TOXIC BLUE-GREEN ALGAE

The Report of the National Rivers Authority

September 1990

NRA
National Rivers Authority

Water Quality Series No. 2

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A report by the
National Rivers Authority

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PREFACE

Following the occurrence of blooms of blue-green algae in freshwaters during the late summer of 1989, some of which were known to produce toxic substances, it was clear that an appraisal of the phenomenon was urgently required. The National Rivers Authority thus set up a working group, of both NRA and non-NRA experts, to address the question of what needed doing should a similar outbreak occur in 1990, and to advise on longer-term solutions. This report is the result.

Because of the recurrence of blue-green algal blooms early in 1990, a number of short-term measures have already been put into effect. The report, however, goes much wider than this. It is, essentially, the first major appraisal of the subject as a whole within the UK and will be of interest to a wide audience.

The NRA would like to thank the group for its hard work and diligence in producing the report in such a short time.

Dr R J Pentreath
Chief Scientist

The Chairman of the 'Task Group' wishes to express his personal thanks to all members of the group for their commitment, support and professionalism in the compilation of this report.

A special vote of thanks goes to Ms C Phillips, the Chairman's Secretary, for her exceptional assistance and infinite patience, perseverence and dedication in the typing of the report.

Thank you all.

M. Pearson

M. J. Pearson

Chairman of Task Group

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1 TERMS OF REFERENCE

The Task Group was established to produce a report on toxic blue-green algae by summer 1990.

The report should include the following aspects:

- An assessment of the 1989 problem
- Historical problems in the UK and abroad
- A review of factors affecting blue-green algal blooms
- A review of the influence of nutrients
- A review of the influence of biotic factors
- A review of Water Quality Management techniques
- A review of toxicological aspects
- Short-term measures to manage the problem in 1990
- Identification of Research and Development requirements
- Recommendations for the future

2 NRA TOXIC ALGAE TASK GROUP MEMBERSHIP

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3 EXECUTIVE SUMMARY

Introduction

3.1 Blue-green algae are organisms with some properties characteristic of both bacteria and algae. They are capable of photosynthesis and the pigment required for this process often gives them a blue-green colour. Many species of blue-green algae have the ability to fix gaseous nitrogen. Under suitable physical and chemical conditions, particularly in still waters, populations may grow to extremely high densities and, under certain circumstances, a scum of algae will form on the surface which can accumulate downwind; these algae are also known to produce chemicals which can be toxic to mammals, including man.

3.2 The development of a bloom of blue-green algae at Rutland Water in the summer of 1989 resulted in the production of substantial quantities of scum containing toxins, and this led to the deaths of several sheep and dogs which had ingested the scum. An assessment was subsequently made by the NRA of the extent of the potential problem throughout England and Wales. Blooms of blue-green algae were found to be widespread, and 60 to 70% of those tested were found to be producing toxins. The results from this 1989 survey, and a description of how the events were managed, are presented in this report.

3.3 In order for the events of 1989 to be seen in perspective, summaries are given of the present knowledge of the occurrence of blue-green algal blooms, their recognised toxins, and the factors affecting the production of both blooms and toxins. Proposals are made for a uniform approach to the problem in the future, and for research to be carried out to improve our understanding and management of waters affected.

Factors Affecting the Incidence of Blooms

3.4 The factors leading to blooms of blue-green algae are many and complex. Physical factors are the most important in determining which species of blue-green algae will, in general, dominate in particular types of lakes or reservoirs. These factors include the size of the waterbody, the extent of mixing of the water layers, and the depth of light penetration.

3.5 Blue-green algae grow relatively slowly; a long period of stable weather, giving a constant physical (hydraulic) environment, is therefore required for large populations to develop. Within this constraint, the temperature and the nutrients available will determine the population size which may be achieved if good growth conditions persist. In most places in southern and eastern England, nutrient availability is more than adequate and grazing by zooplankton is usually minimal, thus blue-green algae normally become dominant in the algal community in mid- to late-summer.

3.6 Blue-green algae are capable of regulating their buoyancy. Normally this keeps them away from the surface; occasionally, however, buoyancy cannot be adjusted quickly enough to accommodate sharp changes in wind-induced water mixing. The cells may then become too buoyant for their depth in the water column, and thus rise rapidly to the surface if the wind abruptly subsides, forming scums. Such blooms and scums are a widespread phenomenon, with a long history; reports in the UK go back to the twelfth century.

Toxin Production

3.7 About 25 species of blue-green algae have been implicated in poisoning incidents worldwide. Confirmation that an alga can produce toxins is a difficult and lengthy process, and has been carried out for at least eleven of the commonest species implicated in poisoning incidents. Blooms capable of producing toxins have been reported from all over the world, including many European countries; up to 75% of all such blue-green algal blooms tested have been found to produce toxins. The toxicity of a single bloom however, may fluctuate rapidly both in time and in space. The physiology, biochemistry and genetics underlying toxin production are poorly understood, and the function of the toxins is unknown.

3.8 Toxins produced by freshwater species of blue-green algae fall into three categories: neurotoxins, hepatotoxins and lipopolysaccharides. Their toxicity has usually been studied by intra-peritoneal injection into mice.

3.9 Neurotoxins, most of which are alkaloids, have been shown to be produced by species of *Anabaena*, *Aphanizomenon* and *Oscillatoria.* Several toxins have been identified, some of which are similar or identical to saxitoxin, which is produced by some marine dinoflagellates and causes paralytic shellfish poisoning (PSP).

3.10 Hepatotoxins, which all appear to be peptides of similar structure, are produced by species of *Microcystis*, *Oscillatoria* and *Anabaena*. These toxins, called microcystins, are the best studied of the toxins and have been implicated in the majority of environmental incidents involving toxic freshwater blue-green algae.

3.11 Lipopolysaccharides (LPS) are produced by many blue-green algae, as normal components of their outer layers, in common with some bacteria such as *Salmonella*. These chemicals may be responsible for reports of irritation of the skin made by swimmers who have been in contact with toxic blooms, and for gastrointestinal upsets.

3.12 Deaths of mammals, birds, amphibians and fish, which have been suspected to be a consequence of ingesting toxic blue-green algae, have been reported world-wide for over a century. The deaths of sheep and dogs at Rutland Water in 1989 probably resulted either from their drinking from the scum around the water's edge or, in the case of dogs, licking algal material from their coats after immersion.

3.13 There are no confirmed reports of deaths in humans which can be directly attributed to toxins produced by blue-green algae. There are, however, many reports of human illness associated with the presence of toxic algae, particularly in North America, Australia and Europe — including the UK. These include skin irritation and gastrointestinal upsets in swimmers, elevated blood levels of liver enzymes among patients supplied with drinking water from a source with a dense bloom producing toxins, hepatoenteritis following a dense bloom of blue-green algae in a drinking water reservoir, and 'Haff disease' on the Baltic Coast after ingestion of fish livers tasting of musty flavours from blue-green algae. None of these outbreaks has been unequivocally ascribed to the presence of blue-green algal toxins, but the available evidence is consistent with this hypothesis.

3.14 An incident in 1989 involving young soldiers who encountered a dense bloom of blue-green algae in Rudyard Lake, Staffordshire, whilst immersed in the water during canoeing exercises, is one of the best investigated; the problems which they experienced were probably due to poisoning by blue-green algal toxins.

3.15 It is not possible to control the production of toxins by blue-green algae, but it may be possible to control the formation of the blooms.

Detection and Analysis of Toxins

3.16 The potential toxicity of a bloom or scum cannot be determined by its appearance, odour, texture or any other simple feature.

3.17 The only comprehensive bioassay for blue-green algal toxins at present is by assessment of their toxicity to laboratory rodents; this method can detect all the different toxins collectively. There are a number of possible supplementary assays which need further development.

3.18 Qualitative chemical analysis of those toxins which have been chemically characterised, based on high-performance liquid chromatography (HPLC) is well established; but there is a need for quantitative methods which can be routinely applied to the analysis of toxins in water and other environmental samples.

The 1989 Event

3.19 Various NRA regions were becoming aware of problems with substantial growths of blue-green algae during August and early September 1989. Following the reports of the deaths of sheep and dogs at Rutland Water in Leicestershire, NRA Head Office asked the NRA regions to assess the extent of the problem throughout England and Wales.

3.20 Each region inspected a large number of waters and sampled all of those suspected of having 'problems' with blue-green algae. These samples were subject to microscopic examination, and lists of all those which contained blooms of potentially toxic algae were compiled and submitted to Head Office.

3.21 Regions which had significant perceived problems set up teams to manage them: their actions included further monitoring and toxicity testing; informing the owners of affected waters, Environmental Health Officers (EHOs), Medical Officers of Environmental Health (MOEH) and the Ministry of Agriculture, Fisheries and Food (MAFF); responding to inquiries from the public; issuing press releases, dealing with the media, and suggesting precautions to take to avoid further problems.

3.22 The Toxic Algae Task Group was then set up in December 1989 to review the problems associated with toxic blue-green algae, and to make recommendations to minimise the problem in the future. The Task Group requested information from the NRA Regions, English and Welsh water undertakers, Scottish River Purification Boards and Regional Councils, and the Department of the Environment Northern Ireland.

3.23 The review has shown that the NRA regions inspected 915 waters, of which 686 were sampled for their algal content. A total of 594 were found to have blue-green algae present as the dominant type and, of these, 169 were considered to have sufficiently high densities (blooms) to warrant alerting the owners and EHOs.

3.24 The species most commonly encountered was *Microcystis aeruginosa*; other frequently-found species were *Aphanizomenon flos-aquae*, and those of *Anabaena*, and *Oscillatoria*.

3.25 Toxicity tests were carried out on algae collected from 78 bodies of water, of which 53 (68%) were found to be positive. There were wide variations in toxicity both at, and between, individual sites.

3.26 There was little quantitative information on the numbers of blooms, or on surface scum formation, in waters prior to 1989. Anecdotal evidence suggests that the problems were greater in 1989 at some sites than in previous years, particularly at Rutland Water.

3.27 Much of the work carried out by the water undertakers paralleled that of the NRA. In general, few problems were reported with water treatment processes and there was insufficient evidence to assess whether or not 1989 was any worse than previous years.

3.28 The results of inquiries in Scotland and Northern Ireland showed a similar picture to that found in England and Wales, in that the information was of variable quality. The extent of the problems encountered appeared to be on a reduced scale, but there were at least four cases of dense surface scums and confirmed toxicity.

3.29 Problems with blooms of blue-green algae in 1989 are also known to have occurred in Australia, USA, Finland, Sweden, Norway and Chile.

An Explanation of the 1989 Event

3.30 The high incidence and abundance of scums, particularly of *Microcystis aeruginosa*, in the UK in 1989 can be primarily accounted for by a combination of factors including a mild winter, high mid-summer temperatures and sunshine, and calm weather in July. Of particular importance were the long periods of stable weather conditions.

Monitoring in 1990 and Beyond

3.31 Monitoring recommendations for 1990 were produced before this report was published, in order to ensure that adequate information was available for managers, owners, EHOs, MOEH and MAFF as early as possible. This was considered to be particularly important in relation to alerting water users and the general public to the potential risks, and the care that must be taken in using affected waters. To this end it was recommended that the NRA should provide a public information leaflet, and this has been produced. The 1990 monitoring programme will be assessed and, if necessary, modified for future years.

Methods of Controlling Blue-Green Algae in the Longer Term

3.32 Blue-green algae in reservoirs and lakes may be controlled by direct and mostly non-selective algicidal techniques, or by the artificial enhancement of natural selection through physical, chemical and biological methods. The use of algicidal techniques is not considered advisable, however, because toxins may be released into the water during cell breakdown. Enhanced 'natural' controls may be effective, but only under certain conditions.

3.33 Reducing phosphorus availability would be effective, but even total control of point sources is likely to leave diffuse sources which may be adequate for blue-green algal bloom production. Control of diffuse sources is much more difficult, and would still leave the previously-introduced phosphorus within lake and reservoir muds being available for several years.

3.34 Permanent destratification methods are likely to depress the growth of blue-green algae in reservoirs indefinitely, but only if the mixed depth considerably exceeds the depth which sustains algal growth. Intermittent destratification would be subject to similar conditions and, whilst it could depress the growth of all major algae, it is a technique untried on the full reservoir scale.

Research and Development

3.35 Research and development needs in relation to blue-green algal blooms and their toxins fall into three broad areas: those related to the formation and control of blue-green algal blooms; research specifically related to the toxins they produce; and research into the effects of the toxins.

3.36 A number of possible methods for controlling algal populations have been suggested in the report, all of which require improvements or basic research before they could be described as being fully effective. These involve catchment management, and physical, chemical and biological methods of control. Environmental Impact Assessments would need to be made in many cases.

3.37 The chances of success with any of the methods would be greatly enhanced by the development of properly validated mathematical modelling techniques to simulate the origin, growth and bloom-forming properties of the algae.

3.38 Little is known about the environmental behaviour and fate of toxins produced by blue-green algae. Better analytical techniques, toxicity testing methods, and reference collection material are needed, as is research to determine the mechanism used by the algae for, and the effect of environmental controls on, toxin production.

Discussion

3.39 The evidence presented in the report is discussed in detail, particularly in relation to the problems of 1989, and the state of knowledge regarding the formation of blooms of blue-green algae and their toxins. The control options which are currently available have been examined, and the chances of success of these measures explored in the context of the NRA's future needs. It is concluded that, in the short term, the threat to human health, livestock, and pets associated with contact with, and ingestion of, the toxic scums can be greatly reduced by increasing public awareness of the potential problems. In the longer term, it is necessary to consider individual waters on a case-by-case basis in order to determine the best means of reducing the problem. There are no quick and easy solutions to reducing the occurrence of toxic blooms of blue-green algae.

Recommendations

3.40 Many actions have already been taken by the NRA in 1990 to reduce the risks associated with toxic blue-green algal blooms this year.

3.41 There are a number of recommendations for future action in the report, the key one being that an action plan should be produced for each waterbody affected by blue-green algal blooms. These plans should indicate the control options presently available, and the work necessary to enable more effective management actions to be taken. A procedure in the form of a decision-tree is presented, to assist in the production of these action plans. Key research needs are identified and recommendations made regarding longer-term control measures. These include various approaches to nutrient control, where appropriate. The need for quality standards relating to blue-green algae and their toxins needs to be addressed.

3.42 The Toxic Algae Task Group will continue to meet to assess the results from the monitoring and research programmes and, in the light of these, to review NRA policies on monitoring and control measures.

4 GENERAL INTRODUCTION

4.1 The NRA's launch as a national body in September 1989 coincided with an extensive occurrence of blooms of blue-green algae in reservoirs and lakes throughout England and Wales. The Water Act 1989 gives the NRA wide ranging duties and powers, including those relating to monitoring, maintaining and, where necessary, improving water quality. It also allows for statutory water quality objectives to be set by the Secretary of State, who has joint responsibility with the NRA to ensure compliance. Such objectives have yet to be set; although certain standards are embodied in various EC Directives, for which the NRA is the 'competent authority' to carry out the monitoring work. The NRA therefore assumed responsibility for monitoring with respect to Directive 75/440/EEC concerning the Quality of Surface Water intended for the Abstraction of Drinking Water, commonly referred to as the 'Surface Water Directive', but this did not contain any standards relating to algae.

4.2 Thus, although it was appreciated that the presence of algal blooms in inland waters was often regarded as a nuisance, there were no specific 'standards' being breached; an excessive input of nutrients to inland waters was usually cited as the cause. It was also known that certain species of blue-green algae could produce toxins. The extensive blooms of blue-green algae in the late summer of 1989, however, were accompanied by reports of the deaths of sheep and dogs at Rutland Water, and of the suspected poisoning of young soldiers at Rudyard Lake in Staffordshire. The NRA had to carry out extensive monitoring of waters, including toxicity testing; many waterbodies were closed to the public. All of these events were widely reported in the media.

4.3 Once the 1989 event had subsided, the NRA decided to conduct an enquiry into the causes and effects of toxic blooms of blue-green algae, and to produce a report. This has been achieved by setting up a 'Toxic Algae Task Group' of both NRA and non-NRA experts. The Task Group was asked to make a full assessment of the problems which occurred in 1989 in the UK and abroad, and to carry out a review of the factors which influence the production of blue-green algal blooms and their toxins. It was also asked to make recommendations for monitoring and to suggest measures to be taken to minimise the problem in the future. Its remit did not, however, include an extensive investigation into the human-health related aspects of blue-green algal toxins, because this is not the responsibility of the NRA. Since its formation in December 1989, the Group has met twelve times, and has been in regular communication to consider various aspects of the production of the report.

4.4 As part of the investigation, the scientific literature was searched for publications on the production of toxins by blue-green algae, and on their toxicity. Searches were also carried out on twelve major commercial databases, and on the internal Water Research Centre (WRc) Environmental Toxicology Database. References to marine blue-green algae were excluded, and no search was made of the substantial literature on the general biology and ecology of freshwater blue-green algae.

4.5 A number of workers of note, and centres of expertise, emerged from the review process. Workers in seven countries (UK, USA, Australia, Norway, Finland, Japan and the Soviet Union) were found to be particularly active, with additional interest being expressed by individuals in a number of other countries; in most countries there was one particular individual or centre of expertise, sometimes with support from other centres or individuals with a particular skill. The most active have been the groups in the UK, USA, Australia and, more recently, Finland. There are other centres of expertise in different parts of the world whose interest is primarily in marine algal toxins.

4.6 The review of the events in 1989 has included a summary of all the information obtained by the ten NRA Regional units since their formation on 1st September 1989. All water supply undertakers, Scottish River Purification Boards, Scottish public water supply authorities, and the Department of the Environment Northern Ireland were asked to supply information on any problems they experienced with blue-green algae in 1989. In addition, contacts were made with colleagues in Europe, Australia, Japan and elsewhere. The review includes a full description of what actually occurred in 1989, what the probable causes were, and who was affected. It also contains a summary of the current extent of knowledge on the wide variety of toxins known to be produced by freshwater blue-green algae, because such an understanding is an essential precursor to assessing the factors affecting their production, and to understanding their importance.

4.7 In the middle of the review exercise, it became apparent that extensive blue-green algal blooms could occur again in 1990. Thus short-term recommendations were made with respect to monitoring waters likely to be affected, and to the best means of informing relevant authorities and the public. These recommendations have already been implemented. The report therefore addresses both the short-term and the long-term aspects of the problem. It has been recognised, however, that there are no easy solutions.

4.8 The report has been produced in a relatively short time-scale. It is not intended to be a scientific document; however, a list of references is provided, plus a glossary. A number of recommendations have been made, which the NRA will have to consider and prioritise. These will undoubtedly have to be reviewed in time; it has been agreed, in any case, to maintain the Task Group in its present form in order to review the events of 1990, the effectiveness of the short-term measures, and the implementation of the longer-term actions.

5 BLUE-GREEN ALGAE AND THEIR TOXINS

Introduction

5.1 Many microscopic organisms pass their lives in suspension in the open water of lakes and reservoirs. Those that are able to sustain their growth and energy requirements by photosynthesis are grouped under the main heading of phytoplankton. Most species of phytoplankton are true algae, but many are more primitive plants called cyanobacteria, having some properties characteristic of both bacteria and algae. Because of their distinctive colour and characteristics, they are more commonly known as blue-green algae, and this report will refer to them as such. Many species of blue-green algae are at a competitive advantage over other algae because they possess the ability to 'fix' gaseous nitrogen dissolved in water. They are therefore potentially, at least, capable of living in media with low levels of combined nitrogen. One other distinctive characteristic is the possession, by some species, of specialised intracellular gas-vesicles. Stacks of these minute (< 300nm) proteinaceous hollow cylinders maintain a gas-filled space in the cell which, cumulatively, may occupy some 2 to 20% of the volume of the intact cell. The effect of this space is to lower the density of the organism, potentially below that of the surrounding water, such that it becomes buoyant.

5.2 At times, it is possible for buoyant blue-green algae to accumulate at the surface of the lakes in which they grow. When large numbers of cells are concentrated by wind drift to lee shores, the intensity of the buoyant scums, the resultant discoloration of the water, and the rapidity of change, are immediately apparent. These mass aggregations have earned the collective term, 'water blooms'; because common usage of the word 'bloom' now refers to high concentrations of algae throughout the water column, the word 'scum' is used in this report to refer to surface aggregates.

5.3 A further distinctive feature of some blue-green algae, mainly of the genera *Anabaena*, *Aphanizomenon*, *Microcystis* and *Oscillatoria*, is that some species are known to produce chemicals which are toxic to mammals. It is not clear whether they produce the toxins only under certain environmental conditions, whether 'non-toxic' strains become 'toxic', or 'toxic' strains vary in toxicity at different times. At present, it is reasonable to regard all blooms of such species as being 'potentially able to produce toxins'.

Historical and International Perspectives

5.4 It is important to emphasise that the incidence of blooms and surface scums in UK lakes and reservoirs in 1989 is by no means unprecedented. The first authentic description of a scum on Llangorse Lake, Powys, dates from the twelfth century. In parts of the Midlands, scum formation was sufficiently common to have ominous and portentous significance in local folklore. Fossil evidence from the sediments of these lakes points to the occurrence of bloom-species there for at least 3500 years!

5.5 Not even the reports of animal deaths in 1989, in which blue-green algal poisoning was implicated, are new. Deaths of fish, birds and cattle, after contact with bloom material, have been reported in the scientific and technical literature for many years, although the reports are usually circumstantial rather than proven. In some instances, these deaths may have been attributable to other toxic organisms, such as the bacterium which causes botulism and which is sometimes found associated with algal scums.

5.6 The incidence of blue-green algal toxicity is well known in many countries. Investigations into the causes have been under way for many years, particularly in the USA, Australia and Scandinavia, from where some of the clearest cases of lethal and sub-lethal animal poisonings have come. Blue-green algal blooms are widespread in fertile lakes and they occur more frequently in the warmer, tropical countries, although they also occur in Norway and Denmark where there has been public recognition of the associated problems for several years. These problems have been accepted and accommodated in water management, and their potential adverse health affects advertised by public awareness campaigns.

Review of Toxins, Their Production and Their Effects

5.7 The blue-green algae which commonly form blooms in UK and European fresh waters belong to groups which include species capable of producing toxins. Such blooms consist of either one, or a mixture of two or three, species. When poisoning incidents have been suspected, following ingestion of bloom material by animals, samples of the algae have usually been collected and tested for toxicity using laboratory mice. About 25 species of blue-green algae have been suspected of producing toxins, because they were the dominant species present at the time. Confirmation requires that the suspected species be isolated, grown in culture in the laboratory, and re-tested. This has been done for at least 11 species, and the signs of poisoning in animals caused by the algae have been reproduced. Without this procedure the possibility cannot be discounted that the bloom toxicity could be due to minor components, including other blue-green algal species or associated bacteria.

5.8 Not all blue-green algae suspected of being toxic have been successfully isolated and grown in the laboratory to date, although toxins have been extracted and purified from a number of freshwater species (Table 1). These include *Microcystis aeruginosa*, which has been most often cited in confirmed and suspected animal and human blue-green algal poisoning incidents world-wide, and species of *Anabaena*, *Oscillatoria* and *Aphanizomenon*, which are also widely implicated in poisoning episodes. Work is continuing at the University of Dundee, and several overseas laboratories, on the isolation of toxic strains and purification of the toxins.

5.9 It must be emphasised that toxin-forming blue-green algae are all naturally occurring members of the phytoplankton of freshwaters. There are also many other toxins which are produced naturally. Table 2 shows a comparison of toxicity values, derived from laboratory experiments, for a range of biological toxins.

Occurrence of Toxic Blue-Green Algal Blooms in European Freshwaters

5.10 Toxic blue-green algal blooms have been reported from 16 European countries: Czechoslovakia, Denmark, Finland, France, the German Democratic Republic, the German Federal Republic, Greece, Hungary, Italy, the Netherlands, Norway, Poland, Portugal, Russia, Sweden and the UK. Although cases of animals, fish and birds suspected of being poisoned by blue-green algae have been reported in several European countries, including the UK, the positive results from testing blooms for toxicity have clearly shown that the incidence of toxic blue-green algae is much wider than would be inferred from suspected poisoning incidents.

Table 1 Freshwater blue-green algae in blooms implicated in poisoning incidents: confirmed toxic blue-green species and purified toxins

Species	*As bloom components*	*As pure cultures*	
		Cells	*Purified toxin*
Anabaena circinalis	+	+	+
Anabaena flos-aquae	+	+	+
Anabaena lemmermanii	+	nd	na
Anabaena solitaria	+	nd	na
Anabaena spiroides	+	nd	na
Anabaena venenosa	+	nd	na
Anabaenopsis milleri	+	nd	+
Aphanizomenon flos-aquae	+	+	+
Coelosphaerium kutzingianum	+	nd	na
Cylindrospermopsis raciborskii	+	+	na
Cylindrospermum sp.	+	+	+
Gloeotrichia ecinulata	+	+	na
Gloeotrichia pisum	+	nd	na
Gomphosphaeria lacustris	+	nd	na
Gomphosphaeria naegeliana	+	nd	na
Microcystis aeruginosa	+	+	+
Microcystis incerta	+	nd	na
Microcystis viridis	+	+	+
Microcystis wesenbergii	+	nd	na
Nostoc sp.	+	+	+
Oscillatoria agardhii	+	+	+
Oscillatoria agardhii var. isothrix	+	+	+
Oscillatoria rubescens	+	nd	na
Oscillatoria sp.	+	nd	na
Synechocystis sp.	+	nd	na

+ = toxic in mouse bioassays
nd = not determined
na = not available

5.11 Toxicity assessments of over 200 blue-green algal blooms from European countries prior to 1989 revealed that 44 to 75% had produced toxins. In the case of the small number of blue-green blooms analysed in Hungary, Greece, and Italy; all had produced toxins. These data are given in Table 3. In 1989, 60 to 70% of the blooms tested in the UK had produced toxins.

5.12 Both the presence and the extent of toxicity of blue-green algal blooms in a single freshwater body have been shown to vary widely when compared on a weight-for-weight basis of algal material. Such variation may be observed at a single waterbody between areas of surface scum in a mosaic fashion, and from week to week at a single sampling site. Although bloom toxicity varies widely within any one year, sampling at Loch Balgavies, Scotland, a site which supports blooms of *Microcystis aeruginosa*, has demonstrated that blooms have produced toxins on some occasions each year since sampling began in 1981. Toxic blue-green algal blooms have even been identified under ice cover in December in Scotland and Finland.

Table 2 Comparison of toxicities of biological toxins

Toxin	*Source*	*Common Name*	*Lethal Dose** (LD_{50})
BOTULINUM TOXIN-a	*Clostridium botulinum*	(BACTERIUM)	0.00003
TETANUS TOXIN	*Clostridium tetani*	(BACTERIUM)	0.0001
RICIN	*Ricinus communis*	(CASTOR BEAN PLANT)	0.02
DIPHTHERIA TOXIN	*Corynebacterium diphtheriae*	(BACTERIUM)	0.3
KOKOI TOXIN	*Phyllobates bicolor*	(POISON ARROW FROG)	2.7
TETRODOTOXIN	*Sphaeroides rubripes*	(PUFFER FISH)	8
SAXITOXIN	*Aphanizomenon flos-aquae*	(BLUE-GREEN ALGA)	9
COBRA TOXIN	*Naja naja*	(COBRA)	20
NODULARIN	*Nodularia spumigena*	(BLUE-GREEN ALGA)	30-50
MICROCYSTIN-LR	*Microcystis aeruginosa*	(BLUE-GREEN ALGA)	50
ANATOXIN-a	*Anabaena flos-aquae*	(BLUE-GREEN ALGA)	200
MICROCYSTIN-RR	*Microcystis aeruginosa*	(BLUE-GREEN ALGA)	300-600
CURARE	*Chrondodendron tomentosum*	(BRAZILIAN POISON ARROW PLANT)	500
STRYCHNINE	*Strychnos nux-vomica*	(PLANT)	500
AMATOXIN	*Amanita phalloides*	(FUNGUS)	600
MUSCARIN	*Amanita muscaria*	(FUNGUS)	1100
PHALLATOXIN	*Amanita phalloides*	(FUNGUS)	1800
GLENODIN TOXIN	*Peridinium polonicum*	(DINOFLAGELLATE ALGA)	2500
SODIUM CYANIDE			10000

* The acute LD_{50} in µg per kg bodyweight: intra-peritoneal injection: some with mice, some with rats

Table 3 Incidence of toxicity of blue-green algal blooms in European fresh waters prior to 1989

Origin	*Number of Sites with blooms tested*	*Number of Sites with toxic blooms*	*% incidence of bloom toxicity*
United Kingdom	24	18	75
Norway, Finland and Sweden (joint programme)	51	30	59
Sweden	27	15	56
Finland	103	45	44
Hungary	3	3	100
Greece	4	4	100
Italy	2	2	100

Structure and Activity of Blue-Green Algal Toxins

5.13 Only in the past 10 years has rapid progress been made with the identification and characterisation of blue-green algal toxins.

Those produced by freshwater species fall into three categories:

- neurotoxins, some of which are alkaloids;
- hepatoxins, which are peptides; and
- lipopolysaccharides (LPS) which are compounds of fats and sugars

5.14 In order to assess the potential hazard associated with the toxins, it is first necessary to make an assessment of their toxicity under laboratory conditions; this requires giving doses to laboratory animals. The demonstration of toxicity does not therefore necessarily indicate an environmental hazard. Toxicity depends upon the route of administration, the size of the dose, and the period of exposure. The results of the tests are categorised into high, medium and low levels of toxicity.

Neurotoxins

5.15 Neurotoxins are produced by several blue-green algae, including species of *Anabaena*, *Aphanizomenon* and *Oscillatoria*. Two *Aphanizomenon* toxins have been identified; these are alkaloids, of the same or similar structure to saxitoxin, and other neurotoxins, produced by some marine dinoflagellate algae and which are responsible for paralytic shellfish poisoning (PSP).

5.16 Several *Anabaena* toxins exist. One, anatoxin-a, is a structural analogue of cocaine and is a potent neuromuscular blocking agent. Another; anatoxin-a(s), which is a potent inhibitor of acetylcholinesterase (an enzyme important in neurotransmission), is an organophosphorus compound. Neurotoxins from *Oscillatoria agardhii* and from Scottish blooms of *Anabaena* have recently been found. These have not been chemically characterised, but have a similar effect to anatoxin-a(s).

5.17 Signs of poisoning in animals which have ingested scums containing blue-green algal neurotoxins from the edge of a waterbody; include paralysis, respiratory arrest, muscular tremor, salivation, staggering and convulsions.

Hepatotoxins

5.18 The hepatotoxins, or liver toxins, produced by several blue-green algal species, are by far the most commonly encountered and have been implicated in the majority of environmental incidents involving toxic freshwater blooms. These toxins are produced by strains of species of *Microcystis*, *Oscillatoria* and *Anabaena*. Signs of poisoning in animals ingesting scum include weakness, vomiting, cold extremities, piloerection, diarrhoea, heavy breathing and death due to circulatory shock within 2 to 24 hours. Circulatory shock is induced by pooling of blood in the liver, where the toxins have been shown to accumulate rapidly. The toxins also cause atypical pneumonia in laboratory animals.

5.19 In vertebrates, the liver appears to be the prime site of action for the toxins, but the specificity for this organ has not been fully explained. Microcystin-LR, the best studied of the toxins, has been shown to be toxic to liver cells in tissue culture, but claims of specificity when compared with other cells in culture have not been confirmed, because toxicity has been shown to affect a range of cell types. The toxins cause major perturbations to the protein skeleton which maintains cell structure and which is important in cell division. The primary mode of action of microcystin is currently being studied.

5.20 Several names have been given to the hepatotoxins, including cyanoginosins, cyanoviridin and microcystins. The name microcystin is now most favoured. The toxins are variants of a cyclic structure which contains seven amino acids and has a molecular weight of about 1000. Nine structural variants have been isolated, with molecular weights from 909 to 1044, with some variation in their reported acute toxicity to mice by intra-peritoneal injection. Microcystin-LR appears to be the most commonly encountered variant, and is produced by at least one strain of *Anabaena flos-aquae* and several strains of *Microcystis aeruginosa*. The latter species produced the principal algal toxin identified at Rutland Water in the autumn of 1989. Many laboratory strains, and natural algal blooms, produce more than one variant of the toxin.

5.21 The toxicity of microcystin-LR has been better studied than other variants and it appears to be one of the most toxic. The acute LD_{50} in mice, by intra-peritoneal injection of a single dose of pure toxin is about 50µg per kg bodyweight. A 100% lethal dose by this route is about 1 to 2µg of pure toxin per mouse; however, toxicity by oral administration requires a dose which is about an order of magnitude greater.

5.22 A one-year study has been carried out in Australia, in which extracts of toxic *Microcystis* bloom material containing microcystin were given to mice in their drinking water. It is not clear from the report which variant of the toxin was present, or whether or not several forms of microcystin were included. Furthermore, there were no control groups using non-toxic strains of *Microcystis*. The undiluted extract was reported to have a toxin concentration of 56.6µg per ml. In a 23-day preliminary study, raised serum enzyme levels, indicative of liver damage, were observed in animals given one quarter dilution, one half dilution, and undiluted extract. In the long-term (1 year) study the only significant, treatment-related, effects were increased mortality – particularly in males – receiving greater than one sixteenth dilution. Liver damage was only observed in the groups receiving undiluted or one half dilution extract. Animals in these groups did not survive beyond 9 and 14 weeks respectively.

5.23 The limited data on reproductive toxicity of algal toxins also relate to the hepatotoxin of *Microcystis*. These studies indicate that the toxins are embryotoxic following the administration of very high doses to pregnant females by intra-peritoneal injection. Haemorrhages, observed in internal organs of foetuses, indicate that the toxin may be able to pass through the placenta. There are also only very limited data indicating a possible adverse (teratogenic) effect on the foetus following exposure to high doses by the oral route.

5.24 Extracts of toxic blooms of *Microcystis aeruginosa* and microcystin have been tested for mutagenicity in short-term tests *in vitro* and in whole animals. Results from the Ames test, and other bacterial mutagenicity assays, indicate that these toxins are not mutagenic in bacteria. There are some data to suggest that they may cause damage to chromosomes and stimulate cell division in mammalian cells in tissue culture, but limited *in vivo* studies with rats produced conflicting results.

5.25 One brief incomplete report of an experiment in mice raised the hypothesis that unspecified doses of extracts of *Microcystis* given by mouth could increase the size of skin tumours caused by another chemical (dimethylbenzanthracene) applied to the skin, i.e. they exhibited tumour promoting properties. Unpublished studies of the effect of microcystin on enzymes *in vitro* may indicate a possible mechanism for such an effect. It is not known if these findings are relevant to the very different circumstances of exposure of humans and animals to blue-green algae in freshwater.

Lipopolysaccharides

5.26 Many blue-green algae, in common with some bacteria such as *Salmonella*, produce lipopolysaccharides (LPS) as normal components of their outer layers. LPS vary in chemical composition and consist of chemical combinations of fats and sugars; some also contain phosphate. This variation occurs even between different strains of a single blue-green algal species. There are few data on the toxicity of blue-green algal LPS, although they are lethal to mice by injection. They are less toxic than *Salmonella* LPS toxin. It has been reported that injections of 1.0 to 1.2mg per mouse of LPS from *Microcystis aeruginosa* is lethal within 48 hours. It is possible that LPS may be responsible for the irritation of skin observed in swimmers in contact with algal blooms in the UK, and for gastrointestinal disorders associated with blooms in the USA.

Factors Affecting Toxin Production

5.27 In order to understand the variability in toxin levels in blue-green algal blooms, and to provide a rationale for the prediction and limitation of the formation of these compounds, it is necessary to acquire knowledge of the regulation of toxin production. Information is needed at the physiological, biochemical and genetic levels.

5.28 Some research has been carried out into the factors affecting toxin production by pure cultures under laboratory conditions, although these studies relate only to microcystin and anatoxin-a. Early studies were limited to estimates of the effects of varying conditions on the toxicity of crude cell preparations, as determined by mouse bioassay. Although microcystin levels are influenced by temperature and light, further studies are needed to clarify the effects of these factors. It has been shown that the transfer of *Microcystis* cells from phosphate-rich to phosphate-free media prevented a further increase in biomass, but the toxicity per unit biomass remained constant. The removal of nitrate and bicarbonate from the media, however, resulted in a decrease in toxicity per unit biomass.

5.29 There has been some research into the genetic basis of toxin production by blue-green algae. Studies have shown that the genes responsible for the regulation of toxin production are not connected with extra-chromosomal DNA, present as plasmids, although the possibility remains that plasmid DNA which has become integrated into the chromosome may be involved in some way. It is unlikely that such relatively complex, though small, molecules will be produced by a single gene. They may be secondary products of cell metabolism which are formed by complex biosynthetic pathways, requiring the participation of several enzymes and genes.

5.30 Toxin production by algal strains maintained in the laboratory is generally a very stable phenomenon. Toxic strains of *Microcystis* have been maintained at the University of Dundee for 14 years, and non-toxic strains for 4 years, without change. Recently, however, a strain of *Anabaena flos-aquae*, which produced both hepatotoxin and neurotoxin, spontaneously lost the ability to produce either. The reason for this is not known. Knowledge of the genetic basis of blue-green algal toxin production would help in the understanding of toxin formation in waterbodies and may enable diagnostic tests to be developed in the future as an aid to toxic bloom recognition.

The Release of Blue-Green Algal Toxins Into Water

5.31 Toxin release varies between species of blue-green algae, but this subject has not been extensively studied under different environmental conditions. Laboratory studies with toxic *Microcystis* strains collected from lakes have shown that a substantial release of toxins from the cells into the water occurs when the blooms die, because of cells breaking down (Table 4). Whether or not these laboratory observations resemble events during the end-of-season die-off of blooms in lakes is not known, but if so, then a rapid transfer of toxins from cells to water may occur. Most of the microcystins produced by pure *Microcystis* cultures in the laboratory are also retained within the cells, until they eventually break down and die. A substantial release of microcystins from healthy growing cultures of *Oscillatoria* has, however, been observed. Reports of microcystins found in lake water during the course of a bloom also suggest that a significant release of the toxins occurs before the blooms age and break down.

Table 4 Distribution of microcystins during laboratory culture of Microcystis aeruginosa

Age of Culture	*% Distribution of Toxins*	
	Cells	*Water*
Young, slowly-growing cells	100	0
Young, rapidly-growing cells	75-90	10-25
Old slowly-growing intact cells	70-80	20-30
Old decaying cells (leaking cell contents)	30-40	60-70

It is, therefore, conceivable that there is some release of toxin from the blooms during their growth phase, with a greater release of microcystins upon cell death. This also raises the possibility that treatments which may kill blue-green algal blooms by causing the cells to burst (e.g. copper sulphate addition, or chlorination) may also cause a sudden release of toxins into the water. There are no data available on the release of neurotoxins or lipopolysaccharides into water. There is a need to study toxin release from the blooms in the field, because it is essential to know whether the toxins are actively secreted into the water or passively released only when the cells die.

The Functions of the Toxins

5.32 Although the structure and basic toxicological properties of several toxins are known, their biological functions are not. Some *Microcystis* hepatotoxins have been shown to be toxic to filter-feeding water fleas (*Daphnia*) which are potential consumers of the algae, and to some protozoan ciliates. They may, of course, be produced for purposes quite unrelated to their toxicity.

Detection and Analysis of Blue-Green Algal Toxins

5.33 Detection of the toxic properties of blue-green algae has been largely dependent on the intra-peritoneal injection of extracts of algal material into laboratory mice. This assay has the particular advantage of being rapid and sensitive to any toxin present. There is a need to replace these tests with chemical methods, although even with the development of analytical techniques for at least some of the toxins, there remains a need for rapid bioassays for use in conjunction with chemical analysis. It is desirable that such bioassays are sufficiently robust and simple to be used in small laboratories without specialised equipment and facilities. It is also desirable that no more laboratory vertebrates, particularly mammals, are used than is necessary.

5.34 At present, the best developed biological techniques are those using mammalian cells in tissue culture. Cell damage, following the introduction of toxin, is examined by microscopy or by measurement of enzyme leakage from the cells. The assays are, however, relatively lengthy and labour intensive compared with the mouse bioassay. They have been tested primarily using the microcystins, but there is some information to indicate that they are poor at detecting neurotoxins. There appear to have been no attempts to assess LPS by this method. These cytotoxicity assays offer considerable scope for blue-green algal toxicity assessment, but further research and development is needed.

5.35 The toxins from blue-green algae have not been systematically tested against bacteria; biochemical evidence has so far suggested that they are particularly active against animal and plant cells rather than bacteria. Recent observations of the effects of microcystin against a light-emitting bacterium, however, indicate measurable toxicity. The potential advantages of such an assay in terms of speed and cost make further investigation highly desirable.

5.36 Agglutination of isolated red blood cells from mammals has also been examined as a possible screen for toxicity; however, the original results have been difficult to reproduce. This approach, therefore, appears unlikely to be worthy of further consideration.

5.37 A specific assay for LPS already exists and is available in the form of commercial kits; this is the *Limulus* amoebocyte lysate (LAL) gelation assay, developed to detect LPS from bacteria.

The technique has not been systematically evaluated with LPS from blue-green algae and there is a need to carry out further work on this assay for routine screening purposes.

5.38 A further approach which may offer a rapid and simple screening test is that of immunoassay. This type of test could be used by field officers to determine whether a bloom is producing a toxin and, if so, to establish the nature of the toxin. This technique is based on the production of antibodies against the toxin and the attachment of a specific enzyme to them. When the antibodies attach to the toxin, the enzyme can be used to produce a reaction with further reagents to give a colour change. This is the basis of the enzyme-linked immunosorbent assay (ELISA) which is widely used for the assay of biological products. Antibodies have already been produced against microcystin and demonstrated to be specific. Tests with ELISA have shown this to be at least as sensitive as the mouse bioassay. The potential of this technique, to provide either broad spectrum or specific toxin assays, warrants further investigation.

5.39 One of the analytical problems has been the lack of well established and validated methods to enable the accurate quantification of toxin concentrations in environmental samples. The difficulties of developing and applying such methods are compounded by the complexity of the samples and the need to separate the toxins from other constituents. This problem is even greater when attempting to identify toxin in tissues from animals suspected of being poisoned by blue-green algae.

5.40 Three approaches have been used for the detection of hepatotoxins: thin-layer chromatography (TLC), high-performance thin-layer chromatography (HPTLC), and high-performance liquid chromatography (HPLC). TLC and HPTLC have been shown to give good qualitative analysis of the toxins, but HPLC is the method of choice for accurate quantification. However, before analysis there is a need to extract the toxins from the cells, to recover free toxin from water, and to clean up the samples by removing most of the unwanted material. It is the extraction and clean-up procedures which, potentially, introduce most of the problems. Areas of particular concern are efficiency of recovery of the toxin from the original sample, losses of toxin in the extraction and clean-up procedures, and the co-extraction of interfering substances which may distort the final result.

5.41 The approach most commonly favoured is solvent extraction after disruption of the cells, followed by concentration and clean up. Analysis is by HPLC. The performance of the method is assessed by adding known quantities of pure toxins and carrying out standard analytical procedures. It is important that a proportion of results, particularly in the event of wide fluctuations in the data, should be confirmed by an additional method of identification, such as Mass Spectrometry.

5.42 Methods for the detection and quantification of neurotoxins from laboratory cultures and scums are available, but require standardisation. As with microcystins, procedures for the quantitative recovery of these toxins from water are needed. Chemical and biological techniques also exist for the identification of blue-green algal LPS, but quantification has not been developed.

6 REVIEW OF FACTORS AFFECTING THE INCIDENCE OF BLUE-GREEN ALGAL BLOOMS

Introduction

6.1 Until rapid assays for toxicity become available, the assumption must be that all blooms of blue-green algae may be toxic. Several aspects of the biology of blue-green algae need to be considered to understand why and where blooms occur, including the factors which contribute to their abundance, and those contributing to the formation of scums on the surface.

Factors Favouring Abundance

6.2 Generally in the UK, most waters supporting blue-green algal growth have a sequence of algal dominance; for instance, diatoms in the spring, then green algae, followed by blue-green algae in the summer. No single factor is crucial to the growth of blue-green algal populations; instead, a number of criteria have to be satisfied which are not the same for all species. There is an extensive literature on the topic, though it has to be said that some aspects continue to be debated.

6.3 The blue-green algae owe their name to the presence of accessory pigments, called phycobilins, which intercept light energy required in photosynthesis. These can make the cells appear not just blue-green but, sometimes, browny red. They can utilise low light intensities by absorbing light over a wide band of the visible spectrum. This has earned the blue-greens a reputed preference for low-light environments. Though this has been shown to be true for the filamentous forms like *Oscillatoria*, it does not seem to apply to the colonial forms like *Microcystis*. Artificial mixing into the darker depths of reservoirs provides an effective way of preventing *Microcystis* growth, but it is also quite effective in promoting the growth of *Oscillatoria*.

6.4 The rates of growth of most blue-green algae are generally slower than those of many other planktonic algae, especially in cold (< 8°C) water. Slow growth rates also require long hydraulic retention times in order to achieve a substantial increase in population. Blue-green algal blooms do not normally occur in highly flushed systems, with replacement times of less than 5 to 10 days, nor in the open channels of rivers.

6.5 Because the increased abundance of blue-green algae was often observed in lakes undergoing nutrient enrichment (or eutrophication), it was thought that these algae had an unusually high demand for phosphorus. The idea persisted, despite the paradox that the blue-green algae were abundant at those times of year when phosphorus concentrations were lowest, until techniques were developed sufficently to measure the requirements of cultured strains. It is customary to refer to a kinetic value, K_S, to describe the external nutrient concentration to maintain half the maximum growth rate. The K_S values of blue-green algae for phosphorus and for nitrogen are unremarkable, and actually lower than those of many other species. Two factors may assist blue-green algae to grow for longer in enriched lakes:

(i) more phosphorus may still be available after the demands of spring growth of algae have been satisfied; and

(ii) the blue-green algae are particularly efficient at storing phosphorus – enough to support up to two or three more doublings of cell numbers (i.e. a 4 to 8 fold increase) after phosphate has been exhausted from the water.

6.6 Blue-green algae have been shown to be dependent upon a number of trace elements – including sulphur and iron – but in Britain, even in upland, nutrient-poor, waters the amounts are generally more than sufficient for their needs.

6.7 Nitrogen is required by all algae, but several blue-green algae, including *Anabaena* and *Aphanizomenon*, can use gaseous nitrogen dissolved in water. If other nitrogen sources are deficient, these blue-greens therefore have an advantage over other planktonic algae and, provided phosphorus and iron are abundant, can dominate for long periods.

6.8 It is possible that other blue-green algae 'fix' nitrogen, but there is little evidence to show that they do so in the open water of lakes. Nevertheless, a low ratio of the availabilities of nitrogen (N) to phosphorus (P) has been shown to favour blue-green algal abundance. Experimental evidence has shown that, in comparison with the ratio of the optimum requirements of most algae (generally 16 to 23 molecules N:1 of P), it is actually lower (10 to 16 N:1 P) among the bloom forming blue-greens. However, this would only be important if one or both nutrients were in short supply. Work in Canada indicates that the phosphorus content of the water alone is the best predictor of blue-green abundance.

6.9 Other work has focussed upon the carbon requirements of the algae. Carbon is required for the sugars manufactured in photosynthesis and in proteins for building the cells. It is taken up as carbon dioxide (CO_2) in solution from the water, where it is replaced by a finite rate of absorption from the atmosphere. If there is rapid algal production, such as might be supported in nutrient-enriched waters, then CO_2 gas will be withdrawn from solution faster than it is replaced. In turn, the water loses acidity and the pH starts to rise. In soft waters, the pH may rise substantially, but in hard waters, buffered by bicarbonate, more CO_2 is released from the bicarbonate in solution, thus maintaining a carbon supply and keeping the pH steady. Blue-green algae seem to have lower K_s values for CO_2 uptake than most, but not all, green algae and so they should clearly benefit in productive soft waters. They are also able to use bicarbonate as a carbon source, but so can many other algae and the advantage is less clear. The above view is not universally accepted, but experimental evidence does suggest that it is important under some circumstances.

6.10 Whereas many planktonic algae are consumed directly by planktonic water fleas, copepods and protozoans, most of the blue-greens are not extensively eaten, except by some rarely-observed explosions of ciliate or rhizopod protozoa. Blue-green algae are susceptible to fungal, bacterial and viral attacks, but collapse of populations due to these agents are not well known in nature. Moreover, being buoyant when most competitors are heavier than water, reduces the risk of loss by sedimentation. It is clear that, by avoiding cropping by grazers and by reducing sedimentary losses that beset their competitors, blue-green algae are not always handicapped by having slow rates of growth.

Buoyancy Regulations

6.11 Buoyancy in the blue-green algae is not a passive condition but is actively regulated. Over periods of hours to days, the buoyancy of the cells is altered under physiological control. Cells receiving too little light become more buoyant and float upwards to where the light is stronger. If they start to receive too much light, buoyancy is lost and the cells can sink back. The main control operates through photosynthesis and breaks down if there is too little carbon. If there is too little phosphorus or nitrogen, they sink further before regaining buoyancy and thus may gain access to nutrients not otherwise exploited by other algae. The net effect of this mechanism is roughly to poise the algae at an intermediate point in the light gradient. Some *Oscillatoria* species can do just that.

6.12 Besides the regulated density of the cell, there is another factor in buoyancy which determines how fast or how far the algae move. Large objects float or sink faster than small ones of the same density, and spheres move faster than threads of the same volume and density. Thus, for a given adjustment of buoyancy, where an *Oscillatoria* filament might move 1m vertically in 3 days, a *Microcystis* colony would move the same distance in about 30 minutes. *Oscillatoria* are much more adept at forming their plate-like layers in the water column than *Microcystis*.

6.13 Such behaviour cannot occur in a waterbody whilst it is actively mixed throughout its depth. Input of solar heat warms water near the surface, so that it tends to float on top of the deeper, colder, water. The wind energy required to maintain full mixing is therefore increased, and if the energy available is less than that required to bring about full mixing, the interface between the warm and cold water moves towards the surface. Moreover, this warmer surface mixed layer continues to isolate the deeper, colder water until either the surface cools or wind action is strong enough to start mixing the two layers. In this way, the upper and lower parts of the water mass become separated, a process known as thermal stratification. The stratification may persist for a few hours, a few days, or for much of the summer.

6.14 Variability in wind strength and sunshine intensity ensures that the surface mixed layer of a stratified lake, or the entire water column of a shallow lake, are constantly liable to be mixed by vigorous wind action. When the wind drops, mixing will cease and the water will tend to stabilise towards the surface; although residual motion may take several hours to subside. The depth of the mixed layers is rarely less than the full depth of a shallow lake, but it can remain close to the surface for several months in a deep, sheltered one. Between these extremes, many lakes oscillate back and forth, stabilising in calm sunny weather and mixing down again on cooler windier days. As a result, the environment of the plankton is extremely dynamic, yet its importance to the ecology of the organisms has only come to be fully appreciated during the last decade, in which the physics of turbulence has been described mathematically. This concept of 'hydraulic variability' is particularly important to the biology of blue-green algae.

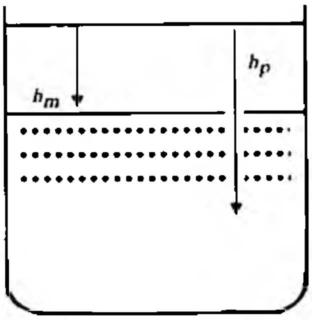
6.15 Because the speed at which the water currents are driven, and the depth to which the circulation is forced, are both dependent on the wind speed then, in general, the times taken to mix shallow layers and deep layers are about the same, within the range 5 to 50 minutes. It is therefore clear that the time taken to mix a water column, even if only a few metres in depth, is an order of magnitude less than the time taken for blue-green algae to reach, let alone remain at, a particular depth. The cells are, therefore, randomised and dispersed through wind-mixed layers.

6.16 It therefore follows that the algae can actively stratify only in the water below the depth of the mixed layer (h_m). Yet, for the buoyancy-regulatory mechanism to work, the depth of water to which adequate light for photosynthesis penetrates (h_p) has to be greater than the mixed layer ($h_p > h_m$). This is the typical location for species of the *Oscillatoria rubescens-Oscillatoria profilica* sub-group. In a permanently well-mixed lake, especially if it is rich in nutrients, and hence algae, it is particularly advantageous to be a good light receptor.

6.17 Buoyancy of blue-green algae is thus a vital factor in their ecological distribution. Different species of blue-green algae are especially successful in particular kinds of lake; examples are shown in Figure 1.

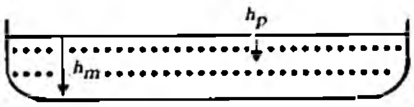
Figure 1 The relationship between mixed depth (h_m) and photosynthetic depth (h_p)

(a) Deep stratifying *Oscillatoria*



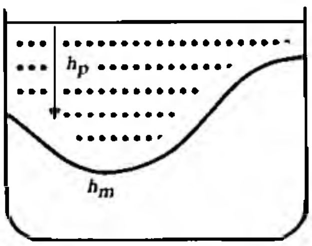
(a) Represents a deep, clear lake in which *Oscillatoria* can stratify at depth.

(b) Shallow mixed *Oscillatoria*



(b) Represents a shallow, well mixed turbid lake in which *Oscillatoria* can stratify at depth.

(c) Hydraulically variable *Microcystis*



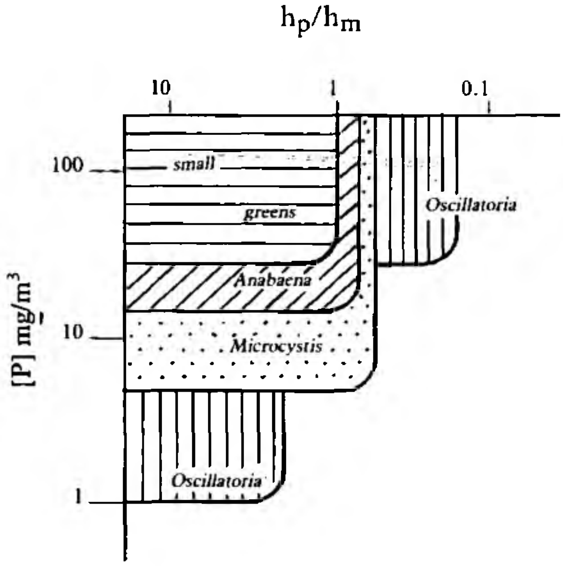
(c) Represents a lake in which the mixed depth (h_m) changes frequently and blue-green algae such as *Microcystis* attempt to adjust their buoyancy accordingly.

Distributions of Blue-Green Algae

6.18 Several deductions can therefore be made about the distribution of blue-green algal populations. Interactions between hydraulic mixing and light penetration may throw up extreme combinations (Figures 1(a) and 1(b)) in which *Oscillatoria* species may be favoured. Several good UK (Lough Neagh, Dogmersfield Pond, Shustoke Reservoir) and European (Veluwemeer, Wolderwijd, Norrviken, Schlactensee) examples of well-mixed, shallow or exposed lakes dominated by *Oscillatoria agardhii/Oscillatoria redekei* are available; examples of lakes with deep stratifying *Oscillatoria rubescens* populations come from alpine Europe and glaciated Norway. In the UK, the best examples have been in the smaller lakes of the English Lake District (Esthwaite Water, Blelham Tarn, Loweswater). In hydraulically variable habitats, there will be times of vigorous mixing, separated by periods of relative calm. A reduction in mixing will leave slow-moving *Oscillatoria* either high or low in the light gradient, but the more rapidly moving *Microcystis* will have adjusted their buoyancy and migrated towards a more favourable depth. As a consequence, in some tropical lakes, where solar heating is intense by day but night time cooling brings about a convective 'overturn' of the water, often assisted by afternoon winds, *Microcystis* is usually common and often overwhelmingly dominant (Figure 1(c)). These extremes are distinguished in Figure 2(a) in which the ratio of the depth to which light penetrates to the wind-mixed depth is plotted against the winter phosphorus concentration (P).

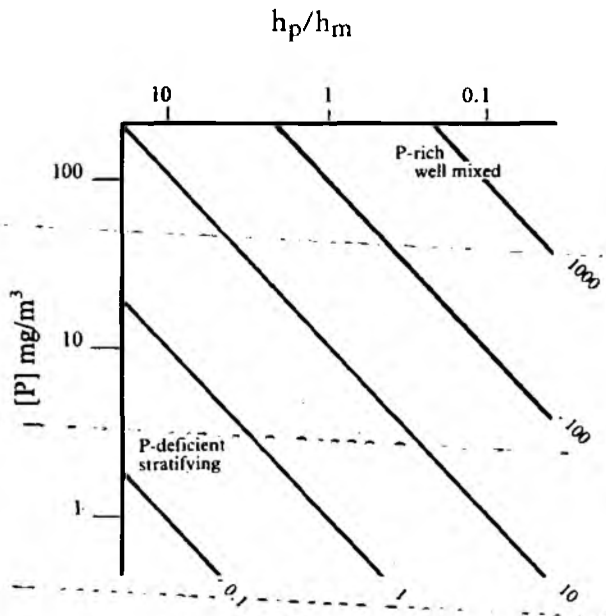
Figure 2 Representations of the distribution of blue-green algae in lakes and reservoirs

(a) Typical distribution related to light, mixing and P



Note to (a)
The h_p/h_m ratio is plotted against phosphorus concentration so that genera characteristic of more oligotrophic lakes appear towards the bottom of the diagram. Various species of *Oscillatoria* dominate at extremes while other blue-green algae such as *Microcystis* must compete with other types of planktonic algae in the more favourable environments.

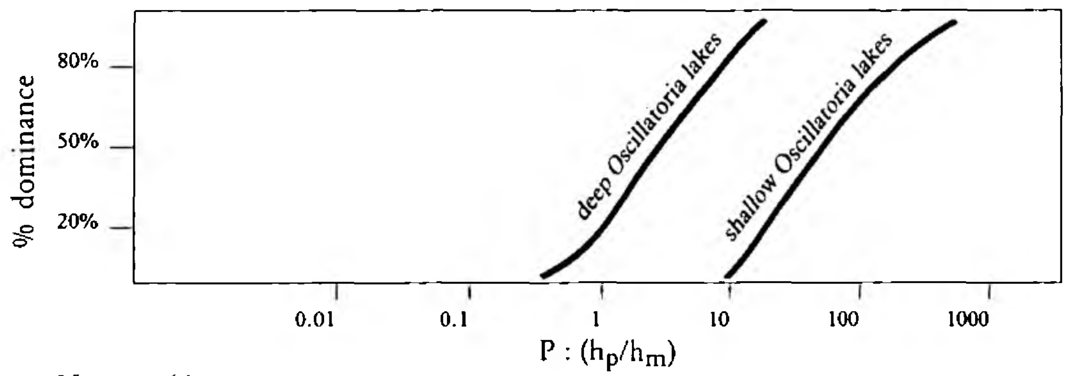
(b) Contoured matrix of parameters



Note to (b)
The matrix is contoured according to the ratio of P : (h_p/ h_m). Typical distribution of blue-green algae may be estimated by overlaying figure 2(b) with figure 2(a).

Figure 2 Representations of the distribution of blue-green algae in lakes and reservoirs (continued)

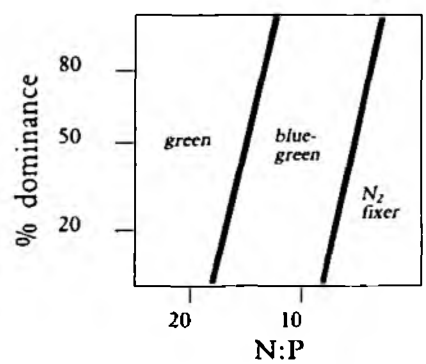
(c) Percent dominance by blue-greens



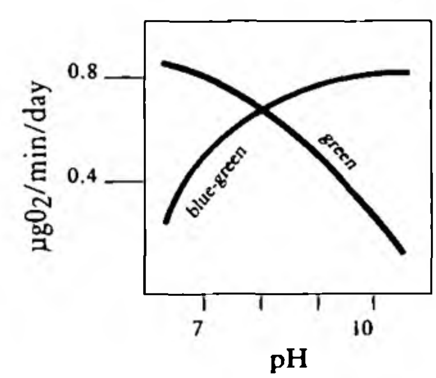
Note to (c)

The distribution of *Oscillatoria* dominance against P : (h_p/h_m) is shown; other algae will dominate in the mid ground between the two plots. The outcome of competition in this mid ground between blue-green algae such as *Microcystis* and other algal types is represented in terms of:

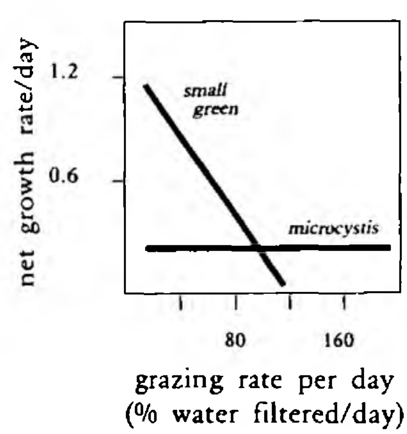
(d) Dominance



(e) Photosynthetic rate



(f) Net growth rate



6.19 Deep *Oscillatoria* layers may become prevalent where there is a modest increase in phosphorus availability. At higher phosphorus concentrations, however, more of these algae can be supported. These reduce the depth to which light penetrates and populations float higher in the lake (the ratio h_p/h_m diminishes towards 1), and eventually other algae compete more successfully than *Oscillatoria* for the nutrients. *Oscillatoria* are, however, more successful in competing for small amounts of light. If contours of the ratio $P:(h_p/h_m)$ are drawn (Figure 2(b)), then the frequency of *Oscillatoria* dominance can be represented in terms of that ratio (Figure 2(c)), which is based on a review of European experiences in lake restoration. In both cases, an increase in this ratio favours more *Oscillatoria*. The curves in Figure 2(c) are well separated. In the mid-range [$P: (h_p/h_m) > 3 < 300$], most other algae compete for living space. Figures 2(d), 2(e), and 2(f) show, respectively, how blue-greens like *Microcystis* may be favoured generally by N:P of < 10:1, pH > 8.5, and grazing rates when 80% of the total volume of water is filtered per day. All benefit from mild eutrophication, as indicated in the graphs, but the link between blue-greens and the concentration of available phosphorus is complicated by interactions with other factors.

6.20 The blue-green algae are extremely adept in responding to small or gradual changes in their environment. This enables them to compete successfully with less specialised species. Thus the principal factor in their dominance is that conditions do not change violently. Deep stratified lakes, shallow exposed ones, or even tropical lakes mixed each day, will continue to favour blue-green dominance for as long as conditions are constant. This is equally true for the more variable UK lakes and reservoirs, because although they support the same blue-greens each summer, the length of the growing season may well be crucial. In a summer of frequently altering conditions, blue-green algal dominance may be achieved only late in the year, if at all. Under 'constant' conditions, either with continuous wind mixing or a long spell of warm anticyclonic stability, the appropriate blue-green algae will be the more strongly selected.

Scum Formation

6.21 The preceding account has emphasised the importance of environmental conditions meeting the requirements of blue-green algal species, both physically and chemically, and of having an uninterrupted period of constant or regular mixing of the water, which allows sufficient opportunity for their growth to achieve a large or dominant population. In other words, the longer the period of environmental constancy, the bigger the 'bloom-forming' capacity. The assembled algal mass therefore represents the scale of surface scum formation that might occur but, if it is sufficiently windy, surface aggregation will not take place. Moreover, even when the wind stops, the buoyancy-regulation mechanism should ensure that surface-scum formation is avoided. The reason it does occur is that the algae are then less dense than the surrounding water, for which the term 'overbuoyant' has been used. The algae then float rapidly towards the surface, which they may reach before buoyancy can be reversed.

6.22 'Overbuoyancy' occurs as a natural response of the regulatory mechanism to environmental conditions at the time. Thus, for example, if the lake is mixed to 5 metres because of wind action, and this upper layer supports a growing population of *Microcystis*, as the algae increase in number, so the light penetration will decrease and, as the depth to which sufficient light penetrates becomes less than the mixed depth, the *Microcystis* will increase their buoyancy. Alternatively, if the wind mixing becomes more vigorous and the mixed depth increases to 10 metres, then as the cells are swirled through the mixed zone they spend more time in low or zero light and, again as a natural response of the regulatory mechanism, the *Microcystis* actively increase their buoyancy. If the wind now drops abruptly, the mixing stops but the algae continue to rise at the rate of, perhaps, 2 metres per hour, and become concentrated into a surface film.

6.23 During the night, the algae have no reference point, and do not actively regulate their buoyancy. Thus if they are wind-mixed during the day, and if the wind abruptly falls off at night, they rapidly float to the surface. The opportunity to reverse excess buoyancy in darkness is non-existent. Quite literally, scums can appear overnight. Thus, whereas this sudden appearance of a mass of algae at the surface — either at day or night — was once considered to be the product of explosive growth, it is now quite clear that surface scums are a product of a change in the weather acting on existing populations of blue-green algae, which had become large as a result of stable weather conditions.

6.24 The scum can be quickly broken by wave action and redispersed by renewed wind mixing. If, however, the breezes are too light to break the surface (< 1 metre per second), the scum merely drifts downwind and is deposited on lee shores and in quiet bays. It does not survive this treatment for very long: cells become stressed, releasing their contents and the distinctive copper-blue pigment into the water, and eventually die. Bacterial decomposition aids the rapid putrefaction of the material. The in-shore deposit is, at best, unsavoury, often repulsive and as is now fully appreciated, potentially toxic to livestock and other animals. Public distaste of scums is compounded by the suddeness of their appearance. Scum material may take rather a long time to disperse, either as a result of wave wash or, ultimately, disintegration.

7 IMPACT OF BLUE-GREEN ALGAL TOXINS ON WILDLIFE, DOMESTIC ANIMALS, AND HUMANS

Introduction

7.1 The tendency of most of the species of blue-green algae listed in Table 1 to form surface scums provides a means of concentrating the biomass many-fold. This concentration can be amplified and localised in a particular part of the waterbody, which may be the down-wind shore if a gentle breeze is blowing, or the scum may be more thinly dispersed over the entire lake surface in calm weather. A shoreline accumulation may be stranded on the surrounding stones or beach if the water level falls. The gas-vesicles of the blue-green algae also allow the cells to form subsurface bands under some conditions, so that the concentrated algal biomass is less readily observed. The accumulation of these scums along shorelines can present animals with a highly concentrated dose of cells, and possibly toxins, if they drink from the water's edge.

7.2 Published reports of animal deaths attributed to blue-green algal blooms extend back for more than a century, and relate to incidents world-wide. Cases have included sheep, horses, cattle, pigs, dogs and farmed fish. Wild animal poisonings attributed to blue-green algae have included rodents, amphibians, fish, water-fowl, bats, zebras and rhinoceros.

7.3 Documented cases of freshwater blue-green algal toxins suspected of causing human toxicity have never been properly confirmed. A number of illnesses, allergic reactions and skin reactions have, however, been ascribed to the accidental ingestion of, or contact with, blue-green algal blooms and scums.

Hazards to Wildlife and Domestic Animals

7.4 A few reports exist of the deaths of aquatic wildlife associated with toxic blue-green algal blooms. There are conflicting data on the toxicity of algal toxins to freshwater invertebrates, but there are indications that small aquatic animals, such as the water flea *Daphnia*, may avoid microcystin, and that the single-celled *Paramecium* are killed by microcystin in laboratory trials. It is not known whether these effects occur in lakes. It is not known whether fish can accumulate toxins, although the transmission of algal toxins through fish (particularly fish livers) was one theory advanced to explain the outbreaks of 'Haff disease' in fish-eating peoples around the Baltic. There is, in fact, very limited analytical evidence to indicate which species might accumulate toxins, and where in the body they will accumulate; without this information, it is not possible to assess the hazards to fish-eating birds and mammals.

7.5 A history of fish kills, which have occurred during periods of heavy blue-green algal blooms in freshwaters, does exist; although there is little direct evidence that the fish deaths were specifically due to blue-green algal toxins. Nevertheless, fish killed in blooms of hepatotoxic *Oscillatoria* in Scandinavia showed liver damage consistent with the effects of the toxins. Intra-peritoneal administrations of microcystins to rainbow trout and common carp, and of the neurotoxin anatoxin-a to goldfish, cause fatalities with the same gross symptoms and susceptibilities as in mammals. Because these fish are not plankton-feeders, it is not known whether they would normally ingest these toxins in freshwaters. Death due to deoxygenation of the water by decaying blooms has been postulated in the cases of trout deaths, and it is conceivable that plankton-feeding fish would normally be more susceptible to poisoning by the toxins. Deaths of large numbers of roach, bream, orfe and pike have been ascribed to microcystin poisoning in Scandinavia, although again this is not proven. Little is known of the possible irritant effects of LPS on fish gills.

7.6 There is clear evidence that microcystins and anatoxin-a can be accumulated by the freshwater Swan Mussel, *Anodonta cygnaea*. These filter-feeders can digest blue-green algae and can accumulate the toxins in their tissues. No evidence for mussel deaths due to microcystins is available, but small numbers of Swan Mussel fatalities due to exposure to neurotoxic *Anabaena* have occurred in laboratory trials.

7.7 Herbivores are known to drink from blue-green algal scums in periods of dry weather, when the moisture content of their forage grass is reduced and they are particularly thirsty, or when access to open, clearer water is restricted. Deaths of dogs have almost invariably occurred when the animals have been allowed or encouraged to enter water through the scum. When leaving the water, the animals have licked the scum adhering to their coats in grooming themselves and have thereby ingested a lethal dose.

7.8 It must be emphasised that in many of the reported cases of suspected blue-green algal poisoning, no subsequent investigation was carried out, and indeed autopsy confirmation has been hampered by the shortage of suitable analytical techniques.

7.9 The effects of blue-green algal toxins on wildlife are little understood, although occasional poisoning incidents which occur in waterbodies supporting toxic blooms indicate adverse effects on mammal, fish and bird populations. If livestock and pets are allowed to drink from the margins of lakes containing toxic scum, then illness and fatalities are likely to occur.

History of Suspected Blue-Green Algal Poisonings in Humans

7.10 Reports have been made, over the last 60 years, of the adverse effects on human health caused by blue-green algae and their toxins in fresh waters. These reports have emerged from the USA, India, Canada, Zimbabwe, Norway, the Baltic coast, the USSR, Australia and, more recently, the UK and fall into two main groups, which are discussed below; it should be noted, however, that no attempt has been made to evaluate their content.

Allergic Reactions and Skin Irritations

7.11 Isolated reports exist of incidents of swimmers developing adverse reactions after bathing and showering in water containing blue-green algal blooms. Reports of allergic reactions, asthma, eye irritation, rashes and blistering around the mouth and nose attributable to blue-green algal blooms are available.
Typical examples are as follows.

1945, 1951 (USA)
Positive reactions to *Oscillatoria* were obtained in skin tests.

1940-1980s (USA, Europe, UK)
Contact skin irritation or dermatitis from bathing in waters containing blooms of *Anabaena*, *Aphanizomenon*, *Gloeotrichia* and *Oscillatoria* have been observed in the USA and Europe, including the UK. The agents responsible have not been identified, but it is possible that algal LPS is involved in some of these incidents.

1980s (Norway)
Rashes and respiratory complaints were reported by people after showering in water containing toxic *Oscillatoria*.

1985 (UK)

Skin rashes were reported by people after sail-boarding on water containing toxic blue-green algal blooms.

Gastroenteritis and Hepatoenteritis

7.12 Most early reports are from the USA and Canada; they include information on gastrointestinal disorders, abdominal pain, cramps, and diarrhoea after accidental ingestion during swimming. Blue-green algal toxicity has been suspected where other likely causal agents (viruses and bacteria) were not found.

Typical examples are as follows:

1920-1930 (Baltic Coast and USSR)

Blue-green algal toxins were suspected of causing 'Haff disease', which affected large numbers of fish-eating people along the Baltic coast. Muscular pains, vomiting, respiratory distress, brownish-black urine and even death resulted from eating fish, particularly the livers which were regarded as a delicacy if tasting of musty blue-green algal-type flavour compounds. Similar effects have been reported in humans in the USSR following the eating of fish from waters containing heavy growths of blue-green algae. It cannot be proved that these illnesses were due to blue-green algal toxins, but the possibility of at least some species of fish accumulating these toxins in some organs cannot be ruled out.

1930s (USA)

Transient gastroenteritis outbreaks were reported from town populations taking water from the Ohio river, which contained a bloom of blue-green algae.

1960 (Canada)

Pain and diarrhoea were experienced by people after accidental ingestion of scum whilst swimming.

1961 (USA)

Diarrhoea and allergic reactions were reported by people in Pennsylvania, following the recreational use of lakes containing a bloom of *Anabaena*.

1966 (Zimbabwe)

Gastroenteritis was reported in children taking drinking water from a source with a *Microcystis* bloom.

1970-80 (USA)

Outbreaks of waterborne gastroenteritis and fever in dialysis patients have been linked to LPS from blue-green algal blooms in the reservoirs supplying the tap water used in dialysis.

1975 (USA)

Blue-green algal LPS may have contributed to human gastroenteritis, diarrhoea, cramps, and nausea recorded in swimmers in the USA. Although evidence was sought for the involvement of enterobacteria and viruses in these outbreaks, none was found and blue-green algal LPS remains a possible cause.

1983 (Australia)

An epidemiological study was carried out which examined routine liver function tests in patients at a local hospital, following a heavy *Microcystis* bloom in a water supply. The study also included patients from areas with different water supplies. A significant increase in one serum enzyme, taken as indicative of sub-clinical liver damage, was observed only in individuals receiving potable water from the reservoir containing the hepatotoxic *Microcystis* blooms.

1983 (Australia)

An outbreak of hepatoenteritis in Queensland has also been attributed to a toxic algal bloom. After a dense bloom in the local reservoir had been treated with copper sulphate, 139 children and 10 adults developed symptoms of hepatitis, followed by lethargy and later diarrhoea. Subsequently, laboratory cultures of the blue-green alga *Cylindrospermopsis raciborskii*, isolated from the reservoir after the outbreak had ended, have been shown to be hepatotoxic in mice.

Potential Hazards Related to Water-based Recreation

7.13 Blue-green algal scums can occur around the shore, and on the surface away from the shore, of affected waterbodies. These scums are obvious, but large numbers of algae dispersed below the surface of the water are more difficult to see.

7.14 For blue-green algal toxins to constitute a hazard to water users, the user must come into contact with the toxins. The scale of the hazard, or risk of injury, will increase with the increasing level of contact; ingestion of concentrated algal cells in the form of scum constitutes the greatest hazard. The potential risk of contact from various activities will, therefore, vary from zero if there is no contact, to 'high', depending on the likelihood of that activity bringing the individual into contact with the scum. Pleasure cruising, for example, would constitute a 'low' risk activity, and swimming, particularly from the shore, a 'high' risk activity. The use of wet-suits for water sports may also result in a greater risk of rashes, because algal material in the water trapped inside the wet-suit will be in close contact with the skin for long periods of time.

7.15 The hazards from blue-green algal toxins can be reduced by avoiding contact with high densities of algae, especially scums, and by preventing access of livestock and pets. Blooms of toxic blue-green algae have been recognised for several years at some locations in the UK without apparent problems.

7.16 The Task Group was unable to come to any firm conclusions regarding the level of risk from the consumption of fish, particularly trout, from affected waters. The limited information available indicates that there is unlikely to be a major hazard from eating muscle tissue, but there is a need for more information, particularly with regard to the consumption of fish livers.

8 THE 1989 EVENT

Introduction

8.1 During August and early September 1989, NRA staff in the various regions were becoming aware of local problems resulting from substantial growths of blue-green algae. Two particular incidents brought the blooms to the attention of the public at a national level.

8.2 These incidents were the deaths of sheep and dogs at Rutland Water, Leicestershire, and the hospitalisation of two junior soldiers who had been canoeing in Rudyard Lake, Staffordshire. The former received by far the greatest attention from the media.

Rutland Water

8.3 Rutland Water is located in an agricultural area near Oakham in Leicestershire; spanning an area of approximately 1260 hectares, it is considered to be the largest man-made lake in Western Europe. The reservoir supplies water directly to 450,000 people, but as an integral part of the Ruthamford water supply network, together with Grafham and Pitsford reservoirs, it is capable of providing water to 1.5 million people. Construction of the reservoir started in 1971. When the dam was completed in 1975, the reservoir started to fill from the natural catchment and pumping started from the Rivers Welland and Nene in 1976. By March 1979 the reservoir was full. Rutland Water is thus a pump storage reservoir, with a capacity of 124 million cubic metres. Its natural inflow is derived largely from two rivers, the North and South Gwash, whose confluence was flooded to form the reservoir. Only a small proportion of the reservoir is fed from these rivers, however, as more substantial inputs are obtained from pumping stations on the River Welland at Tinwell and the River Nene at Wansford.

8.4 Rutland Water is an established watersports and leisure centre of international repute. Thousands of visitors come each year to enjoy the range of recreational activities available which include sailing, fishing, bird-watching, walking, picnicking and sight-seeing. It is also a Site of Special Scientific Interest (SSSI) and a wetland of international importance designated under the Ramsar Convention.

8.5 In common with many other large impoundments of nutrient-rich lowland waters, Rutland Water suffers from algal blooms which can cause a number of problems. Treatment problems may include unpleasant tastes and odours associated with the decay of algal cells, filter blockage, reduced filter runs and variable pH. The possibility of encountering such problems was foreseen during its design stage and a number of engineering and management decisions were taken, aimed at controlling and minimising algal growth. The reservoir has a multiple draw-off system, consisting of four different levels, which allows a degree of control over water movement, thus aiding destratification of the water. A further installation includes a grid of twelve compressed air guns, of the helixor type, which are located in the main reservoir body to enhance artificial overturn of the water mass.

8.6 A limnological tower is located in the main body of the reservoir to aid continuous monitoring of various water quality determinands — such as temperature and dissolved oxygen concentrations. The ability to change the timing and quantity of water entering the reservoir can be constrained by the inflowing raw water quality. Potable water derived from the reservoir is treated at Wing and Saltersford treatment works, both of which are equipped with granulated activated carbon filters to deal with taste and odour problems, and other organic constituents. Treated effluent from Oakham Sewage Treatment Works is discharged directly into the reservoir.

8.7 It was predicted, during the early stages of Rutland Water's development, that demand for water was almost certain to increase. The indications were that this would result in a reduction in water retention time and, consequently, an increase in nutrient-loading and algal growth. Problems related to algae were, therefore, expected to increase in future years as demand for water increased. Even at the design stage it was perceived that Rutland Water would be a highly eutrophic impoundment. Mean nutrient loading from 1975 to 1977 was 55g nitrogen per square metre and 3g phosphorus per square metre, double that of recognised eutrophic waterbodies such as Loch Neagh (N. Ireland), Chew Lake (England), and Loch Leven (Scotland), but lower than other pump storage reservoirs such as Farmoor (England).

8.8 In 1975, approximately 20 species of diatoms dominated the algal community, but by mid 1977 it had diversified to some 50 different algal species, and by 1980 over 100 species were identified. Initially, these were characteristic of lowland river environments, but more typical stillwater algal species were subsequently identified, such as the planktonic *Stephanodiscus astraea* and the blue-green alga *Aphanizomenon flos-aquae*. During the period 1975 to 1980 the annual dynamics and composition of species succession at Rutland Water showed a remarkable similarity to that of other temperate water impoundments, such as Grafham Water and Farmoor. Generally, a spring diatom outburst of *Stephanodiscus astraea* and *Asterionella formosa* occurred, followed by an increase in unicellular algal species. By mid-summer buoyant blue-green algal species such as *Anabaena* and *Aphanizomenon* out-competed non-buoyant species during intermittent periods of stratification. For example, in 1976 and 1977 a mixed blue-green bloom of *Anabaena circinalis*, *Microcystis aeruginosa* and *Aphanizomenon flos-aquae*, all of which are potentially toxic species, dominated during the latter part of summer. Unusually, blue-green algae such as *Gomphosphaeria naegeliana* and *Aphanizomenon flos-aquae* were usually dominant during winter.

8.9 In 1989 the development and composition of algal communities, throughout spring to mid-summer, showed little variation compared with previous years. From mid – to late-summer *Anabaena* and *Aphanizomenon* were dominant; however, from late August, *Microcystis* dominated the phytoplankton forming extensive scums around the whole perimeter of Rutland Water.

The Deaths of Sheep and Dogs

8.10 On 21 August, Anglian Water's Western Division received notification from a local farmer that six sheep had died after allegedly entering the water at the northern end of the dam. Samples of the scum, which was then very visible, were collected by the farmer and taken, together with two dead sheep, to the MAFF Veterinary Investigation Centre at Lincoln. Post-mortem revealed that the dead sheep had blue-green algae in their rumens. By 5 September a number of reports were received of dog deaths, again allegedly associated with contact with the scum.

8.11 Samples of algae from the raw water and from scum, taken by Anglian Water Services (AWS), were subsequently identified as the blue-green alga *Microcystis aeruginosa*. Samples of the scum were sent to the University of Dundee, where they were found to be toxic, by injection, to mice. In view of the potential problems associated with toxic blue-green algae, the decision was taken by AWS on Thursday 7 September 1989 to close Rutland Water to water-contact sports, and on Friday 8 September to close the fishery. Advice was given by AWS to members of the public and dog owners to avoid the algal scums. The closure remained in force until 18 October 1989.

8.12 The NRA Anglian Region was unaware of these events until 8 September. Within 24 hours of being notified by AWS that a problem existed at Rutland Water due to toxic algae, the NRA had carried out its own independent surveys to satisfy itself that a pollution problem did not exist, and to confirm the AWS statement of the presence of toxic blue-green algae. The sequence of events was as follows.

7 September	Evening TV announcement by AWS that there was an algal problem at Rutland Water.
8 September	Invertebrate surveys, visual inspections for dead fish, birds, wildfowl, etc, full chemical analysis and algal samples for species identification and mammalian toxicity tests, by the NRA.
11 September	Chemical survey of Rutland Water catchment area including main rivers and all major effluent inputs, by the NRA.
12 September	NRA expanded their survey to some 150 waters of primary concern. Algal species lists were produced and samples taken for toxicity testing where blue-green algae identified.
14 September	National press release identified further sites within Anglian Region where blooms were producing toxins, as determined by mouse bioassay.
14 to 28 September	Further samples taken, re-samples, inspections, etc.

8.13 By mid-September, 20 sheep and 15 dogs were reported to have died after alleged contact with the water during the period of the bloom. There were no reports of fish, bird or other animal deaths. Also, no adverse health effects to humans apparently exposed to the scum were reported. AWS decided, however, to prohibit the use of all of their reservoirs for recreational purposes.

8.14 The circumstances concerning the deaths of the sheep and dogs at Rutland Water in September 1989 are consistent with death due to poisoning by toxic blue-green algae. Supporting evidence includes: the ingestion of *Microcystis aeruginosa* scum; very high toxicity of the scum according to mouse bioassay; confirmation of the presence of microcystin-LR toxin in the scum and in the rumen of the sheep by chemical analysis; signs of illness in the animals; time of death; and the veterinary reports of pathological biochemical analyses. The above evidence is as detailed and consistent as any obtained previously in the world where animal deaths have been attributed to microcystins. The evidence from the Rutland incident therefore leads the Task Group to suspect strongly that the animals died from microcystin poisoning.

The Hospitalisation of Two Soldiers in Staffordshire

8.15 Rudyard Lake in Staffordshire is owned by the British Waterways Board, and is used by the Army for training junior soldiers in canoeing techniques. The canoeing courses include a swimming test from the bank, an introduction to canoeing, and practical exercises in capsize and 'eskimo roll' procedures. In late September 1989, it contained an intense algal bloom of *Microcystis aeruginosa*. Two recruits who had recently taken part in canoe exercises in Rudyard Lake were admitted to hospital on 26 September 1989. Their case histories have since been published in the British Medical Journal. The reference is given in Chapter 14.

8.16 The sequence of events was as follows.

18 to 20 September	Canoeing courses took place.
19 September	Samples taken by NRA for algal identification as part of a general survey, and British Waterways Board informed of the bloom.
21 September	British Waterways Board closed the Lake to public access.

26 September	Two of the junior soldiers were admitted to hospital and the Environmental Health Department notified.
27 September	The NRA was informed and samples were taken from the lake for virological, bacteriological and algal toxin analysis. These samples indicated no enterovirus contamination and levels of total coliforms and *Escherichia coli* bacteria were consistent with relatively clean surface water. Results of algal toxicity tests were positive.
9 October	Samples taken by Environmental Health Officers had quite high levels of *E.coli* at the dam end, indicating some faecal contamination. Water levels at the time of the incident were only 20% of normal. Algal monitoring by the NRA continued until early November.

8.17 During later investigations, the soldiers reported that the onset of symptoms occurred the day after their course was completed, but that they did not report sick until 23 September. Symptoms included abdominal pains, vomiting, diarrhoea, blistering of the mouth and sore throats. On 26 September the two soldiers were transferred to the George Eliot Hospital, Nuneaton. (8 other soldiers from the group of 16 reported influenza-like symptoms, but did not need hospital treatment; none of these soldiers reported skin irritation or blistering of the mouths).

8.18 The hospital diagnosed atypical pneumonia with consolidation of the left lower lobe of the lung, dry cough, abdominal tenderness and low platelet counts, which subsequently increased to more normal levels. Both soldiers were severely ill. One had slightly raised enzyme levels in liver function tests. Both soldiers had blistering around the mouth. The hospital carried out a range of tests on sera for viral infections, all of which were negative. They were discharged on 5 and 6 October and given 14 days leave. Subsequent clinic visits showed no further problems. Scientific and medical assessments concluded that the symptoms observed might have been associated with blue-green algal toxin poisoning as indicated in the published literature, although pneumonia had not been described in previous incidents.

8.19 Blue-green algal samples from Rudyard Lake were collected by the NRA and examined for toxicity. The material exhibited a characteristic blue-green algal toxicity and microcystin-LR — a blue-green algal hepatotoxin — was identified by HPLC. These findings, together with the epidemiological and clinical observations, have led the investigators of the incident to infer that the illness experienced by the soldiers was associated with contact with, and ingestion and/or inhalation of, toxic blue-green algae.

Management of the 1989 events

8.20 Following the reports and events at Rutland Water, the Chief Scientist of the NRA requested an assessment of the potential problem throughout England and Wales. It appeared that the initial examination of a large number of waters was often cursory, and it became evident that a more rigorous approach was needed. Lists of significant waters, in terms of size and use, were therefore drawn up and samples of water taken from all. These were subjected to microscopic examination, blue-green algal species were identified, and an assessment of abundance made. The results were reported to Head Office.

8.21 As it was known that many blue-green algae can produce toxins, a number of actions were taken in those regions where the problem was, or was perceived to be, greatest, and task teams were set up. Their actions included:

- monitoring and toxicity testing;
- informing owners, EHOs, MOEH, MAFF;
- suggesting a number of precautions;
- issuing press releases and dealing with the media; and
- responding to inquiries from the public.

8.22 There was an enormous reaction from water owners and the public, with telephone calls coming in to some regions almost continuously. One major problem which developed was the circular pattern of requests for advice. When the NRA suggested to owners that they seek advice on health-related matters from EHOs, the latter then returned to the NRA for help.

8.23 Initially, as a safety precaution, the NRA suggested the following to owners of badly affected waters:

- that a ban on recreational activities should be considered e.g. sail-boarding, fishing and sailing;
- that they should advise the public (where there was access to the site) not to swim, paddle or handle the water;
- that livestock should be kept away from the water; and
- that dog owners should not let their pets drink, or swim in the water.

8.24 It was made clear to the Regions from Head Office, that the NRA must not give advice on public health matters or on the consumption of meat, fish or wildfowl; these should be dealt with by EHOs and MAFF. Accordingly, stronger links were made with those bodies.

8.25 As the blooms of blue-green algae diminished during autumn and winter, owners and involved organisations were informed by the NRA that the risks of exposure to the algae were no longer considered to be a problem.

Events of Toxic Blue-Green Algae in 1989 Throughout the UK

8.26 In order to obtain a comprehensive account of the nature and extent of toxic blue-green algae in the U.K. throughout 1989, the Task Group circulated questionnaires to the ten NRA regions and the ten Water Services Companies in the private sector. In addition, information was also requested from all the 'original' water companies in England and Wales. To obtain details of blue-green algae in Scotland and Northern Ireland, the relevant authorities were contacted through the Scottish and Northern Ireland Forum For Environmental Research (SNIFFER). The detailed information received is summarised in Appendix A.

8.27 The results of this survey indicate that the ten NRA regions inspected 915 different waters, and a total of 2171 inspections were made during 1989; some waters being visited on more than one occassion. A total of 686 individual waterbodies were sampled for algae, of which 594 (87%) had blue-green algal species as the dominant group. On average, three samples per site were taken for analysis; however, the number of waters sampled by each region varied markedly.

8.28 A total of 169 individual waters in England and Wales were considered to have 'problems' with blue-green algae during 1989, in that similar events to those experienced at Rutland Water could have occurred in any other waterbody. Table 5 gives the number of waters for each region.

Table 5 Number of waters considered to have blue-green algal 'problems' in the ten NRA regions

Anglian	53
Northumbrian	0
North West	50
Severn Trent	18
Southern	1
South West	27
Thames	0
Welsh	1
Wessex	13
Yorkshire	6
Total =	169

8.29 Five NRA regions organised toxicity tests for 78 waters, as detailed in Table 6.

Table 6 Numerical results of sampling and of toxicity tests in five NRA regions with waters affected by blue-green algae

Region	*No of waters with blue–green algal problems*	*No of samples taken for toxicity testing*
Anglian	53	87
Severn Trent	18	2
South West	27	32
Wessex	13	2
Yorkshire	6	4
	Total = 117	Total = 127
Region	*No of waters tested for toxicity*	*No of waters found to be toxic*
Anglian	53	37
Severn Trent	2	1
South West	17	10
Wessex	2	1
Yorkshire	4	4
	Total = 78	Total = 53

8.30 The data in Table 6 show that 53 out of the 78 (68%) waters that were tested for algal toxicity in England and Wales gave positive results. The 53 waters are listed in Table 7.

8.31 A number of waters were not tested for their algal toxicity, but could be considered as potentially having toxins present on the basis of the abundance and composition of their blue-green algal species. Wide variations in algal toxicity were observed on different

Table 7 Waters identified as having toxic algal blooms by the NRA during 1989

Anglian	**Severn Trent**
Blickling Lake	Rudyard Lake
Fritton Lake (Lound Run)	
Barton Broad	
Cadney Reservoir	**Wessex**
Covenham Reservoir	Hawkridge Reservoir
Cransley Reservoir	
Denton Reservoir	
Eyebrook Reservoir	**South West**
Pitsford Rservoir	Old Mill Reservoir
Rutland Water	Porth Reservoir
Sywell Reservoir	Bussow Reservoir
Whisby Nature Reserve Lake	The Lake, Bicton
Grafham Water	Ornamental Pond, Bicton
Meadow Lake, St Ives	Meldon Pool
Mount Farm Balancing Lake	Drift Reservoir
Scoulton Mere, Scoulton	Langarth Lake
Wyboston Lake, South Lagoon	Main Pond, Bradley
Hoverton Great Broad	Stafford Moor
Lake Meadow, Billericay	
Seamere	
South Walsham Broad	**Yorkshire**
Aldwicle Pit (Merchant Venturers)	Silsden Reservoir
Hollowell Reservoir	Beaver Dyke Reservoir
Hughes & Sons Lake, Skellingthorp	John O'Gaunt Reservoir
Overstone Lower Lake	Welton Water
Ravensthorpe Reservoir	
Teals Pit, Lincoln	
Abberton Reservoir	
Alton Water	
Ardleigh Reservoir	
Broome Pit (No 4)	
Filby Broad	
Hanningfield Reservoir	
Homersfield Lake	
Ormesby Broad	
Rollesby Sailing Club	
Toft Newton Reservoir	

occasions from samples collected from the same site. Examples of this include Pitsford and Hanningfield Reservoirs in the Anglian Region, and The Lake, Bicton (Figure 3) and Bussow Reservoir in the South West Region. This illustrates the variability and complexity of blue-green algal population dynamics and the variation in the degree of toxicity that may occur in a single lake over a short period of time. The rapid fluctuations in toxicity were recorded on a rather irregular sampling pattern, and it is difficult to assess the precise nature of these changes with time.

8.32 Results were also obtained from Scotland and Northern Ireland, and these data are also given in Appendix A. Only three algal toxicity tests were carried out in Scotland, and one in Northern Ireland; all were positive. A summary of the information is given in Tables 8 and 9.

Figure 3 The Lake, Bicton

Changes in blue-green algal populations and their toxicity in 1989

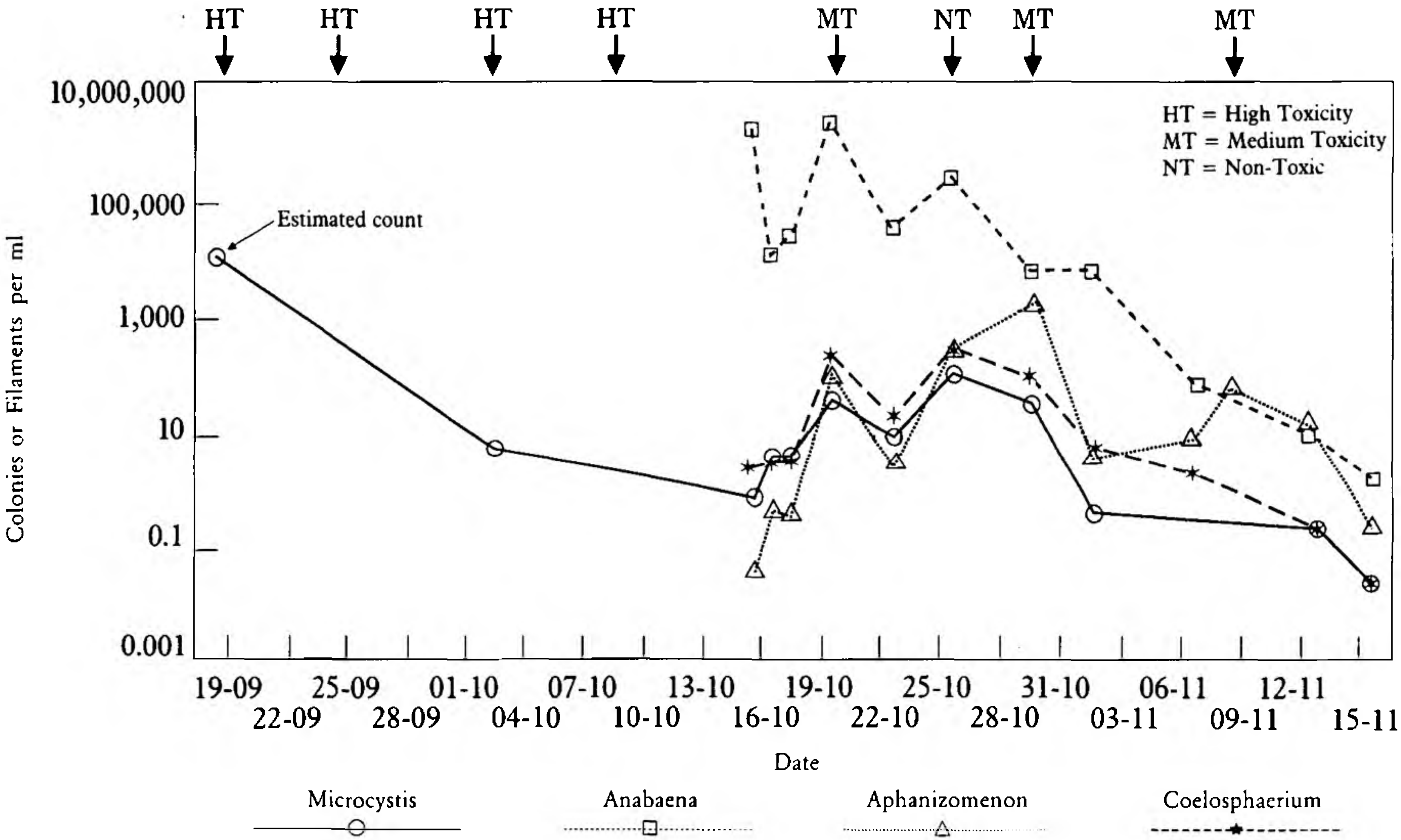


Table 8 Summary of information received from Scotland and N. Ireland

River Purification Board or Regional Council	*No of Sites Sampled for Algae*	*No of Sites with Blue-Green Algae*	*No of Sites Considered to be a Problem*	*No of Sites Where Samples Were Taken for Toxicity Tests*	*Results of Toxicity Tests*
Central Scotland Water Development Board (CSWDB)	2	0	0	0	NT
Tay River Purification Board (TRPB)	1	1	1	0	NT
Forth River Purification Board (FRPB)	3	2	1	0	NT
Clyde River Purification Board (CRPB)	12	2	1	0	NT
Highland River Purification Board (HRPB)	3	3	2	0	NT
Solway River Purification Board (SRPB)	11	3	2	1	+
Borders Regional Council	0	0	0	0	NT
Highland Regional Council	3	1	1	1	+
Fife Regional Council	8	2	1	0	NT
Tayside Regional Council	0	0	0	0	NT
Lothian Regional Council	4	3	2	0	NT
Dumfries and Galloway Regional Council	15	15	5	0	NT
Strathclyde Regional Council	97	18	1	1	+
Total for Scotland	159	50	17	3	
Total for Northern Ireland	36	18	3	1	+

\+ = Positive
NT = Not tested

Table 9 Waters considered to have blue-green algal problems in Scotland and Northern Ireland

Site	*Board*	*Genera*	*Toxicity*
Loch Earn	TRPB	*Coelosphaerium*	NT
Loch Leven	FRPB	*Anabaena*	NT
Loch Fad	CRPB	*Microcystis*	NT
Loch Kemp	HRPB	*Anabaena*	NT
Loch Sgamhain	HRPB	*Anabaena*	NT
Mill Loch	SRPB	*Microcystis*	+
Black Loch	SRPB	*Microcystis*	NT
Loch Muidhe	Highland RC	*Anabaena*	+
Glenfarg Reservoir	Fife RC	*Anabaena*	NT
Gladhouse Reservoir	Lothian RC	*Oscillatoria*	NT
Donolly Reservoir	Lothian RC	*Oscillatoria*	NT
Winterhope Reservoir	Dumfries & Galloway RC	*Anabaena*	NT
Loch Roan	"	*Oscillatoria*	NT
Loch Rutton	"	*Microcystis*	NT
Loch Milton	"	*Anabaena*	NT
Purdenstone Reservoir	"	*Coelosphaerium*	NT
Loch Neilston	Strathclyde RC	*Anabaena*	+
Lough Neagh	N Ireland	*Oscillatoria*	NT
Ballinrees	N Ireland	*Oscillatoria*	NT
Lough Island Reavy	N Ireland	*Synechococcus*	+
Totals Scotland 16 N Ireland 3		Number of sites where toxicity was confirmed	4

+ = Positive
NT = Not tested

Evidence to Determine if Blue-Green Algal Populations and Their Toxins Were Greater in 1989 Than in Previous Years

8.33 Historical details of algal populations are highly variable from region to region; in many cases, such information does not exist.

8.34 In the Welsh Region, anecdotal evidence indicates that blooms occurred in open water in many small waterbodies during 1988. This has been attributed to weather patterns in Wales which were considered to be conducive to bloom formation. Long-term records to support this evidence are available. The size of the scums at Ynys-y-Fro during 1988 and 1989 were similar, although species composition was different.

8.35 In the North West Region, particularly in the Cheshire Meres, blooms of blue-green algae are a common phenomenon. The Institute of Freshwater Ecology has long-term records for Lake Windemere which indicate an increase in *Oscillatoria* populations in 1989.

8.36 In the Severn Trent Region a number of Leicestershire reservoirs and the Shropshire Meres annually experience scums of blue-green algae. In previous years blooms of *Oscillatoria* have been particularly common at Kingsmill Reservoir, an amenity lake in Sutton-in-Ashfield, Nottinghamshire and are regularly the subject of public complaints.

Table 10 Results of toxicity tests on blue-green algae in the Anglian Region

Water	*Date*	*Toxicity*
R Ouzel	6.7.83	–
Gravel Pit Bedford	18.8.83	+
Grafham Water	11.7.83	–
	18.7.83	–
	25.7.83	–
	1.8.83	–
	8.8.83	–
	15.8.83	–
	22.8.83	+
	30.8.83	–
	5.9.83	+
	12.9.83	–
	19.9.83	–
	26.9.83	–
	3.10.83	+
	2.6.84	–
	16.7.84	–
	23.7.84	–
	6.8.84	–
	13.8.84	–
	28.8.84	–
	3.9.84	–
	8.7.85	–
	15.7.85	–
	22.7.85	–
	27.8.85	–
	2.9.85	–
	4.9.85	–
	16.9.85	–
	24.9.85	–
	30.9.85	–
	7.10.85	–
	13.9.89	+
	18.9.89	+
	28.9.89	+
Ardleigh Reservoir	14.7.83	–
	28.7.83	–
	4.8.83	–
	4.8.83	+
	11.8.83	+
	18.8.83	+
	25.8.83	+
	1.9.83	+
	8.9.83	+
	15.9.83	+

Table 10 Results of toxicity tests on blue-green algae in the Anglian Region (continued)

Water	*Date*	*Toxicity*
	6.8.84	–
	13.8.84	–
	28.8.84	–
	3.9.84	–
	18.9.84	–
	25.9.85	–
	1.10.85	+
	9.10.85	+
	22.10.85	+
	11.11.85	+
	27.9.89	+
Covenham Reservoir	6.7.84	–
	14.8.84	+
	20.8.84	+
	10.9.84	+
	15.9.89	+
	4.10.89	+
Pitsford Reservoir	10.7.84	+
	24.7.84	–
	28.10.85	–
	15.9.89	+
	18.9.89	+
	4.10.89	+
Rutland Water	22.6.84	–
	15.9.89	+
	21.9.89	+

+ = Positive
– = Negative

8.37 In the Anglian Region there is anecdotal evidence of the formation of blue-green algal scums in previous years on a number of reservoirs, such as Grafham and Ardleigh, and on a number of lakes, such as Fritton and Blickling. Although it was obvious that the scums formed at Rutland Water were greater in 1989, this was not the case at all the other waters.

8.38 Tests for toxicity of blue-green algae were carried out on seven waterbodies by Anglian Water between 1983 and 1985, the results of which are shown in Table 10, together with the toxicity results for those waters in 1989. The results of the tests from 1983 to 1985 confirmed the expected rapid fluctuations in toxicity which take place over a period of time at individual waterbodies. Results from Grafham Water and Ardleigh Reservoir in 1983 illustrate these changes very clearly.

8.39 Although the results provide evidence that blue-green algal blooms in these waters were intermittently toxic in the past, the rapid fluctuations in toxicity preclude proper evaluation of differences in the degree of toxicity of the blooms between 1989 and previous years.

Weather Conditions 1989: An Explanation of the Event in the UK

8.40 The high incidence of blue-green blooms in 1989 has been attributed, somewhat glibly, to the 'long hot summer'. This is an oversimplification but contains an element of truth. As explained in Chapter 6, scum-forming blue-green algae are relatively slow-growing and they often begin their annual growth from small numbers of cells present in the water. Moreover, their growth rate is accelerated by higher temperatures and the long photoperiods found during high-latitude summers, and stable, near-surface stratification. Conversely, cooler and windier summers, leading to weaker stratification and/or deeper mixed layers, are not conducive to the development of large populations. It is not so much that large populations develop in response to warm, sunny weather, as to the length of the period during which conducive weather conditions persist.

8.41 With the benefit of hindsight, it can be seen that 1989 coincidentally produced a series of events that would have benefitted the development of scum-forming blue-green algae in deeper lakes and reservoirs. The 1988/89 winter was unusually mild. In common with many other parts of Britain, the East Midlands experienced higher than average temperatures. According to the Meteorological Office's monthly reports, the temperatures experienced from December to March inclusive were 2.0 to 2.5°C above the monthly mean accumulated since 1941. After a cold, wet April, springtime temperatures were 0.5 to 2.0°C above normal and sunshine totals were 20 to 50% above average. In addition, the dominant feature generating this fine weather was a prolonged series of stable high pressure systems; these divert the depressions and circumpolar frontal systems, which are responsible for the changeability that normally characterises the oceanic climate, to the north. The combined effects on the underwater conditions would have been firstly to promote the survival of small blue-green algal populations from 1988 through the winter, secondly to provide a good starting population to take advantage of an earlier-than-usual growing season, and thirdly to provide a less erratic environment allowing population growth. The relatively dry conditions prevalent throughout the period would also have contributed, by reducing flushing of developing populations from standing waters. The role of eutrophication is secondary, although an important contributory factor in that the high growth capacity is realised only when the other environmental conditions enable the algae to exploit more completely the available nutrients.

8.42 On the basis that the formation of scums cause the blue-green algae to die, and that scums should not occur if the organisms continue to regulate their buoyancy in line with the hydrodynamics of the water, the prevalence of scums during the late-summer requires additional explanation. The scale of blooming is not directly dependent upon the size of the population, although it is obvious that if the latter is negligible, any scums which do form will necessarily be minor. Rather, it is the result of coincidences between water column stability and high buoyancy of the organisms. Again, inspection of the Meteorological Record reveals several key events. After the dominance of high-pressure systems from May to July, August became more unsettled and, even though rainfall was mostly confined to the north of Britain, several depressions and weak frontal activity did bring windier and slightly cooler weather to the East Midlands. This would have increased mixing in reservoirs and the depth to which mixing penetrated. It has been shown repeatedly in the past that these circumstances lead to increased algal buoyancy. It is reasonable to assume that this occurred in the case of the *Microcystis* in Rutland Water.

8.43 At the end of August, air pressure rebuilt rapidly over England and a further period of stable weather followed, which persisted until mid-September. As would be predicted, the effect of weakening winds, renewed heating, and of near-surface stratification, would have been to cause the rapid migration of the buoyant *Microcystis* to the surface. Without strong winds to disperse the surface scum, its downwind accumulation on light breezes was inevitable. This would have been the origin of the heavy, now notorious shoreline scums which were actually the outcome of a series of weather-driven events, each of which is known to play a key part in the development of bloom-forming populations or their eventual surface accumulation.

Impact on the Community

8.44 Overall, the development of intense algal blooms, the formation of scums, the deaths of sheep and dogs, and the subsequent events that followed in autumn 1989, caused a number of problems across the country. Difficult decisions were necessary on the complete or partial closure of waterbodies, often with limited information and only rudimentary knowledge of the 'phenomenon' and possible adverse health effects. The implication of these actions were only fully appreciated later.

8.45 A wide range of stillwaters was affected, ranging from the smallest lake or pond with a single water-based activity, to the largest reservoirs, owned by the Water Companies, supporting numerous recreational activities, and areas for livestock watering and public amenity. Fishing, both coarse and trout, sail-boarding, water-skiing, sailing, canoeing and other similar activities were halted. Many events, competitions, regattas and day trips were cancelled. Livestock watering was stopped and public access restricted. Fences were erected at some locations. Warning notices and press statements were used to educate and inform members of the public of the potential dangers. Many clubs and associations were compelled to find alternative venues for their activities. The consequences of the closures and restrictions led to financial loss and, in some cases, dissatisfaction with the decisions taken.

8.46 A number of unconfirmed verbal reports were received by members of the Task Group of health effects following contact with, and ingestion of, water containing dense populations of algae or scum. Symptoms of gastroenteritis and skin rashes were the most commonly described.

8.47 Attitudes towards the problems differed. The majority of owners closed their waters immediately upon receipt of positive toxicity results. Some owners declined to close their waters to the public, even though test results indicated a 'high' level of toxicity. Some fishing clubs offered to provide the NRA and owners with written statements to the effect that their members would accept full responsibilities for any adverse health effects suffered as a consequence of fishing in affected waters. Such offers were misdirected, because decisions relating to the closure and re-opening of waters were the responsibility of the owners. Such offers, however, demonstrated the depth of feeling and frustration felt by many angling clubs and other societies at the loss of their leisure activities during the 'wonderful' summer/autumn period of 1989. Worried school teachers, parents and club secretaries were in contact with the NRA, seeking advice and guidance.

8.48 There were, however, a number of positive aspects to the event. The public became more aware of the actual and potential problems at specific sites due to the closure of waters, warning notices, media broadcasts and press articles. This increased public awareness may have resulted in a reduction in the number of cases of adverse health effects suffered by humans, pets and livestock. Consultation, liaison and communications improved between the various organisations dealing with the problem, as they clarified and accepted their responsibilities. Good working relationships were established which created a firm foundation for future co-operation in dealing with these issues.

Reports of Incidents and Problems Associated with Blue-Green Algal Blooms Outside the United Kingdom in 1989

8.49 In order to complete the review of 1989, inquiries were made of colleagues in water research institutes, government environmental health laboratories, and universities in other countries. The following comments have all been obtained as personal communications to Professor Codd from researchers with first-hand experience of blue-green algal toxins and associated research.

JAPAN

8.50 No suspected blue-green algal poisoning incidents were recorded in 1989, although one of the researchers experienced rashes after collecting *Microcystis aeruginosa* scum, containing microcystins, from a lake.

AUSTRALIA

8.51 Problems are currently occurring (1989/90) with blooms of *Microcystis*, *Anabaena* and *Nodularia*. Public awareness was increased by the showing on television in January 1990 of a 10 minute film on algal toxin problems. Locations affected by toxic algal blooms in 1989/90 included Lake Alexandria near Adelaide, the scene of sheep deaths attributed to toxic *Nodularia* by George Francis in 1878.

DENMARK

8.52 *Microcystis* blooms were common in several lakes in 1989, but no toxic effects have been registered with Environmental Health Officers. Dead swans were observed in a small lake in a park near Copenhagen during a heavy *Microcystis* bloom, but investigations showed that the swans died of *Clostridium* poisoning (botulism). Suspected poisonings during *Microcystis* blooms were last registered in July 1985 when several cows miscarried after drinking water from Lake Arre. In 1974, convulsive fits were registered after cows drank water from Lake Orum during a *Microcystis* bloom.

FINLAND

8.53 A hepatotoxic bloom of *Oscillatoria* was present in Lake Ostra, Kyrksundet in the summer of 1989, which disappeared by August. There was also a toxic bloom of *Oscillatoria* at Dragsfjord, southern Finland. This is a drinking water supply, and complaints of blue-green algal flavours were received. *Oscillatoria* filaments and free hepatotoxin were present in the distributed water.

SWEDEN

8.54 A bloom of *Anabaena flos-aquae* developed at Lake Tullingesjon, near Stockholm in 1989. The bloom was highly toxic and attracted much attention from the press and TV. Bathing was forbidden, but no animal poisonings were reported. Similar cases occurred in 1989 elsewhere in Sweden: at Boden, in the north, with blooms of *Anabaena circinalis* and *Microcystis aeruginosa*, and at Lake Finjasjon, Scania, in southern Sweden (*Microcystis wesenbergii*). Lake Finjasjon provides drinking water for the town of Hassleholm and the lake was closed in the summer during the bloom period. This lake was investigated by colleagues at Uppsala and it is understood that research is in progress to try to identify toxins in the drinking water. Cattle drinking from a small river coming from the lake had increased levels of enzymes in their blood, when compared with control animals, indicative of liver damage.

NORWAY

8.55 Many wild birds died at Lake Ostensjo, near Oslo, which supported a toxic bloom of *Microcystis* and *Anabaena*. No mammal deaths were reported at this site. There was a hepatotoxic bloom of *Microcystis* at Lake Akersvatn (a scene of toxic blooms for the past decade). No animal deaths were reported. An *Aphanizomenon* and *Anabaena* bloom (highly neurotoxic) developed in the Haldenvass Draget, a watercourse, but no poisonings were reported. The eutrophic lakes of Rogaland, the low-lying agricultural hinterland of Stavanger, again produced toxic blue-green algal blooms. No animal deaths were reported and several lakes were closed to the public during the bloom season. The lack of animal deaths in 1989 in Norway contrasts with the losses of animals at several lakes in the country 5 to 15 years ago.

CHILE

8.56 Reports of acute toxicity of blue-green algal blooms in Chilean reservoirs were presented at the Second Biennial Water Quality Symposium: Microbiological Aspects, held in Chile in August 1990.

GREECE

8.57 Decreasing supplies of groundwater in Northern Greece have promoted an interest in the development of surface sources which presently contain toxic *Microcystis*, *Anabaena* and *Anabaenopsis* blooms. It is understood that enquiries are currently proceeding.

SUMMARY

8.58 In reports of this nature, clearly it is not possible to draw quantitative conclusions about the incidence of toxic blooms; in general, where toxicity studies have been carried out — as in Scandinavia — about half to two-thirds of the bloom samples analysed were found to be toxic.

8.59 Without public knowledge and awareness, poisoning incidents may occur and perhaps be unrecognised or unreported. If farmers, tourists and water-users are aware of the hazards involved, then the incidence of poisonings would be expected to decline if precautions are taken. This may be the case in Scandinavia: animal deaths and human health problems due to blue-green algal blooms came to wide public attention about 10 years ago, and it is noticeable that fewer animal deaths have been reported from this region over the past 3 or 4 years. The actual incidence of blue-green algal bloom development, and bloom toxicity, does not seem to have declined in the Nordic countries over recent years.

9 APPROACHES TO CONTROLLING BLUE-GREEN ALGAL POPULATIONS

Introduction

9.1 It must be emphasised that there is nothing either new or unnatural about the occurrence of bloom-forming populations of blue-green algae, or their tendency to accummulate in scums. It is recognised that their presence in many recreational waters is unwelcome, is deleterious to their aesthetic quality and, as this report explains, is potentially hazardous to water users. This section of the report reviews the control options available for the prevention or reduction of bloom-forming populations, considers whether this is both desirable and feasible, sets criteria for their selection, and offers some remedial measures for tackling potentially toxic scums in those situations where bloom-forming populations cannot be prevented.

9.2 The need to eradicate blue-green algal blooms will be strongest for reservoirs and lakes with high amenity value, and for lakes supporting high-risk water-based recreational activities. There will be many cases where elimination of blue-green algae is neither practical nor appropriate. Thus shallow lowland lakes, fed by groundwater naturally enriched with nutrients, may well support blue-green algal populations which would be almost impossible to control artificially. In addition, control of algae could prejudice the natural ecosystem functioning in lakes having a high conservation value; for example, those designated as Sites of Special Scientific Interest. Moreover, even where a technique is likely to be effective, its use may be inappropriate because it may adversely affect other legitimate uses of the water; for example, the use of algicides in lakes and reservoirs used for potable supply. In every case, expert advice is required and, for some of the treatments recommended, there is a statutory requirement to obtain approval from the NRA.

Nutrient Deprivation

9.3 Without significant quantities of essential nutrients, principally nitrates and phosphates, algae will not reach bloom proportions. Nutrients are available to the algae either from the surrounding water or, under certain conditions, from the bottom sediments. Where eutrophication has been implicated in the deterioration of water quality in lakes and reservoirs, attention has often been directed towards reversing these effects by managing the input of nutrients, either by tackling the level of nutrients generated upstream, or by taking steps to remove them directly from the lake or reservoir.

9.4 In continental Europe and in North America, eutrophication problems have been recognised for several decades. In the latter, emphasis has been placed on reducing the amount of phosphates discharged to sewage treatment works, and there have been attempts to reduce the use of polyphosphate-based detergents. It is rare, however, that detergent-phosphorus accounts for more than 25% of the load to sewage treatment works, the bulk being derived from human waste. In Europe, effluent diversion or, in some instances, treatment to reduce ('strip') phosphate from lake inflows has been employed more effectively.

9.5 The addition of chemicals to source waters in order to reduce nutrient availability and, in turn, reduce the intensity of algal blooms, has been much researched and widely used. In theory, the reduction of any one of the essential nutrients to insignificant levels in the reservoir water could be expected to bring about an appropriate reduction in fertility. In practical terms, only reduction of the phosphorus input offers a realistic option. The requirement among algae is universal; the chemistry of phosphorus is such that its removal is effective and irreversible. The technology is well developed: it can be as sophisticated as the installations at the Wahnbach Talsperre Reservoir, suppling Bonn and Cologne in West Germany, or as relatively simple as the direct dosing and settlement lagoons, introduced at selected reservoirs by Anglian Water. The chemistry is identical in these cases; ferric salts – chloride or sulphate – are dosed to the incoming water, or to the existing water mass, to precipitate phosphorus.

9.6 In theory, the effectiveness of nutrient removal ('stripping') as an algal control measure is determined by two main factors. The first is the extent of removal of phosphate, which is always likely to be incomplete without the application of stringent quality control. The operational requirement should be to reduce the dissolved phosphorus (P) concentration well below 10µg P per litre before the potential algal population might be usefully restricted, and to less than 5µg per litre at all times to ensure that algal growth is controlled.

9.7 The second factor is the concentration gradient between phosphate-stripped water in the reservoir and the interstitial water in the superficial sediments. Phosphate will have accumulated in the sediment during the previously phosphorus-rich phase and will, for a time, provide an internal phosphorus-load to the water. This relationship is frequently misunderstood, in that it is not necessarily a pre-requisite of phosphorus release that the bottom water is anoxic, neither is it prevented by oxygenation. Much phosphorus can be recycled quickly from shallow-water sediments subject to, or distributed by, wave action. Conversely, it seems to be only the top 2 or 3 cm of sediments that are normally involved in attaining a new equilibrium between water and sediment. The rate at which the new equilibrium is reached depends upon past inputs, the restorative measures, the shape and dimensions of the lake basin, and the rate at which it is flushed. Pragmatic appraisal of a series of European restoration projects indicates that although some lakes may respond immediately, the norm for recovery is between 2 and 7 years.

9.8 Consideration may be given to reducing the internal phosphorus-loads, either separately or in conjunction with external phosphorus-load reduction. Pumping-out of mud deposits has been achieved successfully in restoring smaller shallow Norfolk Broads, and this approach has also been successful in earlier schemes in Sweden and the USA. The amount of material to be removed from a waterbody will be dependent on its area, but the deeper the water the more difficult will be this solution. Moreover, it has to be ascertained in advance that sufficient depth of sediments can be removed to ensure that the operation does not simply uncover a deeper source of phosphorus.

9.9 A similar form of control can be achieved in storage reservoirs equipped with deep scour valves. Activation of these enables the upper, most recent, thin layer of sedimentary material to be disturbed and flushed out of the reservoir; in this way the year-to-year accumulation of recyclable phosphorus is usefully countered.

9.10 Sediment sealing by, for instance, a layer of nutrient-poor sand has been suggested on occasions, but has not been attempted on any large or systematic scale. There are practical problems of laying and maintaining an even cover, and the accelerated accumulation of sediments is scarcely compatible with other objectives of reservoir operation. Also, the ferric hydroxide floc, precipitated following dosing of a reservoir or lake with ferric salts, will act as a sealing-layer to reduce the re-solution of phosphorus from the sediments, although it could result in the bottom sediments becoming anaerobic.

9.11 The reduction of internal phosphorus-loading is usually a secondary objective and an adjunct to lowering the phosphorus content of the source water.

9.12 The capital costs of phosphorus-stripping plants are high. Because the method is essentially a contact process, the surface area, land requirement, and constructional effort increase in proportion to the volumes of water to be treated and to the desired effectiveness of removal. The contact required to remove 80% of dissolved phosphorus is about half that to remove 95%. Although all algae need phosphorus, phosphorus-stripping is no panacea. Besides requiring a rigorous cost-benefit analysis in every instance, very careful attention must be paid to the sources and quantities of phosphorus to be controlled. For instance, a pumped storage reservoir receiving a single source water from a single abstraction point should, at first sight, be amenable to phosphorus-stripping prior to storage, and show some rapid improvement in quality, subject to equilibration of the internal phosphorus-loading. On the other hand, the recovery of a lowland reservoir or a natural lake with several main inflows, each receiving sewage effluent discharges and draining either mixed farmland or urbanised/industrialised catchments, would be extremely costly to achieve if phosphorus inputs were to be reduced or eliminated at source. Even removing 95% of the phosphorus from the sewage treatment works' effluents might well fail to reduce the total phosphorus-load sufficiently to bring about significant mid- or long-term improvements in stored-water quality, due to the input of phosphorus from diffuse sources. In such circumstances it may be more appropriate to dose the abstracted river water, in addition to treating the existing water in the reservoir, with ferric salts; the latter step would, however, require a thorough environmental impact appraisal before being attempted.

Physical Controls

9.13 The surest way of preventing algal growth is to exclude light. This deceptively simple expedient has been successfully adopted only in the case of small service reservoirs and water towers. Elsewhere, the maintenance of light-restricting covers, whether permanent or temporary, or whether of floating objects or sheeting, has been found to be extremely impractical.

9.14 Provided a reservoir is deep enough to become thermally-stratified through the summer, the possibility of regulating the biomass-supporting potential of its water-column, and biassing the natural selection of its dominant species by means of artificial destratification techniques, may be considered. Thames Water has managed its major Thames-Valley reservoirs in this way for many years. By keeping the water-supply reservoirs continuously mixed, diatom populations should be maintained, rather than the bloom-forming blue-green algae. (The principle invoked is that illustrated in Figure 2(b) on page 37, where the algae are deliberately maintained at a low h_p/h_m ratio: the greater the exceedence by the mixed depth (h_m) over the net photosynthetic depth (h_p), the greater the benefit). The draw-back is that the selective advantage will pass, ultimately, to other blue-greens i.e. *Oscillatoria*. This does not appear to be a problem in the Thames-Valley reservoirs, which may be due to the short retention time. The faster growth rates of the diatoms establish them as better competitors, while their nutrient requirements, including that for dissolved silicon, continue to be met by the inflowing water. In lakes with rapid rates of water renewal and short retention times, slow-growing algae are unable to increase their population size. Rapidly flushed waters with a retention time less than 5 to 10 days, or others subject to periodically high flows, generally tend not to support blue-green algal populations.

9.15 Because the physical environment is so strongly selective, another approach is to adopt intermittent destratification. By alternating between growth conditions required by, for example, diatoms and those preferred by bloom-forming blue-green algae, neither group is allowed sufficient time to develop large populations before the other is selected. In this way, an artificially low biomass with a reduced component of blue-green algae could be maintained throughout the main growing season. This method has been successfully tested on a pilot scale, by the Institute of Freshwater Ecology's Blelham Tarn experiments, sponsored by the Department of the Environment (DOE), but its value as an operational strategy for an entire reservoir has never been tested. Several recent analyses of algal dynamics in lakes and reservoirs, where extreme variability in the stability of stratification is imposed naturally through the interplay of wind-mixing and solar-heating, have shown that the same principles are substantially upheld. There is obvious virtue in further experimentation at the reservoir scale.

Modelling Physical and Chemical Control of Plankton Populations

9.16 Now that computer modelling of algal dynamics is improving, a further possibility might be to set up site-specific simulation models of the response of the plankton to different frequencies and extents of destratification, although this would call for rather more sophisticated models than currently exist.

9.17 Even with such models, successful application of intermittent mixing to reservoirs might prove cumbersome in practice, and demand more monitoring of the algal populations than is possibly now the case. It would be quite ineffective in the waters where the total depth (H) did not considerably exceed the natural wind-mixed depth, h_m, and did not simultaneously exceed the net photosynthetic depth, h_p. This is because the mixing only works through gross, unnatural alterations of the environment in which the algae are growing.

Biomanipulation Techniques

9.18 Over the past fifteen years there has been increasing interest in the use of 'biomanipulation' techniques for reducing the effects of eutrophication. These techniques rely on artificially-induced changes in the trophic structure of lake ecosystems by the removal or addition of particular species or groups of species.

9.19 Most of the research on whole lake biomanipulation has so far been carried out on relatively small waterbodies, or in artificial enclosures. The results are promising, particularly where the experiments have been carried out in a controlled manner. There is a wide variety of options available, but the choice of the right option depends very much on the trophic structure of the lake.

9.20 Reductions in phytoplankton populations have been achieved in two principal ways, both of which are aimed at a decrease in their abundance by increased grazing pressure. The grazing pressure can be increased directly by the introduction of planktoniverous fish such as the silver carp, or indirectly by removing the fish and allowing for an increase in the population of zooplankton.

9.21 The removal of fish from a lake reduces the loss of zooplankton, thus allowing for substantial increases in grazing pressure by the zooplankton on the algae. In one instance in the USA, this has been calculated as being a two- to three-fold increase following lake manipulation with a consequential reduction in algal problems. In the case of colonial blue-greens, however, this may not be the most effective technique, due to the generally low grazing pressure exerted on them.

9.22 A reduction in nutrients following the removal of fish has also been noted, but the mechanism for this is not known and, until it has been deduced from further experimental work, this technique cannot be used specifically for nutrient reduction.

9.23 The addition of algal-eating fish species has sometimes been successful, but not always; most fish species adapted to eating plankton are either non-selective for phyto- or zooplankton, or actually show a preference for zooplankton. Most plankton-eating species collect the plankton through the use of modified gill rakers (projections on the gills). As a result, they often collect larger species of algae, which allows smaller unicellular species to develop. This could be an advantage in the case of blue-green algal control, because most species which produce toxins are colonial.

9.24 Although the juveniles of most fish species eat plankton, there are few indigenous species of truly planktoniverous fish in Britain, none of which are common. There are three species of coregonids, such as the Powan, or Gwyniad, (*Coregonus lavaretus*), which are generally confined to deep oligotrophic lakes in the mountainous regions and feed mainly on zooplankton. The clupeids also feed on plankton, but the two species found in Britain, the Allis and Twaite Shads, (*Alosa alosa* and *Alosa fallax*), are confined to the lower reaches of rivers and estuaries.

9.25 The only exotic species of planktoniverous fish known to survive in British lakes is the Silver Carp, (*Hypophthalmichthys molitrix*). This species has not been found to breed in Britain, but has been used in biomanipulation experiments for lake restoration in Europe. The use of this species for controlling blue-green algae would, however, have to be researched under controlled conditions prior to making any recommendations for general use. This is particularly important because silver carp show dietary preferences for different types of algae.

9.26 Prior to the transfer of non-British species to new environments, or to the introduction of exotic species to lakes for plankton control, careful consideration of the effects of these introductions must be made. The NRA would not issue Section 30 (Salmon and Freshwater Fisheries Act 1975) Consent for the introduction of any of these species until it was satisfied that there would be no adverse ecological side effects. In the case of exotic species such as the Silver Carp, a licence to introduce these fish would, in any case, be required under the Wildlife and Countryside Act 1981. These licences are issued by MAFF, who would also be unlikely to issue the licence unless they could be assured that the introduction would be effective in controlling blue-green algae and that there would be no adverse ecological effects.

Algicides

9.27 Although a number of compounds could be considered as being universally toxic to algae, there are few which are exclusively algicidal. For many years, copper sulphate was dosed to reservoirs during the development of algal blooms, at concentrations between 0.3 and 1mg per litre. At these concentrations, the algae are killed off and sink to the bottom sediments. The effects, however, are exclusively short term, for the cleared water is soon amenable to support another phase of growth. Each population event requires a separate treatment.

9.28 Operational experience and scientific evidence have shown blue-green algae to be generally less sensitive to algicides than diatoms. Thus standard dosing might actually favour blue-greens, at least insofar as it reduces their competitors. Other difficulties include its toxicity to cladocern water fleas and, especially in soft waters, the risk of exceeding environmental quality standards for designated fisheries. Frequent or persistent use of copper salts as an algicide is prejudicial to the maintenance of a robust food web, which supports fish production, and the wisdom of deliberately encouraging the accumulation of copper in the superficial sediments is questionable. The addition of copper salts to raw waters which are then treated for potable supply may also lead to increased copper levels in distributed water.

Copper sulphate is not an approved algicide as defined in the Food and Environmental Protection Act of 1985. However, copper sulphate is still used occasionally as an aquatic algicide in the UK.

9.29 Two aquatic herbicides, Diquat and Terbutryn, have an incidental effect upon some kinds of planktonic algae. Chlorination, although effective, is only a temporary solution against algal blooms. A further complication to the use of any algicide is that toxin is liberated to the water when the cells break down. There is a need for some better quality data and more intercomparative testing, before the wider use of algicides could be seriously advocated as a method for controlling blue-green blooms.

9.30 A technique increasingly employed in water-treatment is flocculation with powdered activated carbon (PAC) to remove organic molecules. Dosing PAC directly to productive reservoirs will accelerate settlement of particles, and an excess of carbon in suspension could significantly reduce the light penetration into the water, and hence restrict the photosynthetic capacity. Such techniques, however, could clearly have far-reaching implications for the ecology of reservoirs and must not be contemplated as a means of algal control without extensive Environmental Impact Assessments being undertaken.

9.31 Reference should also be made under this section to renewed interest in the use of barley straw as a means of combatting algal growth. The technique has been in use for some years in small ponds and watercourses affected by sources of organic carbon (for instance, from partially treated sewage), where the vast surface area available supports a huge bacterial population. It has been frequently observed that the quantities of filamentous algae, that might otherwise have been maintained downstream, are greatly reduced after treatment with straw. The precise mechanism has not been clarified systematically, though it was thought that the bacterial growth was so effective in removing and retaining nutrients that little remained to sustain downstream algal growth; alternatively, microbial activity may produce algal-growth inhibitors, but these have not been isolated or characterised.

9.32 In spite of suggestions that the treatment would be equally effective against planktonic algae in much larger lakes and reservoirs, there is at present little evidence to contend that this might be either effective, practicable or, in the long-term, desirable. The amounts of straw required to attain the equivalent 'dose' to a large storage reservoir could prove to be substantial. The amount of oxidisable carbon could represent a formidable oxygen demand and a consequential water quality problem in a deep reservoir. Nevertheless, this is a topic where more research might usefully be directed.

Other Controls

9.33 There has been renewed interest in methods of collapsing the blue-green algal gas-vesicles which impart the buoyancy to floating scums. These structures were shown long ago, in laboratory experiments, to be sensitive to a sudden change of external pressure. Translating these results to natural populations of blue-green algae is not straightforward, where the problem is to gain a sufficient pressure change in a relatively short period of time. Experiments have been undertaken in which high explosives were detonated over the water surface. The shock waves were sufficient to achieve a positive effect, and to make the algae sink. The technique, however, also kills fish by bursting their swim bladders! Experiments have also been conducted in which algae were pumped to a depth sufficient to achieve the collapse of their gas-vesicles.

9.34 Rendering blue-green algae non-buoyant will certainly remove them from scum. The settled algae may, however, produce new vesicles and recover their buoyancy over a period of several days. While the live algae remain in the water column, the scum-forming potential persists.

Biological Controls

9.35 Bloom-forming blue-green algae are known to be subject periodically to control by other organisms. Most of these organisms specifically graze on blue-green algae, without interfering with the dynamics of other planktonic algae. For instance, the major planktonic grazers, the crustacean water-fleas (Cladocera), calanoid copepods, and rotifers tend not to feed on larger colonial and filamentous blue-green algae; their activities may therefore selectively favour the blue-greens. Conversely, blue-green algal populations have been observed occasionally to collapse as a result of grazing by ciliates (*Nassula, Ophryoglena*) and rhizopod protozoans (*Pelomyxa*). Most blue-green algal species are vulnerable to attack by aquatic fungi, and by algal-lysing bacteria and viral bacteriophages.

9.36 The notion of harvesting and maintaining stocks of naturally occurring biologically based blue-green algal control agents has been expressed many times, but the maintenance of sufficient stocks in cultures carries daunting problems. However, improved techniques of protozoan culture and much enhanced understanding of their life histories now make the possibility of using ciliates a realistic objective. *Nassula*, for example, could be cultured in the laboratory and its resting spores stored with a view to 'seeding' developing blue-green algal populations before they achieve nuisance proportions. This unusual approach to combatting blooms with a perfectly natural and strongly-targetted biological agent deserves further research and development. Most promising of all, perhaps, would be the use of bacteriophages. These can be very target-specific, and can be easily stored. For all of these techniques, however, research and development plus Environmental Impact Assessments, are essential.

Scum Coralling and Removal

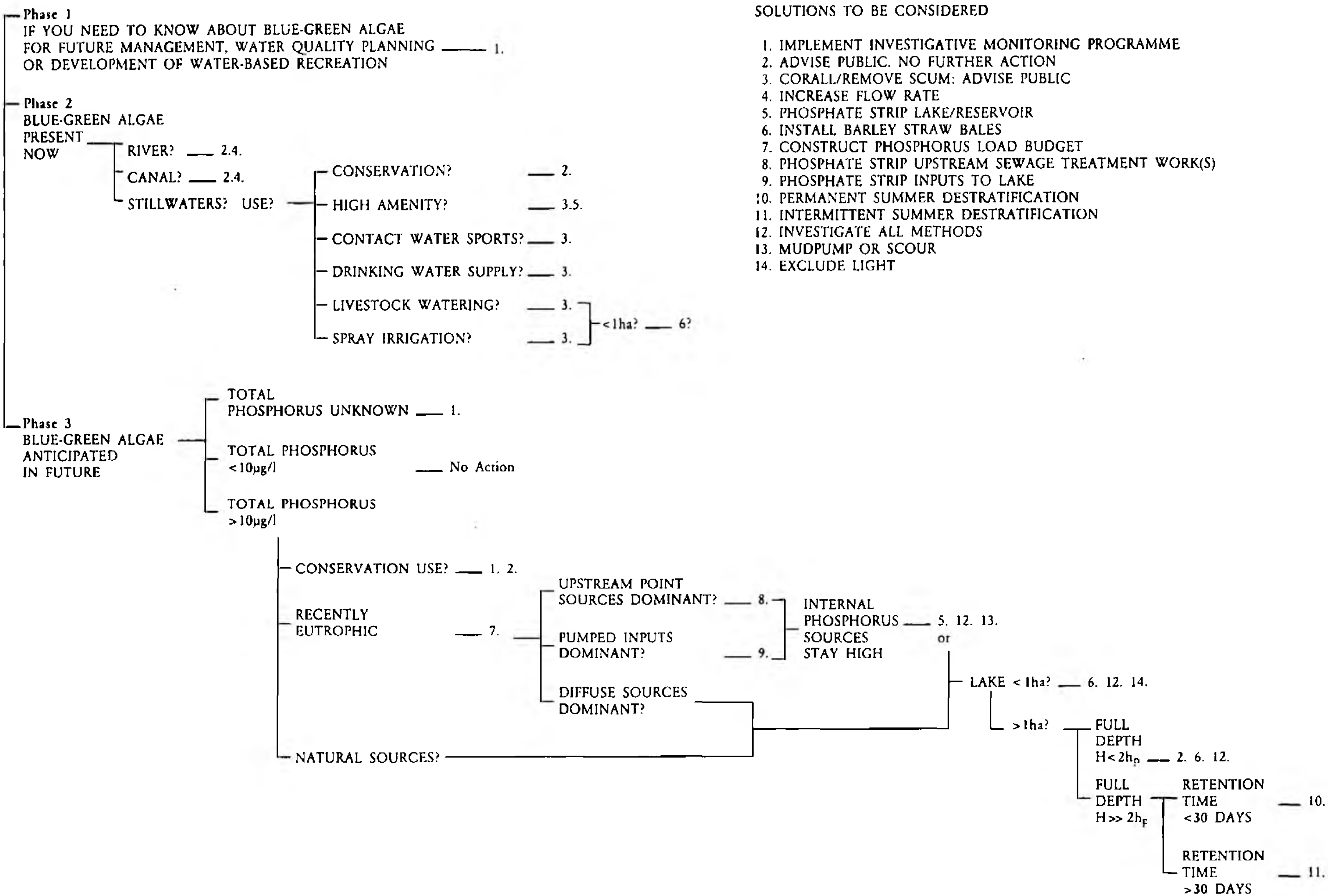
9.37 In many instances, it may be desirable physically to remove the surface scums of blue-green algae that have developed. Experiments have been carried out to test the efficacy of corralling, or enclosing scum material, by the careful use of booms – such as the type which were designed to collect oil slicks. These units can be sited, or dragged by boat, to collect and harvest scum material in such a way that most of the floating material is enclosed. The top layer can then be 'pumped' off and removed from the lake. This approach can never be fully effective, but is a useful palliative to improving the lake appearance and in minimising shore-line depositions. Due to the variability in scum formation, the timing of its collection is important in order to minimise effort and maximise effectiveness. The disposal of these scums may also present problems. Physical removal around the edge of the water can be very difficult to achieve – especially on rocky shores.

Summary

9.38 The various options for the management of blue-green algal populations are shown in the form of a decision-tree in Figure 4. This scheme has been devised as an aid to the decision making processes which are a pre-requisite to any action to control the algae. The system suggested is not intended to cover all situations. The possible solutions given in this diagram are only those where some experience of their effectiveness is available. In the future, some of the other options mentioned in this chapter, such as the use of bacteriophages, may become available as realistic alternatives.

9.39 The scheme has been divided into three main phases. In the first, a decision has to be made as to whether or not a problem is likely to develop. If not, a basic monitoring programme should be implemented.

Figure 4 Decision-tree for eutrophication control points



9.40 The second phase relates to situations where blue-green algae are sufficiently abundant to form scums, or where the scums have already formed. In these cases short-term remedial measures can be considered in order to reduce the problem. These depend on the type of waterbody. For example, rivers have few available short-term options for control measures. If increasing the flow rate is not feasible it may only be possible to inform owners, EHOs, MOEH, MAFF and the public that there is a potential problem. The appropriateness of short-term measures are also heavily influenced by the uses of the water body, particularly for lakes. Where the control option would result in the breakdown of the algae and possible release of toxins, consideration should be given to the potential effects on the users, such as those engaged in contact watersports.

9.41 In the third phase, where blue-green algae are known to cause a problem, long-term measures to reduce these problems should be considered. In the first instance, a decision has to be made as to whether or not a significant reduction in algal populations would be detrimental to the overall ecological characteristics of the water. This is particularly true of sites which have been identified as being of high conservation value, such as Sites of Special Scientific Interest. If control options are appropriate, then an ordered consideration of the various options is necessary.

9.42 The possible control options fall into two main categories: those where the overall levels of algal populations are to be reduced, and those where the environment or biota are manipulated to reduce the dominance by blue-green algae. In either case, the choice of option is currently constrained by variations in their potential effectiveness. In this scheme, phosphate control is given high priority because this approach has been widely used and, in some cases, has been shown to be effective.

9.43 Where phosphate control is not possible, or is found to be inappropriate on other grounds, a number of other options are available for consideration. These include the use of physical controls, such as permanent or intermittent destratification. Destratification may be a high priority option in deeper waters, because its implementation can be effective immediately after installation. This method is only likely to work where the total depth (H) of the waterbody is at least twice the depth sustaining algal growth (h_p), the method of use depending on the retention time of the water in the lake or reservoir.

9.44 In small waters the exclusion of light or the use of barley straw may be effective, but the former is likely to be impractical and the latter is not well researched. In the future, bio-manipulation techniques will improve with experience and, in view of their potential for natural restoration, may become more favoured.

9.45 It is clear from the description of available options in this chapter that there are no easy solutions to the overall problems of controlling blue-green algae. Care is needed to ensure that the right options are chosen and that the benefits from introducing the options outweigh the possible damage caused by the control methods being considered; a cost/benefit appraisal would need to be made on a case-by-case basis. Environmental Impact Assessment studies will also usually be required.

10 MANAGEMENT IN THE FUTURE

Short-Term Measures for 1990

10.1 During early discussions of the Task Group, following its formation in December 1989, it became evident that recommendations contained in the final report could be too late to deal with algal blooms which developed in the spring and summer of 1990. As it may be many years before any significant reductions are noted in those lakes and reservoirs that have experienced intense algal blooms, even if control measures are introduced in the immediate future, it was considered that priority should be given to the development and implementation of a series of short-term measures.

10.2 The Task Group drafted material which was subsequently used, with additional material from Head Office, to inform owners, relevant Government Departments, and the press of the NRA's strategy and action. Head Office arranged for statements to be used in an NRA leaflet and in letters relating to public and animal health, which were kindly provided by the Department of Health and the Ministry of Agriculture, Fisheries and Food respectively.† The entire package, and course of action, was subsequently approved by the NRA Board and implemented in May 1990.

Monitoring Programme 1990

10.3 The programme was developed in order to provide sufficient information for the NRA Regions to take appropriate action on blue-green algal bloom formation in 1990. Its basis is that waters are categorised according to the risk of direct contact with, and ingestion of, scum by humans, pets and livestock. Three categories are identified as follows.

	Level of Risk of Contact	
High	*Medium*	*Low*
Paddling, Swimming	Canoeing	Fishing
Diving, Sail-boarding	Sailing	Irrigation of Crops
Water-skiing	Rowing	Pleasure Cruising
Livestock Watering	General Public Amenity	

10.4 All public water supply reservoirs, with associated public or livestock access or recreational facilities, are monitored, together with a minimum of 10% of the 'high risk of contact category' in most regions. These latter sites are chosen at random. Analysis of total phosphorus, identification of algal species, and an algal abundance estimate is carried out on a monthly basis at each site. Results are reported to owners, local EHOs, MOEH and the local MAFF office. If 25% of the monitored sites are considered to have exceeded the criterion which is indicative of bloom formation, a regional 'general alert' is issued. Full details of the monitoring programme and the general alert are given in Appendix B.

Standard Letters

10.5 In order to have a consistent approach to supplying the results of monitoring to owners and relevant authorities, letters have been prepared for use by all NRA regions. Copies of

† The NRA wishes to acknowledge its gratitude for the prompt and positive responses received from these Departments.

the letters are given in Appendix C and contain advice provided to the NRA by the Department of Health and from MAFF. The recipients are listed below.

a) A standard letter to water owners when potentially toxic algal blooms are identified in their waters.

b) A standard letter to:
   - Chief Environmental Health Officers;
   - Medical Officers of Environmental Health; and
   - MAFF Regional Offices

   when potentially toxic algal blooms are identified in specific waterbodies.

c) A standard news release for use when an individual site has been identified as containing a bloom of potentially toxic blue-green algae.

Clarification of Responsibilities

10.6 The intensity of the blue-green blooms experienced in August and September 1989 created immediate difficulties for owners of affected waters and the various organisations involved in dealing with the problems. Liaison, communication and decision making was initially hampered because the roles and responsibilities of interested parties was not always entirely clear. The intervening period has been productive. Following meetings and discussions with other organisations, responsibilities in relation to toxic blue-green algae have been clarified and are listed below.

NRA Responsibilities
- Monitoring controlled waters.
- Informing owners/local EHOs, MOEH and MAFF of any actual or suspected blooms.
- Informing owners/local EHOs, MOEH and MAFF of results of any NRA analyses.

Owners Responsibilities
- Warning the users of their waters of any potential dangers.
- Decisions relating to possible closure of recreational facilities and public access.
- Liaising with local EHO on any health or related medical issues.
- Liaising with MAFF and EHOs on problems associated with livestock watering.
- Liaising with MAFF on matters relating to consumption of meat, fish, game and wildfowl.

EHO Responsibilities
- Providing advice to owners and public about human health issues.
- Providing precautionary health safety advice to owners and the public.
- Liaising with the NRA on local aspects of monitoring.

MAFF Responsibilities
- Animal health issues.
- Consumption of meat. ⎤ In conjunction with
- Consumption of fish, game and wildfowl. ⎦ Dept of Health and EHOs
- Effect on crops of spray irrigation.

Publicity Leaflet

10.7 There was clearly a requirement to alert and educate members of the public and owners of affected waters of the need to avoid direct contact with, and ingestion of, the scums and blooms, and of the potential dangers associated with the toxins. Such leaflets are thought to have been shown to be effective in reducing health problems in humans, pets and livestock in other countries.

10.8 The NRA therefore produced a two-fold leaflet. An initial print run of 250,000 copies was made and distributed to owners of recreational facilities, Environmental Health Officers, clubs associated with water-based sports, schools, tourist organisations, and so on. A copy of the leaflet is given in Appendix D, as part of the media package.

Media Briefing and Press Conference

10.9 On 6 June 1990, the NRA Head Office issued a national press statement launching the publicity leaflet and monitoring programme. Each region was then requested to inform the local media and commence distribution of the leaflet in the most appropriate manner. A copy of the media package is given in Appendix D.

Future Monitoring in 1991 and Beyond

10.10 Detailed plans for a basic monitoring programme in 1990 have been implemented by the NRA to provide a consistent approach across all the regions. It will be necessary to review the methodology and efficacy of the programme at the end of this year, in order to determine whether or not any changes are required. A clear example of this is in the collection and analysis of the samples. It has not been possible to determine the relationships between standard analytical techniques for algal populations, such as chlorophyll-*a* analysis or algal cell counts, and the level of problems which arise. This partly results from the variability in the levels and types of toxins in blooms, and from differences in the buoyancy regulation mechanisms of the different algal species.

10.11 The methods of assessment of the likelihood of scum formation, and of algal population abundance, will have to be reviewed in the light of the results of future research into the significance of the toxins. There are no 'standards' for blue-green algal populations or toxins in relation to either environmental waters or potable waters.

10.12 The 1990 programme has not recommended any routine monitoring of the toxicity of the blooms: this is because, although potential toxin-forming blue-green algal species are identifiable, they can exhibit rapid fluctuations in toxicity, both spatially and temporally, and it is not possible to predict these changes.

10.13 The NRA will also need a considerable amount of information on nutrient concentrations in surface waters, and on the effects of nutrient removal, before any measures can be introduced to control them. Monitoring will also be required to obtain information on the effects of these measures when, and if, they are introduced.

Long-Term Reference Sites

10.14 During the course of this investigation, it became clear that there was a shortage of information from long-term studies into changes in lake ecosystems. This gave rise to difficulties in distinguishing between changes induced by climatic aberrations, and those caused by the activities of man. The lack of long-term data on eutrophication generally, and on changes of blue-green algal blooms in particular, is highlighted by the information available from Rutland Water. This reservoir had been monitored and researched in some detail by Anglian Water, and by a number of academic establishments, from the start of impoundment in 1976 until the end of the summer in 1988. Determination of the causative factors of the intense blue-green algal bloom, and the very large scums around the margins at Rutland Water encountered in 1989, was made particularly difficult because the monitoring was reduced in the very year that problems developed. There is also a lack of data and detailed information from other reservoirs in the vicinity.

10.15 The 'NRA Unit' (which was later to become NRA Anglian Region) was established in September 1988, one year prior to the NRA being formed as a national body under the Water Act (1989). For the majority of this period the monitoring of water quality in reservoirs was considered to be the responsibility of Anglian Water Services. It appears, however, that no data were collected routinely for chlorophyll-*a* between April and June 1989 from Rutland Water. In July 1989, the Secretary of State designated reservoirs as controlled waters under the Water Act (1989) via Statutory Instrument 1149, (The Controlled Water (Lakes and Ponds) Order 1989). Under this Statutory Instrument, the NRA was given the powers and responsibility to monitor water quality in reservoirs. From August onwards both the NRA, due to their new responsibilities under the Water Act (1989), and Anglian Water Services, due to the problems experienced at Rutland Water, recommenced monitoring for chlorophyll-*a*.

10.16 Information obtained from other NRA Regions and water companies also indicated that routine monitoring in a consistent manner was sporadic. As a result, most responses to requests for information to make an objective assessment of the extent of blue green-algal blooms in Britain in 1989 were severely restricted by a lack of relevant information.

10.17 When the NRA implements schemes to reduce the incidence of toxic blooms of blue-green algae by eutrophication control, reference sites will be needed. These will provide information on long-term changes associated with such influences as climatic change or trends in water quality associated with land-use change.

10.18 This report has highlighted the complexity of interactions between environmental variables and their influence on the production of blue-green algal blooms and their toxins. Data from reference sites will not only provide information on long-term trends but also provide data to aid further research on the influence of environmental variables on the blooms and toxins.

10.19 The use of long-term monitoring information in the management of water quality in rivers and groundwaters, but not lakes, is an inherited standard procedure for the NRA. (The value of this type of information has recently been demonstrated in the development of Nitrate Sensitive Areas, a scheme aimed at the long-term reduction of nitrate concentrations in potable waters. Historical data from a number of river and borehole sites clearly demonstrated increases in nitrate concentrations over the past 20 years, which can be correlated with an increased use of nitrogenous fertilizers). Unfortunately, there are few similar records to demonstrate the effects of eutrophication on lake phytoplankton by increases in phosphate concentration.

10.20 The need for long-term reference sites for lakes has also recently been identified by the Natural Environment Research Council, for very similar reasons. This organisation has identified a need to select 'primary' sites; lakes where the ecological changes have been monitored over long periods of time in a consistent manner. The reasons for this need are research-orientated, rather than lake-management related, but the biological and chemical monitoring requirements and methodologies are similar.

10.21 It is, therefore, recommended that the NRA should monitor a few key sites, geographically dispersed, in order to provide what must be considered a minimum amount of information on long-term change due to both natural and land-use changes. These sites should be monitored by standard methods to give comparable information on environmental variables and the biota.

11 RESEARCH AND DEVELOPMENT

11.1 It is clear from the preceding chapters that there is still much to be learned about blue-green algae, their toxins, and their effects. The needs for research and development therefore fall into three broad headings:

- the formation and control of blooms;
- the production, regulation and analysis of toxins; and
- the fate and biological significance of toxins.

Formation and Control of Blooms

Formation of Blooms

11.2 If blue-green algal blooms were prevented from developing, the problems associated with their toxins would not occur. The control of bloom formation has been considered for many years, to limit the nuisance aspects of algae — such as colour, odour, taste, and filter blocking in water treatment. The additional hazards presented by the toxins provide further justification to prevent or limit bloom formation. Several options exist, and it may be several years before any improvements are apparent. In the meantime, measures to control blooms are needed. Physical, chemical and biological options are available, and these should be further investigated. Topics requiring research and development include the following.

Simulation Modelling of Bloom Dynamics

11.3 A properly validated mathematical model to simulate the origin, formation, growth, and demise of blooms would be a valuable tool, but does not seem to exist. Such a model could be used to make predictions of bloom behaviour, to test possible options for remedial measures at individual sites, and to assess their cost-effectiveness.

Nutrient Control

11.4 Although much research has been carried out on the nutrient requirements of phytoplankton, there is still some uncertainty about the mobility and availability of phosphorus in water, in organisms, and through the sediment-water interface. More work is required in order to predict the impact of possible remedial measures.

11.5 The effect of land-use and agricultural practices on the nutrient loads of drainage water entering rivers upstream of reservoirs and lakes needs to be studied. The possibility exists, in the Water Act (1989), of setting up Water Protection Zones, but the effectiveness of these would need to be carefully considered, and would involve a substantial monitoring effort.

11.6 Research may be useful to assess the effects of different types of vegetation, such as reeds, shrubs and trees, used as a protective strip to trap excess nutrients entering the water, and to compare these with natural and man-made wetlands.

11.7 Further development is needed of techniques for nutrient removal from point sources, the disposal of nutrient-rich material, and the cost-effectiveness of different options. There is also a need to refine the means by which Environmental Impact Assessments should be carried out, because these are a pre-requisite of any large-scale *in situ* nutrient removal processes.

Biological Control

11.8 Although most species of zooplankton avoid blue-green algae, there are a few which occasionally graze on them. There is some scope for investigating which species might be capable of reducing blue-green algal populations and how these species might be exploited. Similarly, there are other possibilities — such as the use of bacteriophages — which have promise; a short study would be valuable to assess all of the biological-control options, in order to identify those most worthy of further research.

Chemical Control

11.9 A chemical which selectively reduced blue-green algal blooms would clearly be of value. If it existed, however, its use would have to be very strictly controlled; blue-green algae are a natural component of freshwater ecosystems. The precise action of barley straw has yet to be clarified.

Monitoring

11.10 The predictions of blooms by detecting pre-bloom conditions would be very useful. If this could be achieved by remote sensing (satellites) then this would be a great advantage. The possibility of such an approach should be investigated.

The Production, Regulation and Analysis of Blue-Green Algal Toxins

Production of Toxins

11.11 It will clearly take some time to learn more about the factors which lead to the production of blooms of blue-green algae, and of possible remedial measures. In the meantime, it is worth finding out more about the factors which affect the production of the toxins, and of their environmental effects. Such work, however, requires further development of the techniques necessary to apply to environmental samples; these include chemical and biological methods.

Regulation of Toxin Production

11.12 Preliminary laboratory studies have indicated that nutrient supply has selective effects on the levels and types of microcystins produced by individual species of *Microcystis* and *Oscillatoria*. The effects of environmental conditions such as temperature, light, acidity/alkalinity and nutrient supply on toxin production should be further investigated on all the principal blue-green algal species.

Method Development for the Identification and Quantification of Toxins

Chemical

11.13 In the short-term, HPLC techniques offer the best prospects for identification and quantification of blue-green algal toxins, and these should be improved. Current HPLC methods are satisfactory for purifying microcystins from scums and concentrated bloom samples, but procedures for the quantitative recovery of microcystins from open water samples are needed. A single 'accredited' HPLC method needs to be estabished, and for this a 'library' of purified, characterised toxins for reference purposes is required. Research would be needed on toxin structure and storage characteristics in order to establish a reference library.

Biological

11.14 Additional methods of microcystin detection and measurement involving toxin-sensitive animal cells, microbes and immunological techniques are also needed, because these will require less sophisticated equipment than HPLC technology and should, in time, be suitable for wider use by less highly trained personnel. Such methods have shown considerable promise in laboratory trials so far, but further work is needed to reduce the time to carry out the tests, confirm specificity, and to define sensitivity.

The Fate and Biological Significance of Blue-Green Algal Toxins

Release into Water

11.15 The fate of blue-green algal toxins released into the water must be understood. The regulation of partitioning between cells and surrounding water should be investigated, because this will also be useful in determining reservoir management strategies. If the toxins are largely inside the cells, then filtration or scum removal should effectively remove the toxins from a waterbody; if however, the toxins are released from the algal cell into the surrounding water, then cell or scum removal is insufficient. Similarly, the specific actions of algicides in killing toxin-forming species and on the release, or otherwise, of their toxins to water, should be investigated. The stability of toxins in the water column also needs to be investigated.

Sampling Strategies for Toxins in Lakes and Reservoirs

11.16 Estimates of the toxicity of blue-green algal scums have shown considerable variation at individual sites, over several weeks during blooms, and also between sites in a single lake on the same day. These estimates have been on the toxicity of the blue-green algal cells only. It should be determined whether levels of free toxin in the water also vary with time and place within individual lakes. The distribution of toxins between cells and surrounding water should be determined on temporal, horizontal and vertical bases in order to establish a detailed picture of toxin levels at selected sites.

Effects of Toxins on Aquatic Life and Food Chains

11.17 Laboratory experiments with purified microcystin have shown that isolated members of the aquatic zooplankton community are susceptible to this toxin; when single-celled animals and water fleas are exposed to the toxin, and are prevented from avoiding it, the toxin can be lethal. The possibility that zooplankton could pass the toxins to higher members of the aquatic food chain needs to be studied, including the significance of blue-green algal toxins to plankton-feeding fish.

Mammalian Toxicity of the Toxins

11.18 There is a need for basic mammalian toxicity studies in order to give a firm basis for hazard assessment to water users. These could include the following.

- A short-term comparative study needs to be made to compare intra-peritoneal, oral, and inhalation dosing in the mouse, with both pure toxin and extracts of a toxic algal strain containing known concentrations of toxin.

- Longer-term studies on the effects of intake of low-levels of toxin should be carried out, using both pure toxin and extracts of toxic algal strains containing known concentrations of toxins; in the latter case, it would be important to include a control group exposed to extracts of non-toxic algal strains.

11.19 The metabolism of radio-labelled microcystin by mice has been studied, but more comprehensive studies would be advisable. This is also necessary for other toxins, in order to learn more of their fate, effects, and methods of treatment.

12 DISCUSSION

12.1 It would appear that the development of toxic blue-green algal blooms in 1989 was not a unique event — either in the UK or abroad — but the extent of such blooms, and in particular the occurrence of scum material around the shores of lakes and reservoirs, may well have been greater than in previous years. This can be primarily attributed to stable environmental conditions during the summer, preceded by a mild winter. There is a lack of sufficient evidence to determine whether or not there is a long-term trend in the occurrence of such blooms, but it is accepted that action is required to reduce their occurrence and to minimise their potential effects.

12.2 There is also no doubt that, following the deaths of sheep and dogs at Rutland Water, and the hospitalisation of soldiers after canoeing in Rudyard Lake, urgent action was required to increase public awareness of the potential threat to human and animal health posed by blue-green algal scums on stillwaters. The closure of certain lakes and reservoirs to recreational activities in 1989 undoubtedly reduced the chances of any further animal deaths, and may have helped to avoid further human health problems.

12.3 A review of blue-green algae and their toxins has therefore been carried out, with the aim of determining the significance of the toxins and the factors leading to the production of blooms. The results indicate that most common species of planktonic scum-forming blue-green algae are capable of producing toxins, and that although the chemical characteristics of some of the commonly occurring toxins are known, the biochemical pathways leading to the production of toxins, and their regulation, are poorly understood. There may well be toxins yet to be identified.

12.4 Knowledge of the environmental effects of the toxins is largely based on circumstantial evidence. Toxic blue-green algae have been recorded from UK lakes for many years, although no major ecological perturbations have been attributed directly to the effects of the toxins. Their potential for causing problems is well documented. Toxicity data, obtained by intra-peritoneal injection, indicate that the toxins produced by blue-green algae rank amongst the most toxic compounds of biological origin. The main uses of water which are most affected are those of general amenity, recreation, and livestock watering. A discussion of the significance of the toxins in relation to human drinking water supply has been beyond the scope of this report; but because the NRA is responsible for the quality of surface waters abstracted for potable treatment, it retains an interest in any work which may be undertaken on this particular aspect. Similarly, the significance of the toxins in relation to the consumption of fish and shellfish by man is not the direct responsibility of the NRA, but the results of this study show that there are very limited data on the accumulation of these compounds by such biota.

12.5 It is, nevertheless, important to place the hazards from toxic blue-green algal blooms and scums into perspective with risks from other natural biological materials in the environment. These algae are natural inhabitants of freshwaters and the formation of blooms has been a common feature in UK lakes and reservoirs for many years. Although sporadic reports of poisoning incidents and adverse health effects have been documented and reported verbally, there have been no regular reports of any health-related problems ascribed to blue-green algal toxins.

12.6 The dangers of the blooms and scums to water users in 1989 can be set in context by consideration of the number of deaths by drowning, which were reported by the Royal Society for the Prevention of Accidents (RoSPA). There were 135 such deaths in lakes, reservoirs and canals alone in 1989, which does not include rivers and streams. In contrast, no deaths of swimmers or bathers have been attributed to blue-green algal toxins.

Blooms and Their Toxins

12.7 The production of blue-green algal toxins has been found to be temporally and spatially variable. Tests for toxicity of individual blooms may be misleading unless very extensive monitoring is carried out. Data obtained by the NRA during 1989 confirmed the results of earlier work in the UK and abroad, which show that there is at least a 60 to 70% chance of any particular bloom selected for testing as being toxic. The environmental and biochemical factors leading to variations in the levels of the toxins are poorly understood. There are no currently available methods for directly controlling the production of the toxins in the field. In view of the lack of such methods, the only practical means of minimising the occurrence of the toxins is to reduce the incidence of the blooms.

12.8 There is an extensive literature on the factors giving rise to the formation of dense blooms of many types of algae in lakes. Much of this work has resulted from a purely academic interest, from a need to reduce the adverse effects which particular species of algae have on treatment processes for water supply, and from generally unacceptable environmental effects. Although the occurrence of algal blooms in general is a natural phenomenon, they can be accentuated by nutrient enrichment. This enrichment may be naturally caused by run-off from nutrient-rich soils, or induced by the activities of man. In both cases, the process is called eutrophication.

12.9 Many other factors affect the growth of algal populations, including light attenuation, water temperature, lake morphometry, water circulation and grazing by zooplankton. These additional factors determine the species composition and abundance. Under normal circumstances, the constant changes in environmental conditions result in a succession of dominant species during the year. There are over 1000 species of planktonic freshwater algae, each of which thrives under a specific and often narrow range of environmental conditions, so the period of dominance of any particular species is usually short. Because blue-green algae generally grow more slowly than other groups, they are normally most abundant towards the end of the growing season in mid — to late-summer, although this does not preclude them from dominating at other times of the year if conditions are suitable for their persistence.

Control Options

12.10 Because lake size, shape and circulation are important factors in determining algal species succession and abundance, it is essential that control options for populations of blue-green algae must be considered on an individual lake or reservoir basis. Quantitative modelling of relationships between environmental variables, and the abundance of phytoplankton species, are at the development stage; but there is sufficient evidence to indicate that the development of populations of particular species is predictable. Predictions for changes in whole communities are not yet available, but the development of these models is an important step towards evaluating control options. Some of these options, such as eutrophication control, have been attempted; but it must be stressed that many options are largely untried, and all may have varying degrees of success, depending on local factors.

12.11 Eutrophication control has been largely directed at reduction in phosphate concentrations, with varying degrees of success; this is primarily attributed to the very low levels of phosphate required to sustain blooms of algae – approximately 5µg per litre. Point source discharges could be controlled by setting consent conditions for phosphate concentrations in effluents, and diffuse sources could be reduced by restricting the use of phosphate in lake or reservoir catchments by setting up Water Protection Zones. The technology to achieve significant reductions in phosphate concentrations in effluents is available, but experiments with sewage treatment works discharging to rivers — even with up to 95% phosphate removal — have indicated that residual concentrations in the river from effluents, diffuse sources, and internal recycling of nutrients remained in excess of 100µg per litre.

12.12 Improvements have been achieved when a reservoir or lake itself has been treated. Historically, ferric salts have been used for this purpose to precipitate the phosphate, but iron is a List II substance under the EC Dangerous Substances Directive, and therefore its annual average concentration in the water needs to be carefully monitored and assessed, and its introduction considered very carefully in terms of its potential environmental impact. The cost benefit of this type of treatment also needs to be carefully evaluated, both in terms of finance and possible environmental damage, before any widespread eutrophication control is implemented. It is evident that careful monitoring of algal populations will be required to determine the success of eutrophication control measures, and to provide long term records of changes in plankton populations.

12.13 Direct chemical control of large blooms and surface scums is possible with algicides, but this is not advisable because of the potential release of the toxins to water.

12.14 Permanent destratification of the water column by physical means will depress the growth of buoyant algal species, but only where the mixed depth exceeds considerably (probably by a factor greater than 2) the depth of water through which light penetrates. This method has also been used to control the formation of surface scums of the buoyant species. By-pass and circulation systems used in reservoirs — such as those in the Thames Water area — have also been successful, but these need to be incorporated into the design of a reservoir or artificial lake prior to its construction. Intermittent artificial destratification regulates the period available for growth of particular algae, but this has only been demonstrated experimentally on a small scale.

12.15 Barley straw has been alleged to control algal populations in small waterbodies, but its mechanism is unknown. Farming protozoan ciliates and silver carp are suggested means of biological control through their direct grazing capacity, but have never been attempted. The use of bacteria and viruses for controlling blue-green algae has also been the subject of research, but this has never been tried on a large scale. Such methods should all be considered as options for controlling algal populations. The degree of success will depend on the individual circumstances of each waterbody and the availability of detailed knowledge on the relevant factors likely to affect the growth of plankton within it. Such methods may need careful Environmental Impact Assessments to be undertaken.

12.16 The clear message, however, is that there are no easy options and many of the control methods currently available are not likely to be effective in the short term. The possible exceptions to this are where there is sufficient depth for destratification to be effective.

Research and Development

12.17 An important result of this enquiry has been the identification of research and development needs. There is limited knowledge of the nature of the toxins or of how they are produced. An important precursor to any environmental studies, however, is the need to develop standardised quantitative analytical techniques for the recovery and analysis of the toxins from different materials.

12.18 There has been limited research on the effects of the toxins on the flora and fauna of lakes and receiving watercourses. It is not known whether such toxins have adverse environmental effects, particularly on freshwater fisheries or other wildlife, and there is a need to gain further knowledge on the reasons for variations in toxicity of the blooms. The NRA needs to address these problems.

12.19 Although the NRA has no direct responsibility for assessing human health aspects of blue-green algal toxins, such as those affecting recreational and potable supply uses of the waters, it does appear that testing methods, additional to the mouse bioassay, are required. It would be of considerable benefit to develop cytological and immunoassay testing procedures to a level where they could be reliably used on a regular basis, but these biological methods should be complemented by high quality chemical analytical techniques to confirm the identity and quantity of the toxins.

12.20 Research on methods for the control of the blooms themselves is at a relatively advanced stage, but a number of areas of further research have been identified to improve the chances of success. These include the further development of mathematical models to predict changes in blue-green algal populations, which are required to aid management plans for individual waters. This would greatly enhance the currently low chances of success. Research is also required on the use of biological control methods, and on direct chemical methods.

Public Awareness

12.21 The problems relating to the production of toxins by blue-green algae are not going to be resolved rapidly, and are likely to remain for the foreseeable future. It is important, therefore, to ensure that the public are made aware of the need to avoid contact with, and ingestion of, the scums of live and decaying blue-green algae on the surface and shores of lakes and other stillwaters. This is being achieved by carrying out monitoring programmes and distributing information material. Eventually, the risks should become common knowledge. A number of terrestial plants are potentially toxic; for example buttercup, laburnam, lupin or sweet pea would be poisonous by ingestion and/or would cause irritation or allergic reactions in humans following contact. This also applies to some food stuffs, such as kidney beans and green potatoes. Certain types of fungi, mistakenly collected and consumed as edible mushrooms, pose a health risk; however, poisoning incidents are rare because, over the years, the public have been made aware of the potential problems and have taken appropriate precautions.

12.22 The problem of toxic plants, such as ragwort, is very familiar to farmers. Although livestock normally find these unpalatable, there are occasions — such as die-off following herbicide treatment — when animals will eat them. Again, however, awareness of the situation enables farmers to take appropriate action to avoid any potential problems.

12.23 The general public is already familiar with the use of warning notices which indicate a need for sensible awareness of potential hazards from biological toxins in recreational areas. The familiar 'Beware of adders' notices in heathland areas are seen each summer. This does not prevent access to these areas, but does require that additional care be taken. A parallel can be drawn with toxic blue-green algae.

12.24 It is conceivable that the weather patterns of the previous two years, with mild winters and long stable periods of warm summer weather, suitable for causing and sustaining intense blue-green algal growths, will continue and lead to a more regular occurrence of these blooms. With an increasing use of water for recreation there will, inevitably, be a greater chance of incidents involving humans, pets and livestock. It will not always be possible to prevent bloom formation, and in order to avoid such problems being more than an inconvenience, public awareness of the potential dangers is essential.

13 RECOMMENDATIONS

Practical Short-Term Management of the Problem

13.1 Each Region of the NRA should review the circumstances at each waterbody recently affected by blue-green algae. It is recommended that an action plan should be developed for each waterbody, or group of such waters, and this should indicate the control options currently available, and the work necessary to enable more effective management actions to be taken.

13.2 When giving information to water owners on the control of blue-green algal blooms, it is recommended that algicides which cause blue-green algae to break down should not be used, because it may lead to the release of toxins into the water.

Eutrophication Control

13.3 Where eutrophication control is considered to be necessary, it should be made clear that, in most cases, these measures will only be effective in the long-term. It is recommended that an evaluation of any proposed scheme should be carried out, including consideration of the necessity for in-lake treatment, mud-pumping and control of both point source and diffuse inputs of nutrients. It may be necessary to develop a catchment management plan, so that controls can be exerted on significant nutrient sources which may be far removed from the affected waterbody.

13.4 When giving information on control measures, it is recommended that it should be made clear that the lack of knowledge of the range of blue-green algal toxins, their properties, and the factors affecting toxin production, constrain any short-term development of measures for controlling the production of the toxins themselves.

Long-Term Monitoring

13.5 It is recommended that long-term monitoring should be carried out at a minimum of six key reference sites in England and Wales to determine changes in algal populations and the toxicity of blue-green algal blooms, in relation to natural and enhanced levels of nutrients and to changes in land usage.

Research and Development

13.6 It is recommended that the use of predictive models, to quantify the development of blue-green algal blooms in relation to changes in environmental variables, should be further evaluated. If necessary, further research should be initiated so that such models can be used to devise management plans for different bodies of water.

13.7 It is recommended that further research be initiated to evaluate and develop measures to control eutrophication to minimise the development of blue-green algal blooms. This should include investigations of:

- the effects of land-use practices on phosphorus run-off;
- the effectiveness of nutrient traps;
- the precipitation of phosphorus;
- the impact of increased use of phosphate-free detergents; and
- the mechanisms controlling the mobility of phosphorus between water and sediment.

13.8 Chemical alternatives to the mouse bioassay test for determining the toxicity of algal blooms need to be developed and evaluated; it is recommended that these include 'standard' quantitative analytical techniques for which a national reference collection of purified blue-green algal toxins needs to be established.

13.9 Research should be initiated on factors leading to temporal and spatial variations in blue-green algal toxin levels in stillwaters; it is recommended that this should be aimed at determining the transport, fate and biological significance of blue-green algal toxins in aquatic environments.

13.10 It is recommended that a research programme should also be initiated on the physiological, biochemical and genetic mechanisms involved in toxin production.

13.11 It is recommended that the use of barley straw bales in small, highly eutrophic ponds should be further investigated and the results monitored in relation to toxin levels. If this method is effective in controlling blue-green algal blooms, the reasons should be investigated. The use of biological control methods, however, should be thoroughly researched before any consents for their introduction are issued.

13.12 It is recommended that collaborative research programmes on the topics identified in this report should be developed with other interested parties in the UK and abroad.

Administrative Management

13.13 The NRA Toxic Algae Task Group should continue to meet to address the results from monitoring and research programmes and, in the light of these, to review NRA policies on monitoring and control measures. In particular, the results from the 1990 monitoring programmes should be reviewed and modified in the light of experience.

13.14 Links with appropriate authorities in other countries, particularly in Europe, known to be affected by blue-green algal toxins should be developed further. Indeed, some form of liaison group should be set up to discuss problems relating to blue-green algae and their toxins.

13.15 The NRA should consider the need for, and practicability of, use-related Environmental Quality Standards for blue-green algae and their toxins.

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15 GLOSSARY OF KEY TERMS

BOD	–	Biochemical Oxygen Demand, a standard test measuring the microbial uptake of oxygen, an estimate of organic pollution
DNA	–	Deoxyribonucleic acid, the genetic material of chromosomes
ELISA	–	Enzyme-linked immunosorbent assay, a technique for immunoassay
h_m	–	the depth to which mixing penetrates
h_p	–	the depth to which adequate light for photosynthesis penetrates
K_s	–	external concentration to maintain half the maximum growth rate
LAL	–	Limulus amoebocyte lysate, a type of bioassay
LD_{50}	–	Lethal Dose Fifty – a calculated dose which has caused the death of 50% of a defined experimental animal population: may be short or long term
nm	–	nanometre, 10^{-9}m
pH	–	scale of acid to alkali
sp.	–	species
Acetylcholinesterase	–	enzyme involved in transmission of nerve impulses
Acute LD_{50}	–	The quantity of toxin estimated as being capable of killing 50% of the exposed test population, following the administration of a single dose by a specified route. Death may occur in a short time period, up to several days, after the administration of the dose
Algicide	–	a chemical that kills algae
Alkaloid	–	chemical of a large group of nitrogenous bases of vegetable origin
Allergenic	–	having properties to cause excessive sensitivity (allergy)
Ames Test	–	standard test for measuring mutagenicity (genetic change) in the bacterium *Salmonella*
Amino acids	–	nitrogenous carbon compounds which can be joined together to make proteins
Anoxic	–	without oxygen
Bacteriophage	–	virus which attacks bacteria
Bioassay	–	measurement of the effect of substances on organisms
Biosynthesis	–	production of chemicals by living organism
Biphasic	–	host and parasite organisms simultaneously grown in the same laboratory culture
Blastoclad fungus	–	aquatic fungi
Chytrid fungus	–	aquatic fungi
Chromatography	–	separation of substances by slow passage through adsorbing material
Chromosome	–	thread-like structure of DNA organised into genes
Ciliates	–	protozoa with hairlike processes
Circumpolar Frontal Systems	–	boundaries between warm and cold conditions around the poles
Copepods	–	small crustaceans, aquatic animals with an external skeleton
Cyanobacteria	–	blue-green algae
Cyanophages	–	viruses which attack blue-green algae
Cytotoxic	–	poisonous to cells
Depression	–	centre of area of low atmospheric pressure
Dermatitis	–	inflammation of the skin
Dialysis	–	removal of substances by selective passage through a membrane
Dinoflagellates	–	single-celled motile algae; including toxin-forming algae associated with paralytic shellfish poisoning
Embryotoxic	–	poisonous to the embryo
Endotoxins	–	toxins retained within the algal cell
Epilimnion	–	upper layer in a stratified lake

Erythematous	–	redness of the skin
Eutrophication	–	increase in the rate of income of nutrients, typically leading to increased algal growth
Filamentous	–	threadlike
Gastroenteritis	–	inflammation of the intestine
Gas-vesicles	–	bladderlike buoyancy-conferring cavities in blue-green algae
Genus	–	a number of closely-related species
Hepatocytes	–	liver cells
Hepatoenteritis	–	inflamation of the liver
Hepatotoxin	–	toxin affecting the liver
Hydraulic Retention Time	–	time that water remains within the lake
Intra-peritoneal	–	within the peritoneal cavity of the abdomen
in vitro	–	in laboratory cultures outside the organism
in vivo	–	within the living organism
Limiting Factor	–	circumstance or substance which restricts growth when in short supply
Lipopolysaccharide	–	a fat molecule combined with a carbohydrate
Lyse	–	disintegrate
Lysosome	–	part of the cell that contains digestive enzymes
Macrophytes	–	large aquatic plants, e.g. lilies, reeds
Mesotrophic	–	average nutrient status
Metabolite	–	chemical involved in processes resulting in growth and energy production in living organisms
Mitochondria	–	part of the cell that contains enzymes for metabolic processes, particularly respiration
Mucilage	–	a sticky mixture of carbohydrates
Mutagenicity	–	ability to cause transmissable changes to the genes
Oligotrophic	–	having little available nutrients for plants and algae
Peptides	–	two or more amino acids joined together; small proteins
Photoperiodism	–	response of organism to day length
Photosynthesis	–	manufacture of carbohydrates using energy from light
Phycobilins	–	proteinaceous pigments including phycocyanin (blue) and phycoerythin (red)
Phytoplankton	–	floating or weakly motile small aquatic plants
Piloerection	–	erection of hairs on the skin or fur on animals
Planktonivorous	–	plankton eating
Plasmid	–	genetic material outside of the chromosomes
Polymerisation	–	bonding of chemicals of the same compound to form larger molecules, often into chains
Prokaryotes	–	single-celled organisms containing one chromosome per cell, not located in a membrane-bound nucleus; bacteria including cyanobacteria (blue-green algae)
Protozoa	–	small single-celled animals
Ramsar Convention	–	A wildlife convention for protecting wetland sites of international importance, held at Ramsar in Iran
Rhizopod protozoa	–	protozoa similar to an amoeba
Standing crop	–	total biomass (e.g. amount of algae) at any one time
Stratification	–	formation of layers
Teratogenic	–	producing anatomical or biochemical adverse effects on the developing foetus
Tumour promoting properties	–	properties which allow tumours to grow faster (this is not carcinogenicity)
Zooplankton	–	small animals which are weakly motile or are carried passively in the main body of water

APPENDIX A

Reports Received from England and Wales

The Anglian Region

The Northumbrian Region

The North West Region

The Severn Trent Region

The Southern Region

The South West Region

The Thames Region

The Welsh Region

The Wessex Region

The Yorkshire Region

Reports Received from Scotland

Reports Received from Northern Ireland

Reports Received from England and Wales

A1 Completed questionnaires were received from all the NRA regions (Figure 5) and, in a number of cases, replies were accompanied by additional information related to various aspects of eutrophication and the incidence of toxic blue-green algae. This information has also been summarised in the report.

A2 Replies were received from nine of the Water Services Companies (Figure 6). The Yorkshire NRA also provided details of algal monitoring carried out by Yorkshire Water Services Limited.

A3 The results of the completed questionnaires received from each NRA region and its 'equivalent' Water Services Company are discussed separately, but are presented under the heading of the appropriate NRA region. Information concerning the incidence of toxicity in waters owned by the 'original' Water Companies has also been incorporated separately, but under the nearest appropriate NRA region. The 'original' Water Companies, are those statutory Water Companies that existed prior to the Water Act (1989). (In some cases the boundaries of the 'original' water companies do not coincide with those of the NRA).

The Anglian Region

NRA Anglian Region

A4 A total of 351 waters were inspected and 830 visits were made. From 198 individual waters, 544 algal samples were taken of which 396 (73%) showed blue-green algae to be dominant. Table A1 lists those waters considered to have blue-green algal 'problems' in 1989.

A5 Of the 53 sites sampled for blue-green algal toxicity, the Anglian Region identified 37 waters (70%) to be toxic. Toxicity ranged from low to high. The first ever reported case of toxic *Gomphosphaeria* in the U.K. was identified at Scoulton Mere.

A6 Problems experienced by humans, livestock and domestic animals associated with blue-green algal blooms and scums were first brought to the attention of the NRA during September 1989 at Rutland Water, as discussed in Chapter 8. Later, verbal reports indicated that sail-boarders at Rutland Water experienced rashes and gastrointestinal problems after contacting and ingesting affected water.

Anglian Water Services Limited (AWS)

A7 The large bloom identified along parts of the shoreline at Rutland Water, and the reports of the sheep and dog deaths during August and September 1989, caused a great deal of concern to AWS. As a result of monitoring, *Anabaena* and *Aphanizomenon* were identified as the dominant algae during June, July and August. By the end of August, and into early September, AWS identified *Microcystis aeruginosa* as the dominant species, which had formed a heavy scum along the entire shoreline. Throughout September and October this species persisted, in association with *Aphanizomenon*. Positive blue-green algae toxicity results were also obtained for a number of other lakes and reservoirs owned by AWS, notably: Grafham Water, Alton Water, Covenham Reservoir, Pitsford Reservoir, Ravensthorpe Reservoir and Hollowell Reservoir.

A8 AWS made extensive efforts to measure microcystin in the raw water from Rutland. Traces of what could have been microcystin were detected, but interpretations of the analytical results were complicated. These problems were discussed in a report produced by AWS in March 1990.

Figure 5 The ten NRA regions in England and Wales

Figure 6 Water Service Companies in England and Wales

Table A1 Waters considered to have blue-green algal 'problems' in the Anglian Region during 1989

Lake/Reservoir	*Dominant Genera*	*Toxicity*
Abberton Reservoir	*Aphanizomenon*	+
Aldwincle Gravel Pit	*Aphanizomenon, Microcystis*	+
Alton Water	*Microcystis, Oscillatoria*	+
Apex Lake	*Aphanizomenon*	–
Ardleigh Reservoir	*Aphanizomenon, Oscillatoria, Anabaena*	+
Barton Broad	*Oscillatoria, Anabaena, Aphanizomenon*	+
Blickling Lake	*Microcystis, Aphanizomenon*	+
Brooke Farm Reservoir	*Anabaena*	–
Broome Pit No 4	*Aphanizomenon*	+
Cadney Reservoir	*Aphanizomenon, Microcystis, Anabaena*	+
Covenham Reservoir	*Microcystis, Ahpanizomenon*	+
Cransley Reservoir	*Microcystis, Coelosphaerium*	+
Decoy Broad	*Aphanizomenon, Oscillatoria, Anabaena*	–
Denton Reservoir	*Microcystis, Lyngbya, Oscillatoria*	+
Ease Drain	*Oscillatoria, Lyngbya*	–
Eyebrook Reservoir	*Microsystis, Anabaena, Oscillatoria*	+
Ferry Meadows Childrens' Lake	*Aphanizomenon, Anabaena*	–
Filby Broad	*Anabaena, Aphanizomenon*	+
Foxcote Reservoir	*Aphanizomenon, Microcystis*	–
Fritton Lake	*Microcystis*	+
Grafham Water	*Microcystis, Aphanizomenon*	+
Hartsholme Country Park	*Anabaena*	–
Hanningfield Reservoir	*Microcystis*	+
Hickling Broad	*Aphanothece, Lyngbya, Aphanizomenon*	–
Hinchingbrooke Lake	*Microcystis*	–
Hoverton Great Broad	*Oscillatoria*	+
Hoverton Little Broad	*Aphanizomenon*	–
Hollowell Reservoir	*Anabaena, Microcystis*	+
Homersfield Lake	unknown	+
Hughes and Sons Lake Shellingthorpe	*Microcystis, Aphanizomenon*	+
Lake Meadow	*Aphanizomenon*	+

Table A1 Waters considered to have blue-green algal 'problems' in the Anglian Region during 1989 (continued)

Lake/Reservoir	*Dominant Genera*	*Toxicity*
Meadow Lake, St Ives	*Microcystis*	+
Mount Farm Balancing Lake	*Aphanizomenon*	+
Ormesby Broad	*Aphanizomenon, Anabaena*	+
Overstone Lower Lake	*Aphanizomenon, Oscillatoria, Microcystis*	+
Pitsford Reservoir	*Microcystis, Aphanizomenon, Coelosphaerium*	+
Ravensthorpe Reservoir	*Microcystis, Anabena, Lyngbya*	+
Ranworth Broad	*Oscillatoria, Aphanizomenon*	−
Rollesby sailing club	*Aphanizomenon*	+
Rutland Water	*Microcystis, Aphanizomenon*	+
Salhouse Broad	*Oscillatoria, Aphanizomenon*	−
Scoulton Mere	*Gomphosphaeria*	+
Scamere	*Aphanizomenon, Oscillatoria*	+
South Holland Main Drain	*Prorocentrum*	−
South Walsham Broad	*Oscillatoria, Anabaena*	+
Sywell Reservoir	*Microcystis, Anabaena*	+
Teals Pit, Lincoln	*Anabaena, Microcystis*	+
Toft Newton Reservoir	*Microcystis, Aphanizomenon*	+
Turnbulls Pit	*Microcystis, Oscillatoria*	−
Whisby Nature Reserve	*Anabaena, Microcystis*	+
Willen North	*Aphanizomenon, Lynbya*	−
Wroxham Broad	*Aphanizomenon*	−
Wyboston Lakes	*Aphanizomenon*	+

\+ = Positive
− = Negative

'Original' Water Companies in the Anglian Region

A9 Five of the 'original' water companies are located in the Anglian Region. The Cambridge Water Company has no supply reservoir of its own. During 1989, Essex Water Company monitored Hanningfield and Abberton reservoirs at monthly intervals, both of which had blooms of *Microcystis* which were found to be toxic.

A10 The Corby (Northants) and District Water Company has only one reservoir in their area, Eyebrook, a non-potable supply reservoir, which supplies water to Corby Tube Works only. This reservoir had not been sampled for algal toxicity by the Water Company, but had been so sampled by Anglian NRA on two occasions. On 13 September, toxicity was categorised as medium and *Microcystis* was dominant in association with *Anabaena* and *Oscillatoria*; on 2 October, toxicity was high and *Aphanizomenon* had replaced *Oscillatoria*. Following the confirmation of positive toxicity results, only fishermen were allowed access to the reservoir. Notices were erected by the Water Company instructing the public to keep out, and also to keep their dogs out of the area. Fishermen were advised on a daily basis not to fish in areas where the algal blooms and scums had collected. Virtually all fishing was from boats in clear water, because bank fishing was prevented by the dense growth of aquatic weed. As a precautionary measure, fishermen were requested to wash their hands on completion of fishing.

A11 Ormesby Broad and Fritton Lake, owned by East Anglian Water Company, were identified as toxic from samples taken by Anglian NRA. At Ormesby Broad toxicity was low and was associated with a bloom of *Aphanizomenon* and *Anabaena*. A scum was present on the shoreline during the period of sampling. Fritton Lake was initially identified as having a high algal toxicity, but a sample taken five days later was of medium toxicity. Both samples were associated with a bloom of *Microcystis*.

The Northumbrian Region

NRA Northumbrian Region

A12 The Northumbrian Region inspected 28 waters during 1989, but blue-green algal 'problems' were not perceived. The only previous significant incidence known was in 1976, when an *Anabaena* bloom occurred at Hallington Reservoir, reported by Newcastle and Gateshead Water Company.

Northumbrian Water Limited

A13 Northumbrian Water did not experience any significant blue-green algal blooms during the summer of 1989. This may be explained by the fact that most of their reservoirs are located in upland, nutrient-poor, regions and their trophic status tends to be low.

'Original' Water Companies in the Northumbrian Region

A14 Three of the 'original' water companies are located in this region: Hartlepool Water Company, Sunderland and South Shields Water Company, and Newcastle and Gateshead Water Company. Each of these operates surface impoundment reservoirs, but did not experience any problems with toxic blue-green algae during 1989. Most of the waters owned by these water companies are oligotrophic.

The North West Region

NRA North West Region

A15 Individual waters were inspected and sampled on request, and not as part of a routine monitoring programme; thus it is not known precisely how many waters were visited or how many samples were taken, but approximately 50 waters were sampled and these were dominated by blue-green algae. The most common ones encountered were *Microcystis aeruginosa*, *Aphanizomenon flos-aquae*, and species of *Anabaena* and *Oscillatoria*. In many of these waters, such algae occur regularly from year to year.

A16 A single sample from a shallow isolated bay of Lake Windermere was tested for algal toxins, and gave a positive result. The actual sample itself was not considered representative of the whole lake. There were no reports from members of the public concerning problems associated with blue-green algal scums or blooms, despite the fact that a number of waters with dense blooms were fished and used for recreational purposes. A dog became ill after ingesting water from a British Waterways Board Reservoir which had a mixed bloom of *Anabaena*, *Aphanizomenon* and *Microcystis*. The cause of the illness was not determined.

A17 Anecdotal evidence of algal toxicity in this region was first noted in 1979, when three cattle died after ingesting water from Rostherne Mere which contained a bloom of *Oscillatoria*. Further blooms from this water were found, by mouse bioassay, to be toxic during the 1980s.

North West Water Limited

A18 Most of the water supplies are situated in oligotrophic (low nutrient status) upland lakes or reservoirs where chemical and physical conditions are not conducive to abundant algal growth. Occasionally there are transient small blooms of *Microcystis*, which appear to cause no major problems.

'Original' Water Companies in the North West Region

A19 There are no 'original' water companies in the North West Region.

The Severn Trent Region

NRA Severn Trent Region

A20 A total of 80 waters were inspected and 153 visits were made. From 44 individual waterbodies, 133 algal samples were taken, of which 32 samples had a dominance of blue-green algae. Table A2 lists those waters considered to have blue-green algal 'problems' in 1989.

A21 Rudyard Lake and Kingsmill Reservoir were tested for algal toxicity, but only Rudyard Lake gave positive results. Another 16 waters were dominated by blue-green algae, but were not tested for algal toxicity although, on the basis of their algal abundance and composition, they were considered to be potentially toxic. Scum removal techniques were employed at Kingsmill Reservoir to alleviate public complaints concerning unpleasant odours from rotting scums.

Severn Trent Water Limited

A22 Severn Trent Water did not report 'problems' with toxic blue-green algae in 1989, although six reservoirs had dense blue-green algal populations. Samples were not tested for toxicity. In the eastern area three reservoirs, namely Blackbrook, Swithland (both private fisheries with rowing boats) and Thornton (a fishery and boys' sailing club), were greatly affected by blue-green algae. Although warning signs were erected, recreational activities were allowed to continue. Most of the blooms were in patches and were dominated by *Aphanizomenon*, with a secondary dominance of *Microcystis* and *Anabaena*. Staunton Harold Reservoir also had a scum of blue-green algae during 1989 and was subsequently treated with copper sulphate, which caused fragmentation of the algal scum.

A23 Blue-green algal biomass increased at many sites in Severn Trent's southern area, but these were only significant during 1989 at Stanford Reservoir, where the bloom was dominated by *Aphanizomenon* and *Microcystis*, and at Lower Shustoke Reservoir (a trout fishery and sailing reservoir).

Table A2 Waters Considered to have blue-green algal 'problems' in the Severn Trent Region during 1989

Lake/Reservoir	*Dominant Genera*	*Toxicity*
Ball Mill Pools	*Oscillatoria*	NT
Blackbrook Reservoir	*Microcystis*	NT
Black Prince Marina	*Microcystis, Gomphosphaeria*	NT
Bomere Great Pool	*Anabaena*	NT
Colemere	*Microcystis*	NT
Daneshill Nature Reserve	*Microcystis*	NT
Kings Mill Reservoir	*Oscillatoria*	–
Knypersley Reservoir	*Microcystis*	NT
Naseby Reservoir	*Microcystis, Anabaena, Aphanizomenon*	NT
Rudyard Lake	*Microcystis*	+
Sulby Reservoir	*Microcystis, Oscillatoria*	NT
Swithland Reservoir	*Microcystis*	NT
The Mere, Ellesmere	*Microcystis*	NT
Thornton Reservoir	*Microcystis*	NT
Trentham Gardens	*Microcystis*	NT
Welford Reservoir	*Microcystis, Oscillatoria*	NT
Westport Lake	*Microcystis*	NT
White Mere	*Microcystis*	NT

\+ = Positive
– = Negative
NT = Not tested

A24 There were no reports of adverse health affects experienced by humans, wild or domestic animals, or livestock. Fish kills were reported on the River Avon, which flows in and out of Stanford Reservoir, but the cause of death was not determined. Lower Shustoke Reservoir was dominated by *Oscillatoria argardhii* during 1989 to extremely high levels. Sailing and trout fishing continued throughout the period of the bloom, and no reports of adverse health affects were received.

A25 In Severn Trent Waters' northern area, there were no problems with blue-green algae in supply reservoirs. Many of the reservoirs are too shallow for full stratification to develop, and the majority are mesotrophic to oligotrophic.

'Original' Water Companies in the Severn Trent Region

A26 Two of the 'original' water companies are located in this region. No reply was received from South Staffordshire Water Company, and East Worcestershire Waterworks Company has no surface water impoundments.

The Southern Region

NRA Southern Region

A27 A total of 8 waters were inspected and sampled for blue-green algae and 26 individual samples were taken. Only Bewl Water (owned jointly by Southern Water Services Limited and Mid Kent Scientific Water Services) was considered to have 'problems' with blue-green algae. Samples were not tested for blue-green algal toxicity.

A28 A single incident of adverse health problems apparently associated with a blue-green algal bloom was reported by both Southern NRA and Southern Water Services Limited in 1989. This was from an angler who had regularly fished Bewl Water for ten years. During August and September, the angler developed 'blotchy' skin on his face and hands after handling the water. He reported that such problems had occurred on three separate occasions, within two hours of arrival. The symptoms took several days to clear.

Southern Water Services Limited

A29 Bewl Water, Darwell Reservoir and Weir Wood Reservoir contained blooms of blue-green algae in 1989. Of these, only Bewl Water had a sufficiently high biomass to be considered to be a 'problem'. Weekly algal samples were collected from each water during September, and algal identification and biomass estimates were carried out.

Bewl Water

A30 During September, algal scums developed and were blown to the dam end and to various confined areas of Bewl Water. The algae were identified as *Microcystis* and their abundance was consistent with a high algal biomass. Samples were not tested for blue-green algal toxicity. As a precautionary measure, walkers were advised to keep their dogs away from the waters edge, and certain small bays were fenced off.

Darwell Reservoir

A31 *Microcystis* was identified as the dominant alga; this persisted throughout the sampling period. Samples were not tested for blue-green algal toxicty.

Weir Wood Reservoir

A32 The dominant alga was identified as *Aphanizomenon*; *Microcystis* was also present, but neither was sufficiently abundant to cause concern. Samples were not tested for blue-green algal toxicity.

'Original' Water Companies in the Southern Region

A33 Six of the 'original' water companies are located in the Southern Region. Mid Kent Scientific Water Services has only one surface water supply reservoir – Bewl Water. During 1989 *Coelosphaerium* was identified as the dominant algae; *Microcystis* was not found. Such findings conflict with those of Southern Water Services Limited.

A34 Folkestone and District Water Company has one small surface water supply reservoir, which was unaffected by blue-green algae.

A35 Portsmouth Water Company pumps surface water from the River Itchen near Eastleigh, in Southampton, to an impoundment reservoir. During 1989 blue-green algae were not present.

A36 Eastbourne Waterworks Company has only one surface water supply reservoir, at Arlington in Sussex. Each year low levels of blue-green algae are detected, but are not considered to be a 'problem'.

A37 Mid-Sussex Water Company and West Kent Water Company did not have any surface water supply reservoirs affected by blue-green algae during 1989.

NRA South West Region

A38 A total of 254 waters were inspected and sampled for algae, and 689 visits were made. During each inspection, a single sample was taken for algal assessment. A total of 27 waters were considered to have 'problems' with blue-green algae and 17 were tested for toxicity, of which 10 (63%) were found to be toxic. Table A3 lists those waters considered to have blue-green algal 'problems' in 1989.

Table A3 Waters considered to have blue-green algal 'problems' in the South West Region during 1989

Reservoir/Lake	*Dominant Genera*	*Toxicity*
Alder Reservoir	*Anabaena*	NT
Argal Reservoir	*Anabaena, Microcystis, Coelosphaerium*	–
Bicton Stream	*Anabaena*	NT
Bradley Main Pond	*Microcystis, Anabaena, Coelosphaerium*	+
Bussow Reservoir	*Microcystis, Coelosphaerium*	+
Drift Reservoir	*Aphanizomenon*	+
Exeter Canal	*Aphanizomenon*	–
Fulford Pond	*Coelosphaerium*	–
Fulford Stream	*Coelosphaerium*	NT
Grand Western Canal	*Anabaena*	NT
Higher Marsh Pond	*Anabaena*	–
Hollocombe Main Pond	*Microcystis*	NT
Jennetts Reservoir	*Anabaena, Microcystis, Coelosphaerium*	–
Langarth Lake	*Oscillatoria*	+
Loe Pool	*Microcystis*	–
Lower Clicker Quarry	*Oscillatoria*	NT
Lower Tamar Lake	*Coelosphaerium*	NT
Meldon Pool	*Anabaena, Oscillatoria*	+
Old Mill Reservoir	*Microcystis, Anabaena, Coelosphaerium*	+
Ornamental Pond, Bicton	*Microcystis, Anabaena, Aphanizomenon*	+
Porth Resevoir	*Microcystis*	+
River Otter	*Anabaena*	NT
Slapton Ley	*Microcystis, Anabaena*	NT
Splatton Riddon Lower Pool	*Anabaena, Microcystis*	NT
Strafford Moor	*Microcystis, Oscillatoria, Coelosphaerium*	+
The Lake, Bicton	*Microcystis, Anabaena, Aphanizomenon*	+
Upper Tamar Lake	*Microcystis, Coelosphaerium*	–

+ = Positive
– = Negative
NT = Not tested

A39 Adverse health affects possibly associated with blue-green algal scums and blooms were experienced by NRA staff, livestock and wild animals. These are detailed below.

a) Some NRA staff experienced tingling sensations on their hands, after sampling water-bodies containing potentially toxic blue-green algal species.
b) Two calves were stillborn in a field downstream of The Lake, Bicton, but the actual cause of this was not determined.
c) There was an unconfirmed report of dead rodents and birds identified at Porth reservoir; the carcasses were not traced.

South West Water Services Limited

A40 Two cases of algal toxicity were identified by South West Water Services Limited during 1989. These were from surface samples from Porth Reservoir and Old Mill Reservoir, which were also found to be toxic by South West NRA. Toxicity ranged from low to medium and was consistent with microcystin toxicity. Both waters were dominated by large populations of *Microcystis aeruginosa*. The following waters contained large populations of potentially toxic species of blue-green algae, but were not tested for algal toxicity: College-Argal, College No. 4, Colliford, Darracott, Gammaton-Lower, Gammaton-Upper, Jennetts, Slade-lower, Squabmoor, Stithians, Tamar-Lower, Tamar-Upper and Wistlandpound. Several brown trout deaths were noted at Squabmoor Reservoir, which contained a large bloom of *Anabaena*. The cause of death is unknown.

'Original' Water Companies in the South West Region

A41 There are no 'original' water companies in the South West region.

The Thames Region

NRA Thames Region

A42 A total of 25 waters were inspected and sampled for algae; 39 inspections were made. Blue-green algae were dominant at 21 waters. Common blue-green algae associated with apparent problems included *Microcystis aeruginosa*, and species of *Anabaena*, *Aphanizomenon* and *Oscillatoria*.

A43 Samples were not tested for algal toxicity and there were no reports of any health problems associated with blue-green algal scums and blooms. The Thames Region regularly receives complaints of algal scums each year, particularly in the north and south west areas, which contain a large number of reservoirs; however, more complaints were received in 1989 than in previous years.

A44 Historical data on blue-green algal 'problems' exist for Farmoor Reservoir, which annually develops large algal blooms during the summer; associated complaints have been received related to the flavour of fish and the taste and odour of water. This has been attributed to the presence of *Oscillatoria*, which is known to produce 'geosmin' (an odour-producing compound).

Thames Water Utilities Limited

A45 During 1989, Thames Water Utilities took 228 samples from 20 waterbodies during the period 15 September to 17 November 1989. Blue-green algal species were present in 93 samples, but in most cases they did not reach high levels of abundance. The common species involved were *Aphizomenon flos-aquae*, *Anabaena flos-aquae* and *Microcystis aeruginosa*. Only Warwick East and Warwick West Reservoirs had dense blooms of *Microcystis*. Visual observations revealed that small scums were present on some reservoirs, but these were not considered to be a 'problem'.

A46 When problems were reported by other water companies, and by the NRA, Thames Water Utilities Limited reacted by erecting fences to exclude grazing animals from areas where scums were present. Public access for recreational activities, such as sailing and fishing, continued throughout the bloom period, but no reports of any health problems associated with blue-green algal blooms and scums were received.

'Original' Water Companies in the Thames Region

A47 Seven of the 'original' water companies are located in the Thames Region. Lee Valley Water Company, Mid Southern Water Company and the Sutton District Water Company do not have any surface water supply reservoirs. East Surrey Water Company has only one surface water supply reservoir, at Bough Beech in Kent. Low levels of *Microcystis* were identified but were not considered to be a 'problem'.

A48 No replies were received from Colne Valley Water Company and North Surrey Water Company. Rickmansworth Water Company did not have any 'problems'.

The Welsh Region

NRA Welsh Region

A49 A total of 12 waters were sampled for algae, and 250 individual samples were taken for analysis. Only Ynys-Y-Fro had a blue-green algal bloom of serious proportions. The most common blue-green algae in 1989 were *Aphanizomenon flos-aquae* and species of *Oscillatoria*. Toxicity tests were not carried out.

A50 Two reservoirs with algal blooms had been tested for algal toxicity in previous years. In 1987, Llyn Alaw (Anglesey) had a *Microcystis* bloom which was found to be toxic, and in 1988, a toxic *Microcystis aeruginosa* scum was associated with a mortality of fish fry in a bay of Llandegfedd Reservoir.

Welsh Water Services Limited

A51 During the summer, weekly algal samples are collected on an annual basis from 23 waters. In 1989, seven waters had blooms of blue-green algae, of which 4 developed surface scums. Common species associated with these scums included *Microcystis aeruginosa*, and those of *Anabaena*, *Aphanizomenon*, *Oscillatoria* and, to a lesser extent, those of *Coelosphaerium* and *Gleotrichia*. No reports of toxicity or suspected toxicity were received. The only known case of algal toxicity testing was at Llyn Alaw, North Wales, but the results were inconclusive.

A52 In general, blue-green algal blooms and scums are a common feature of many waters owned by the Welsh Water Services Limited, but no confirmed cases of toxicity are known.

'Original' Water Companies in the Welsh Region

A53 Two of the 'original' water companies are located in the Welsh region. The Welsh Development Agency do not have any surface water supply reservoirs. Chester Water Company's surface supply is the River Dee, from which it is pumped to a storage reservoir. Problems were not experienced with blue-green algae during 1989. No reply was received from Wrexham and East Denbighshire Water Company.

The Wessex Region

NRA Wessex Region

A54 A total of 32 waters were inspected and sampled for algae during 1989. Blue-green algae were dominant in 13 waters, all of which were considered to be a 'problem'. These waters are listed in Table A4.

Table A4 Waters considered to have blue-green algal 'problems' in the NRA Wessex Region during 1989

Lake/Reservoir	*Dominant Genera*	*Toxicity*
Ashford Reservoir	*Microcystis*	NT
Blashford Lake (a new reservoir)	*Gleotrichia, Anabaena, Microcystis*	NT
Clatworthy Reservoir	*Oscillatoria*	NT
Durleigh Reservoir	*Microcystis*	–
Gasper Lake	*Microcystis*	NT
Hawkridge Reservoir	*Microcystis, Anabaena, Aphanizomenon,*	+
Ivy Lake	*Microcystis*	NT
Moors Valley Lake	*Anabaena*	NT
Shearwater Lake	*Microcystis*	NT
Stourhead Lake	*Microcystis*	NT
Turners Paddock Lake	*Microcystis*	NT
Tokenham Lake	*Oscillatoria*	NT
Willow Lake	*Anabaena*	NT

\+ = Positive
– = Negative
NT = Not tested

A55 The only suspected case of toxicity in previous years occurred in 1988, when a large *Oscillatoria* bloom was associated with fish kills in a gravel pit used as a trout fishery. Algal toxicity tests were found to be negative.

Wessex Water Services Limited

A56 High blue-green algal counts were recorded at Durleigh Reservoir, Hawkridge Reservoir and Luxhay Reservoir. In all three reservoirs *Microcystis*, and to a lesser extent *Anabaena*, were dominant. At Durleigh Reservoir, a large *Microcystis aeruginosa* bloom caused problems with water treatment processes, but it was not necessary to withdraw water supply. Hawkridge Reservoir also experienced a large bloom of *Microcystis aeruginosa*, but water treatment problems were not encountered. Samples sent for algal toxicity testing were found to be positive.

A57 At Luxhay Reservoir, despite the use of destratification equipment, a large bloom of *Microcystis* developed, and persisted, causing operational difficulties. Flocculation problems were encountered during treatment, and filter beds were clogged. After treatment with an algicide, further problems with a residue of mucopolysaccharides occurred, and persisted for a few weeks. Ashford Reservoir, Clatworthy Reservoir, Ivy Lake and Spinnaker Lake all developed blue-green algal species during the summer of 1989, but were not considered a 'problem'. Algal toxicity tests were carried out on Ivy and Spinnaker Lakes only, both of which contained *Gleotrichia*, but the results were negative.

'Original' Water Companies in the Wessex Region

A58 Four of the 'original' water companies are located in the Wessex Region. During 1989, Cheddar Reservoir and Barrow No. 1 Reservoir were sampled for blue-green algae by Bristol Waterworks Company. Both contained high levels of potentially toxic species, but algal toxicity tests were not carried out. Cholderton and District Water Company, West Hampshire Water Company and Bournemouth and District Water Company do not have surface water supply reservoirs.

The Yorkshire Region

NRA Yorkshire Region

A59 Between August and December 1989, Yorkshire NRA inspected 69 waters. A total of 81 inspection visits were made and 63 waters were sampled specifically for algae. Collaborative work between the Yorkshire NRA and Yorkshire Water Services Limited identified 6 waters that had blue-green algae as the dominant group, and were considered to be a 'problem'. These are listed in Table A5. Algal toxicity tests were carried out for the NRA by the MAFF laboratories in Weymouth. Crosslands Lake and Hay-a-Park were not tested for toxicity, but could be considered as potentially toxic on the basis of their algal composition.

Table A5 Waters considered to have blue-green algal 'problems' in the Yorkshire Region during 1989

Lake/Reservoir	*Dominant Genera*	*Toxicity*
Beaverdyke Reservoir	*Microcystis, Anabaena*	+
Crosslands Lake	*Aphanizomenon*	NT
Hay-a-Park Lake	*Anabaena, Microcystis*	NT
John O'Gaunts Reservoir	*Microcystis, Anabaena*	+
Silsden Reservoir	*Microcystis*	+
Welton Water	*Anabaena*	+

\+ = Positive
NT = Not tested

A60 There was little evidence of problems experienced by members of the public, livestock, or domestic and wild animals associated with blue-green algal blooms or scums. Rashes were reported by water users at Welton Water, which contained a scum of *Anabaena* during September and October 1989. On 12 October 1989, a dog became ill after falling in Hay-a-Park Lake which contained a bloom of *Anabaena* and *Microcystis*.

'Original' Water Companies in the Yorkshire Region

A61 Only one 'original' water company is located in the Yorkshire region. This is Yorkshire Waterworks Company which does not have any reservoirs.

Reports Received from Scotland

A62 The organisation and structure of water services in Scotland is independent and distinct from the remainder of the UK. Pollution control and water services responsiblities are divided amongst River Purification Boards (of which there are seven), Regional Councils (of which there are nine), three Islands Councils which are all-purpose authorities, and the Central Scotland Water Development Board (Figures 7 and 8). The Board is an independent bulk supply authority and covers an area which includes the Central, Lothian, Fife, Tayside and Strathclyde regions in which almost 80% of the Scottish population is located. Bulk supplies are provided to four of these regions from Loch Lomond and Loch Turret. The information received from Scotland is discussed below.

Central Scotland Water Development Board

A63 No 'problems' with blue-green algae were experienced in Loch Lomond and Loch Turret during 1989.

River Purification Boards

Tay River Purification Board

A64 This Board does not have any routine sampling programmes for monitoring algal populations; however, during December 1989, only Loch Earn was the subject of public complaint due to an unsightly algal scum. The alga was identified as *Coelosphaerium*. No algal toxicity tests were carried out.

Forth River Purification Board

A65 A total of 17 waters were inspected during 1989, but only 3 were sampled for algae. Of these, only Loch Leven was considered to have 'problems' with large populations of blue-green algae, and during 1989 many complaints were received related to unsightly algal scums. The dominant alga was identified as *Anabaena*. Toxicity tests were not carried out.

A66 There was a significant increase of *Oscillatoria* in Loch Ard during the summer of 1989, but this was not considered to be a 'problem'. Before 1983, *Oscillatoria* abundance was low, but has progressively increased since then.

Highland River Purification Board

A67 The Board is currently setting up a register of the occurrence of algal blooms to see if they occur on lochs with fish farms. Algal blooms were identified at 3 Lochs in 1989: in Loch Kemp in Whitebridge, Loch Tollaidh in Wester Ross, and Loch Sgamhain in Glencarron, near Achnasheen.

A68 During 1989 the nutrient status and blue-green algal numbers in Loch Kemp increased, and in early July a bloom dominated by *Anabaena* was identified. No 'problems' were noted, although a local farmer was advised to move his cattle away from the loch, as a precautionary measure, for the duration of the bloom.

A69 Monitoring of the winter total phosphorus levels in Loch Tollaidh was carried out by the Board during early 1987; a general upward trend was observed in 1989. During the summer months of 1989, algal growth increased only gradually, but the species were not identified. Anecdotal evidence indicated that a scum did occur, but this was not observed during any of the site visits by employees of the Board. There were no reports of any adverse human health effects associated with the Loch, and so toxicity tests were not carried out.

A70 Nutrient levels, particularly phosphorus, in Loch Sgamhain increased during 1989 and this sustained a dense blue-green bloom of *Anabaena*. No toxicity tests were carried out and no evidence of toxicity was noted. Blooms have been observed in previous years, but no scientific data exists to confirm this.

Figure 7 Scottish River Purification Authorities

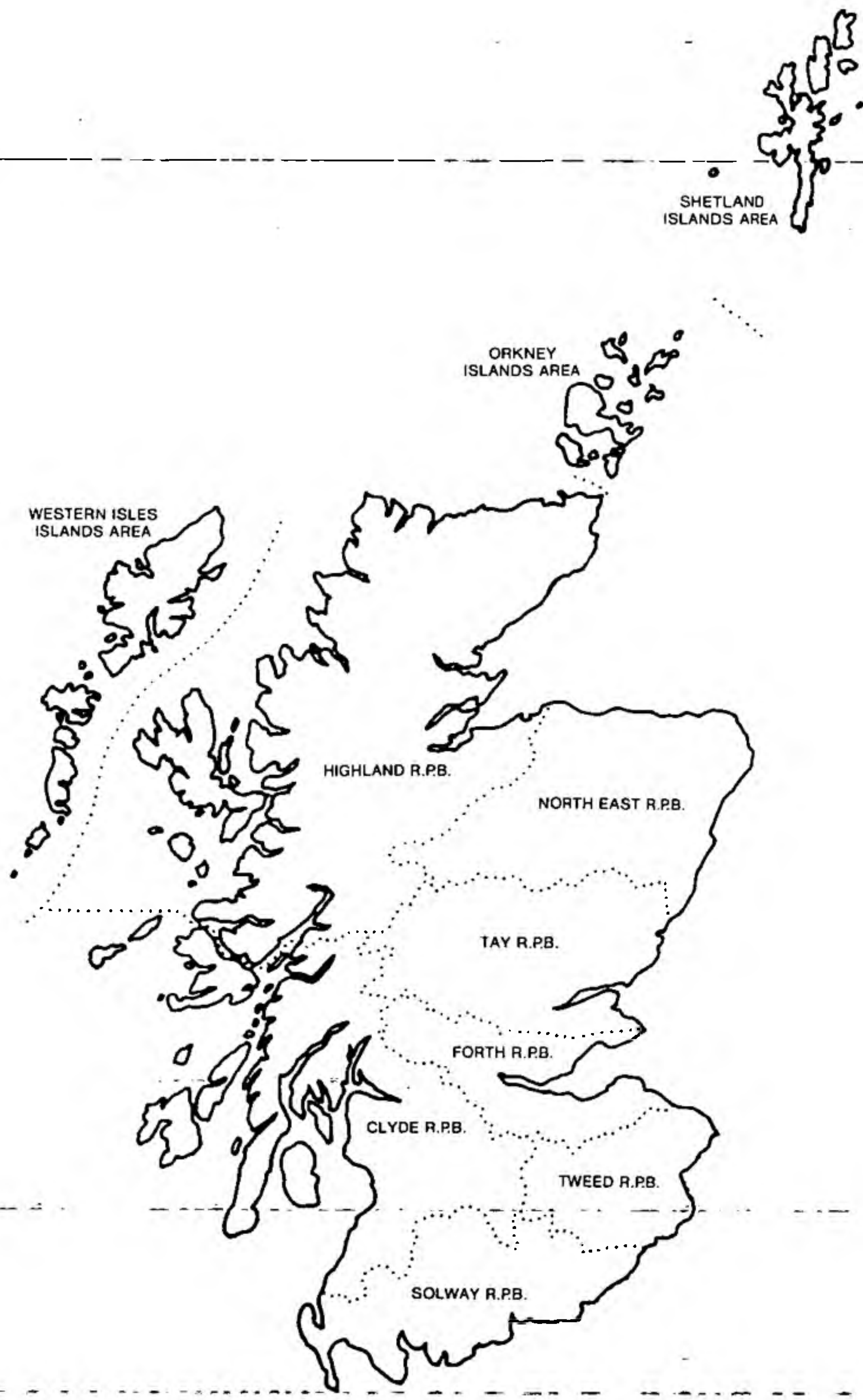


Figure 8 Scottish Regional Councils Water and Sewage Services

Clyde River Purification Board

A71 The Board monitors the trophic status of a number of freshwater lochs. Blooms of blue-green algae are of common occurrence and, in previous years, fish mortalities have been linked with such blooms. It has not been established whether these mortalities were caused by toxins from blue-green algae: the Board has not analysed samples for toxicity. During 1989, blooms of blue-green algae were confirmed in Long Loch and Loch Fad. *Microcystis* was recorded in Loch Fad, which contains a large-cage fish farm and is subject to frequent algal blooms. There were no cases of suspected toxicity associated with blue-green algae in the Clyde area during the year.

Solway River Purification Board

A72 A total of 15 algal samples were taken from 11 lochs; 2 of these – Mill Loch and Black Loch – had large scums of *Microcystis* during 1989. Mill Loch is considered to be highly eutrophic. Samples of algae from the Loch were shown to be toxic, consistent with the presence of microcystin. As a precautionary measure, access to Mill Loch was prohibited and notices were erected informing the public to keep out. No toxicity tests were carried out on Black Loch.

A73 Annandale and Eskdale District Council employed gully emptiers to draw-off the scum from the water surface of Mill Loch in 1989. A further scum later re-appeared, but subsequent weather conditions were not conducive to its persistence and algal numbers declined.

Tweed River Purification Board

A74 This Board does not conduct any routine sampling programmes for monitoring algal populations in standing bodies of water. Although historically some lochs have supported blue-green algal blooms, none were the subject of any public complaints during 1989.

Regional Councils

Borders Regional Council

A75 During the summer of 1989, no problems associated with toxic blue-green algae were experienced in this region. In past years, blooms in Alemoor reservoir of *Oscillatoria* and *Anabaena*, together with the diatom *Asterionella*, have caused 'problems' at Roberton Filtration Works. In 1989, these were minimal.

Highland Regional Council

A76 No detailed information on the incidence of blue-green algae in this region was available in 1989; however, a toxic bloom was identified in 1988.

A77 A total of 3 lochs were sampled for algae, and 2 samples were taken from each. Only Loch Muidhe was dominated by blue-green algae at levels considered to be a 'problem'. The dominant alga was identified as *Anabaena*. Two samples were collected for algal toxicity testing; both were found to be positive.

A78 No reports of any 'problems' caused by blue-green algae to members of the public during 1989, or in previous years, were received by the Council, although there were regular reports of scum formations.

Fife Regional Council

A79 A total of 8 reservoirs were sampled for algae in the Fife region, but only 2 had blue-green species as the dominant algae – Glenfarg and Lochmill (Newburgh). Both lochs were dominated by *Anabaena*, but only Glenfarg was considered to have a high blue-green algal biomass. Algal toxicity tests were not carried out. Anecdotal evidence indicates that the algal blooms and concentrations at Glenfarg were, in fact, worse in 1989 than in previous years.

Tayside Regional Council

A80 The Council reported that algal 'problems' were not experienced in this region during 1989. This conflicts with information received from Tay River Purification Board.

Lothian Regional Council

A81 During 1989, 4 reservoirs were sampled for algae and approximately 200 samples were taken. The following 3 waters were dominated by blue-green algal species: Gladhouse Reservoir, West Water, and Donolly Reservoir, of which Gladhouse and Donolly Reservoirs were considered to have 'problems'. In both cases, the dominant alga was a species of *Oscillatoria*. The dense blooms caused a green colouration to the surface waters of both these reservoirs and, consequently, Donolly Reservoir was taken out of service. Algal toxicity tests were not carried out.

Dumfries and Galloway Regional Council

A82 A total of 15 waters contained blue-green algal species; these were sampled either monthly or fortnightly. The following 5 waters were considered to be a 'problem': Winterhope Reservoir, Loch Roan, Loch Rutton, Loch Milton (not used for public water supply) and Purdomstone Reservoir. At Purdomstone Reservoir a small scum developed towards the end of 1989. The common algal species associated with these 'problems' were *Microcystis aeruginosa* and those of *Anabaena*, *Oscillatoria*, and, to a lesser extent, of *Coelosphaerium*. Algal toxicity tests were not carried out.

Strathclyde Regional Council

A83 In this region approximately 97 lochs were sampled for algae throughout 1988 and 1989. During 1989 blue-green algae were dominant in 18 waters, but only Long Loch, near Neilston was considered to have a 'problem', primarily with *Anabaena*. Algal blooms have been noted prior to 1989 on various waters in the Strathclyde region, but no reports of algal toxicity were received. In most cases such blooms were of *Anabaena* or *Oscillatoria*.

A84 A total of 6 samples from Loch Neilston were subject to algal toxicity testing and analysis for microcystin. All 6 exhibited low toxicity, which subsequently declined. The presence of microcystin was confirmed by HPLC.

Island Councils

Shetland Islands Councils

A85 The Council carried out investigations at the Loch of Brough, Yell where there was an increase in the levels of algae, although there was no evidence of bloom conditions. *Anabaena* was present at low density. Also, a bloom of blue-green algae was recorded from Turgdale Water.

Reports Received from Northern Ireland

A86 Responsibility for all water and sewage services in Northern Ireland lies with the Department of the Environment for Northern Ireland and is divided amongst four Water Service Divisions: Northern, Eastern, Western and Southern. A total of 47 waters were inspected, and 36 were sampled for algae. Approximately 480 algal samples were taken, of which 114 were dominated by blue-green algal species.

A87 Only 3 waters were considered to have 'problems' with large blue-green algal populations. These were Ballinrees Reservoir in the Northern Division, Lough Island Reavy in the Eastern Division, and Lough Neagh which serves the Northern, Southern and Eastern Divisions. Only one toxicity test was carried out, on a sample from Lough Island Reavy. This sample was dominated by *Synechococcus* and gave mild positive toxicity results, which were not characteristic of microcystins or neurotoxins.

APPENDIX B

Toxic Blue-Green Algae

Monitoring Recommendations for 1990

The NRA Toxic Algae Task Group was asked to recommend a monitoring action plan for the NRA in 1990, in order to establish the extent of the problem likely to occur this year. Due to the large number of individual waterbodies in any one region it would not be practical to monitor all of them. It was therefore agreed that only a proportion of controlled waters would be monitored.

In the event of a blue-green bloom there is a high probability that toxin will be produced; however, as the concentration of toxin is proportional to the concentration of algal material, the presence of a 'scum' will constitute the highest likelihood of toxins being produced.

The proposed approach to monitoring in 1990, as determined by the group, was therefore as follows.

1 The water to be monitored is categorised according to the risk of direct contact with, and ingestion of, scum by humans, pets and livestock.

	Level of risk of contact	
a) High	*b) Medium*	*c) Low*
Paddling, Swimming	Canoeing	Fishing
Diving, Sail-boarding	Sailing	Irrigation of crops
Water-skiing	Rowing	Pleasure Cruising
Livestock Watering	General Public Amenity	

2 All potable water supply reservoirs will be monitored, except those where there is no public or livestock access; the responsibility in these cases falls to the relevant water undertaker, because the risk is limited to ingestion via the public supply. In addition, a minimum of not less than 10% of all category 'a' waters, chosen at random, will be monitored, unless this is physically impossible because of the numbers of waters involved (e.g. Thames Region).

3 Single monthly samples will be taken from May to October and analysed for total phosphorus (TP). Orthophosphate analysis should not be carried out. This is because orthophosphate is consumed in bloom production and is not, therefore, an index of the biologically available fraction. The analysis must therefore be for TP (Ref 1). It is recognised that this method may not readily achieve a limit of detection of 10µg per litre. If an appropriate method cannot be developed in-house, in the time available, then the use of external contractors should be considered in order to save significant and unnecessary use of biological resources during the summer. If TP analysis cannot be carried out, then monthly algal assessment should be undertaken between May and October.

4 Select a sampling point on the downwind (lee) shore of the waterbody. Note the presence or absence of any surface scums. The minimum sampling requirement is a single one litre surface dip taken at this point. This may be used for both chemical and algal analysis. If the results of chemical analysis in May reveal that:-

a) TP > 10µg per litre — sampling for algae and phosphate is required until October.
b) If TP < 10µg per litre — no further algal or phosphate samples are required.

If no samples are taken before June, then sampling for algae population density and phosphate should continue, whatever the phosphate results, until October.

5 As a rough guide to the blue-green algae abundance, two simple parameters will be used as a measure of this, namely 'present' and 'abundant'. Approximately 0.5 mls of the raw water sample should be examined on a slide under low power with a compound microscope.

a) 'present' — If six units or less are counted after a two minute scan, then continue monthly sampling and assessment of algae. No other action is taken.
b) 'abundant' — If more than six units are counted after a two minute scan, then continue sampling and assessment of algae and inform owners and EHOs of the results.

As algae exist as cells, colonies, threads, etc. it is difficult to give precise definitions of countable entities and the term 'unit' has been introduced.

A 'unit' is defined as a 1 *Microcystis* colony, 1 *Anabaena* filament or ring, 1 *Aphanizomenon* bundle or filament, 1 gas vacuolate *Oscillatoria* filament or any other single countable entity.

6 If more than 25% of the monitored (potable water supply reservoirs and high risk) waters comply with situation 5 b) i.e. > 6 units, a regional general alert is put out.

7 A 'general alert' would consist of:

a) notifying, in writing, all owners of major waters, the Chief Environmental Health Officers, Medical Officers of Environmental Health (or equivalent); and
b) informing all relevant Government Departments (i.e. each region to inform local MAFF office and inform Head Office who will, in turn, inform DoE that a 'general alert' has been called in specific regions) to the effect that:

   - the results of the NRA's monitoring programme indicate that toxic blue-green algal blooms are likely to be prevalent throughout the Region; and
   - that the NRA has received the following general statements in relation to such blooms.

   The Department of Health has issued the following statement.

   'Illnesses including skin rashes, eye irritation, vomiting, diarrhoea, fever, and pains in muscles and joints have occurred in some recreational users of water who swallowed or swam through algal scum. There have been no reports of long-term effects or deaths in humans, but in some cases the illnesses were severe. ALTHOUGH ALGAL SCUM IS NOT ALWAYS HARMFUL, IT IS A SENSIBLE PRECAUTION TO AVOID CONTACT WITH THE SCUM AND THE WATER CLOSE TO IT.'

   Animals can also be affected by the algae and the Chief Veterinary Officer of the Ministry of Agriculture Fisheries and Food has stated:

   'The toxin, which may be produced by the algae, is also poisonous to animals and can cause severe illness and death. FARMERS AND PET OWNERS SHOULD THEREFORE ENSURE THAT THEIR ANIMALS DO NOT HAVE ACCESS TO AFFECTED WATER'.

c) Announcing in a press statement the action which the NRA has taken and the reasons for it.

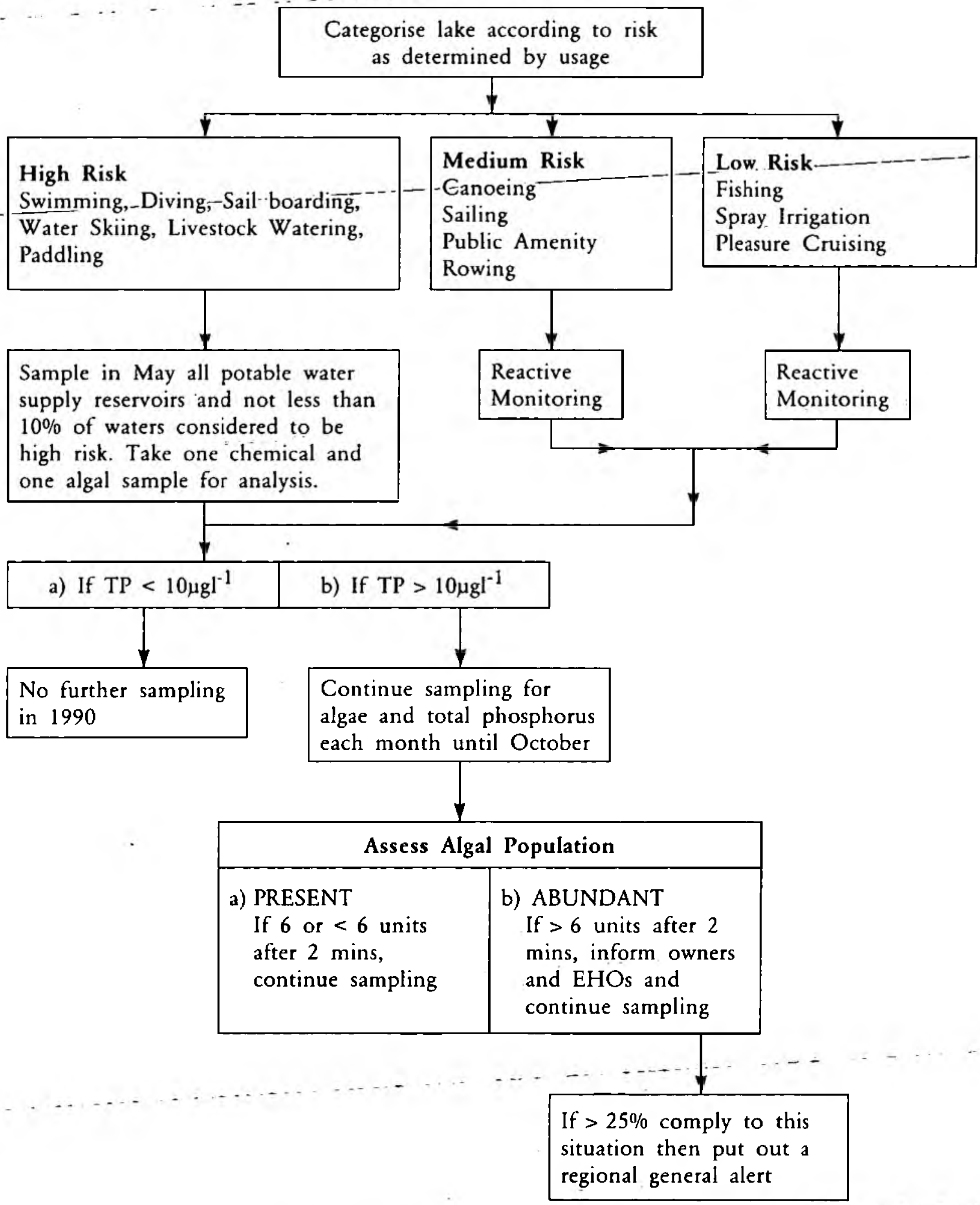
8 Advice on press releases and publicity campaigns will be given by Headquarters, as appropriate.

9 Advice on termination of sampling after October will be given at a later date.

Reference

1 'Phosphorus in Waters, Effluents and Sewage, 1980.' Methods for the Examination of Waters and Associated Materials (blue book). HMSO.

Proposed Approach to Monitoring Blue-Green Algae



APPENDIX C

Standard Letters

DRAFT STANDARD LETTER TO BE SENT TO OWNERS WHEN THEIR WATERS ARE IDENTIFIED AS BEING LIKELY TO DEVELOP POTENTIALLY TOXIC ALGAL BLOOMS

Dear

TOXIC BLUE-GREEN ALGAL BLOOMS

The NRA carries out a regular monitoring programme of the quality of inland waters; this now includes screening for the presence of blooms of potentially toxic blue-green algae. Recent monitoring of waters in your ownership by the ____________________ Region of the NRA has shown that the following sites have developed blue-green algae, at levels which have the potential for surface scum formation and which may be toxic. You are recommended to make regular inspections of these waters to check for evidence of scum formation.

SITE	DATE SAMPLED	ALGAL SPECIES PRESENT

Such algae occur naturally and during spells of warm weather can multiply sufficiently to discolour the water such that it appears green, blue-green, or greenish-brown. During calm weather the algae can rise to the surface to form a scum which may look like blue-green paint, or jelly, and may form flocs. The scum can be blown around the surface of the water and may thus appear at different places at different times. It may disappear and reappear quickly, and accumulate on the shoreline.

These algae may produce toxins; but in view of the rapid fluctuation in toxicity at a single site it is neither practicable nor necessary to assess toxicity on a routine basis. Such toxins are known to have the potential to affect the health of both humans and animals and the NRA has received the following information, of which you should be aware.

The Department of Health has issued the following statement.

"Illnesses including skin rashes, eye irritation, vomiting, diarrhoea, fever, and pains in muscles and joints have occurrred in some recreational users of water who swallowed or swam through algal scum. There have been no reports of long-term effects or deaths in humans, but in some cases the illnesses were severe. ALTHOUGH ALGAL SCUM IS NOT ALWAYS HARMFUL, IT IS A SENSIBLE PRECAUTION TO AVOID CONTACT WITH THE SCUM AND THE WATER CLOSE TO IT".

In contrast to humans, animals may eat or swallow large quantities of algal scum. The Chief Veterinary Officer of the Ministry of Agriculture Fisheries and Food has stated:

"The toxin, which may be produced by the algae, is also poisonous to animals and can cause severe illness and death. FARMERS AND PET OWNERS SHOULD THEREFORE ENSURE THAT THEIR ANIMALS DO NOT HAVE ACCESS TO AFFECTED WATER".

You are therefore encouraged to take whatever steps you consider necessary to inform users of your water of the above statements, by way of notices or other means. The NRA has produced a short leaflet on the subject, which you may find useful. The NRA has also informed your local Environmental Health Officer and the Ministry of Agriculture, Fisheries and Food, as a matter of routine.

The NRA will continue to monitor the situation during the forthcoming months and will inform you when it considers that the blooms have declined and are unlikely to recur; on the basis of past experience, this is likely to be strongly influenced by weather conditions at the onset of winter.

The NRA is carrying out studies to learn more of the causes and effects of such blooms — which occur in many countries in addition to the UK — and is seeking to devise a means of reducing their occurrence and alleviating their impact on water masses.

Yours sincerely

DRAFT STANDARD LETTER TO BE SENT TO CHIEF ENVIRONMENTAL HEALTH OFFICERS, MEDICAL OFFICERS OF ENVIRONMENTAL HEALTH AND TO MAFF REGIONAL OFFICES. THIS SHOULD BE USED WHEN SPECIFIC BODIES OF WATER ARE IDENTIFIED AS BEING LIKELY TO DEVELOP POTENTIALLY TOXIC ALGAL BLOOMS

Dear

TOXIC BLUE-GREEN ALGAL BLOOMS

The NRA carries out a regular monitoring programme of the quality of inland waters. This now includes screening for the presence of blooms of potentially toxic blue-green algae. Recent monitoring by the ____________________ Region of the NRA has shown that the following sites have developed blue-green algae, at levels which may be toxic. Owners have been recommended to make regular inspections of these waters to check for evidence of scum formation.

SITE	DATE SAMPLED	ALGAL SPECIES IDENTIFIED

These algae may produce toxins; but in view of the rapid flucuation in toxicity at a single site it is neither practicable nor necessary to assess toxicity on a routine basis. Experience has shown, however, that where a bloom is identified there is a 60 to 70% chance of it being toxic.

The respective site owners have been informed by way of copies of the attached correspondence. As you will see, this includes statements from both the Department of Health and MAFF received by the NRA. The (regional MAFF Office/Chief Environmental Health Officer/Medical Officer of Environmental Health) has also been informed. The NRA has produced a short leaflet on the subject which you may find useful.

The NRA's screening programme can only cover a limited number of waters. It has therefore been decided that when more than 25% of the monitored waters contain blooms of blue-green algae, a 'general alert' will be issued on a regional basis; you will be informed when this occurs.

Yours sincerely

NEWS RELEASE FOR USE WHEN AN INDIVIDUAL SITE HAS BEEN IDENTIFIED AS LIKELY TO DEVELOP A BLOOM OF POTENTIALLY TOXIC BLUE-GREEN ALGAE

NRA IDENTIFIES WATERS LIKELY TO DEVELOP POTENTIALLY TOXIC ALGAL BLOOMS

The ____________________ Region of the NRA has today confirmed that the following sites have developed blue-green algae, at levels which have the potential for surface scum formation and which may be toxic. Owners have been recommended to make regular inspections of these waters to check for evidence of scum formation.

The location(s) is (are):

SITE	LOCATION

The NRA has informed the owner(s) of the water(s), the local Chief Environmental Health Officer, Medical Officers of Environmental Health, and the area office of the Ministry of Agriculture, Fisheries and Food of the presence of a potentially toxic algal bloom (letters attached).

These algae may produce toxins; but in view of the rapid fluctuation in toxicity at a single site it is neither practicable nor necessary to assess toxicity on a routine basis. Experience has shown, however, that where a bloom is identified there is a 60 to 70% chance of it being toxic. Such blooms can disappear and reappear quickly, and accummulate on different parts of the shoreline.

The owners of affected waters are each responsible for bringing to the attention of their water users, and the general public if appropriate, the precautions which should be taken to avoid close contact with such blooms.

This brings to _____ the number of individual waters identified so far in the ______________ Region as having blooms of potentially toxic blue-green algae.

NOTE TO EDITORS

Attached is a copy of a letter sent to the site owner(s) which contains precautionary advice from the Department of Health and MAFF, and further details about blue-green algae.

APPENDIX D

Media Package

BLUE-GREEN ALGAL BLOOMS

MEDIA BRIEFING NOTE

BACKGROUND

National — In 1989 there were 53 confirmed cases of toxic algae blooms in England and Wales investigated by the NRA. Nearly 2200 inspections were made at over 900 waters.

Regional — In the Anglian region the most serious incident involved the death of a number of sheep and dogs at Rutland Water in Leicestershire. A number of cases were also reported of individuals suffering varying degress of skin irritation, skin rashes and gastroenteritis after taking part in immersion sports.

In the region nearly 400 sites were visited and over 500 samples were taken. Of these samples, nearly 400 were found to have blue-green algae present, and there were 37 confirmed cases of toxic algae.

BLUE-GREEN ALGAE

The occurrence of blue-green algal blooms is not a new phenomenon. It has been studied in this country for more than 20 years and is widespread in parts of many overseas countries including Europe, Scandinavia, Australia and America.

These algae can build up into a surface scum which has the appearance of blue-green paint when blown onto the shore. Commonly occurring species known to produce toxins include:

Microcystis aeruginosa

Anabaena flos-aquae

Aphanizomenon flos-aquae

Oscillatoria aghardhii

BUT NOT ALL BLUE-GREEN ALGAE PRODUCE TOXINS.

It has been calculated that if a blue-green algal bloom is discovered there is a 60% to 70% chance of it being toxic, but this will only be confirmed by specialist analysis.

Effects
The reported effects of the toxin on humans include:

- ★ skin rashes
- ★ eye irritation
- ★ vomiting and diarrhoea
- ★ fever
- ★ pains in muscles and joints

Behaviour
The behaviour of the algae is erratic:

- ★ the level of its toxicity can fluctuate daily;
- ★ it can be toxic one day and not the next;
- ★ it can appear one day; disappear suddenly, and reappear at any time

Causes
It is believed that the major growth of the algae in 1989 was due to an exceptionally dry winter followed by a warm spring and hot summer with long hours of sunshine and high temperatures and still air conditions. The presence of nutrients in the water (such as phosphates and nitrates) was a contributory factor.

THE NATIONAL RIVERS AUTHORITY

Following the outbreaks of blue-green algae in late summer and autumn of 1989 the NRA set up a special task group to investigate the problem.

The membership of the group, which is chaired by Mr Mick Pearson of the NRA's Anglian Region, includes Professor Geoff Codd of the University of Dundee, Dr Colin Reynolds of the Institute of Freshwater Ecology, and Mr John Fawell, The Water Research Centre's Principal Toxicologist, all experts in blue-green algae, together with NRA experts. The group is primarily concerned with the environmental aspects of the problem. The terms of reference† of the task group are:

- ★ an assessment of the 1989 problem
- ★ an assessment of the extent of the problem in the UK and abroad
- ★ a review of the influence of nutrients
- ★ a review of the influence of water quality management techniques
- ★ a review of the influence of biotic factors
- ★ structure, occurrence and persistence of the toxins
- ★ factors affecting toxin release
- ★ identification of research and development requirements
- ★ an assessment of the staff resource implications
- ★ recommendations for monitoring and eutrophication control to minimise the problem in the future.

The group is to produce its report for the NRA's Chief Scientist, Dr Jan Pentreath, later this summer prior to the main season for the development of blue-green algae. The group has contacted all NRA regions, water plcs and water companies which operate lakes and reservoirs, the Scottish Development Department and DoE Northern Ireland for details on the extent of the problem during 1989. The group has received an enormous amount of information which is being collated in order to come to a view on the causes of the problems.

In addition, because problems of a similar nature have been reported in a number of overseas countries' information is being collected from sources overseas. As part of the NRA's research effort, the WRc is carrying out a full literature search and review. The group will collate the information, review the problems and recommend future action to be taken.

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† The terms of reference were modified slightly during the work of the group and are as stated in Chapter 1 of this report. Also, it was decided to leave an assessment of staff resource implications until the extent of the problem was fully appreciated, and this report had been published.

Research needs will be identified and have been budgeted within the NRA's programme to both investigate the problem, and to produce effective systems for monitoring and control.

One of the major problems already identified is the difficulty of analysing the material and assessing its toxicity.

The problem of blue-green algal blooms is a long-standing one, and it is anticipated that the report will identify suitable solutions, or remedial actions. In the interim, the Task Group has devised a monitoring programme to enable areas to be screened for the likely occurrence of blooms. This consists of sampling 10% of those waters where the extent of potential contact between water users and the algae is higher than average (i.e. where immersion sports are practised and livestock is routinely watered). When more than 25% of the monitored sites show positive signs of bloom formation, a general alert will be issued.

RESPONSIBILITIES

The NRA is reponsible for:

- monitoring controlled waters. These are waters such as reservoirs, lakes, ponds, canals and similar sites which are enclosed;
- informing owners and local Environmental Health Officers of any suspected algal blooms;
- informing owners and local EHOs of the results of any NRA analysis.

The owner of the water is responsible for:

- deciding whether to take any action to restrict public access or leisure activities;
- liaising with the local EHO on any human health or related medical issue;
- liaising with MAFF on problems associated with livestock watering.

The EHO is responsible for:

- providing advice to the owner and the public about any human health issues;
- providing health safety advice to the owner and the public;
- liaising with the NRA on local aspects of the monitoring and sampling programme.

The Ministry of Agriculture, Fisheries and Food is responsible for:

- matters relating to animal health and the consumption of meat, fish and wildfowl.

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- matters relating to animal health and the consumption of meat, fish and wildfowl.

BLUE-GREEN ALGAL BLOOMS

NRA

National Rivers Authority

Page 1

What are blue-green algae?

Blue-green algae are natural inhabitants of many inland waters, estuaries and the sea. In still fresh waters, such as lakes, ponds, canals and reservoirs, these algae may multiply sufficiently in summer months to discolour the water such that it appears green, blue-green or greenish-brown.

During calm weather the blue-green algae can rise to the water surface to form a scum which may look like blue-green paint, or jelly, and may form flocs. The scum can be blown around the surface of the water and may thus appear at different places at different times. It may disappear and reappear in subsequent days and, as a result of wind action, it may accumulate on the shore-line. Sometimes these algae may release toxins into the water.

Page 2

The Role of the NRA

As part of its general responsibilities for the quality of inland and coastal waters throughout England and Wales, the National Rivers Authority (NRA) carries out a large monitoring programme. This now includes screening of inland waters to test for the presence of potentially toxic blue-green algae in different regions. In common with practice in other countries where such toxic algae occur, the NRA will inform land owners, Environmental Health Officers, and relevant Government Departments of the presence of such blooms. The NRA is not responsible for drinking water drawn from public supply, nor for contaminated foodstuffs.

The NRA is also studying the factors which cause toxic algal blooms, and the methods by which they could be controlled.

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WARNING: BLUE-GREEN ALGAL BLOOMS

The Department of Health has stated:

"Illnesses including skin rashes, eye irritation, vomiting, diarrhoea, fever, and pains in muscles and joints have occurred in some recreational users of water who swallowed or swam through algal scum. There have been no reports of long-term effects or deaths in humans, but in some cases the illnesses were severe. ALTHOUGH ALGAL SCUM IS NOT ALWAYS HARMFUL, IT IS A SENSIBLE PRECAUTION TO AVOID CONTACT WITH THE SCUM AND THE WATER CLOSE TO IT"

In contrast to humans, animals may eat or swallow large quantities of algal scum. The Chief Veterinary Officer of the Ministry of Agriculture Fisheries and Food has stated:

"The toxin, which may be produced by the algae, is also poisonous to animals and can cause severe illness and death. FARMERS AND PET OWNERS SHOULD THEREFORE ENSURE THAT THEIR ANIMALS DO NOT HAVE ACCESS TO AFFECTED WATER"

This leaflet has been issued by

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from whom further copies are available.

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APPENDIX E

Blue-Green Algae Guidelines for Employees

Blue-green algae, or cyanobacteria, are common in lowland lakes and canals during summer. The water becomes turbid and green, and accumulations of algal cells form scums, particularly on the downwind or sheltered shore, resembling paint or pea soup.

Blooms of some of these species produce toxins which will be concentrated in the scums of algae. The toxins have been known to kill cattle, sheep and dogs when ingested, but more commonly cause skin irritations or rashes from contact with affected water.

Fortunately the distinctive appearance of the algae make it readily identifiable and normal hygiene precautions will prevent any adverse effects.

When working in or near water affected by blue-green algae, wear protective gloves and avoid skin contact with the water. Take particular care when launching boats, handling equipment or dragging nets, etc. through water. Use clean water to wash off any splashes and wash hands thoroughly before eating, drinking or smoking.

If, in the course of your work, you observe any indications of blue-green algae please report the location to your Supervisor who will inform the relevant Area Biologist.

NOTES

NRA

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