A MODELLING APPROACH TO THE DEVELOPMENT OF AN ACTIVE MANAGEMENT STRATEGY FOR THE QUEEN ELIZABETH II RESERVOIR

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Introduction

This article outlines the outcome of work that set out to provide one of the specified integral contributions to the overarching objectives of the EU-sponsored LIFE98 project described in this volume. Among others, these included a requirement to marry automatic monitoring and dynamic modelling approaches in the interests of securing better management of water quality in lakes and reservoirs. The particular task given to us was to devise the elements of an active management strategy for the Queen Elizabeth II Reservoir. This is one of the larger reservoirs supplying the population of the London area: after purification and disinfection, its water goes directly to the distribution network and to the consumers. The quality of the water in the reservoir is of primary concern, for the greater is the content of biogenic materials, including phytoplankton, then the more prolonged is the purification and the more expensive is the treatment. Whatever good that phytoplankton may do by way of oxygenation and oxidative purification, it is eventually relegated to an impurity that has to be removed from the final product. Indeed, it has been estimated that the cost of removing algae and microorganisms from water represents about one quarter of its price at the tap (OFWAT 1994). In chemically fertile waters, such as those typifying the resources of the Thames Valley, there is thus a powerful and ongoing incentive to be able to minimise plankton growth in storage reservoirs. Indeed, the Thames Water company and its predecessor undertakings, have a long and impressive history of confronting and quantifying the fundamentals of phytoplankton growth in their reservoirs and of developing strategies for operation and design to combat them (see Steel & Duncan 1999 for a review).

The work to be described here follows in this tradition. However, the use of our model PROTECH-D (see Reynolds et al. 2005, this volume) to investigate present phytoplankton growth patterns in the Queen Elizabeth...
II Reservoir questioned the interpretation of some of the recent observations. On the other hand, it has reinforced the theories underpinning the original design of this and those Thames-Valley storage reservoirs constructed subsequently. We recount these experiences as an example of how simulation models can hone the theoretical base and its application to the practical problems of supplying water of good quality at economic cost, before the engineering is initiated!

**Background: formulation of the problem**

The Thames Valley Reservoirs were designed and built over a period of seventy years or so, self-evidently, to keep pace with the growth of the demand from the London metropolis. They also fulfilled a greater security of supply and a more reliable quality than was previously possible. All the Reservoirs are of the pumped-storage design, in which reservoirs are filled from the river (in this case, the Thames) when the raw-water supply is plentiful and released to the consumer network on a controlled basis. In addition to providing an operational balance and/or a strategic reserve of water, the reservoirs also furnish a stage in its treatment by allowing a period of sedimentation, during which the particulate load in the river water is separated by gravitation. From the early part of the 20th century, means of filtration and disinfection of stored water, to improve the appearance and microbial potability of the final product, were added to the treatment process.

However, the retention of river water under lake-like conditions presents a potential drawback to improving the quality of drinking water, because of the opportunity it provides for the natural development of a limnoplankton of microalgae, rotifers and crustaceans. Their subsequent removal from the finished water adds significantly to the challenge of treating water adequately and economically. This is not a serious problem everywhere but, as already suggested, the Thames presents particular treatment difficulties. It is essentially a lowland river, draining an area of young and fertile geological formations, much of which is used for agriculture, and its catchment is occupied by a human population of ten million. The result is that the water from the Thames is extremely fertile to microalgal exploitation and, actually or potentially, the removal of algae and their products, together with other components of the plankton, has proved to be much the most expensive part of the treatment process. Through the historic sequence of Thames Valley reservoirs commissioned by the Metropolitan Water Board, the body mainly charged with supplying London’s water during much of the 20th century, there runs a clear progression of approaches to minimising the impact of plankton growth during storage. Increasing water depth and decreasing thermal stability characterises the series beginning with the Staines Reservoirs, the Queen Mary and King George VI, and continuing to the designs of the Wraysbury and Queen Mother Reservoirs.

This development is not entirely pragmatic, for its theoretical basis was worked out empirically and formalised in a number of internal reports and publications in the scientific literature (notably, Ridley 1970; Steel 1972, 1975, 1976; Steel & Duncan 1999). Although nutrients are traditionally viewed as the factor regulating microalgal growth, if their stoichiometric supportive capacities are sufficiently high, other physical or biological factors may intervene first (Reynolds 1997). Light penetration, relative to the depth of microalgal entrainment, is commonly invoked, being the main factor critical to the annual plankton periodicity in deep, stratifying systems. Moreover, the field experiments of Reynolds et al. (1984) had demonstrated that periods of wind-induced mixed-layer deepening disrupted productivity and re-directed species succession in the plankton. Models of the impact of physical mixing on the light-determined carrying capacity (Reynolds 1987, 1997; Steel & Duncan 1999) readily supported the results of the reservoir-scale carrying experiments of Ridley (1970) and Steel (1972), whose findings had also influenced the design of the Queen Elizabeth II Reservoir to combine depth with physical instability of the water column.

The Queen Elizabeth II Reservoir (hereinafter referred to as QEII) was opened in 1962 and has been in almost continuous use as a supply reservoir ever since. In normal working, its 19.6 million m$^3$ (19 600 megalitres) volume is replaced, on average, every 22 days. There are several outlet valves but most frequent use is made of the lowermost, located 1.8 m above the reservoir floor at the outlet tower. River water is input at about 0.6 m above the reservoir floor, either by means of low-velocity valves or through horizontal or fixed-angle jets that are designed to increase mixing with the water mass.

Throughout the subsequent 40 years, the reservoir has generally provided water of good biological quality, with a low (relative to potential) microalgal biomass, dominated typically by filamentous species of diatoms and xanthophytes (especially *Tribonema*), with an encouragingly small component of Cyanobacteria (blue-green algae). The accepted explanation for this, based more on supposition than on exhaustive verification, is that the combination of destratification and the short average hydraulic retention has suppressed the development of phytoplankton generally. The predominant species present, chiefly chain-forming diatoms (e.g. *Aulacoseira* spp.) and xanthophytes (especially *Tribonema*), are those known to be most tolerant of mixed conditions, yet which can grow sufficiently fast on low average doses of light to be able to counter the rate of dilution. However, the populations of individual species in the reservoir
are no longer routinely monitored; only chlorophyll concentrations are measured. When, over the last five or six years, it became evident that chlorophyll concentrations were increasing and that greater algal abundance was impacting upon the filterability and treatment of the raw water, it was supposed that the continuously mixed conditions were somehow promoting the success of these same xanthophyte and diatom species. Thus, the logic of periodically relaxing the mixing to permit the development of other species of microalgae, having higher light demands and greater conversion-to-biomass efficiencies, to inflict a setback on the numbers of filamentous algae, carries appeal. The idea of using intermittent mixing to prevent any single group of phytoplankton to build unacceptably large populations had been advocated and backed by the results of sound, field-scale experiments (Reynolds et al. 1984). Equally, however, managers at Thames Water recognised the danger in the approach and the potential of the re-stratifying reservoir to support a very much larger microalgal population.

This is the sort of question that once would have thrilled experimenters and managers alike but which now carries too many risks to efficient operation. Happily, it is one that can now be deferred to modellers. The original aim of the present exercise was to attempt to simulate the phytoplankton dynamics of QEII, using PROTECH-D (see Reynolds et al. 2005, this volume) and then to test the impacts on the phytoplankton of simulated operational variations. The ecological basis and authenticity of PROTECH models are well-established and tests of the veracity, sensitivity and validity of their capacity to simulate phytoplankton development have been published (Elliott et al. 1999a, b, 2000). The models have a broad client base within the industry (see Reynolds et al. 2005, this volume).

**Approach and first findings**

The first task was to assemble a reasonable base simulation of the structural behaviour of the reservoir and its dominant phytoplankton. PROTECH simulations are driven by the combination of known hydraulic and hydrochemical exchanges, under the physical influence of changing day lengths, variable heat income and stochastic weather effects during the year. We were able to obtain an adequate data set for one calendar year (1999), which became the subject of our first simulation. Its target was a set of outputs that adequately resembled the factual summary of measured chlorophyll concentrations and observed temperature structure in QEII (shown in Fig. 1). Several points emerged from this exercise and these became very important to us in running the later manipulated simulations. The first is that, far from lacking a temperature structure, there was a persistent tendency through the spring months (April, May and June) for the water column to stratify, albeit weakly. Moreover, there was some intermittent stratification in the summer months (July, August, September). The assumption that persistent mechanical mixing continuously suppresses the development of a phytoplankton is without justification. Mixing of the whole water column is sufficiently incomplete to permit the reservoir to support significantly enhanced chlorophyll concentrations, which reached over 80 µg chlorophyll $\text{a l}^{-1}$ towards the end of the June stratification. The
best simulation of PROTECH-D (Fig. 2) showed slight exaggeration of water column stability and of the seasonal distribution of algal chlorophyll (briefly > 100 µg l⁻¹, coinciding with the ends of the most stable simulated phases, in June and August). The simulated performances of *Tribonema* and *Aulacoseira* strengthened during the weak spring stratification but both were overshadowed by the development of the bloom-forming Cyanobacterium *Aphanizomenon* when mixing weakened further (Fig. 3).

**FIG. 2.** First PROTECH-D simulation of thermal structure (*below*; note PROTECH works relative to the bottom of the water column and not from the surface as in conventional observations) and phytoplankton chlorophyll concentration in QEII Reservoir (*above*) during 1999.

**FIG. 3.** Amplification of the aggregate simulated chlorophyll concentration, shown as the individual contributions of eight model species. The simulations cannot be verified against factual data but the prediction of dominance by *Aphanizomenon* was unexpected.
There are no quantitative data against which to assess the prediction, although the qualitative records noted that this and other blue-greens were encountered at that time.

The result, certainly counter to what had been anticipated, can be substantiated in part; however, its plausibility was upheld and amplified by the experiences of the manipulated model runs (see later). For the moment, however, we already had the indication that the starting suppositions were erroneous. There is no surprise that the carrying capacity of the nutrients fails to be achieved, except when the depth of mixing is restricted. Moreover, dominance of *Aphanizomenon* is one of a number of predictable biological responses to the onset of thermal stratification. The point is that the observations are not difficult to explain; the oddity lies in the expectation of mixed conditions and of a plankton dominated by *Tribonema*. The first deduction is that the reservoir is mixed less completely than had been supposed; the second is that the major biomass product was not of species indicative of mixing conditions (such as *Tribonema*) but of those positively favoured by the warm, high-insolation conditions associated with near-surface stratification (such as *Aphanizomenon*). As the weather in 1999 had not been either exceptionally warm or exceptionally wind-free, we doubted that the observations were unlikely to have been unusual.

Exploring this last point a little further, it is interesting that there is a tendency for the reservoir to stratify from quite early in the year, despite a lack of strong insolation and the reservoir being filled from the bottom. Model runs (not shown) that sought to vary the simulated heat income showed that the output in Fig. 2 was remarkably insensitive to any source of environmental variation save the scale of hydraulic exchange. Indeed, when the model was run without any input or output of water, it was found that the water temperature failed to rise above 10 °C and the wind and weather conditions were sufficient to override any tendency to stratify (Fig. 4). It is noteworthy that under these conditions, the model shows only a small production of phytoplankton, to < 8 µg chlorophyll a l⁻¹, dominated throughout by *Aulacoseira*, *Tribonema* and *Asterionella* (Fig. 5). In contrast, the next simulation attempted to show the effect of wind-free conditions on the hydraulically-isolated water mass: a familiar thermal development attributable to solar heating across the surface was evident, enhanced by the buoyancy of the upper layers thus induced (Fig. 6). Under these conditions, the fertility of the water is such to sponsor an enormous phytoplankton crop, but now wholly dominated by *Aphanizomenon* (Fig. 7).

Several deductions can be made at once. Despite the application of mechanical mixing, the reservoir still has a tendency to stratify, mainly as a consequence of the difference in temperature between the water in the reservoir and that of the river water influx, at least during the first half of the year. As colder water is abstracted at depth, warmer waters pervade the full depth later in the summer; indeed, this is the main mechanism of heat flux to the reservoir. Moreover, it is the weak stratification, not the persistent mixing, that is responsible for the generation of unacceptable concentrations of phytoplankton. Trying to build in more quiescence, through reduced mixing would seem more likely to exacerbate the problem than to alleviate it.

![FIG. 4. PROTECH-D simulation of thermal structure (below) and phytoplankton chlorophyll concentration in QEII Reservoir (above) subject to unmodified 1999 natural weather conditions but with all hydraulic exchanges removed. Note the failure of the water to stratify and the modesty of algal growth.](image-url)
FIG. 5. Amplification of the contributions of eight individual species to the simulated aggregate chlorophyll concentration, shown in Fig. 4. Note the dominance of mixing-tolerant *Aulacoseira*, *Tribonema* and *Asterionella*.

FIG. 6. PROTECH-D simulation of thermal structure (below) and phytoplankton chlorophyll concentration in QEII Reservoir (above) subject to hydraulic isolation (as in Fig. 4) and the removal of all natural wind forcing. Under these circumstances, surface warming leads to thermal stratification and realisation of the phytoplankton supportive capacity of the nutrients.
Exploration of management options using PROTECH

Having set up the PROTECH simulation and being keen to exploit the demonstrable sensitivities of phytoplankton production in QEII to physical structure, we explored ways that might nevertheless reconcile the achievement of a modest algal growth with the throughput requirements of normal use of the reservoir. For instance, the latter are unlikely to include the strategic restriction of reservoir exchanges, at least for any long operational period, just because it stops algae growing. However, there is a possibility of intermittent hydraulic exchange, through alternating supply among several reservoirs. In Fig. 8, we show the effect of imposing on the 1999 flows a series of 30-d periods of maximum exchange alternating with 30-d periods of hydraulic isolation. The impact upon the thermal structure was to alternate weak stabilisation with some destratification, although the latter was protracted without simultaneous deep-water abstraction. Nevertheless, there was some benefit to water quality, with lower chlorophyll concentrations than were either observed (Fig. 1) or simulated (Figs 2, 3) under normal operation.

Whether this approach might constitute a viable basis for managing the reservoir is brought into serious doubt by the result of a similar simulation in which the only change was to reverse the alternations of service and hydraulic isolation. In Fig. 9, we show that this simple variation accentuated the warming effect during the spring-time exchanges, which the subsequent isolation (and especially the lack of deep abstraction) failed to overcome, permitting greater and more persistent thermal stability. The inevitable biological response was the production of much heavier phytoplankton crops, in which both Tribonema and Aphanizomenon performed well (not illustrated).

A number of other simulations were tried, in which the exchange volumes were reduced, or the abstraction was maintained while alternation applied to the inflows. The results were interpretable in terms of the interacting effects of stratification and deep-water withdrawal. Overall, however, we were unable to devise a set of simple and adoptable operating rules that would give reliable control of biomass, beyond those that were explicit in the reservoir design: exchange water as fast as possible and prevent the reservoir from stratifying.

‘You needed PROTECH to tell us that?’ Possibly not – but the modelling exercise had identified or confirmed several aspects of the behaviour of QEII. There had been (i) a fundamental misunderstanding of the principal mechanism of reservoir stratification. The modelling exposed (ii) a misplaced faith in the efficiency of artificial mixing to overcome thermal stratification and its associated phytoplankton. It also revealed as a
FIG. 8. PROTECH-D simulation of thermal structure (below) and phytoplankton chlorophyll concentration in QEII Reservoir (above) in relation to alternating (30-d) periods of hydraulic exchange, commencing in March (shown in the middle plot).

FIG. 9. PROTECH-D simulation of thermal structure (below) and phytoplankton chlorophyll concentration in QEII Reservoir (above) in relation to alternating (30-d) periods of hydraulic exchange, commencing in April. Summer behaviour engendered differs strongly from the simulation in Fig. 8.
FIG. 10. PROTECH-D simulation of thermal structure (below) and phytoplankton chlorophyll concentration in QEII Reservoir (above) when hydraulic exchanges are suspended for a single 30-d period in March.

Putting these findings together, we reasoned that a single, 30-day break in the riverine input at the time of maximum difference between river and reservoir temperatures (March) would weaken the spring stratification and militate against its later persistence. This subsequent model run (shown in Fig. 10) vindicates the prediction in part, in that critical thermal stratification was, indeed, shown to be delayed and weaker than in the first simulation (Fig. 2). The magnitude of the *Aulacoseira-Tribonema*-dominated spring growth (30 µg chlorophyll a l⁻¹) was little altered but the summer growth of *Aphanizomenon* was severely truncated in the test.

Even were this to be formulated as a recommendation, it was made clear to us that the practicality of its application would be subject to priority considerations of meeting demand and for gaining the maximum reserve when the river supply is (usually) at its most plentiful. This is, of course, perfectly correct – water can always be treated for consumption, at a price, but only for so long as there is raw material available.

By chance, at the same time as we were completing the model exercises, the Company had been engaged in repairs to another of its Thames Valley reservoirs. The time was approaching when the reservoir could be refilled from the river. Doubtless influenced by our findings, the Company wanted to know whether it mattered when the refilling was carried out. We tried to answer this by using PROTECH to simulate a hypothetical refilling of an empty QEII with source water from the Thames, subject only to the constraints of the pumping capacity and of the competence of the reservoir walls to adjust to the pressure exerted by the water. Thus, in Figs 11 and 12, the rate of refilling is shown as a variable flow. Starting in November, with river water at about 10 ºC and cooling, the underflow of denser water promotes some stratification but it is simply the residual heat of the new water that makes it more susceptible to solar heating and density stratification during March, with an appropriate algal response (Fig. 11). On the other hand, if the filling is started in January when the temperature of the river water is < 6 ºC, the reservoir is shown to remain cold and well-mixed and unable to confine solar heating to the surface layer (Fig. 12). There is no thermal stratification and the chlorophyll concentration peaks at about 9 µg chlorophyll a l⁻¹ in May, much as in the scenario illustrated in Fig. 4.

Conclusions

The work described above went only a short way towards devising operational strategies for effective control of phytoplankton development. This is partly because it quickly confirmed that the existing strategies are
FIG. 11. PROTECH-D simulation of developing thermal structure (below) and phytoplankton chlorophyll concentration in QEII Reservoir (above) were it to be filled from empty, commencing in November.

FIG. 12. PROTECH-D simulation of developing thermal structure (below) and phytoplankton chlorophyll concentration in QEII Reservoir (above) were it to be filled from empty, commencing in January.
entirely appropriate for the reservoir and partly because it was able to demonstrate that the implicit element of uncontrolled phytoplankton development does not owe to a shortcoming in the existing strategy. The opportunity to regulate phytoplankton growth by intermittent mechanical mixing is not pursued as it is not demonstrably beneficial to do so. Prevention of stratification of the stored water should remain the first management objective of the full reservoir. Again, our work highlights the two main (opposing) factors that influence the stratification of QEII reservoir: (i) the difference in density between the inflowing source water (from the Thames) and the water currently in store and (ii) the deep-water outflow through the draw-off to treatment and supply.

We seek to emphasise the uses and sensitivity of PROTECH in separating these complex influences on the magnitude and periodicity of the phytoplankton and upon its dominant species composition. Although we would like to have shown how the model helped Thames Water to select a better operational strategy for the control of phytoplankton, we gain considerable satisfaction in upholding the current strategy and in showing the behavioural peculiarities of the system which interfere with the complete execution of the strategic provisions. In particular, PROTECH confirms that deep mixing is restrictive on carrying capacity. The PROTECH simulations emphasise the critical role of deep-water abstraction in the mixing of QEII exceeding in effectiveness even the jetted inlets in overcoming temperature and density differences. The importance of deep-water abstraction is itself subject to the relative magnitude of the volumes withdrawn and the short average residence times in QEII. As we have shown, this is also crucial to the heat exchange within the system, owing more to the heat content of the incoming and outgoing water masses than to heating or cooling across the water surface.

We conclude that the experiences gained in using PROTECH to simulate phytoplankton growth in the hydraulically and hydrographically complex QEII do not detract from a previous claim (Reynolds et al. 2005, this volume) that the model is adequately versatile and sensitive to be applied to a wide range of limnological problems confronted by the water industry. We could go further by suggesting that it can be regarded as a useful tool in planning and testing engineering solutions.

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References


