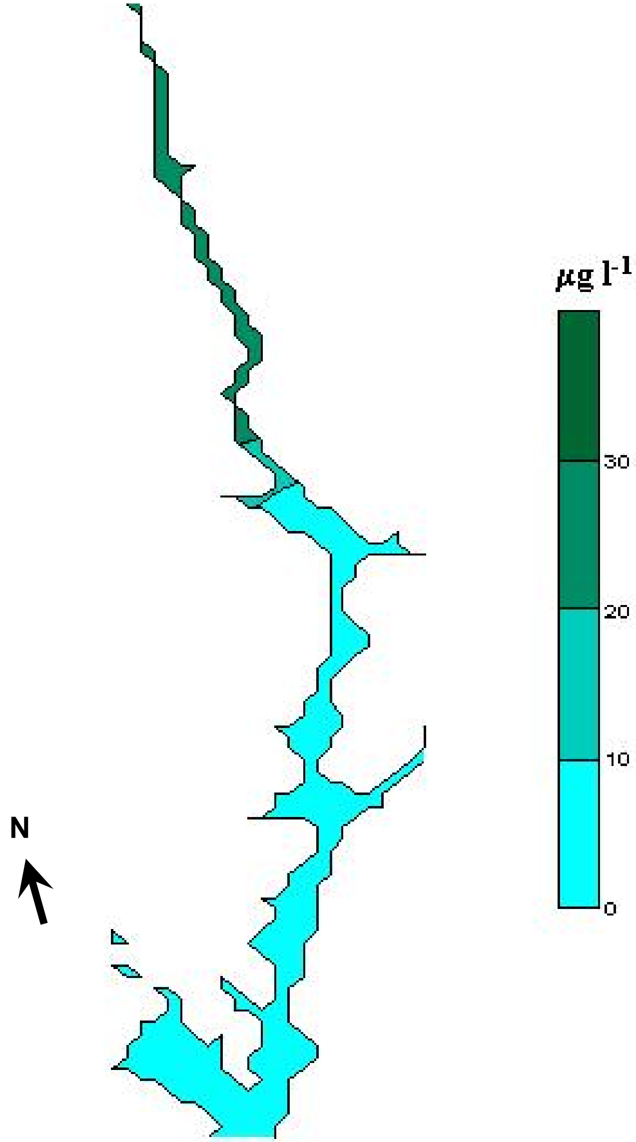

FIG. 6. Map showing the horizontal distribution of *Ceratium* sp. in El Gergal reservoir (measured as chlorophyll, µg l^{-1}) following the transfer of water from La Minilla in May 2000.

control their position in the water column by producing gas vacuoles but the Chlorophyta behave as passive contaminants of the physical flow. Figs 8 and 9 show the way in which organisms concentrated at different depths can be transported in different directions by the wind-induced currents. Fig. 8a shows the trajectory of the surface currents and subsurface currents recorded in El Gergal on the 12th of July and Fig. 8b the direction of the prevailing wind. These trajectories were mapped by tracking a number of free running drogues deployed in a line just north of the dam. The relatively fast surface currents were deflected to the left of the wind by the headland to the north of Cantalobos but the slower 5 m currents were deflected to the right by the Coriolis effect associated with the earth's rotation. As a consequence, the positively-buoyant Cyanobacteria were driven by the surface currents into Cantalobos Bay (Fig. 9a) whilst the non-buoyant Chlorophytes were dispersed by the deeper currents along the longitudinal axis of the reservoir (Fig. 9b).

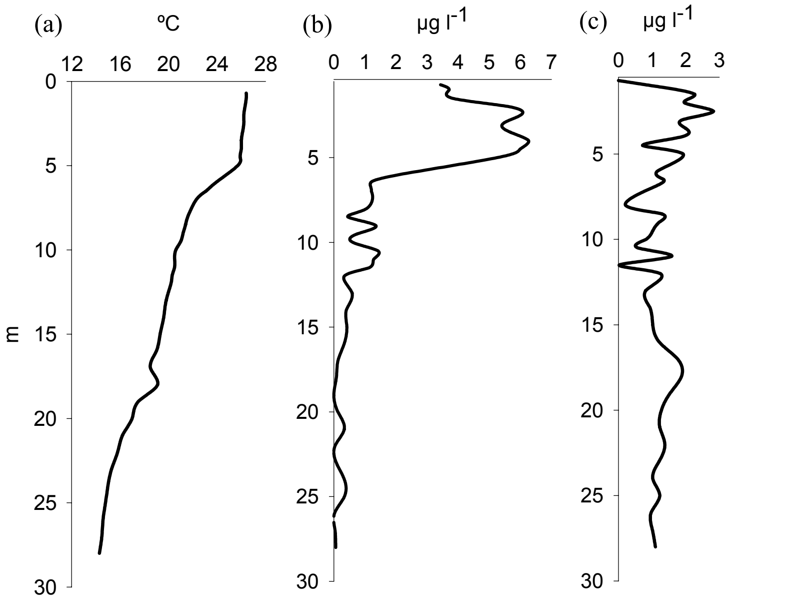

FIG. 7. The vertical variations in (a) the temperature of the water (°C), (b) the abundance of Cyanobacteria (μg l^{-1} chlorophyll) and (c) the abundance of chlorophytes (μg l^{-1} chlorophyll) in El Gergal on 12th July 2002.

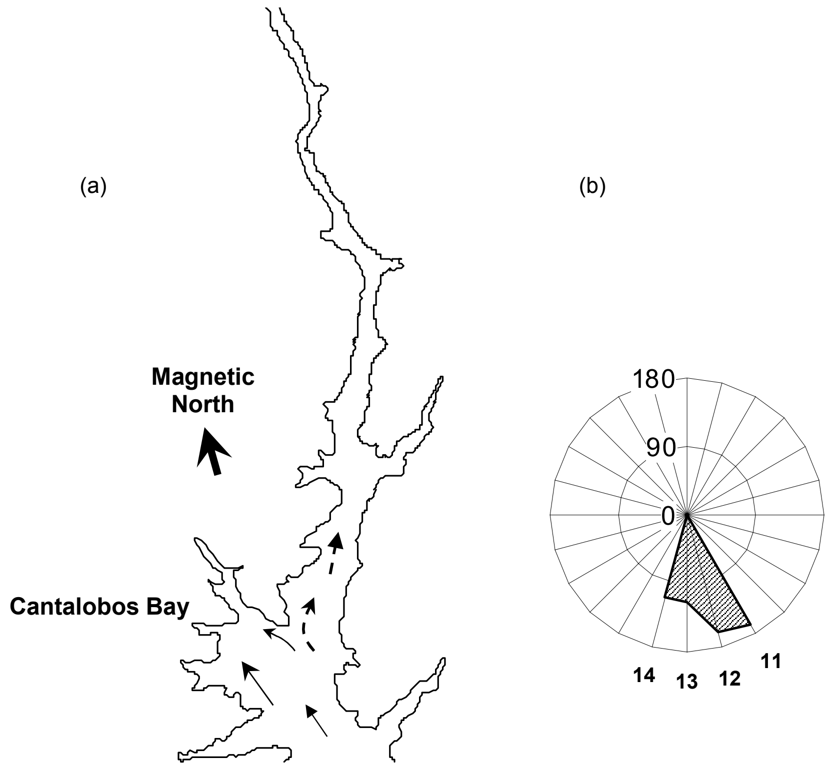

FIG. 8. (a) The trajectory of the wind-induced currents measured in the lacustrine zone of El Gergal on 12th July 2002 (the solid lines show the surface currents and the broken lines the currents at a depth of 5 m). (b) The wind direction at the time of sampling.

Concluding remarks

In this article, we have shown that the quality of the water in El Gergal is strongly influenced by both long-term and short-term changes in the weather. In the 1990s, the most serious weather related problems were those associated with the growth and accumulation of Cyanobacteria when the volume of water contained in the reservoir was very low. In recent years, some of the most striking qualitative and quantitative effects have been those produced by the downstream transfer of the bloom-forming dinoflagellate *Ceratium*. In both cases, the spatial distribution of the

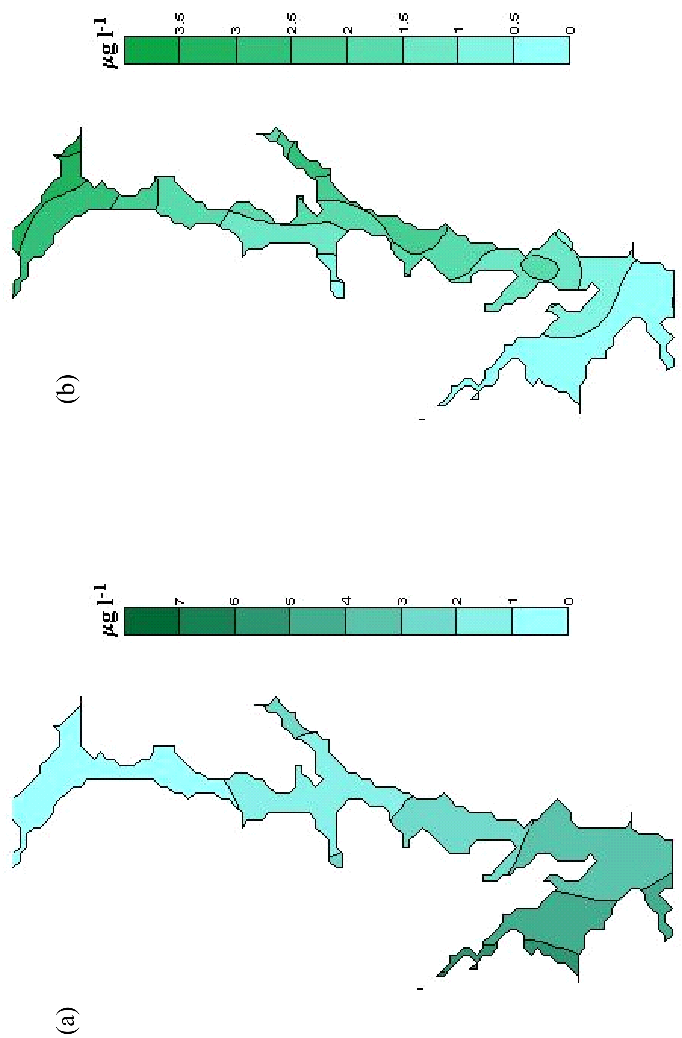

FIG. 9. The horizontal distribution of (a) Cyanobacteria and (b) chlorophytes in El Gergal, measured as chlorophyll *a* (µg l^{-1}) on 12th July 2002.

organisms in the reservoir was strongly influenced by the intensity of mixing and the speed and direction of the wind-induced currents.

In the second year of the project (2001), an Automatic Water Quality Monitoring station of the kind described by Rouen et al. (2005, this volume) was deployed in the main basin of El Gergal. As well as recording meteorological parameters, this system also employs sensors to monitor water quality and a fluorimeter configured to measure chlorophyll *a* concentration. The AWQMS2 was later used to validate the PROTECH model of phytoplankton growth (Elliott et al. 2005, this volume) and to provide an early warning of bloom conditions. Future studies in the reservoir will use the data acquired by the AWQMS2 to quantify the effects of very short-term (hour-to-hour) changes in the weather on the spatial distribution of the phytoplankton. Recent results suggest that local 'patches' of algae are more likely to form in the afternoon since wind-speeds in the El Gergal valley tend to increase in early evening.

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