Introduction

The Mediterranean region is characterised by a variable climate with most of the rain falling during the winter and frequent summer droughts. Such warm, dry periods are ideal for the growth of large algal blooms that often consist of potentially toxic Cyanobacteria. This makes the management of water for human use particularly challenging in such a climate and it is important to understand how such blooms can be avoided or at least be reduced in size.

PROTECH (Phytoplankton RespOnses To Environmental CHange) is a model that simulates the dynamics of different species of phytoplankton populations in lakes and reservoirs (Reynolds et al. 2001; Reynolds et al. 2005, this volume). Its distinct advantage over similar models is its ability to simulate the relative composition of the algal flora, allowing both quantitative and qualitative conclusions to be drawn e.g. whether Cyanobacteria could be a potential problem. PROTECH has been applied primarily to lakes and reservoirs in northern Europe (e.g. Elliott et al. 2000; Reynolds et al. 2000). Recently, however, the model has been applied to water bodies in lower latitudes, including Australia (Lewis et al. 2002), and (in this study) to a water supply reservoir in the south of Spain, El Gergal.

El Gergal is the last in a chain of reservoirs that supply water to the city of Seville (Fig. 1). It was formed by flooding a river valley and has a deep main channel (maximum depth = 38.1 m; 8.8 km long) and shallow side-arms. It was brought into service in April 1979 and has a maximum storage volume of 35 000 000 m$^3$.

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El Gergal is part of a complex system of reservoirs and is one of four owned by the water company, EMASESA (Empresa Municipal de Abastecimiento y Saneamiento de Aguas de Sevilla), the others being Aracena, Zufre and Minilla. There are three other reservoirs in the system, but these are controlled by other authorities so there are cost implications when water from these reservoirs is transferred into El Gergal.

Historically, the algal related problems experienced at El Gergal have been associated with the large Cyanobacteria blooms that develop in the late summer of drought years. This part of Spain experienced a severe drought between 1992–1995 (EMASESA 1997) but during the period of this study (1999–2001), the winters were exceptionally wet. We therefore used PROTECH to simulate the following problems:

- the effect of a large influx of Ceratium biomass into El Gergal from another reservoir
- the effect of using alternative water sources instead of the Guadalquivir River (used occasionally to raise water levels in El Gergal)
- the effect of installing tertiary sewage treatment on the Cala River
- the effect of simulated drought conditions on phytoplankton in the reservoir.

**Field sampling and analysis**

Sampling took place at weekly intervals at the deepest point of the reservoir. Vertical distribution of water temperature was measured using a YSI Model 58 probe. Water samples were taken with 5-litre Van Dorn sampler from regular intervals within the water column and were analysed for chlorophyll a and nutrients. Phytoplankton density was derived from counting Lugol-preserved samples according to the Utermöhl method. Both the sampling and the analysis were carried out by EMASESA within their programme of monitoring of water supply reservoirs for Seville.

The **PROTECH model**

At the heart of PROTECH is the basic state variable equation determining the daily change in the chlorophyll a concentration (\(X\), \(\mu g\) \(l^{-1}\)) of each phytoplankton life-form:

\[
\frac{\Delta X}{\Delta t} = (r^s - S - G - D)X
\]

(1)

where \(r^s\) is the life-form specific growth rate defined as a proportional increase over the PROTECH time step \(t\) (= 24 h), \(S\) is the life-form specific rate of loss due to settling out of the water column, \(G\) is the rate of loss due to grazing (in the model, species with a maximum linear dimension of > 50 \(\mu m\) are not grazed) and \(D\) is the rate of loss caused by dilution due to the inflow and outflow of water within the lake. The routine is repeated for each of up to, usually, eight species, with daily iterations and with the opportunity to vary initial inoculum size. The growth rate (\(r^s\), \(d^{-1}\)) is further defined by:

\[
r^s = \min \left\{ r^s_{(\theta, \phi)}, r^s_{(N, Pr)}, r^s_{(N, Si)} \right\}
\]

(2)

where \(r^s_{(\theta, \phi)}\) is the daily growth rate derived from the temperature and daily photoperiod \((\theta, \phi)\) is further adjusted to include dark respiration) and \(r^s_{(N, Pr)}, r^s_{(N, Si)}\) are the growth rates determined by phosphorus, nitrogen and silicon concentrations.

The physical component of the model divides the simulated water body into 0.1 m layers, whose volume and surface area reflect the morphology of the basin. An initial profile for the water column (containing temperature, nutrient concentrations and inoculum sizes for the algae) is defined for day 1. Daily wind speed, cloud cover, river inflow (including nutrient concentrations) and outflow data are input to the model and insolation is adjusted according to the day of the year and latitude. For each 24-hour time-step, the Monin-Obukhov equation is used to calculate the mixed layer thickness as a function of heat flux and wind mixing on a given day (Imberger & Hamblin 1982). The starting water-column profiles of temperature, nutrients and phytoplankton are changed at the start of each time-step as a result of mixed layer changes. Biological functions are then used to calculate the new biomass and dissolved nutrient concentrations at the end of the time-step, assuming no further vertical movements. More detailed descriptions of the equations involved can be found in Reynolds et al. (2001).

**Modelling the phytoplankton of El Gergal**

In this study, we used a recent version of the model, PROTECH-C. Eight algal life-form types were included in order to simulate the characteristics of Cryptomonas, Stephanodiscus, Ceratium, Aphanizomenon, Anabaena, Chlamydomonas, Melosira and Microcystis species, which were observed to be abundant in previous years. Input and validation data were gathered from on-shore meteorological stations (wind speed, incoming solar radiation, air temperature), the regular sampling programme of EMASESA (phytoplankton counts, nutrient concentrations, inflow/outflow rates) and the Automatic Water Quality Monitoring Station (AWQMS2) on El Gergal.
Modifying the model to improve the simulation of surface water energy-flux

The application of PROTECH to El Gergal was used as an opportunity to advance some aspects of the model, specifically regarding the surface water energy-flux calculations. The model already calculated the daily incoming solar radiation for a given latitude, but used simple equations to calculate the energy loss from the water surface to the air and they were specific to UK latitudes. Thus, the following modifications to the PROTECH code were made using information in Gill (1982).

Firstly, an equation was added calculating the mass of water lost by evaporation processes ($E$):

$$E = \rho_a c_E u (q_s - q_a)$$

where $\rho_a$ is the density of air, $c_E$ is a specific constant, $u$ is wind speed, $q_s$ is the specific humidity at the water-surface and $q_a$ is the specific humidity of the air.

Next, the upward heat flux ($Q_s$) was calculated as:

$$Q_s = \rho_a c_p c_H u (T_s - T_a)$$

where $c_p$ is the specific heat capacity of air, $c_H$ is a dimensionless coefficient, $T_s$ is the surface water temperature and $T_a$ is the air temperature; both are measured in Kelvin.

Finally, the net radiant heat flux ($Q_B$) was calculated by:

$$Q_B = 0.985 \sigma T_s^4 (0.39 - 0.05 e_{a1/2})(1 - 0.6 n_c^2)$$

where $\sigma$ is the Stefan-Boltzmann constant, $e_a$ is the vapour pressure of water and $n_c$ is the fraction of the sky covered by cloud.

Thus, energy loss from the water surface to the air ($Q_{Loss}$) was now calculated by:

$$Q_{Loss} = L_v E + Q_s + Q_B$$

where $L_v$ is the latent heat of vaporization of water. By using the above equations, the energy budget of El Gergal was described well (Fig. 2) with only a slight, but tolerable, deviation in surface temperature in the late summer.

Modifying the model to simulate the internal release of soluble reactive phosphorus

A second and very important change was made to the model to simulate the internal release of soluble reactive phosphorus (SRP) from the littoral and benthic zones. It quickly became clear from examining the data collected in 2000 (and especially in 2001) that during the summer other sources of SRP must exist, other than from the inflow, because the algal populations continued to develop over the summer despite there being little or no inflow. The processes involved in internal nutrient release are poorly understood and not included in PROTECH. Fortunately, EMASESA had measured SRP throughout the water column over 2000–01 and the hypolimnion values recorded in the summer could be used as a guide to how much extra SRP was released to the water column. Thus, between June–August, 50 µg l$^{-1}$ SRP was added to the bottom 20 m of the simulated water column (representing the approximate hypolimnion).

Modifying the model to simulate an influx of Ceratium

In 2000, whilst managing the water level in El Gergal using established methods, a large inoculum of Ceratium was added to the reservoir. It came from Minilla reservoir (see Fig. 1) where the abstraction depth coincided with a Ceratium biomass maxima. Therefore, PROTECH was used to simulate this year to assess the effect the Ceratium inoculum had upon the successional development of the algae in the reservoir. Concentrations of Ceratium at the extraction depth in Minilla were used to create the extra inoculum and a new piece of code was written to add this inoculum into the epilimnion during the period in which Minilla was used as a source of water for El Gergal (in late May–July).
Baseline phytoplankton simulation

After making these specific changes to the generic PROTECH model, it was encouraging how closely simulated total chlorophyll a (measured in the top 5 m of the water column) matched the observed values (Fig. 3), with the notable exception of early spring.

The low level of phytoplankton observed in the early spring (around day 50) is difficult to explain because there were ample amounts of nutrients and light; hence, PROTECH predicted a large spring growth of algae. This PROTECH spring peak mainly comprised *Cryptomonas* and to a smaller extent *Chlamydomonas* and *Ceratium*. Over the rest of the year, PROTECH captures well the characteristics of the most prominent biomass peaks which are dominated by *Ceratium* (peaks centred around the 150th and 340th days) or *Aphanizomenon* (peaks centred around the 212th and 300th days).

The effect of a large *Ceratium* biomass influx from another reservoir

*Ceratium* is a large unicellular dinoflagellate that is capable of regulating its position in the water column through extensive vertical migrations (Reynolds 1984). It also specialises in producing cysts as a perennial resting stage. The effect the *Ceratium* inoculum had on the development of the other phytoplankton species was assessed by running the simulation again, this time with no extra inoculum (Fig. 4). In the absence of the early summer bloom of *Ceratium*, more nutrients were available later in the year. The two *Aphanizomenon*-dominated blooms still occurred, but produced even greater amounts of biomass.

The effect of using alternative water sources instead of the Guadalquivir River

In March and April 2000, EMASESA pumped water from the Guadalquivir River into the hypolimnion of El Gergal in order to raise the water level. The river water was of a very poor quality (Table 1) but could be freely and cheaply pumped into El Gergal because the pumping station is under EMASESA’s direct control.

We wanted to examine what the effect of adding water from an alternative source, Cala Reservoir (see Fig. 1), would have had upon the development of algae in El Gergal. Cala is not controlled by EMASESA and has a greater cost associated with it, compared to extracting water from the Guadalquivir River, but the water is of better quality (Table 1). Therefore, a simulation was run where Cala water was always used as a source of water for El Gergal and the poor quality water of the Guadalquivir and the *Ceratium*-rich Minilla water were not used (Fig. 5).
FIG. 5. A comparison of the original PROTECH simulation of El Gergal 2000 (Fig. 3) with a simulation using only Cala Reservoir water as an external source instead of Minilla Reservoir and the Guadalquivir River.

FIG. 6. A comparison of the PROTECH simulation of El Gergal 2000 using only Cala Reservoir water and the same simulation with 76% SRP removed from the Cala water.

Table 1. Mean (range in parentheses) SRP, nitrate and chlorophyll a concentrations measured in the Guadalquivir River and Cala Reservoir in Spring 2000.

<table>
<thead>
<tr>
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<th>Guadalquivir River (n = 6)</th>
<th>Cala Reservoir (n = 44)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRP (mg l⁻¹)</td>
<td>0.08 (0.02–0.16)</td>
<td>0.20 (0.11–0.27)</td>
</tr>
<tr>
<td>Nitrate (mg l⁻¹)</td>
<td>34.0 (20.6–47.6)</td>
<td>4.9 (3.5–6.6)</td>
</tr>
<tr>
<td>Chlorophyll a (µg l⁻¹)</td>
<td>83.7 (46.1–108.3)</td>
<td>2.2 (2.1–2.2)</td>
</tr>
</tbody>
</table>

The only noticeable difference between these two simulations was that the blooms caused by the Ceratium inoculum were, unsurprisingly, missing. This indicates that sufficient nutrients were still available from the Cala water, compared with the Minilla and Guadalquivir water, and from the nutrients released internally.

However, it has been proposed that a tertiary treatment plant could be built on the Cala River to remove most of the nutrients (e.g. 76% of the SRP). Therefore, PROTECH was run again with 76% of the SRP from Cala removed (Fig. 6). There were no clear differences between the simulated phytoplankton, despite the large reduction in externally supplied SRP. This is likely to be because the inflow in the summer months was so low that the dominant source of SRP for growth was from internal sources. However, although the short-term effect of reducing SRP in the Cala River was minimal, it may have had a long-term impact on the amount of internally released SRP available in future years.

The effect of simulated drought conditions on phytoplankton in the reservoir

One of the original aims of our project was to examine the effect that low water levels had upon the development of phytoplankton in El Gergal. However, during the course of the project, no low-water level event was observed. Nevertheless, by using PROTECH, we were able to simulate a low-water level event and compare it with a baseline simulation for the same period.

It was decided to concentrate on a 4-month period in 2001 (June–September), simulating the original observations in that period and then comparing that simulation to a re-run of the same period, but with reduced water levels.

A combination of EMASESA and AWQMS data was available in that period to drive the model and, with the inclusion of the same routine for internal SRP release to the hypolimnion used for the 2000 simulations, the
A match between the observed total chlorophyll and the initial simulation was close (Fig. 7).

*Aphanizomenon* was responsible for most of the simulated algal biomass and a more detailed examination of its vertical distribution (Fig. 8) gave an insight into how the *Aphanizomenon* biomass accumulated at the surface over the simulated period to form algal scum and the high amounts of chlorophyll found in the top 5 m of the water column. *Aphanizomenon* is a blue-green alga (Cyanobacterium) and is able, by utilising gas vesicles, to float towards the surface of the water column – an adaptation that allows them to persist in stratified conditions. This floating mass of *Aphanizomenon* can reach such large densities that a thick, highly visible, scum forms. Such scums are undesirable for aesthetic reasons and also because the bloom has the potential to exude harmful toxins into the water.

In order to simulate a low-level drought event in the summer, the starting water level was lowered by 10 m and the simulation run again. The effect of low-water levels was remarkable and extreme (Fig. 9). The amount of algal biomass in the upper 5 m of the water column was several orders of magnitude greater in the drought scenario, reaching a sustained maximum biomass of approximately 350–400 µg l\(^{-1}\). The reason behind this large increase in biomass became clear when the spatial distribution of...
**Implications for the management of El Gergal reservoir**

PROTECH has been applied successfully to many water bodies over the last 10 years and, through a combination of extremely detailed data and new coding in the model, El Gergal Reservoir can now be added to that list. Through the scenarios mentioned above, a greater understanding of this very complex ecosystem has been gained. Any management strategy available, however, needs to be balanced between both positive biological impact and practicality, because EMASESA only has direct control over some of the water bodies within the catchment.

It is clear that, in terms of nutrients, El Gergal is probably not greatly dependent on inputs from the catchment, at least in the short-term. This is an important conclusion, because it helps set realistic expectations of the effect that any reduction of nutrient input from the catchment (e.g. from tertiary treatment on the Cala River) will have on the development of phytoplankton populations in the reservoir. However, as the source of the internal SRP is ultimately the catchment, any reduction in SRP input should in the long-term reduce the amount of SRP available internally. Thus, the health of El Gergal could be significantly improved in the long-term.

Another complex factor controlling phytoplankton in El Gergal, highlighted by the *Ceratium* inoculum scenarios, is that because the reservoir is situated at the end of a long chain of reservoirs any locally based management strategies can be disturbed by biological events in the other reservoirs. However, in this case the *Ceratium* inoculum could be regarded as having some positive benefit because the *Ceratium* appeared to be using up resources that otherwise would have been available to the potentially harmful Cyanobacteria species that developed later in the summer.

Finally, the simulated drought conditions highlighted that scum-forming species (e.g. *Aphanizomenon*) would thrive in drought conditions, forming very large surface scums quickly and in large densities. It is difficult to advise how such blooms could realistically be avoided, given the internal nutrient sources, high water temperatures and high incoming solar radiation. The buoyant algal scums could be avoided by abstracting water at depth, but the quality of this water will probably be anoxic and have a poor taste.

Unfortunately, in this energy and resource rich environment, algal species can do little but thrive in reservoirs and with El Gergal being the last in a chain of them, the problems are simply compounded. However, with careful management, it is possible to mitigate their harmful effects and reduce the chance and impact of severe algal blooms.

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**References**

