TOXIC BLUE-GREEN ALGAE: THE "PROBLEM" IN PERSPECTIVE

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Introduction

As the memorable summer of 1989 continued to defy the calendar, tranquil September days still lured stock to water or promised dog-owners another pleasurable stroll with their pets along the banks of Rutland Water. This time, however, it was different: the microscopical cells and colonies of *Microcystis,* themselves unsure whether they are algae or bacteria, had risen to the water surface and been carried downwind by a gentle breeze. Now, a thick, paint-like, shore-line scum of algae, a million times more concentrated than in the open reservoir, festooned the shores. Animals could no longer enter the water without contacting a tacky, viscous deposit of moribund algae. Though undoubtedly constituting a strong deterrent to drinking the water, the mere act of licking fur clean would have resulted in the animals ingesting significant amounts of scum material.

The next part of the story is well known: within days, some 20 sheep and 15 dogs had died, with symptoms consistent with poisoning by blue-green algal toxins. The cause was confirmed with the isolation of the toxin from the algae and from the dead animals. The case received wide coverage in the media and soon generated alarm about the impending invasion of "toxic algae". Reports of blue-green scums flooded in from over a hundred reservoirs where, of those directly tested, nearly 70% were proved to carry toxin. By the time that news broke about two trainee soldiers having fallen seriously ill after undertaking training exercises at a Staffordshire reservoir in the presence of an intense bloom of toxic *Microcystis,* the issue had achieved the proportions of a national scare: reservoirs had already been closed to the public and most recreational pursuits had been curtailed or stopped altogether, especially where direct contact with water was involved.

Understandably, many people have been perplexed by these incidents and by what proved to be something of a re-run in 1990. Why are we suddenly confronted with all these algae? How toxic are they? Is there a risk to drinking water? What should we do about them? These questions have been asked many times during the last year or so.

Historical aspects

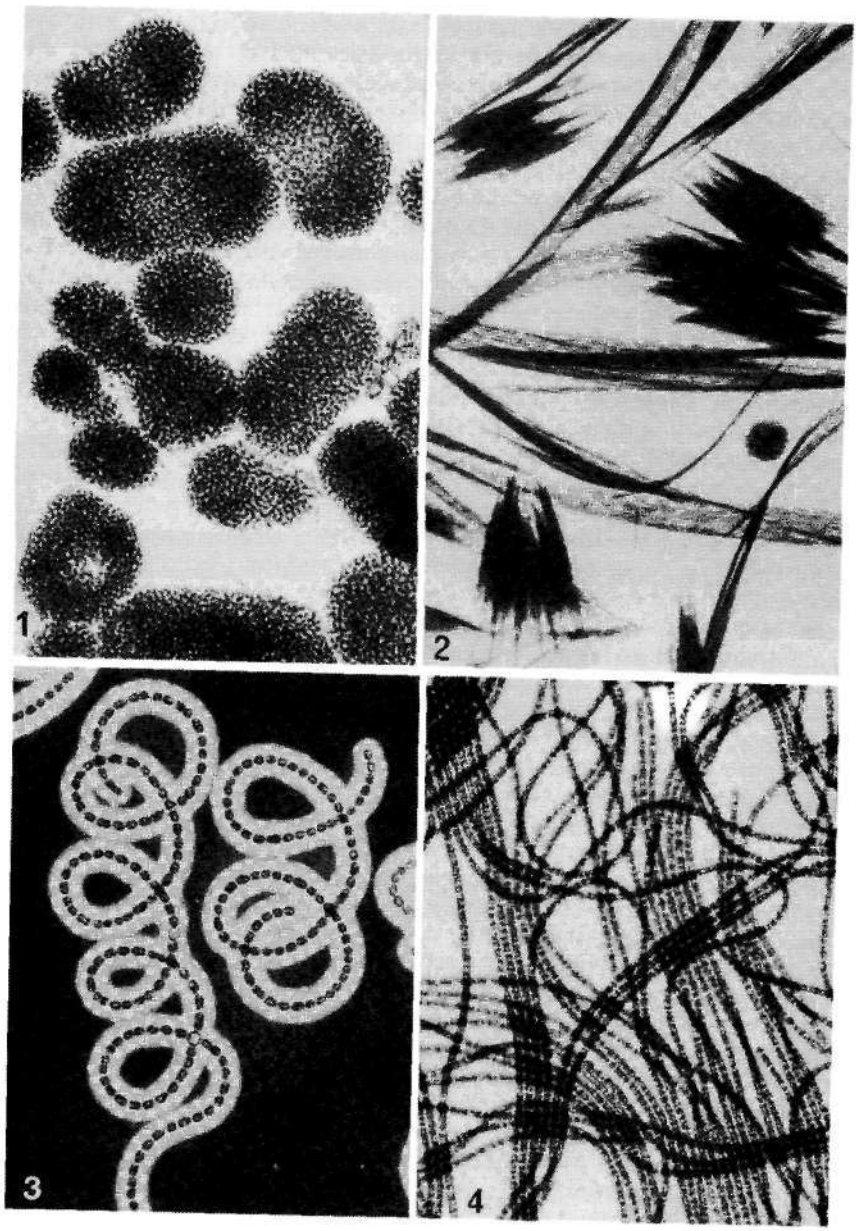
It is important to emphasise that the incidence of blue-green algal blooms and surface scum-formation are certainly not new phenomena. Though lacking the modern benefits of a microscope or a flora, many British and European authors have been faithfully describing the unmistakable symptoms of blue-green algal scums for over 800 years. Palaeolimnologists have been able to trace evidence of large populations having existed in some lakes, several thousands of years previously. The history of blue-green algae on the earth stretches back to the advent of the earliest recognisable organisms - there is no reason to suppose they have remained rarities only until recent times!

Neither are the reports of animal deaths or their associations with blue-green algae new; both have been reported for many years in the technical and veterinary literature, although it has to be said that, in most past instances, the link was generally circumstantial and unproven. Now that the particular toxins have been isolated and their effects in natural material assayed, thanks mainly to the pioneering work of researchers such as Professor G. A. Codd and his colleagues at the University of Dundee, it is safe to assume that the capacity to produce these toxins is certainly a property of many blue-green algae and that the trait has been within the group for a long period of time.

Blue-green algal toxicity

There is no disputing that blue-green algal toxins are extremely harmful. Three quite separate categories of compound have been separated: *neurotoxins,* which are alkaloids, are potent neuromuscular blocking agents; *hepatotoxins,* which are peptides, induce weakness, vomiting, diarrhoea, circulatory shock and acute liver damage; *lipopolysaccharides,* which, although they can be lethal when injected, seem to be the principal cause of the skin irritations associated with blue-green algal contact. However, the 1989 incidents were largely associated with the hepatotoxins produced by *Microcystis, Anabaena* and *Aphanizomenon* (Figs 1-3). In comparison with other biogenic toxins, purified isolates of blue-green algal hepatotoxins rank somewhere between Cobra venom and curare (the extract Brazilian Indians use to tip their arrows), typical lethal doses being within the order of magnitude 30-300|a,g per kg bodyweight (for comparison the lethal dose of sodium cyanide is roughly 100 times greafer!)

FIGS 1-4. *(Opposite).* Planktonic blue-green algae. 1, *Microcystis* (x110). 2, *Aphanizomenon* (x44). 3, *Anabaena* with mucilage envelope (x250). 4, *Oscillatoria* (x156).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Against this we have to set the fact that these substances are not always present in natural populations and, if they are, the quantities are usually trivial, perhaps a few picograms per cell. If we considered a large population of (say) *Microcystis* comprising 200 million cells per litre, fully dispersed through the upper waters of a reservoir, it is conceivable that the water might contain up to 1000ug hepatotoxin per litre; a 50-kg adult would then have to swallow some 5 litres of water in order to ingest a potentially lethal dose of hepatotoxin. Even supposing this case to be extreme (smaller, less toxic populations might not be lethal before a minimum intake of 50 litres), sublethal medical symptoms might be expected at much lower concentrations of algae. The importance of the calculation above, however, is to illustrate the effect of surface scum-formation and lee-shore accumulation of alga. Planktonic blue-green algae nearly always contain specialised gas-containing structures (gas vesicles) and, if sufficient are present, the cells become buoyant. Now, given suitably calm weather, if the same blue-green algal population floated to the surface (say from a 5-m layer to one of 5mm; factor of concentration, 1000) of a 1-km square reservoir and drifted uniformly down wind to one side, then for every metre of lee-shore, the algae would become concentrated by a factor approaching 1 million. Thus, the same adult now need ingest only *five microlitres* of the affected water in order to obtain the same lethal dose of *Microcystis* toxin.

The picture might be even more serious if the variability in toxicity is considered. At present, it is unclear precisely what factors influence the production of toxins, let alone what their function might be. If, as seems increasingly more likely, toxicity is only an incidental property of metabolites produced by stressed or physiologically-impaired cells then it is equally possible that toxicity is greatest in cells recently subject to environmental shock. From the alga's point of view, scum formation may abruptly alter the temperature, light intensity and photoperiod it experiences; accordingly, this would often precipitate a state of physiological shock. Thus, there is every reason to suppose that the inshore scum may be significantly more toxic, per unit algal mass, than the hitherto dispersed populations, even before the concentration factor is accommodated.

It can be seen that there are good reasons for regarding not the dispersed population as the potential health hazard but the inshore scums. Most of the more rational warnings to the public have been founded on this deduction. On the other hand, because we already know how quickly scums can form and because, at present, it is expensive, time-consuming and, as we have shown above, possibly misleading to verify in the laboratory the toxicity of given populations, it is safer to regard all populations as being potentially hazardous under the

appropriate conditions. Although many of our drinking-water reservoirs do support substantial populations of blue-green algae for a substantial part of the year, it has to be admitted that no attestable case of any consequences upon the wholesomeness of the final product has ever been advanced. Yet until it can be confirmed that toxins do not leach out of cells, especially when subject to stresses imposed during filtration, *and* that all cells are effectively removed by the treatment process, it would be complacent to believe that the supply to the consumer is as completely safe as we would wish. To achieve this, it would appear prudent, at least within the foreseeable future, to adopt measures for reducing the quantities of blue-green algae produced in our reservoirs.

Blue-green algal abundance

There is a popular association between blue-green algae and nutrient enrichment ("eutrophication") of water courses. Certainly the main nuisance species - of *Microcystis, Anabaena* and *Aphanizomenon* - are rare in nutrient-poor (oligotrophic) lakes and reservoirs where, at concentrations always less than 10 micrograms per litre, the amount of phosphorus likely to be available imposes a severe control on the ability of blue-green algae to grow at all. This is not because they need more phosphorus, per unit weight, than other kinds of algae, but because they grow rather more slowly than many other species and hardly at all when the water is cold. Nutrient concentrations in water are generally highest during the winter-spring period of maximal leaching from the catchment and minimal biological uptake. As the days lengthen, the planktonic algae which increase and constitute the familiar spring outbursts are generally the cold-water diatoms, like *Cyclotella* and *Asterionella.* These algae use up the phosphorus and perhaps also the silicon in the water and, at the end of the spring growth period, settle out to the bottom, taking most of the phsophorus with them. There is then insufficient in the water to support the growth of summer species, so the open water remains clear.

In lakes which have more natural phosphorus, or receive extra supplies from treated sewage, for example, phosphorus is not exhausted in the spring and other algae, including the blue-greens, may then be able to grow in summer. At these times, blue-green algae generally have an advantage because planktonic animals, especially the water flea, *Daphnia,* scarcely feed on them, if at all. Thus, by avoiding losses due to both settlement and grazing, the slow-growing blue-green algae may become dominant during the summer and, having done so, may persist for some considerable time into the autumn. They may recruit spores or resting stages to the sediments but much of the stock dies off as temperatures fall and day lengths shorten or it is washed out of the lake in

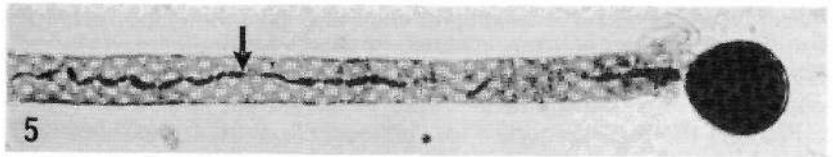
increased autumnal hydraulic throughput.

It is easy to see, then, why blue-green algae have seemed so much more common in Britain over the last couple of years of exceptionally mild and rather dry winters and warm, sunny summers. It is also easier to appreciate why these same blue-green algae have longer periods of prevalence in Mediterranean and sub-tropical climates and why, in many tropical lakes, they may persist all year round.

Controlling blue-green algae

To what extent then, can we apply our knowledge of blue-green algal life-histories, their environmental requirements and ecological responses, in order to control their abundance artificially? Several approaches have been proposed. Some have been successfully implemented while others remain merely attractive theories that are untested at the full reservoir scale. Distinction is also made between methods for discharging blue-green algae already present and methods for averting an anticipated abundance in the future. Considering cases in the former category, the options are not encouraging: several inorganic (copper sulphate) and organic (diquat-type) compounds have a universal (but not uniform) toxicity to algae but are not exclusively algicidal, while their erstwhile liberal use is against EC guidance and is now highly regulated. Treatment with straw bales has been proposed, following successful actions against green filamentous algae in canals and streams, but more investigative work is required before the corresponding doses of straw, which has a high biological oxygen demand, can be advocated for use in lakes and reservoirs. There is no doubt about the effectiveness of viruses, parasitic fungi (Figs. 5-7) and, especially, certain herbivorous ciliates (Fig. 8) which, at times, severely reduce natural scum-forming populations, but the practical problems of harvesting and maintaining sufficient material to provide the infective inocula with which to "seed" the blooms have still to be overcome. Increased flushing (to shorten residence time) of a water-body can be extremely effective in removing slow-growing blue-green algae, where the opportunity exists, but this use of water inherently conflicts with the strategic purpose of many reservoirs, namely that of conserving the resource against vagaries in its supply! Application of chemicals to reduce the nutrients available to support algal growth has been invoked, but experience suggests that treatment is generally more effective before the algae have an opportunity to become abundant and should be categorised as a preventative measure.

FIGS 5-7. *(Opposite).* Fungal parasites (chytrids). 5, apical sporangium of *Rhizophydium* on *Oscillatoria;* stained to show a long internal rhizoid (arrowed) (x755). 6, *Anabaena* parasitized by *Rhizosphon;* there are two live algal cells (a) and two fungal resting spores (r) with rhizoids (arrowed) (x625). 7, *Microcystis* with sporangia (s) of *Chytridium* (x625). FIG. 8, *Nassula,* a ciliate feeding on filaments of *Aphanizomenon* (x62).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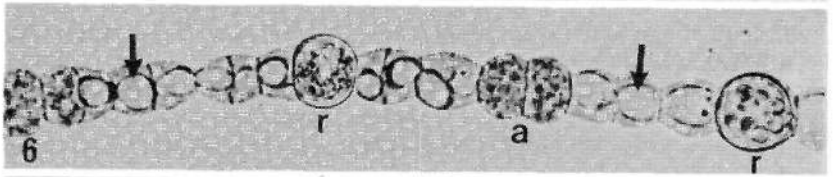
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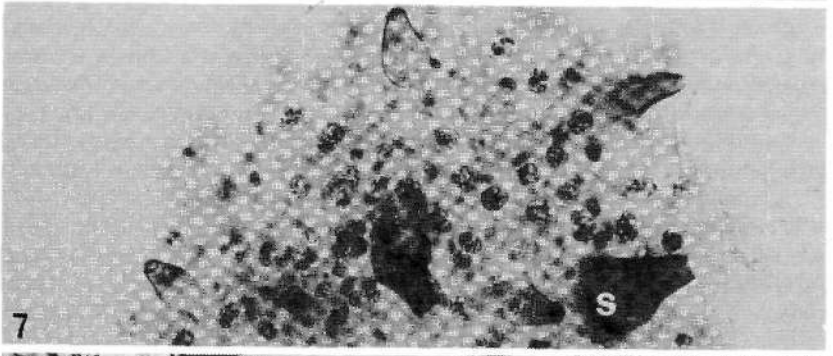
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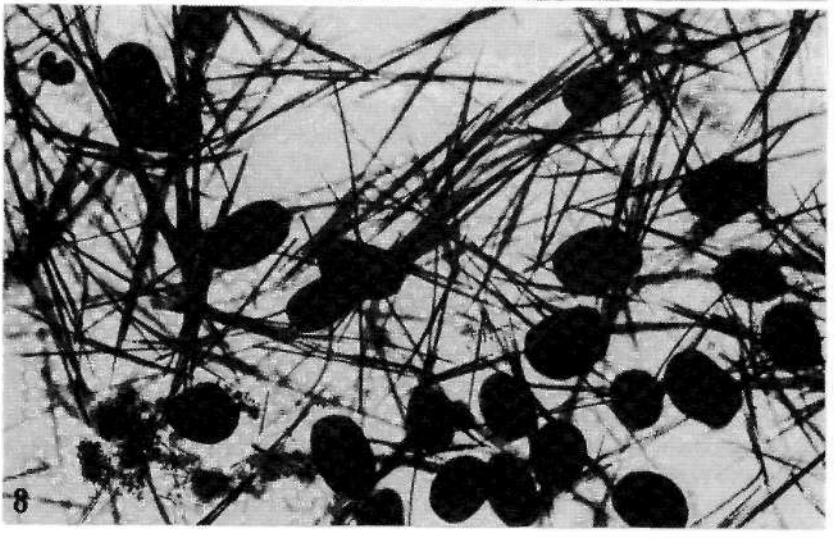
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Available preventative treatments may also be subdivided, according to whether they restrict the *capacity* of a system to support blue-green algal populations or whether they suppress the *rates* at which capacity populations might be attained.

Perhaps the most generally understood capacity component is the availability of nutrients and, because it is not readily shed from natural hydrological catchments, of phosphorus in particular. When phosphorus is scarce, its availability may indeed limit phytoplankton biomass - in the sense of restricting its further increase. Surprisingly robust statistical relationships have been derived relating phytoplankton chlorophyll (as an index of mass) to expressions of phosphorus availability: those attributed to Sakamoto, to Vollenweider and to Dillon & Rigler generally work well and are perhaps the most familiar. For reasons already stated, blue-green algal mass is nor predicted from these relationships: what matters is the quantity of resources available *at the times when the blue-green algae can use them.* Few would argue, however, with the view recently developed through work in Canada that total phosphorus concentration is a good general predictor of the amounts of blue-green algae likely to be present in weakly-flushed lakes.

A reasonable corollary, that reducing phsophorus concentrations would necessarily reduce blue-green algal biomass, is not unequivocal, however. In several lowland rivers and the reservoirs they supply directly, the phosphorus concentration is often so high (in the order of milligrams per litre) in relation to the algal biomass actually supported that, even assuming a single point source of nutrient, a reduction of 95% in phosphorus loading might well prove necessary before any limitation on algal production is imposed. It is important to bear in mind that most currently-available techniques generally remove only some 80-85% of the available phosphorus in the source water, that diffuse sources are difficult to regulate, and that the sediments of *hitherto* phosphorus-rich lakes and reservoirs may contain and give up sufficient phosphorus to offset the loading difference for several subsequent years ("residual internal loading"). Although phosphorus stripping is often popularly demanded and there have been plenty of cases where (mild) eutrophication has been successfully so reversed, great care is still required in determining whether a lake or reservoir is likely to benefit from the installation of a costly plant designed merely to reduce the phosphorus load and, if so, where it might be best sited and how soon it might be before the benefits (quality improvements) are realised.

The second approach to controlling blue-green algal growth on reservoirs is to interfere with the physical environment. One certain way to achieve this would be to exclude, or greatly reduce, the amount of light available to support photosynthetic production. Roofing over

reservoirs or floating cork balls or sheeting on the water, however, are generally recognised to be quite impracticable. In a reservoir of sufficient depth, artificial circulation (using jetted inlets, or Archimedean pumps, or vigorous bubble generation at depth) of the algal population through the entire water column could achieve a comparable effect. What is of greater interest is that artificial mixing beyond the depth of light penetration will reduce the *rates* of growth of planktonic algae. Moreover, some kinds of algae, including the bloom-forming species, are apparently more sensitive and more susceptible to the treatment than others. There are many reports of artificial mixing reducing the quantities of blue-green algae in North America, while prevention of stratification in the deeper Thames Valley Reservoirs has been conspicuously successful in overcoming problems brought about by summer blooms. However, like phosphorus-stripping, reservoir mixing is (wrongly) perceived as being generally effective but, also like phosphorus-stripping, its relative success depends on local characteristics of the site. Clearly, artificial mixing has to bring about a significant environmental change from the alga's point of view: mixing will not alter the environment of a shallow, exposed water-body that is frequently wind-mixed over its full depth; nor will it have much impact unless the new depth of circulation exceeds, probably by a factor of 1.5 to 2.0, the depth of light penetration. It also needs to be said that the deeper-mixed, light-deficient layers thus created generally favour dominance by diatoms or by the solitary filamentous and potentially toxic blue-green alga *Oscillatoria* (Fig. 4): there is therefore a danger of simply replacing one kind of blue-green alga with another. Precisely this response seems to have occurred in the case of some West Country Reservoirs: elsewhere, the reservoir retention time is short enough to ensure water renewal rate offsets the rate at which the *Oscillatoria* population can recruit itself by growth. In deep storage reservoirs with long retention times (>6 months), deliberately varying the extent of artificial mixing, such that its selective effect is intermittent, offers a better option: in theory, the growth conditions favouring diatoms and *Oscillatoria* are alternated with those favouring small, fast-growing green algae; neither become abundant but the onset of blue-green dominance is delayed. This technique has been shown to work on the pilot scale but has not been applied, either directly and systematically, to the operation of an appropriate reservoir. Perhaps this approach - if the frequency-cycle of mixing were correctly judged - might help to identify useful management options for the very enriched reservoirs.

There is a variety of other potential techniques for controlling blue-green algal growth which merit further research and development, including biomanipulation of the trophic pathways, sediment removal

and engineering solutions invoking partitioning of reservoirs and using sections in rotation for greater flexibility of operation. These methods might be used in conjunction with each other or with one of the preventative schemes outlined above. The encouraging feature of the recent shift in attitudes towards algal growth in reservoirs is the realisation that biological problems cannot be overcome exclusively by engineering solutions. Yet biological solutions require a deeper understanding of the relationship between the responses of organisms and the fundamental limnological processes that drive them. The need for competent freshwater ecologists has not been so apparent for many years, neither has there been a more compelling case for maintaining our Association's well-founded traditions of research.

Conclusions

In summary, we can conclude that the recent prominence given to the occurrence of blue-green algal blooms is not wholly misplaced. While the causes *of* their relative abundance *in* recent years are properly understood to be influenced more by year-to-year variability in weather conditions, within present climatic probabilities, rather than to some collapse in the chemical quality of our waters, their incidence serves as a reminder of the insidious rise in nutrient capacities that has occurred in many of our indigenous water sources. If the threatened climatic warming comes about, the frequency of blue-green algal blooms seems set to increase. Moreover, the recognition of the inherent potential toxicity of common species of blue-green algae has necessitated a less complacent attitude to their presence and behaviour in our lakes and reservoirs. In particular, the impact of concentration mechanisms - whether the natural ones of self-harvesting in scum-formation or those designed to accumulate the algae on the filters of treatment plants - constitute the most potent threats to public health. They represent loop-holes which we should strive to close.

Acknowledgement

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Further reading

Toxic Blue-green Algae. National Rivers Authority, London. Water Quality Series No. 2, 1-125.