Monitoring the water quality in Alqueva Reservoir, Guadiana River, southern Portugal

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Abstract: This study presents some physical, chemical and biological monitoring results from the Alqueva Reservoir, located in the Guadiana River Basin, Portugal since the filling phase, providing an evaluation of spatial and temporal variations in water characteristics. The objective is to document changes in water quality due to the impoundment of the Guadiana River during the early stages of the reservoir system while a new ecological balance is getting established. The Alqueva Reservoir (25,000 ha), located along 83 km of the main course of the Guadiana River, constitutes the biggest artificial lake on the Iberian Peninsula. Integrated in Alqueva exploration, another dam was constructed immediately after the Alqueva outlet creating the Pedrogão Reservoir. The Pedrogão Dam is situated 23 km downstream from the Alqueva Dam. The main sectoral uses of water in Alqueva/Pedrogão system are agriculture, urban supply and energy production.

According to climate, Alqueva Reservoir presents monomictic behaviour with a very defined stratification period from May to September. The higher values of soluble reactive phosphorus (SRP) and nitrates were observed during the wet period related to inputs coming from the catchment area. The Discriminant Analysis (DA) using the hydrological year as grouping variable for all the physical and chemical parameters as independent variables, suggests a high inter annual variability in the system relating to a temporal evolution of the Alqueva Reservoir. The algal succession is characterised by a sharp contrast between the two main seasonal periods. A cryptophytes-bacillariophytes-chlorophytes assemblage is characteristic of the wet period. In contrast, in the dry period, cyanobateria were dominant with surface blooms. According to total phosphorus and chlorophyll a, the Alqueva Reservoir was classified as an eutrophic system.

Keywords: Alqueva Reservoir, water quality, monitoring, Guadiana, Portugal

1. Introduction

Artificial lakes, as reservoirs, are formed by the construction of a dam on river courses. From a limnological point of view, Margalef (1983) presented such reservoirs as a hybrid between a river and a lake. In fact, reservoirs as ecosystems have different zones along their longitudinal profile. In the tail area, the system acts as river in contradiction to the zone near the dam, where the system operates as a lake. Among other typical characteristics, Palau (2006) refers to the asymmetric morphology of the basin, the shorter water renewal times compared with lakes, the fluctuations in level greater and independent of the natural regime of the river, and the output of water downstream be almost from the deepest part of the reservoir.

Reservoirs are constructed for many purposes including flood control, power generation, irrigation, livestock watering, fish farming, navigation and municipal water supply. As well as creating a new water resource, a dam involves substantial modifications to the river system, during both construction and subsequent operation (Crouzet & Leonard 1999, Bergkamp et al. 2000). These changes include increases in residence time, temperature, stratification and reduction in turbulence, most often a decrease in particle's number and turbidity and an increase in autochthonous primary production (Friedl & Wüest 2002). The variability and complexity of these changes are reflected in the water quality. Water quality of reservoirs is determined by several factors, among which the interaction of the lacustrine end with the catchment area plays an important role (Carpenter & Cottingham 1997, Margalef 1983). This feature takes on particular importance in newly flooded areas. Thus, the success of a reservoir management and restoration project depends on the detection of the spatial and temporal changes in reservoir status that reflect natural and anthropogenic alterations in the surrounding environment. Climate seasonality is the most relevant natural temporal change, particularly rainfall and solar heating, resulting in seasonal variations in water quality (Chapman 1996).

Seasonal monitoring is of particular importance in the southern semi-arid areas of Portugal, where streams are temporary with discharges ranging from zero in the dry season to high rates during the rainy season. Subjected to a great variability in the hydrologic regime, tributaries experience wide variability in physical, chemical and biological parameters, affecting the reservoir's function downstream (Morais 1995, Morais et al. 2004). Additionally, their special hydrology makes them particularly sensitive to anthropogenic pressure. Most of the quality problems are site specific, but together the different loadings reduce the availability of good water resources. Nutrient leaching from agricultural areas and from municipal sources increase the risk of toxic algae blooms in reservoirs and affect the potable water supply (Price 1999).

The chemistry of standing waters is intimately linked to the physical processes occurring within the water body, as well as in the atmosphere and the catchment. Physical features with high seasonal variation play key roles in most chemical transformations, either by accelerating chemical or enzymatic reactions or by promoting photosynthesis (Boulton & Brock 1999).

Seasonal events can make the spatial structure even more complex, both vertically and horizontally (Catalan & Fee 1994, Margalef 1983). Due to these spatial and temporal variations, monitoring programmes that provide representative and reliable estimations of reservoir water quality are absolutely necessary (Simeonov et al. 2003, Serafim et al. 2006). It is usual to measure multiple parameters chosen for a particular assessment, taken at different monitoring times and from many monitoring stations. Furthermore, it is a common experience to face the problem of determining whether a variation in the concentration of measured parameters should be attributed to pollution (man-made, spatial) or to natural changes (temporal, climatic).

Water quality guidelines and parameters have been used over the years as an important component of the management of water resources. Initially, guidelines focused on quality for domestic drinking water, and on agricultural, recreational and industrial waters. More recently, however, the emphasis has been moved towards ecosystem protection. The reason for this change is related to the progressive alteration of water quality and aquatic habitats, due to the growing demands for water supply causing a series of impacts across several spatial scales from the global down to the local habitat level (Malmqvist & Rundle 2002). On account of these worrying tendencies, the EU Water Framework Directive, WFD (EU 2000), was implemented. This constitutes a landmark for integrated sustainable water management across Europe. Environmental measures are implemented to protect, maintain and improve aquatic ecosystems, which are recognised as integral to the hydrological cycle for all surface water types – rivers, lakes, transitional waters, coastal waters, artificial and heavily modified surface water bodies, within defined water basin districts.

In this context, this study presents monitoring results taken for Alqueva Reservoir (Guadiana River Basin) belonging to a large monitoring programme implemented by the Portuguese enterprise responsible for Alqueva exploration (Empresa de Desenvolvimento e Infra-Estruturas de Alqueva, EDIA). The monitoring programme was implemented at the beginning of the filling phase, providing an evaluation of spatial and temporal variations in water characteristics, fulfilling the requirement of WFD. The objective is to document changes in water quality due to the impoundment of the Guadiana River during the early stages of the reservoir system while a new ecological balance is getting established.

2. Study area

The Alqueva Reservoir, located in southern Portugal along 83 km of the main course of the Guadiana River, constitutes the biggest artificial lake on the Iberian Peninsula (Fig. 1). It can store 4,500 million m^3 of water with a dentiform surface of 25,000 ha. The total catchment area is 55,000 km^2, where Portugal covers only 4,310 km^2. Integrated in Alqueva exploration, another dam was constructed immediately below the Alqueva outlet creating the Pedrogão Reservoir (Fig. 1). The Pedrogão Dam is situated 23 km downstream of the Alqueva Dam with a storage capacity of 97 million m^3. The main uses of water in Alqueva/Pedrogão system are in the agriculture, urban supply and energy production sectors (Serafim et al. 2006).

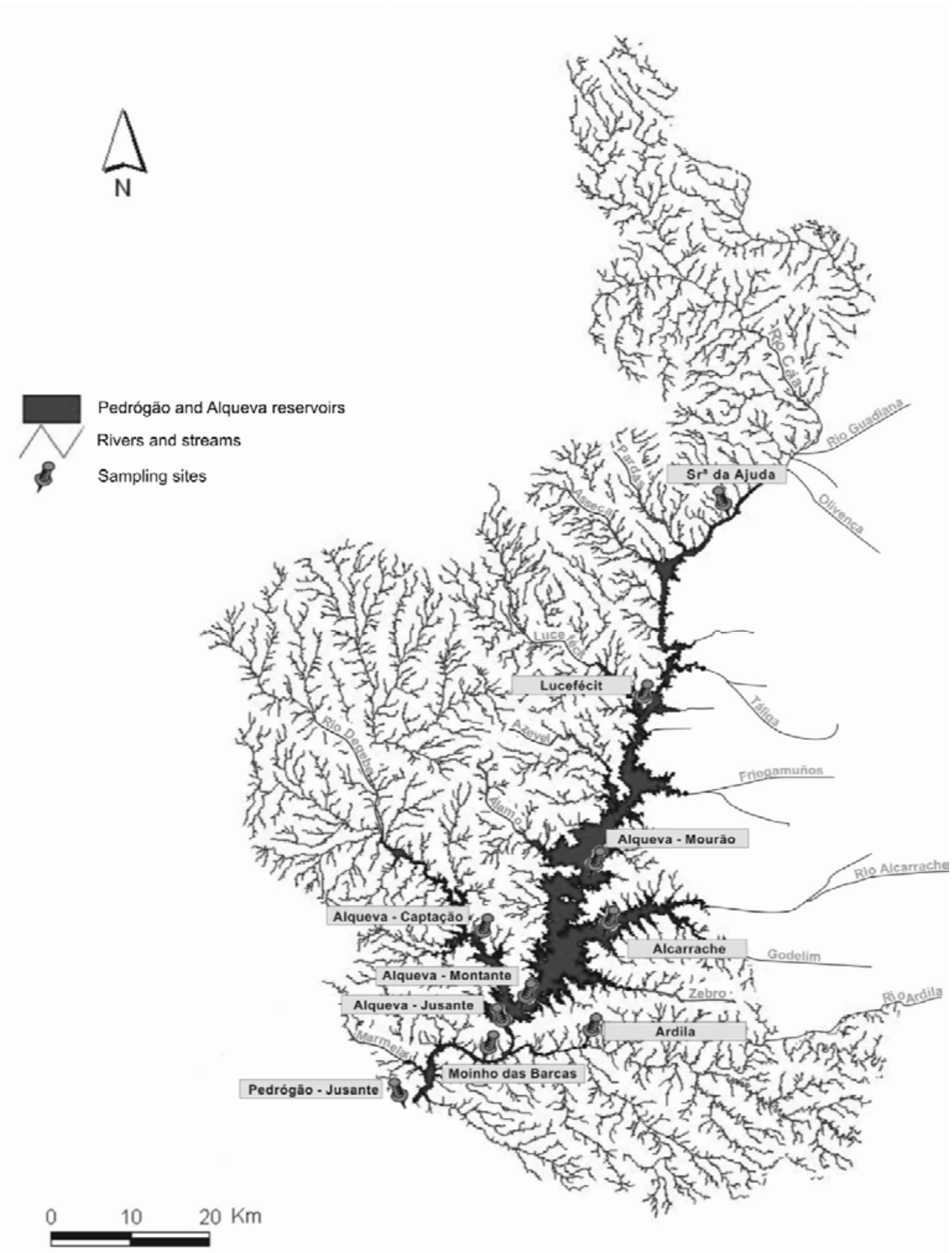

Fig. 1. Alqueva/Pedrógão Reservoirs and principal water courses, location of sampling sites.

The catchment area is made up of granite and gneiss mainly covered by Aluvissolos and Litossolos. Land use on the Portuguese side of the catchment is presented in Table 1, and was calculated using CORINE land cover classes. Notice that 69.8 % is used for agriculture, while the semi-natural areas only represent 28.5 %. The climate is characterized by a mean temperature of 17.5 ºC ranging from 4.5 ºC in January to 33.3 ºC in August. The mean annual precipitation is about 358 mm, irregularly distributed throughout the year and among different years; the potential evapotranspiration is 271 mm and the annual insolation is 2,859 h. Most rainfall occurs seasonally, from late autumn to early spring. Heavy storms may cause streams to flood. Flash floods during spring recede much faster than those in winter and discharge can return to baseflow in a few days. This precipitation regime results in an irregular stream hydrology with lowest discharge usually recorded during summer, when precipitation drops to zero.

Table 1. Land use in the Portuguese side of the catchment using CORINE land cover classes.

CORINE classes	% occupation
Artificial Areas	0.75
Agriculture	69.83
Semi - natural	28.50
Aquatic Areas	0.89
No information	0.03

3. Methods

3.1. Sampling and laboratory processing

In total, 10 collection sites were established, 8 with lentic conditions, sampled at three levels of depth (surface, middle and bottom) and 2 with lotic conditions, respectively at the beginning of the Alqueva Reservoir (Srª da Ajuda) and the other at the end of the Pedrogão Reservoir (Pedrogão Jusante; Fig. 1). These two sites provide information about the input flux from Guadiana River coming from Spain and the output flux in the downstream ecosystem. The other sites, located in the water body, were defined in order to give the state monitoring information.

Monthly monitoring has been carried out since March 2003. Vertical profiles were made for temperature, dissolved oxygen, pH, conductivity and redox potential at each of the 8 sites located in the water body using a multiparametric probe (TURO T-611). Water samples for chemical analysis were collected at the surface, the middle and the bottom, using a Van Dorn bottle. For phytoplankton, samples were taken at euphotic zone, determined by multiplying secchi disc measurements by a factor of 2.7. At the two sites located in lotic conditions (Srª da Ajuda and Pedrogão Jusante) measurements and sampling were done from the bank side at only one level.

In the laboratory, 16 chemical parameters were determined using officially recommended methods of analysis (APHA 1998). Measured chemical parameters were: nitrate, ammonium, total nitrogen (TN), soluble reactive phosphorus (SRP), total phosphorus after acid digestion (TP), 5-day biological oxygen demand (BOD_5), chemical oxygen demand (COD), permanganate oxidizable compounds (POC), magnesium, hardness determined calcium, calcium, chloride, hardness, alkalinity, total dissolved solids (TDS) and total suspended solids. Phytoplankton was identified and quantified according to Utermöhl techniques, and chlorophyll a was determined according to Lorenzen (1967) equation after 90 % acetone extraction.

3.2. Treatment of data

Only one representative site is presented as an example of a typical profile. The contour maps were designed using interpolation software (Surfer 8). Box-and-whisker plots were used to evaluate differences in value ranges of total nitrogen, nitrates, total phosphorus and soluble reactive phosphorus among hydrological years and sites; this type of plot displays the statistics (median, minimum, maximum, 25^{th} and 75^{th} percentile) of a variable of sample units.

Discriminant Analysis (DA) was utilized to test for differences among hydrological years. These analyses were applied to data normalized to zero mean and unit variance (standardized data) in order to avoid misclassifications arising from the different orders of magnitude. For each group, a discriminant function was constructed (Johnson & Wichern 1992, Miller & Miller 2000). The best discriminant function for each situation was selected, considering the goodness of the classification matrix and the number of parameters needed to reach such a matrix. The statistical package SPSS 13.0 was used for calculation.

The trophic state of Alqueva Reservoir was evaluated using the classification system adopted by Portugal (INAG 2002) and developed from OECD (1982) criteria on the basis that the trophic state of reservoirs can be assigned as the probability for a given water body to belong to one of the three classes (oligotrophic, mesotrophic and eutrophic), according to the average of annual total phosphorus concentration or to the average of annual total chlorophyll a concentration, following a stochastic approach (Crouzet & Leonard 1999).

4. Results and discussion

4.1. Physical and chemical processes

Biological communities depend on water circulation and consequently on physical and chemical stratification. As may be expected according to climate data, the Alqueva Reservoir shows monomictic behaviour with a much defined stratification period from May to September. In October, wind and decrease in temperature ensure complete mixing. This process can be identified in temperature and oxygen profiles (Fig. 2 and 3). Note that during the summer stratified period, oxygen values along the entire hypolimnion drop to values near zero (anoxia). At the beginning of the circulation period anoxic water from the hypolimnion is mixed with surface layers promoting a general decrease in oxygen concentration at the surface. This can be a potential threat to biological communities, namely fish. Cumulatively, the associated ascent of nutrients to surface layers can promote primary production.

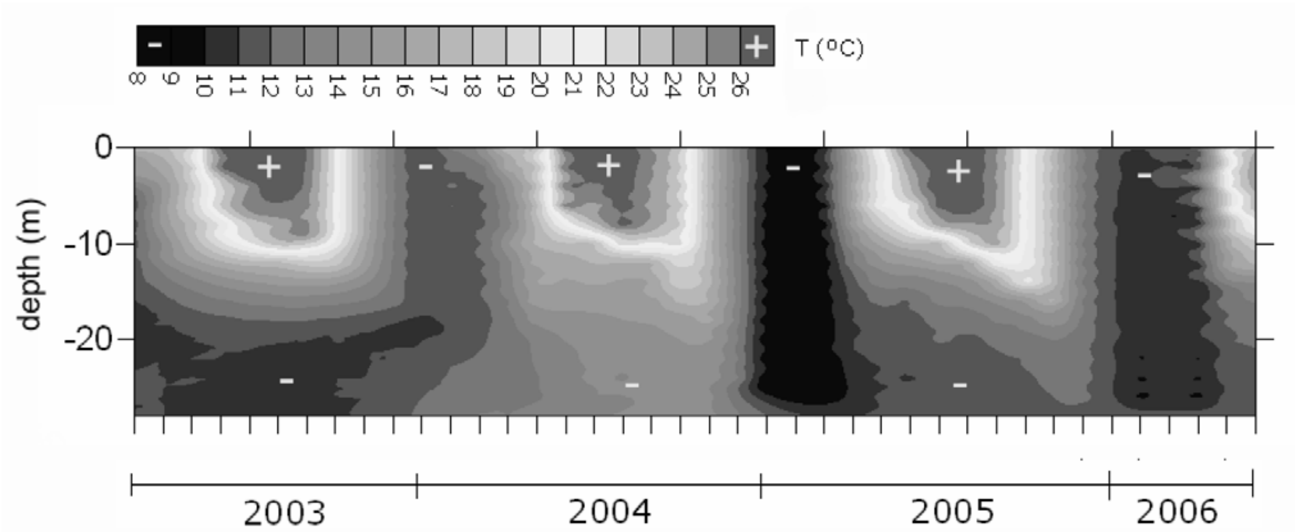

Fig. 2. Depth and temporal (from March 2003 to June 2006) distribution of temperature (º C) isolines in Alqueva Reservoir, Alcarrache site, given are the hydrological years.

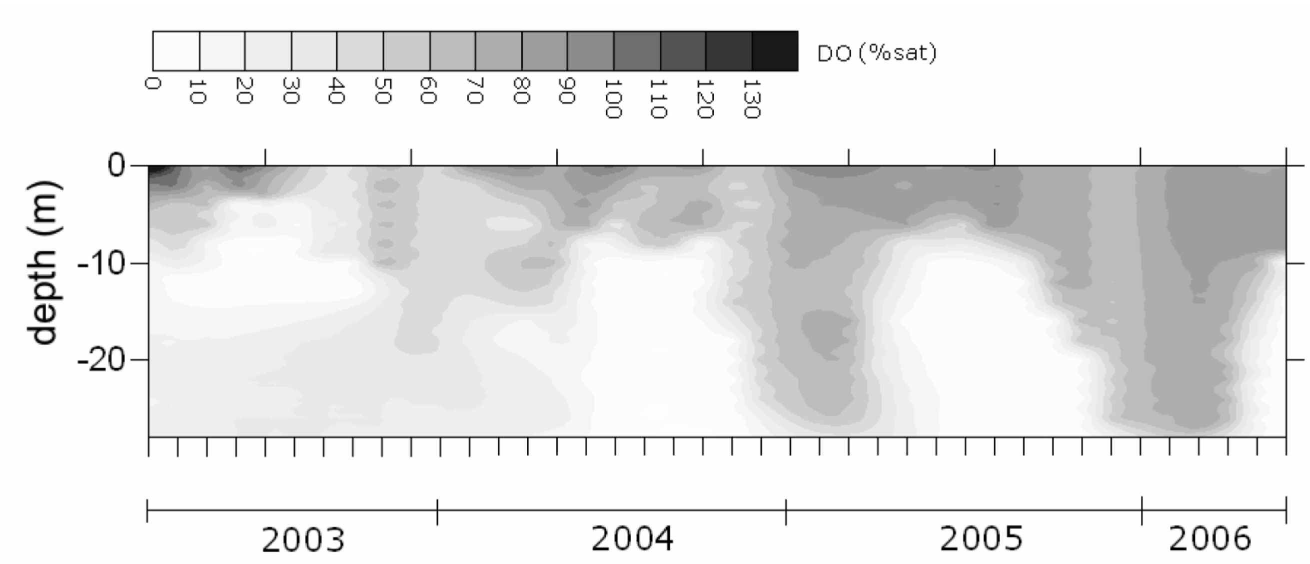

Fig. 3. Depth and temporal (from March 2003 to June 2006) distribution of dissolved oxygen (% saturation) isolines in Alqueva Reservoir, Alcarrache site.

Relating to nutrients (Fig. 4 and 5), higher values of SRP and nitrates are observed during the wet period (corresponding to the mixed period, autumn and winter) related to inputs coming from the catchment area. In the dry period (stratified period, end of spring and summer) decrease of SRP and nitrates at the surface level are possible due to the phytoplankton's high rates of consumption. Temporal analyses for all sites, over the total monitoring period, reveal a decrease in nitrate concentrations. In fact, the Discriminant Analysis (DA) using the hydrological year as grouping variables for all the physical and chemical parameters as independent variables gives a classification matrix with 98 % right assignations (original grouped cases correctly classified), 66 % of them validated (after cross-validated process) using calcium, hardness, conductivity, oxidisability, nitrates and chloride. This result suggests a high inter-annual variability in the system relating to a temporal evolution since the establishment of the Alqueva Reservoir.

The DA results also indicate that the observed evolution is mainly related to water mineralization which suggests an increase in salinity which could be related to the lower rate of water renewal in the reservoir and to the release of salts from submerged land and from the catchment. Nevertheless, these measured values do not present any reason for limitation in water use for irrigation. It is important to remember that the differences between years are also demonstrated by parameters related to quality, namely nitrates and oxidizability, which decrease in their concentrations, indicating an improvement in water quality with time. The ordination of the two first discriminante functions is present in Fig. 6, where the last hydrological year (2005/2006) appears differentiated from the first three years.

4.2. Phytoplankton succession

The composition and abundance of the phytoplankton community may be influenced by changes in climatic seasonality and the hydrological regime (Schindler et al. 1996, Kamenir et al. 2004), food web characteristics (Wellborn et al. 1996) and algal nutrient loads (Cook et al. 1993). The increase in nutrient concentrations determines a sequence of effects, including an increase in phytoplankton biomass, changes in the composition and structure of phytoplankton populations, formation of algal blooms, decrease in water transparency, consumption of hypolimnetic oxygen and formation of reduced chemical compounds (Margalef 1983, Salmaso et al. 2006). Based on these studies, a common pattern of variation and response to seasonal changes has been described for the phytoplankton in general, with dominance of cyanobacteria during summer after nitrogen consumption by the other groups of algae, many cyanobacteria species are able to assimilate nitrogen (N_2) gas in water for protein synthesis. Indeed, in the Alqueva Reservoir the algal succession is characterised by a sharp contrast between the two main seasonal periods (Fig. 7).

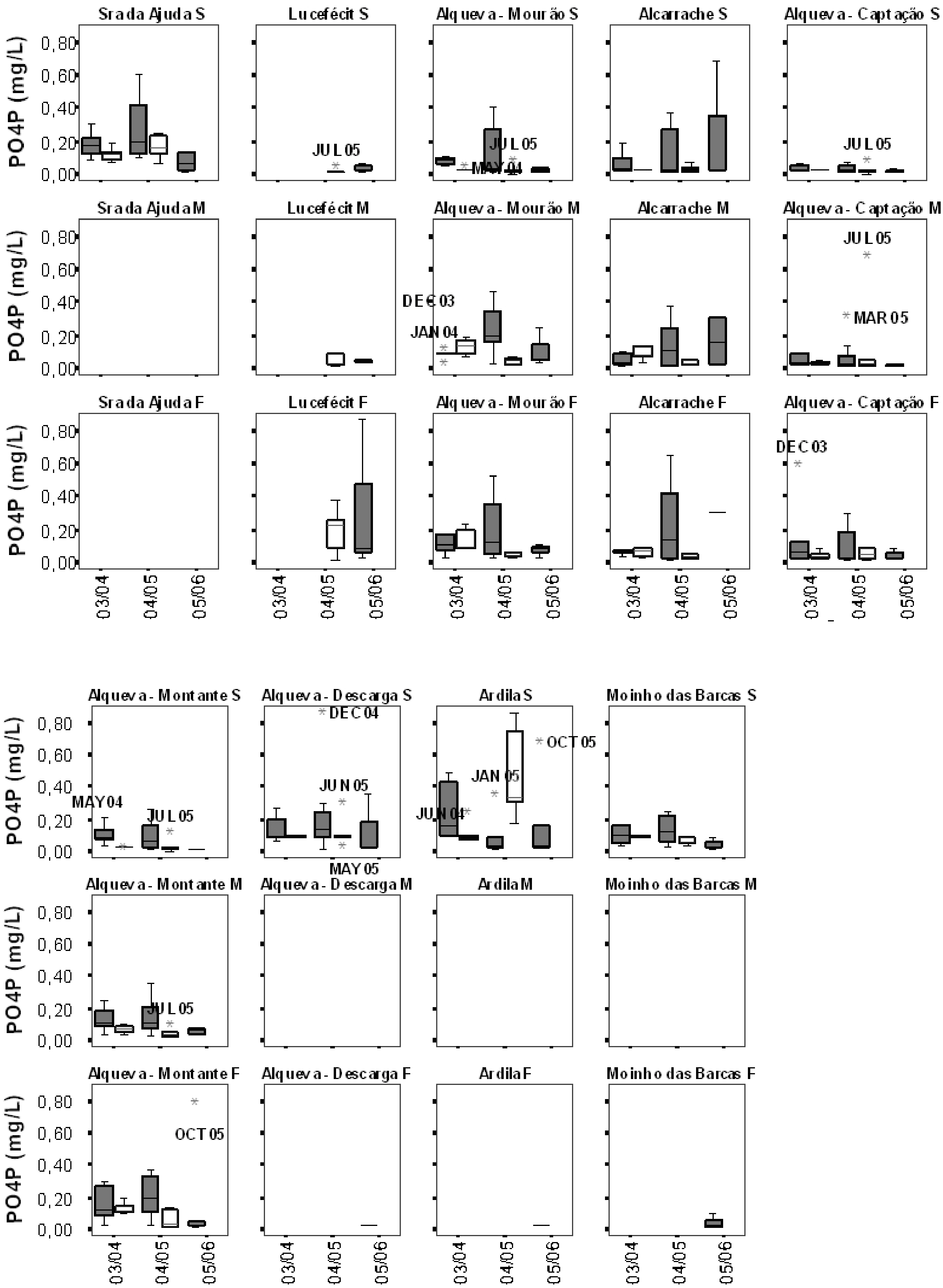

Fig. 4. Intra-annual variation (hydrological year) and seasonal variation (wet period ■, dry period □) of soluble reactive phosphorous (SRP mg/L PO_4-P); box and Wisker representation.

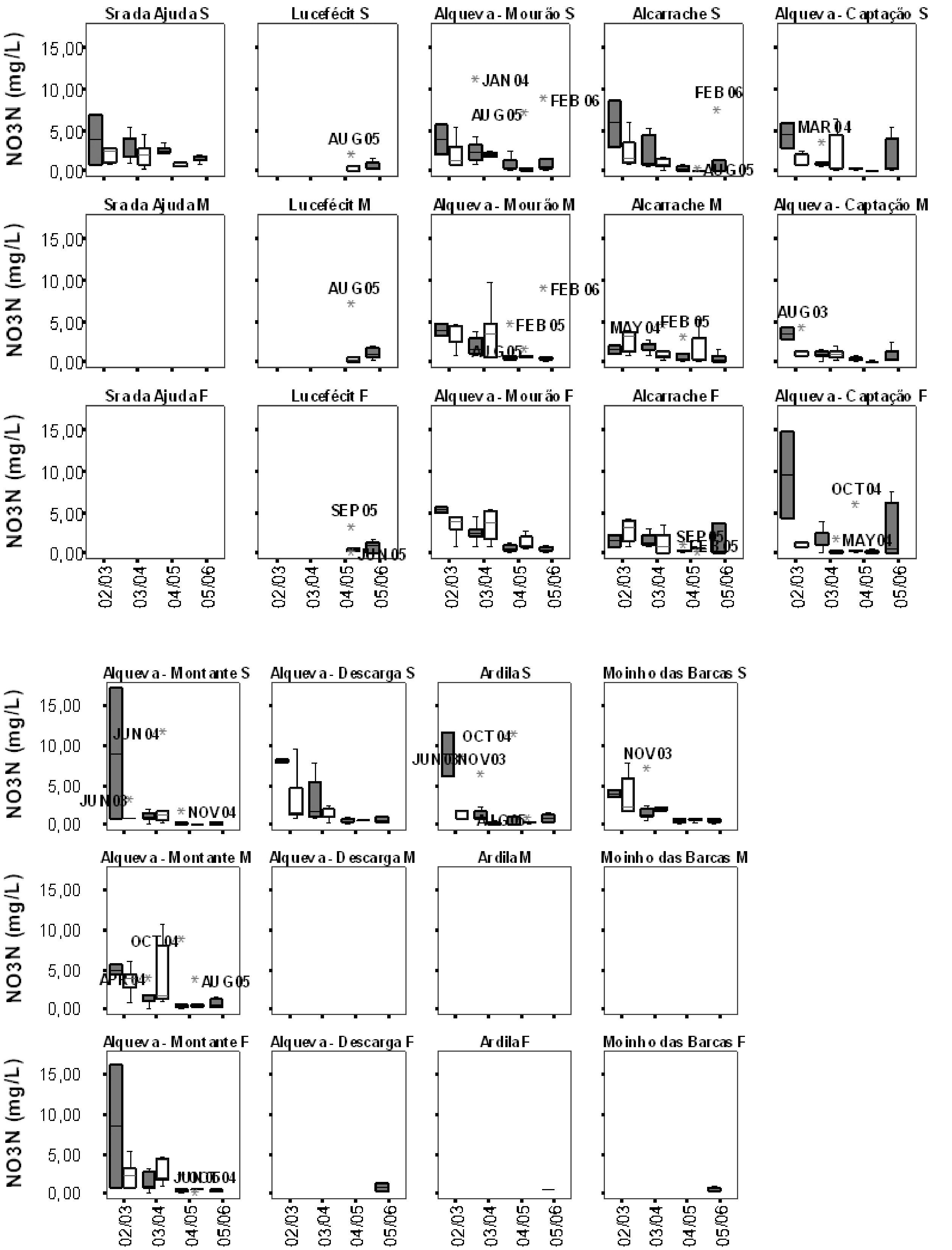

Fig. 5. Intra-annual variation (hydrological year) and seasonal variation (wet period ■, dry period □) of nitrate nitrogen (mg/L NO_3-N); box and Wisker representation.

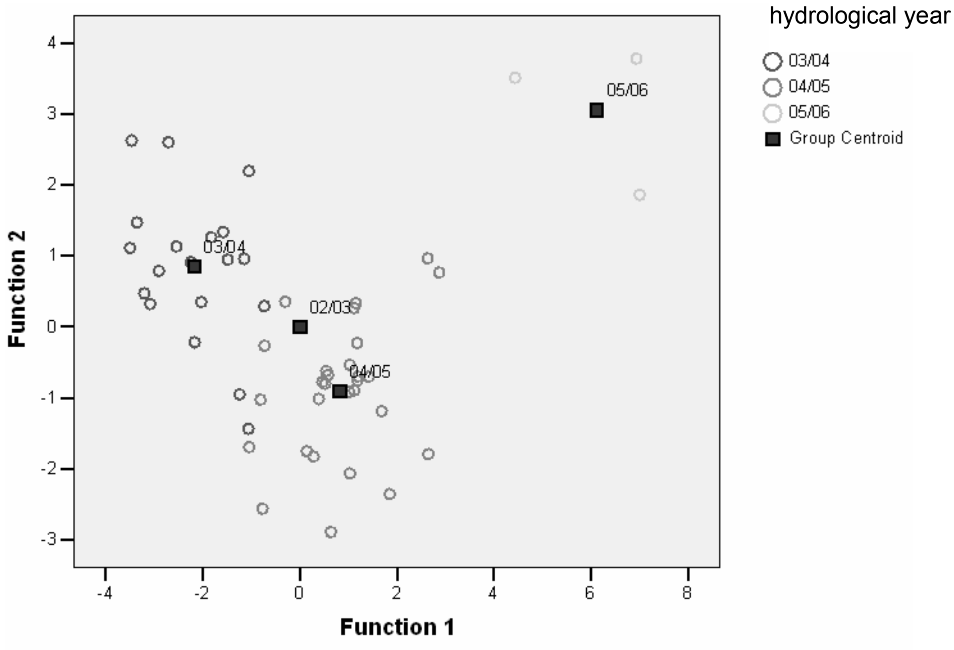

Fig. 6. Hydrological year discriminant function coefficient's ordination.

A cryptophytes-bacillariophytes-chlorophytes assemblage is characteristic of the wet period (October to April) with less light and nutrient availability. In contrast, in the dry period, when stratification occurs, high light and low nutrient availability select for cyanobateria dominance with surface blooms (> 10,000 cells/ml, Fig. 7). Besides other adverse ecological effects, cyanobacteria can produce a broad spectrum of hazardous and toxic substances. Among them are the microcystins, which are of special concern due to reports of wildlife and livestock toxicity and human fatalities (Mez et al. 1997, Jochimsen et al. 1998).

The World Health Organization (WHO 2003) recommends the monitoring of microcystins when cyanobacteria density is higher than 2,000 cells/mL. In the Aqueva Reservoir, microcystin monitoring was carried out over almost all of the summer period. The results obtained revealed a high microcystin concentration

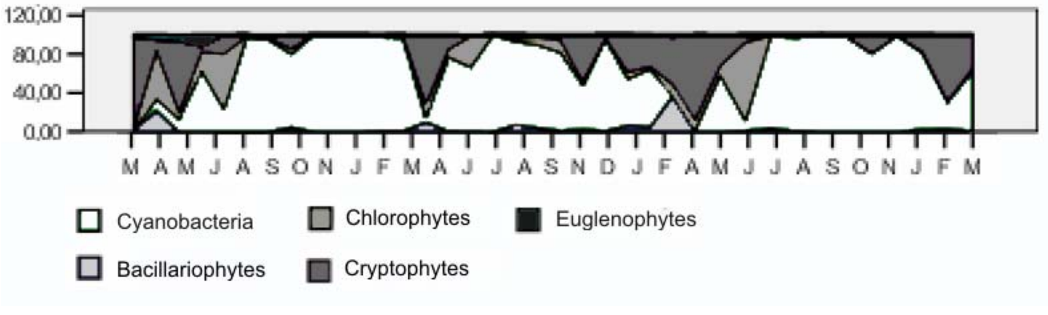

Fig. 7. Phytoplankton succession in Alqueva Reservoir (Alqueva Mourão site) between March 2003 and March 2006 (values in relative abundance, in %).

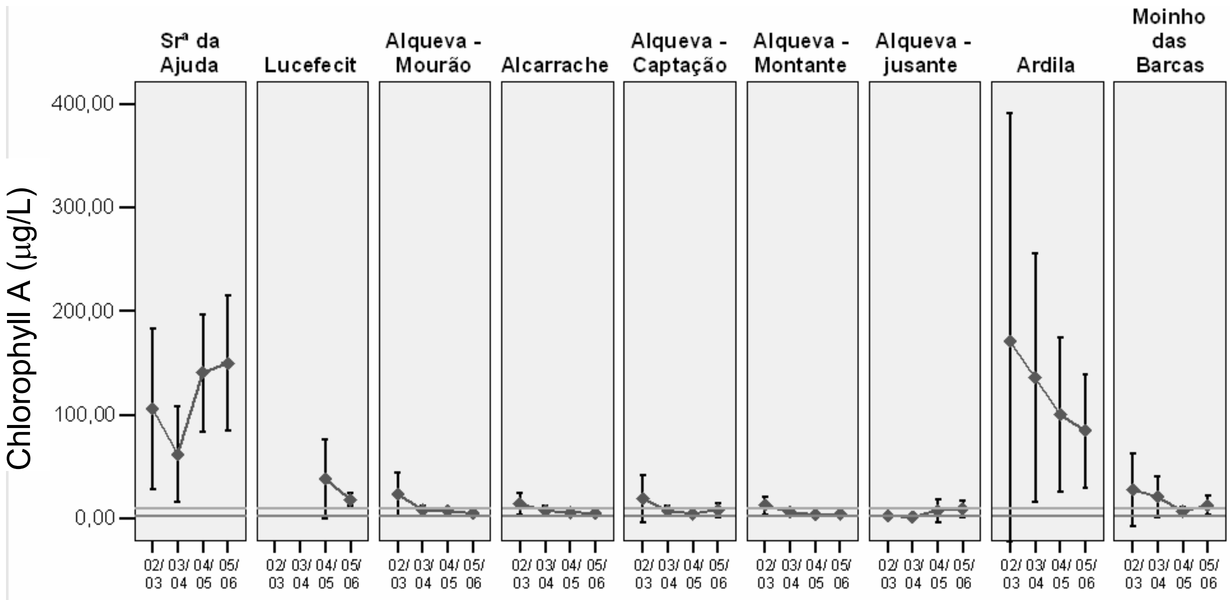

Fig. 8. Chorophyll a error bars (standard deviation around medium levels for hydrological year). Horizontal lines define 2.5 and 10 µg/L limiting oligotrophic, mesotrophic and eutrophic conditions.

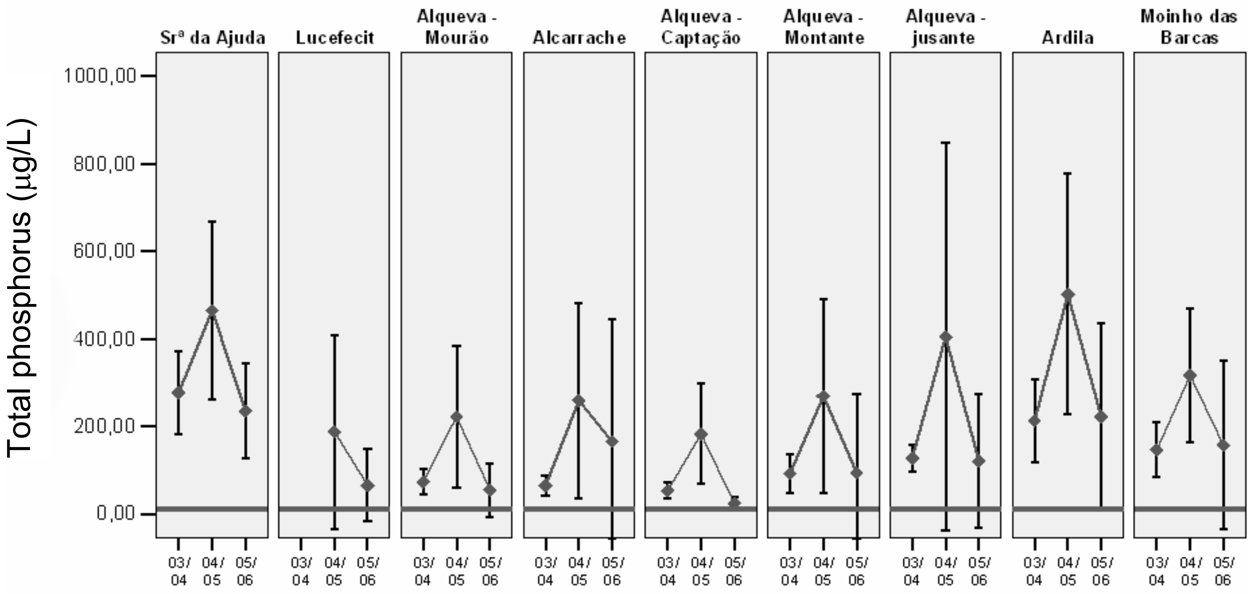

Fig. 9. Total phosphorous error bars (standard deviation around median levels for hydrological year). Horizontal lines define 35 µg/L (above this level eutrophic conditions are verified).

inside cells with values higher than the guidelines defined by WHO (2003), these can result in problems for human health and for the environment (1 µg/l).

This seasonal pattern is almost common for each year, repeating itself every year as demonstrated by DA, done in order to distinguish hydrological years. The results only gave 44.3 % of samples correctly classified, with 41.4 % after cross-validation method, which validate the non-existence of differences among years.

4.3. Trophic state classification

According to total phosphorus and chlorophyll a, and considering the limits adopted by Portugal (INAG 2002), the Alqueva Reservoir can be classified as an eutrophic system (Fig. 8 and 9). Total average annual phosphorus is above the eutrophic limit (> 35 mg P/m^3) in each year for all sites, despite the decrease observed from 2004/05 to 2005/06. For chlorophyll a, values are lower and normally below the eutrophic limit (< 10 µg/L) with the exception of sites Sr[a] da Ajuda and Ardila situated namely in Guadiana River and in Ardila stream and selected to assess the quality of input flux.

It is important to notice that, as well as its stochastic approach, the national criterion for the trophic classification of a water body is based only on a numerical evaluation. Since it has been working on an ecological system, it is essential an accurate analysis, also considering the phytoplankton assemblages with special emphasis on the cyanobacteria group data which relate to density levels (blooms), to the duration of dominance period and to toxicity concentrations.

5. Conclusions

Considerable horizontal variability in water quality develops in large reservoirs and is maintained by a variety of processes dependent on the inflows (Serafim et al. 2006). The dominant flow path of water through a basin defines its interaction with soil and vegetation and thus affects reservoir nutrient concentration and the chemical characteristics. Indeed, based on total phosphorus and on chlorophyll a Alqueva Reservoir was classified as eutrophic, despite the water quality improvement noted in the last hydrological year (2005/2006), validated by discriminant analysis. Nevertheless, it is important to remember that the Alqueva Reservoir is at the beginning of its existence, so it can be expected to be in an eutrophic state due to ecosystem instability. This instability comes from the substantial modifications to the system, during both construction and subsequent operation. When changing a stretch of a river to a reservoir, the slowing of the flow subsequently evokes particle settling, turbidity decreases and light transmissivity increases, enhancing static primary production. Thus, in natural conditions, from the headwater of a reservoir to the dam, the river changes from an allochthonous dominated system to a more lacustrine system, where, normally, autochthonous production of organic matter dominates (Friedl & Wüest 2002). Although, in the presence of point source pollution situations (eg. direct effluents not treated) or diffuse pollution (agricultural), this longitudinal functional pattern can appear completely altered. In fact, the worst water quality in the Alqueva Reservoir area was observed in tributaries, demonstrating how the watershed-reservoir linkage is critical in understanding reservoir ecosystem phenomena and also emphasising the need to take accurate management measures for Guadiana basin, including the Spanish territory.

Thus, the Alqueva Reservoir is determined by seasonal processes of stratification and mixing, determining temporal changes in the lacustrine zone that relate to phytoplankton temporal succession. The phytoplankton results demonstrate the same annually repeated seasonal pattern with dominance by cyanobateria during the summer dry period, with blooms occurrence, which represents a big concern. The primary consequence of bloom occurrence is water quality reduction, which can lead to negative economical, ecological and public health implications (Codd 2000). There is also the production of substances that give a bad taste and odour to the water, along with the fact that blooms of cyanobacteria may become dangerous due to the ability of many cyanobacterial strains to produce toxins that can affect a variety of organisms, including humans (Codd 2000, WHO 2003, Figueiredo et al. 2004, 2006).

Besides this, Alqueva, being an impoundment with multiple uses (agriculture, urban supply and energy), tends to be subjected to stresses arising from management practices. In a reservoir, the deterioration of the water quality may lead it to become unsuitable for its original purpose and costly measures may be required to combat the problem. Consequently, an understanding of various phenomena relating to the characteristics of reservoirs and their catchment areas, which determine the system function, is the most basic step in evaluating water quality and judging specific problems (Hwang et al. 2003). This knowledge is being gained through the periodic monitoring programme already in progress for the Alqueva Reservoir. The assessment of long term trends is related directly to the reservoir management strategies required to understand the processes occurring within the reservoir and to provide more detailed information about a variety of indicators of reservoir condition (Hoyos & Comín 1999, Serafim et al. 2006). Nevertheless, there is a particular need for further evaluation of the monitoring strategies. One emergent evaluation is the need to refine the temporal and spatial scale in order to better understand the spatial and temporal heterogeneity of the water quality. Further, in the context of WFD requirements, biological measures must also be implemented to protect, maintain and improve the ecosystem, which is recognised as integral to hydrological cycle. According to WFD, member states must develop appropriate ecological monitoring systems based on the composition and/or abundance of elements of the aquatic biota plus physical, chemical and hydromorphological quality elements. Understanding and predicting the complex interactions between hydrology, ecosystem processes and biodiversity form the basis for a future sustainable management of aquatic systems that must be taken into consideration with respect to the Alqueva Reservoir, since it constitutes the most important water supply source in southern Portugal, which therefore needs to be protected and preserved.

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Itaparica Reservoir, front: fisherman boots and irrigated agriculture of palm trees, back: remaining vegetation 21 years after dam close.
Fotos: Günter Gunkel

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