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CLIMATE CHANGE AND WATER QUALITY

by

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

1. This report investigates the likely impacts of climate change on water quality. Although water may be considered of secondary importance to the basic changes in temperature, rainfall patterns and sea levels rise it should be remembered that adequate supplies of high quality water are fundamental to human health. Furthermore, water quality standards are unlikely to be relaxed and maintaining these standards under the climate change scenario may require high investment.

2. With the vast increase in man's activities over the past hundred years has come the realization that pollutants exist at every point in global, regional and local water cycles. Atmospheric pollution by oxides of nitrogen and sulphur find their way into rivers, lakes and groundwaters and create problems of water quality. Fertiliser, pesticide and herbicide application create surface and groundwater pollution problems and even land use change can generate significant water quality effects such as the release of nitrates following ploughing and deforestation.

3. Changes in rainfall and hence flow distribution in lowland regions will affect the deposition of pollutants and the flushing of pollutants from urban and agricultural sources. It is estimated that pollution loads draining urban and agricultural areas will increase significantly because of the increase in rainfall intensity. Moreover the effect of lower summer flow conditions will exacerbate pollutant concentrations because of the reduced dilution of industrial and domestic effluents. Also low summer flows will increase stream residence times and enhance algal growth.

4. In upland regions the increased rainfall and cloud cover will enhance pollutant loads by the increased 'washing out' of the atmosphere. Thus acidification processes may be accelerated by increased loadings in SO_x and NO_x.

5. Increased temperature will enhance the mineralization processes operating in soils and could release significant levels of nutrients such as nitrates. This

effect could be particularly severe in upland streams and reservoirs resulting in eutophication and hence increased algal populations in reservoirs. It would also be important in lowland regions where nitrate levels are already high, and close to current EEC limits.

6. An important effect of increased temperatures could be the increased levels of pests on crops and hence the increased use of pesticides and fungicides. Since the residues of these generally move through the hyrological system into water courses there is likely to be concern over levels in rivers, lakes and groundwater. Higher temperatures may lead to a more rapid breakdown of organic pesticides but little is known about the breakdown products.

7. Another effect of increased temperatures could be the increased growth and survival of bacteria such as E. Coli and protozoa such as Cryptosporidium.

8. An extensive range of models are available for simulating water quality. These should be reassessed in terms of climate change to ensure that they are structured correctly and are sufficiently sensitive to investigate questions of climate change. Further process studies may be required to incorporate processes and situations which do not occur at present. Finally, they should be applied in a wide range of situations to evaluate the likely impacts on water quality.

9. Long term monitoring of water quality is required at both upland and lowland sites.

INTRODUCTION AND DOE DESK STUDY

In the first set of DOE desk studies issued in June 1988 topics covered included trees, forests, crops, species, ecosystems and coastal impacts. The principal objectives were to identify critical areas or 'pressure points' in the UK where climate change could have maximum impact, as a basis for identifying gaps in our knowledge and assessing future research priorities. The two possible 'pressure points' in the UK not covered to date are those of water quantity and water quality. Both of these will be directly affected by changes in rainfall intensity and distribution, temperature, sunshine hours, soil moisture changes and sea level changes. Beran and Arnell (1989) have addressed the question of climate change and water quantity. In this report we consider questions of water quality.

The *base scenario used for all the DOE desk studies is as follows:* a predicted doubling of CO_2 from its pre-industrial revolution level to 540 ppm by the year 2050. On this basis models predict

a) a mean temperature rise of 3°C ±1.5°C

b) a change in mean rainfall of ±20%

c) a sea level rise of 80cm.

In the light of recent studies the consensus now appears to be shifting towards a wet winter, dry summer scenario and the following seasonal changes for rainfall are considered reasonable;

winter	+	40mm
spring	+	40mm
summer		30mm
autumn	+	30mm

In this report the impact of these changes on water quality is considered after first reviewing the institutional arrangements concerning water quality, the pollution cycling aspects and the underlying problems that presently exist in the area of water quality.

2. INSTITUTIONAL INFRASTRUCTURE CONTROLLING WATER QUALITY

2.1 England and Wales

The current reorganisation of the Water Industry into privatised water companies and a National Rivers Authority (NRA) will significantly alter the institutional infrastructure controlling water quality in England and Wales. Prior to this reorganisation the water authorities were responsible for the quality of rivers, reservoirs and lakes, and set standards for effluent discharges in order to meet water quality objectives. However, most of the major effluent discharges are from Water Authority treatment works. Under the reorganised water industry structure these treatment works will transfer to privatised water companies, and setting of effluent standards, river quality objectives and the licensing of discharges will be the responsibility of the NRA. The NRA will also license the private water companies for water abstraction. Since rivers are used for both water supply and effluent disposal a careful balance has to be achieved to ensure the safe supply of water for public, industrial and agricultural use. Thus the NRA will have major regulatory and river management functions with regard to water quality, water resources, fisheries, conservation and recreation.

The UK Department of the Environment (DOE) is responsible for the NRA and decides the national policy with regard to drinking water standards and river water quality. However, the EEC plays an increasingly significant role in defining standards and river quality objectives and sets European directives with which member states have to conform. Examples of EEC directives include those for nitrates and pesticides in water supplies. In addition the EEC publishes lists of dangerous substances and DOE have recently identified a Red List of particularly harmful substances.

2.2 Scotland and Northern Ireland

The formation of the NRA will not alter the institutional structure in Scotland and Northern Ireland. At present the Scottish River Purification boards provide the management and control of catchments with regard to water quality and liaise closely with local councils, the Scottish Office and hence the DOE. The EEC directives also apply to Scotland. In Northern Ireland the DOE (NI) administer the water resource and water quality aspects directly.

3. POLLUTANT CLIMATE, RECYCLING AND PATHWAYS

Fundamental to any study of water quality is a knowledge of the hydrological cycle (see Figure 1). The global hydrological cycle consists of the reservoirs of water including the oceans, ice and snow, lakes, rivers, groundwater, clouds and atmospheric water vapour and the fluxes between them. The timescales involved in the various parts of the cycle differ widely from hours in the case of storm events through to residence times of months or years in lakes, decades in groundwaters and centuries in seas and oceans. The concentration and redistribution of pollutants depends largely on the hydrological processes, residence times and movements of water within the cycle. Figure 2 shows in more detail the movement of water from precipitation through the terrestrial environment, through near surface soils and groundwater systems into lakes and rivers. At every stage water quality is altered. For example, the effect of increased evaporation and transpiration is to concentrate pollutants in the remaining surface water. Water quality in groundwaters is highly dependant on the quality of incoming precipitation, the land use, the soil type, the basic geology of the region and the rate at which water moves through the unsaturated (vadose) zone and through the groundwater (phreatic) zone.

The chemical 'climate' is superimposed on top of the hydrological cycle and Figures 3, 4 and 5 show the major transfers of carbon, nitrogen and sulphur around the system. The carbon cycle is not only important because of the

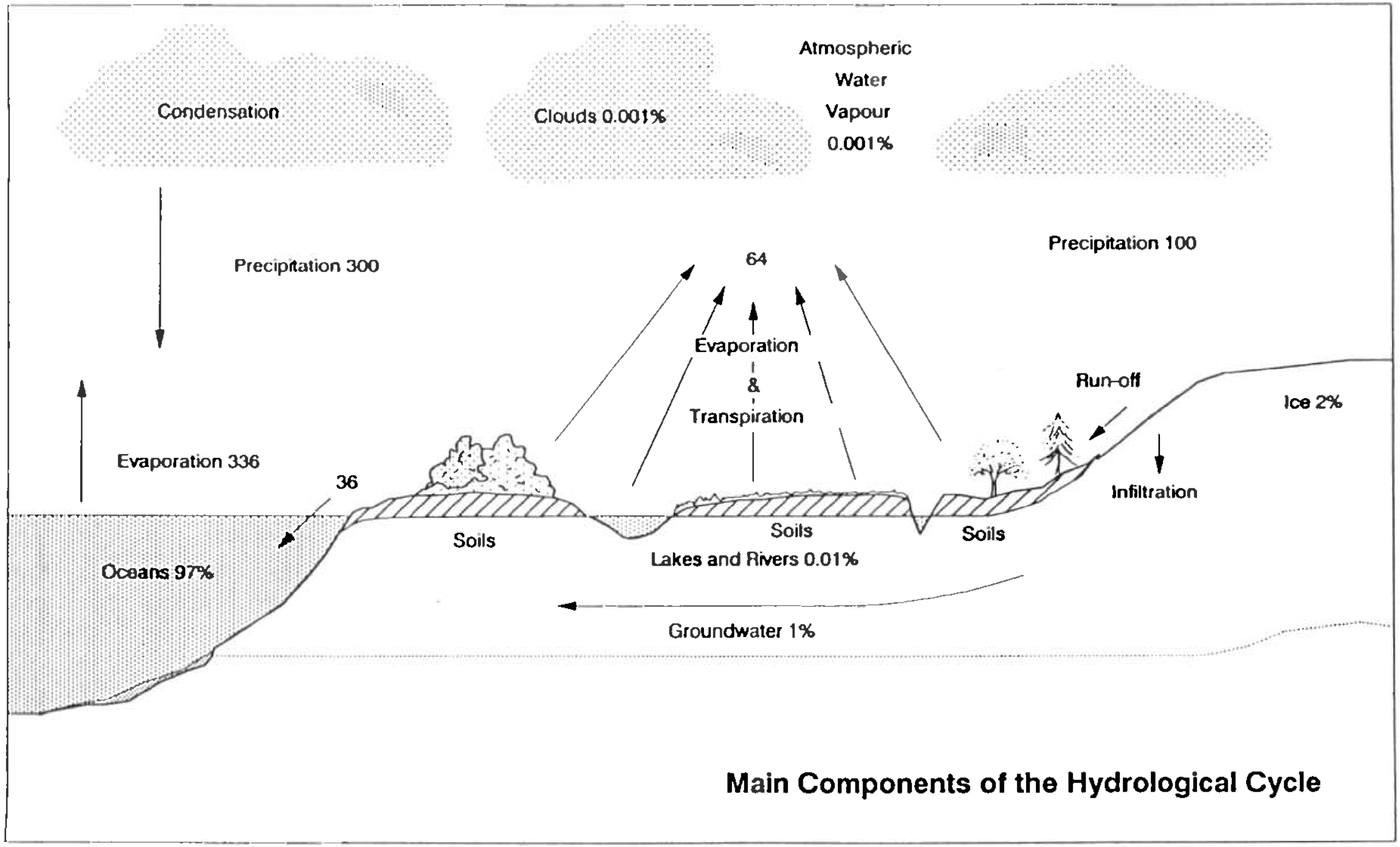

Figure 1 The hydrological cycle. Fluxes are given 10^{15} kilograms per annum: the percentage of total water in the cycle is also shown

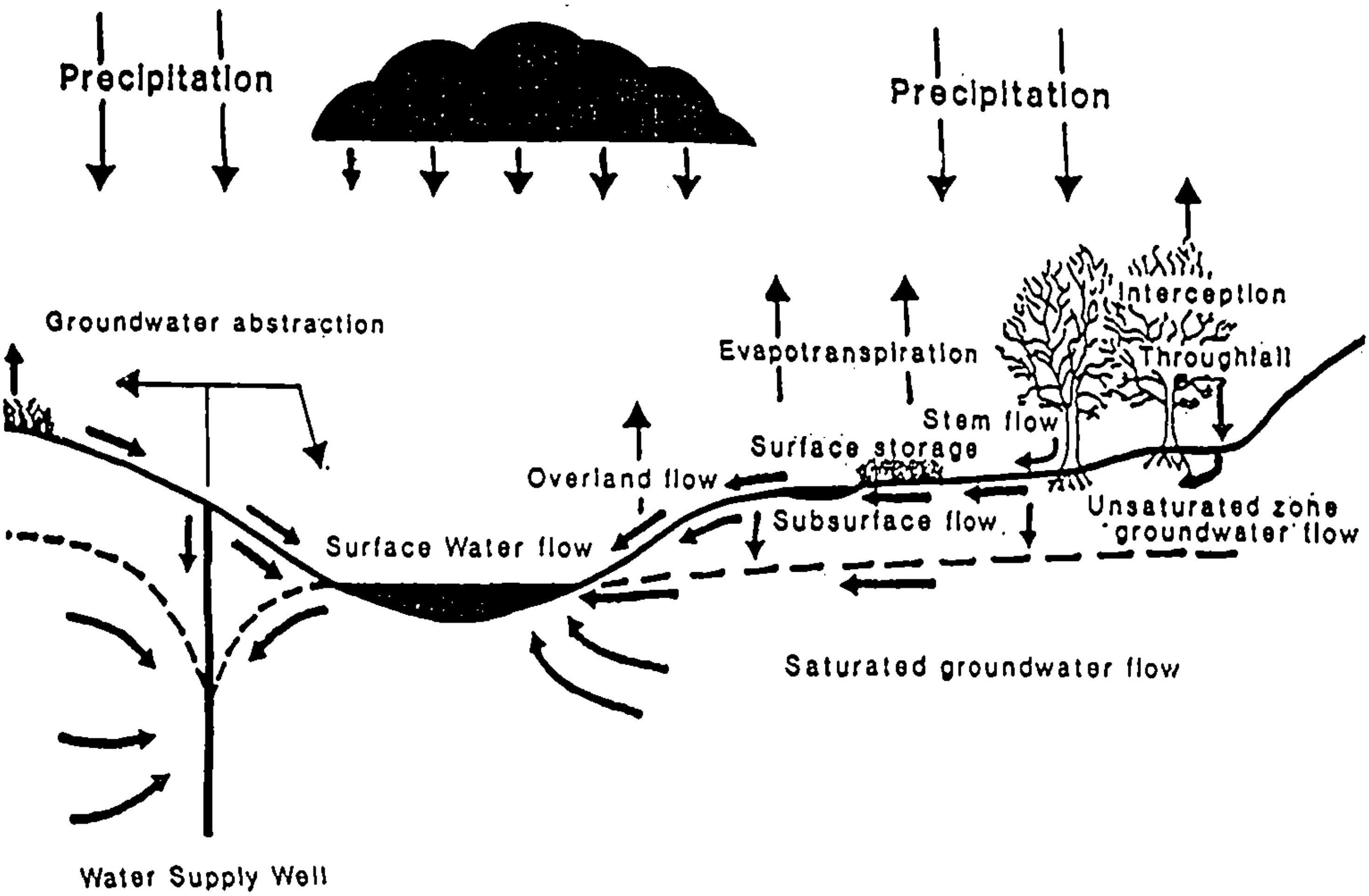

Figure 2 Water movement through the terrestrial environment, soils and groundwater systems

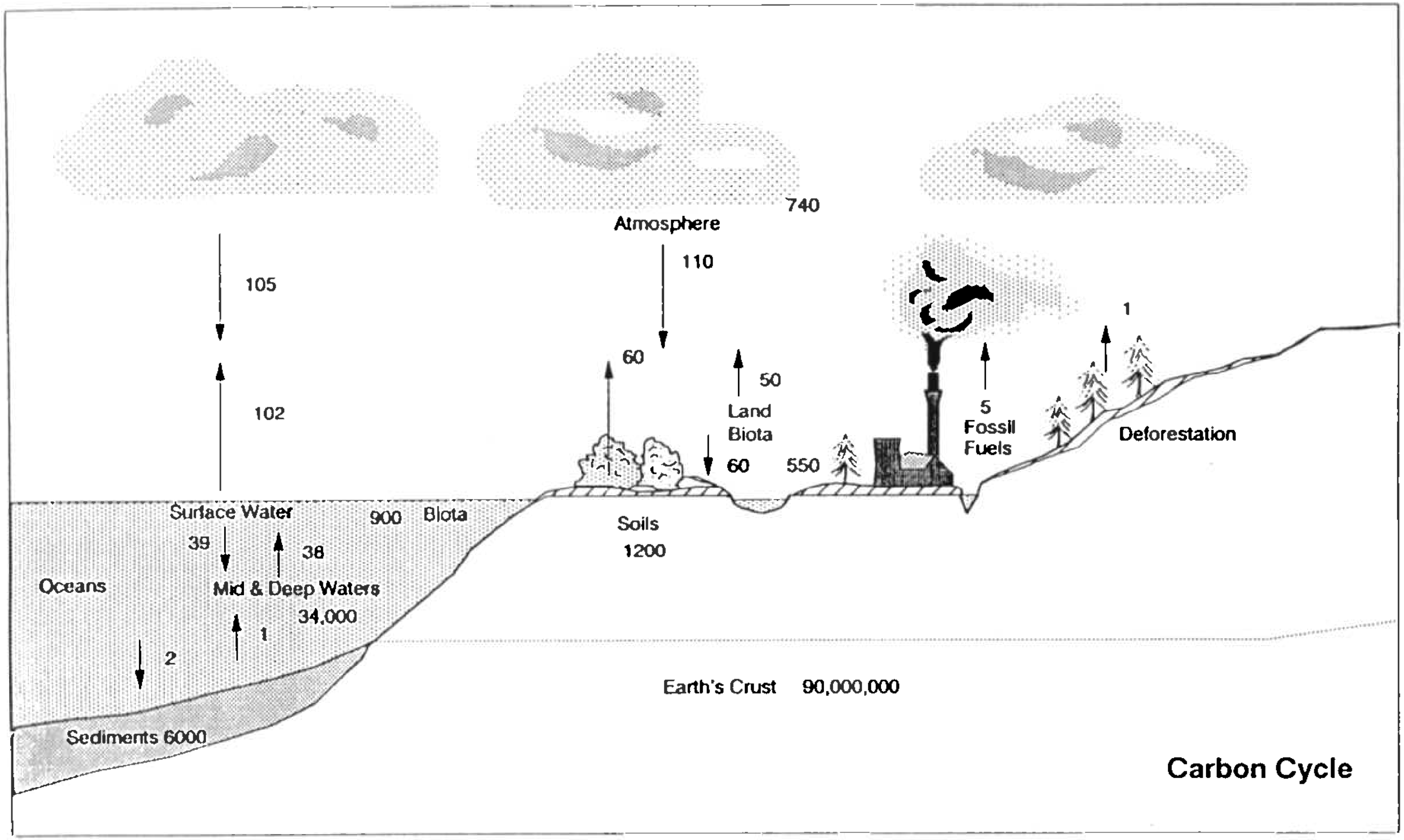

Figure 3 The Carbon cycle showing the estimated carbon content of the principal reservoirs and the annual fluxes between them in units of 10^{12} kilograms

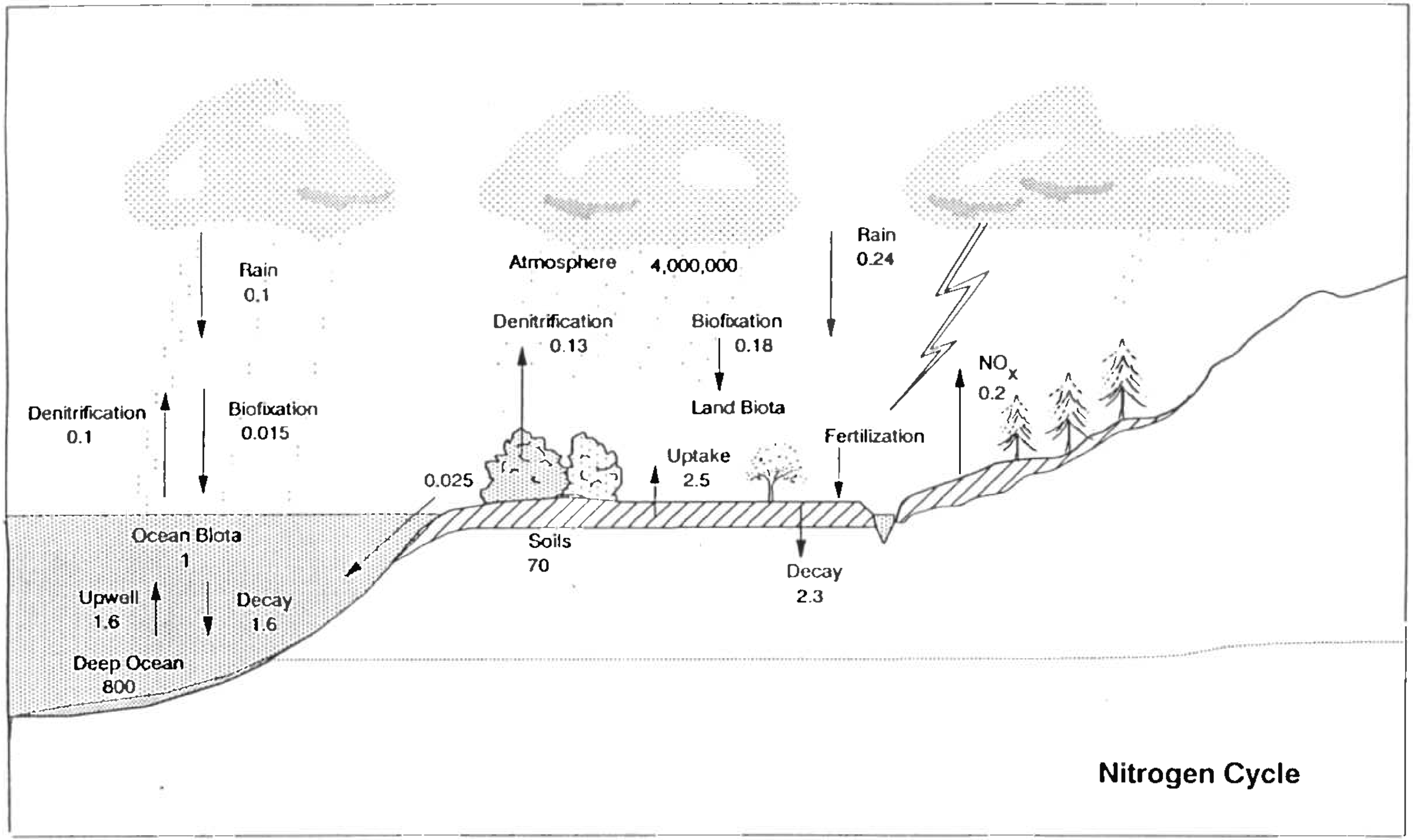

Figure 4 The Nitrogen cycle showing the principal annual fluxes in units of 10^{12} kilograms

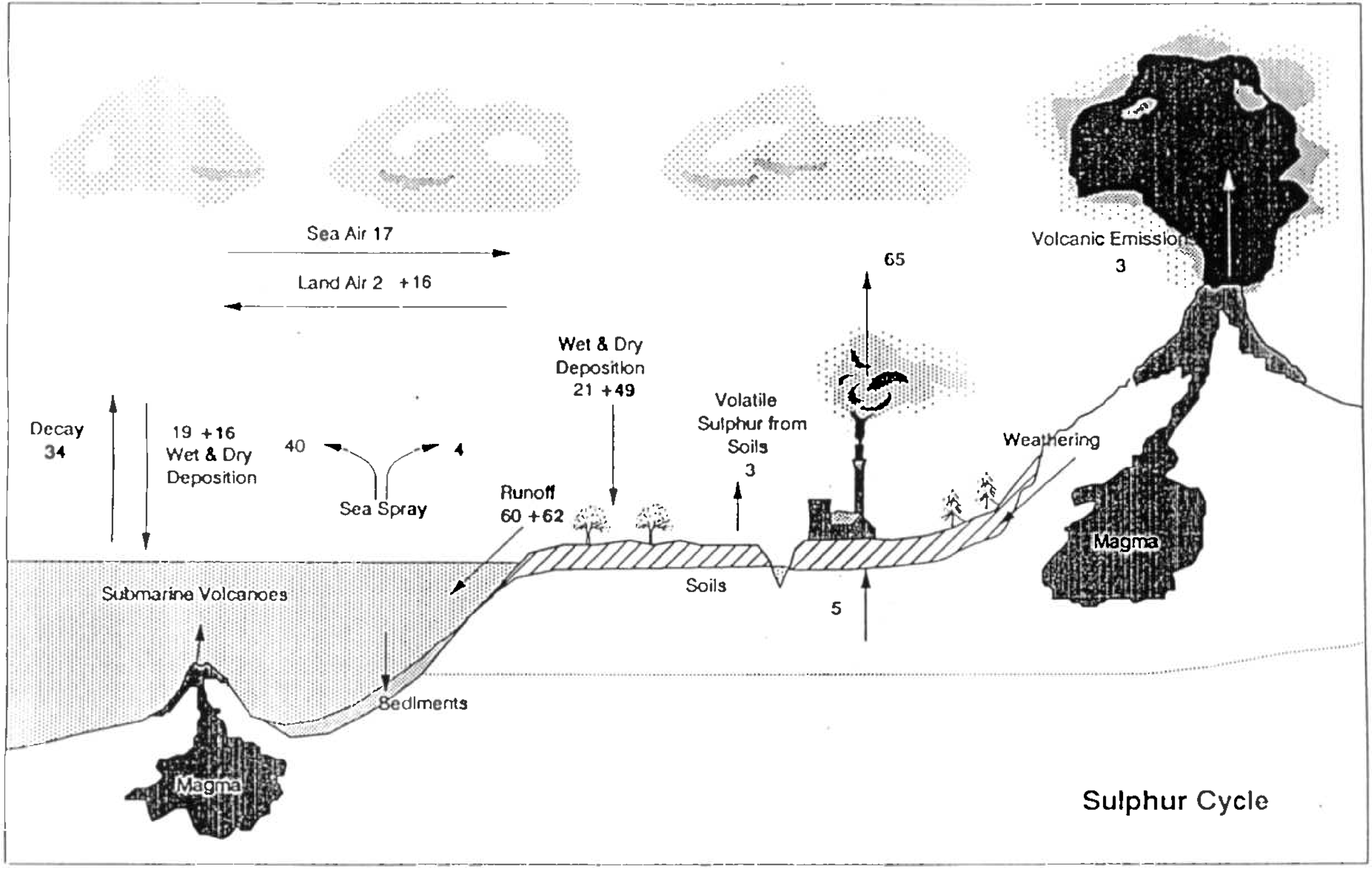

Figure 5 The Sulphur cycle showing annual fluxes in units of 10^9 kilograms

role of CO_2 driving climate change. CO_2 also controls water quality in upland sites where, for example, degassing of soil water CO_2 can significantly affect stream water chemistry (Neal and Whitehead 1988) altering pH and precipitating metals such as aluminium in streams.

Sulphur is important in the biogeochemical system apart from its obvious role in acid precipitation. The total amount of sulphur now entering the atmosphere has doubled owing to human activity. Additionally, the role of sulphur from natural sources is still far from understood as in the contents of volcanic gases, the production of hydrogen sulphide and dimethyl sulphide (DMS) by marine organisms, sulphate in soils and sulphides and sulphates in mineral deposits. DMS when oxidised to sulphate, has implications for policies for the control of acid precipitation in regions where DMS can be a major source of SO_2. It is also significant in the formation of aerosols which then have an effect on cloud condensation nucleation. The main natural source of sulphur is from volcanoes and levels of SO_2 from volcanic sources is both variable and unpredictable. Together with dust, volcanic sulphur-bearing aerosols will have a global effect following a major volcanic eruption. Anthropogenic sources of sulphur far outweigh natural sources and can be up to ten times the natural background levels in heavily industrialised regions. Acidification and stream water quality tends to be dominated, by man-derived sources of sulphur.

Sulphur is deposited on the terrestrial system by wet deposition (rainfall/snow) and by dry deposition. In addition mist droplets often have high concentrations of sulphate and deposition on vegetation and land surfaces via mist can be extremely high. Sulphate interacts with soils leading to soil acidification and hence river and lake water acidification. Again hydrological processes control the movement and concentration of sulphate, the mixing processes and the subsequent release of heavy metals.

Nitrogen produces highly reactive oxides in the atmosphere which interlink with the chemistry of other elements and, in the case of nitrous oxide, acts as a greenhouse gas. The availability of nitrogen controls plant growth and hence the rate of photosynthesis in many terrestrial systems. The magnitude of nitrogen fixation in many biological systems is still far from certain and even if known, the ratio of fixation from natural processes to that resulting from human activity needs to be determined. Similarly, natural denitrification processes require further quantification. The effect of increasing fertiliser application in agriculture is bound to have a multiplicity of effects from its presence in groundwater to an increase in nitrate run-off and hence raising coastal water nitrate levels which will, in turn, influence primary production in the sea. Again illustrated in Figure 5 there is considerable cycling in the terrestrial and aquatic environment and nitrate levels in rivers, lakes and groundwaters have risen significantly in recent years.

Climate change may have profound effects on the biogeochemical cycling processes. For example, one of the major effects of higher temperatures may be an increased mineralization of organic material stored in the soils. Mineralization releases nutrients such as nitrogen and phosphorus which can be leached to streams, lakes and the marine environment causing problems of eutrophication in reservoirs, rivers and coastal regions. If nitrogen is released as nitrate then soil and water acidification will result.

4. WATER QUALITY PROBLEMS

An analysis of the water quality dimension of the effects of climate change may be viewed as particularly important in view of the increasing interest of hydrologists in the quality component of the catchment hydrological cycle, the increasing relevance of quality criteria in the optimum development of limited water resources and given the current public concern for environmental quality. The precise interpretation of the term 'water quality' depends on the perspective of the individual. A water supply engineer is primarily concerned with considerations of potability and the associated quality standards for drinking water whilst a public health engineer might concentrate on effluent standards and the capacity of a river system for effluent disposal. The aim of this section is to provide a broad based and objective review of current water quality problems against which we can assess, and put into context, the likely impacts of climate change.

The pollutant load of a river is determined by factors relating to the input of the pollutant to the catchment system and by the physiographic structure of the catchment which determines streamflow regime and storm response. Pollutant input may take a variety of forms from effluent injection at a point source on a river, through the application of nitrate fertilisers and pesticides at certain distributed locations in a catchment, to widespread deposition of anthropogenic pollutants from the atmosphere. Rainfall may be regarded as the driving force behind, not only the catchment hydrological system, but also the catchment pollution system since it delivers atmospheric pollution to the surface and redistributes pollutants applied at the land surface as rainfall is transformed into streamflow. The rainfall input to the catchment determines volume and seasonality of flow and so influences the degree of dispersion and dilution of point source effluents.

It must be stressed that there are two dominant aspects to be considered in the analysis of climatic effects on river water quality. Firstly, the nature, extent and spatial distribution of significant water pollution needs to be considered as an important control on the water quality of UK rivers and this accounts for the major contrasts in the levels of water quality parameters shown in Table 1. Secondly, attention must be given to background water quality because the effects of pollution are superimposed on a pattern of water quality behaviour that reflects considerable spatial and temporal variation in response to essentially natural controls. In this context, approximately 90% of the total length of non-tidal watercourses in the country with a mean flow greater than 0.05 m^3 s^{-1} may be considered as essentially unpolluted (Walling and Webb 1981). To assess existing water quality problems, therefore, it is convenient to divide the country into upland and lowland areas and assess the pollution problems associated with each. The implications for water supply and effluent discharge in each area category will be addressed where pertinent.

4.1 Upland Water Quality

Upland areas of the UK are characterised by high rainfall and thin, acidic soils often with large areas of peat and organic material. During the winter months, substantial snowfall is common and annual streamflow regimes tend to

TABLE 1 Water Quality on a Range of Rivers (Walling & Webb, 1981)

River	*Sampling point*	*Determinants*								
		Conductivity $\mu S\ cm^{-1}$	*Dissolved oxygen* $mg\ l^{-1}$	*BOD* $mg\ l^{-1}$	*Ammoniacal nitrogen* $mg\ l^{-1}N$	*Nitrite* $mg\ l^{-1}N$	*Nitrate* $mg\ l^{-1}N$	*Chloride* $mg\ l^{-1}$	*Total alkalinity* $mg\ l^{-1}$ $CaCO_3$	*Ortho-phosphate* $mg\ l^{-1}P$
Ribble	Samlesbury	431	10.34	3.0	0.192	0.07	4.12	33.3	102.5	0.286
Tyne	Wylam	266	10.78	2.4	0.279	0.02	0.75	17.9	68.1	0.029
Trent	Yoxall	1039	10.66	4.0	0.229	—	9.28	127.5	164.3	1.170
Severn	Haw Bridge	555	11.62	2.8	0.172	—	6.28	43.9	123.8	0.552
Don	Doncaster	1185	7.60	6.5	5.700	0.68	6.91	219.9	128.7	0.488
Bedford Ouse	Earith	815	9.46	3.1	0.182	—	11.33	60.7	177.1	0.856
Thames	Teddington Weir	554	10.53	2.9	0.192	—	7.97	37.6	186.6	0.768
Exe	Thorverton Road Bridge	161	11.13	2.1	0.078	—	2.81	16.5	38.6	0.069
Dee	Iron Bridge	264	10.20	1.6	0.153	0.03	2.11	26.5	55.1	0.131
Clyde	Glasgow Green	427	8.94	5.9	1.188	0.24	2.60	66.5	97.7	0.423

be markedly seasonal, that is, higher flows in winter than in summer. Generally steep slopes and relatively impermeable geological substrate tend to produce flashy hydrograph response in response to rainfall. Streams are dominantly oligotrophic (nutrient poor) and lakes are well mixed due to the high precipitation input and short residence times. Thermocline development is not uncommon in the deeper lakes in the summer months but eutrophication is not presently a problem in upland areas and these areas have been conventionally viewed as the main source of clean water supplying the country's major centres of population (George, 1988).

Six major water quality problems have been the focus of concern in the uplands in recent years; (i) increased acidification and subsequent mobilisation of aluminium; (ii) increased nitrate concentration; (iii) increased phosphate concentration; (iv) increased water colour; (v) increased bacterial contamination; and (vi) increased sediment and erosion. All have serious consequences for water supply and all are linked with land use and land use change.

(i) Acidification

The impact of anthropogenic deposition on environmentally sensitive ecosystems has focused attention on upland areas throughout Britain. Most of these areas are characterised by high precipitation and acid soils derived from base-poor bedrock which, because of slow weathering rates, may be susceptible to increased acidification. The processes by which sulphur and nitrogen compounds cause increased surface water acidification are beyond the scope of this short review but the net result causes mobilisation of aluminium species. These have been found to be toxic to both aquatic fauna such as salmon and trout and to humans, given the increasing evidence of the link between Alzheimers disease and aluminium The recent final report of the DOE Acid Waters Review Committee (DOE, 1989) summarises the current state of acid waters in the UK and gives some indication of future trends. Figure 6 shows the areas of the UK susceptible to acidification (DOE 1988).

(ii) Nitrate

The concern over nitrates stems from the possible link between infant methaemoglobinaemia, gastric cancer, hypertension and drinking water nitrate concentration (World Water 1980, W.H.O. 1970). Increased nitrate

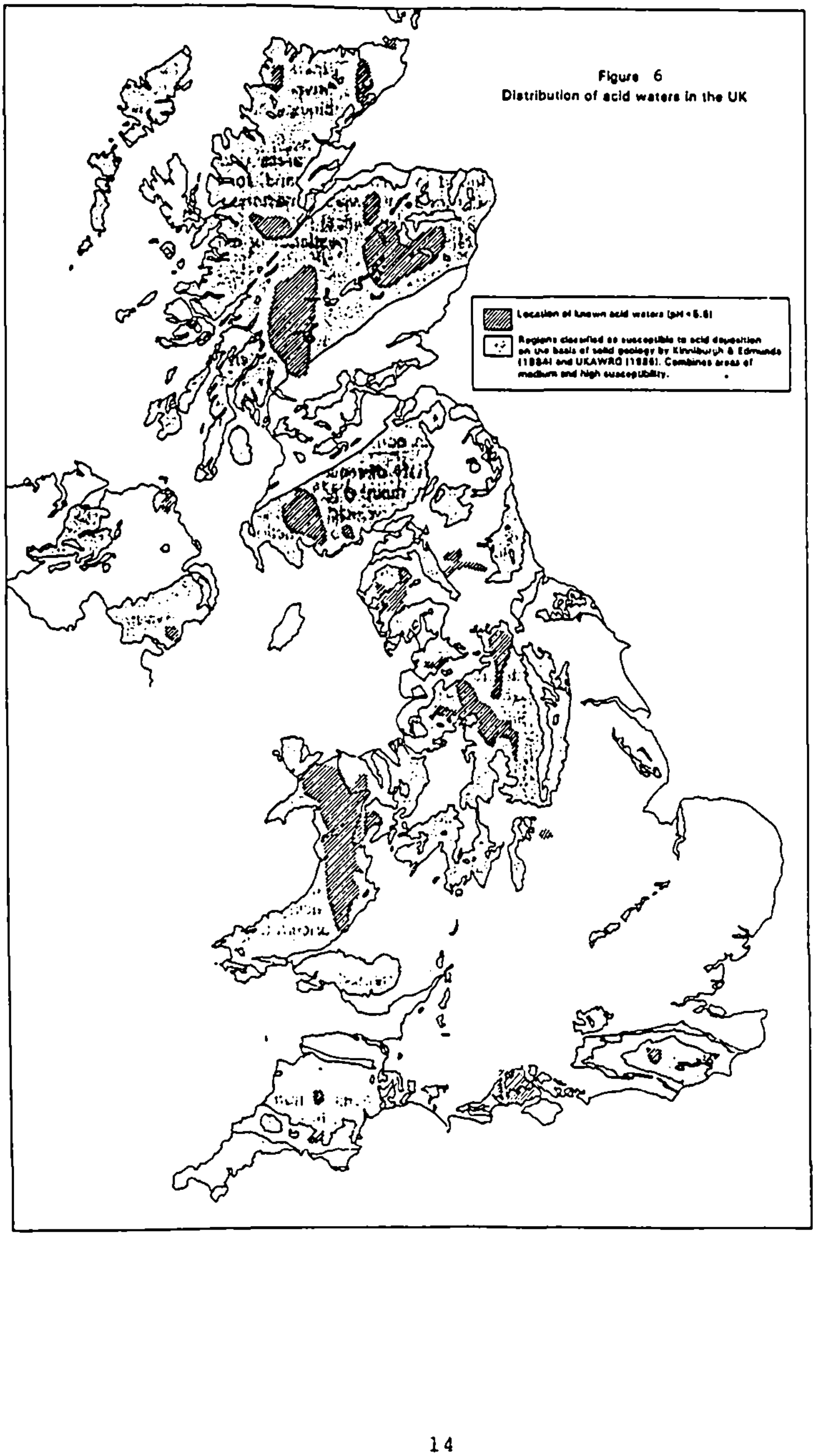

Figure 6
Distribution of acid waters in the UK

concentration stems from two areas; improvement of upland grassland, and subsequent use of nitrate fertilisers (see lowland section 4.2), and increased deposition of nitrogen oxides. Much of this nitrate input is utilised by plant growth. The effects of increased nitrate deposition on the catchment ecosystem, in particular forests, is not clear at present.

(iii) Phosphates

The main use of phosphate in the uplands is for forest fertilisation and there is an established link between impoundment phosphate concentration and algal growth (Gibson 1976, Holden 1976). Calculations indicate that many upland reservoirs would risk algal problems if additional planting of commercial softwood forests is implemented (Youngman and Lack 1981).

(iv) Colour

The uplands of Britain are an important source of water for public supply. Runoff into reservoirs can be highly coloured as a result of dissolved substances derived from peat soils. In some areas there is evidence of rising colour levels, particularly in recent years, probably associated with the aftermath of prolonged dry spells. The extent to which upland waters are coloured varies greatly both from area to area, and over time, with a strong seasonal cycle characterised by higher colour levels in winter. Colour in drinking water is a consumer perceived problem relating to its aesthetic properties and is not harmfull. The cost of 'cleaning' the water, met by the water industry, is substantial.

Research has shown that moisture deficit in peat, whether induced climatically or by man (e.g. by drainage or burning) can lead to a build up of readily soluble material from the decomposition of vegetative matter. This coloured matter can be leached out into streams following moisture replenishment by rainfall.

(v) Microbiological Contamination

Microbiological parameters of water quality are relevant to upland catchment management in two situations; where catchment waters are used for direct contact recreational activities and where waters receiving limited treatment are used for public supply. Low temperatures and rapid lake/reservoir turnover times tend to keep the incidences of bacterial contamination to a minimum in both situations. However, in certain upland communities where small direct rural water supply's are common, bacterial contamination is a problem of major concern.

Research has shown that areas under afforestation are characterised by low bacterial concentrations due to the absence of warm blooded animals on the catchment, whereas pasture land and areas where slurry spreading is widespread, produce high concentrations of bacteria in surface water. In general, once fecal bacteria leave the body they start to die because of the low temperature although prolonged survival of indicator organisms and pathogenic bacteria such as E. coli has been demonstrated in river and lake sediments (Jenkins et al 1984). These bottom sediments are disturbed during storm events causing sharp increases in bacterial concentration.

(vi) Suspended Sediment

Background concentrations of suspended sediments in upland streams are not considered to represent a major problem as reservoir sedimentation is minimal in most areas. The effect of land use change, particularly afforestation and deafforestation, however, can lead to significant problems in some areas.

4.2 Lowland Water Quality

In lowland areas water may become polluted by discharges (e.g. from industry, agriculture and sewage treatment works), runoff (e.g. from roads, industrial sites and land) or incidents (e.g. spillages). Discharges are generally from point sources, runoff is usually viewed as a non-point source contribution whilst incidents can be either. The physiography of lowland areas produces generally damped and lagged response to rainfall with large contributions from groundwater aquifers. It is also worth noting that there is a general reduction in water quality from source to mouth in most British rivers, that is, a systematic deterioration from unpolluted headwaters through doubtful and poor quality to grossly polluted river mouths (Walling and Webb 1981). As a consequence, all of the problems associated with upland water quality are magnified in the lowlands.

It is convenient to discuss lowland water quality problems under four major headings; (i) nitrates and phosphates; (ii) biochemical oxygen demand and dissolved oxygen; (iii) pesticides; and (iv) suspended sediment and bacteria. Clearly there are other contaminants causing problems, notably hydrocarbons associated with spillages, but those listed represent the most problematic at present.

(i) Nitrate and Phosphate

Nitrate deposition from the atmosphere includes both natural and anthropogenic components and this pollutant pathway is a major contributor to nitrate problems in upland waters (see section 4.1). The main source of nitrate in lowland waters is runoff from agricultural land and leaching from the soil (non-point source), although some nitrate goes directly into waterways via sewage works (point source). Figure 7 demonstrates the variation in stream nitrate concentration and emphasises the lowland nature of the problem. The pattern of nitrate concentrations reflects both the magnitude of non-point pollution from agricultural sources and its interaction with rainfall and runoff quantity since a dilution effect must operate in wetter areas. (i.e. the north and west). Figure 8 from Roberts and Marsh (1987) shows that levels of nitrates increase towards the south east.

This pattern of nitrate pollution has serious consequences for water supply. Although river intakes represent only a minor source of potable water, surface water/groundwater interactions will cause an increase in groundwater nitrate concentrations. Groundwater provides approximately 30% of the public water supplies in Britain, being a much higher percentage in the south and east. 152 groundwater sources exceeded the guideline concentration of 50 mg/l nitrate at some time during 1986 whilst 34 surface water sources exceeded the guideline in the same time period (DOE, 1988).

High concentrations of phosphate in lowland streams and lakes stem predominantly from agricultural non-point source runoff following fertiliser application. The problems for the water industry associated with high phosphate levels include the protection of drinking water supply and real time operational

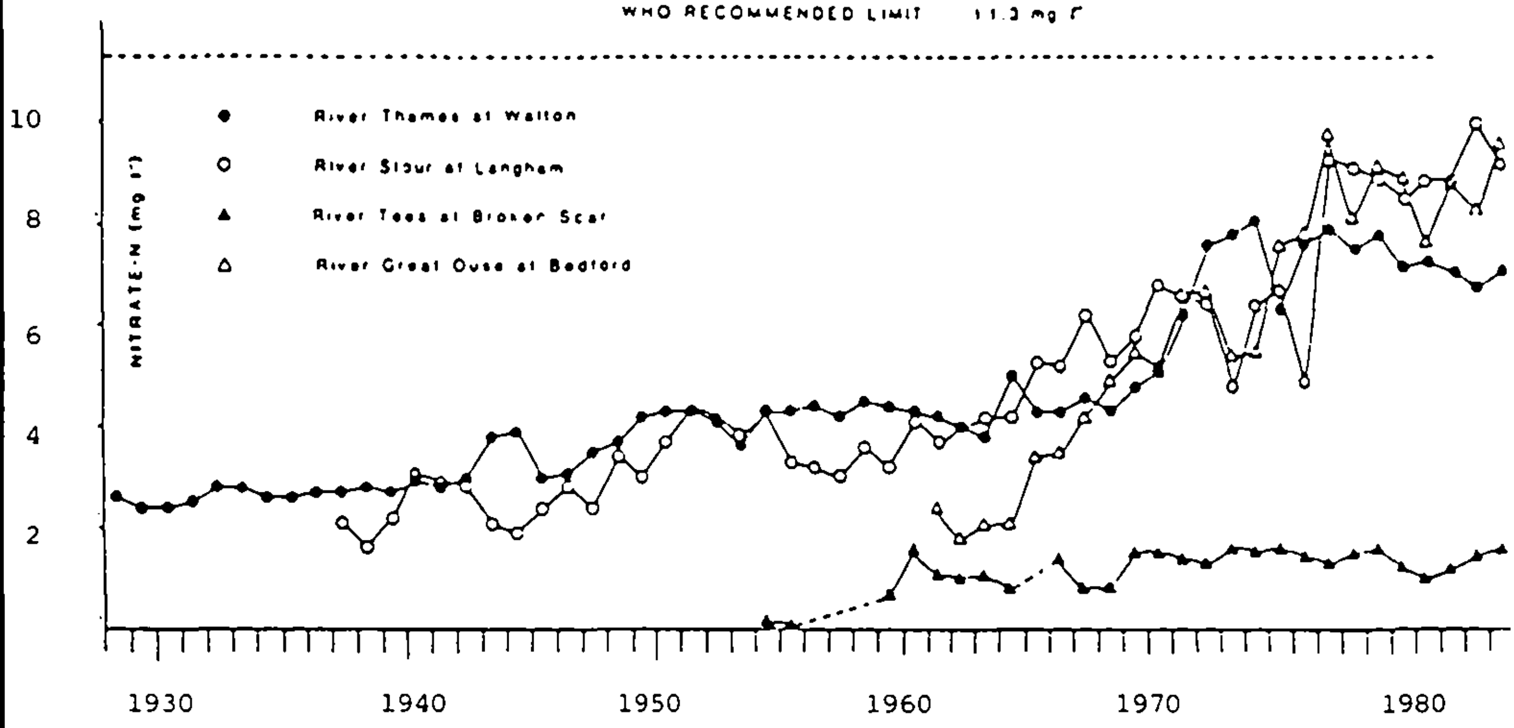

Figure 7 Trends in Surface Water Nitrate Concentrations

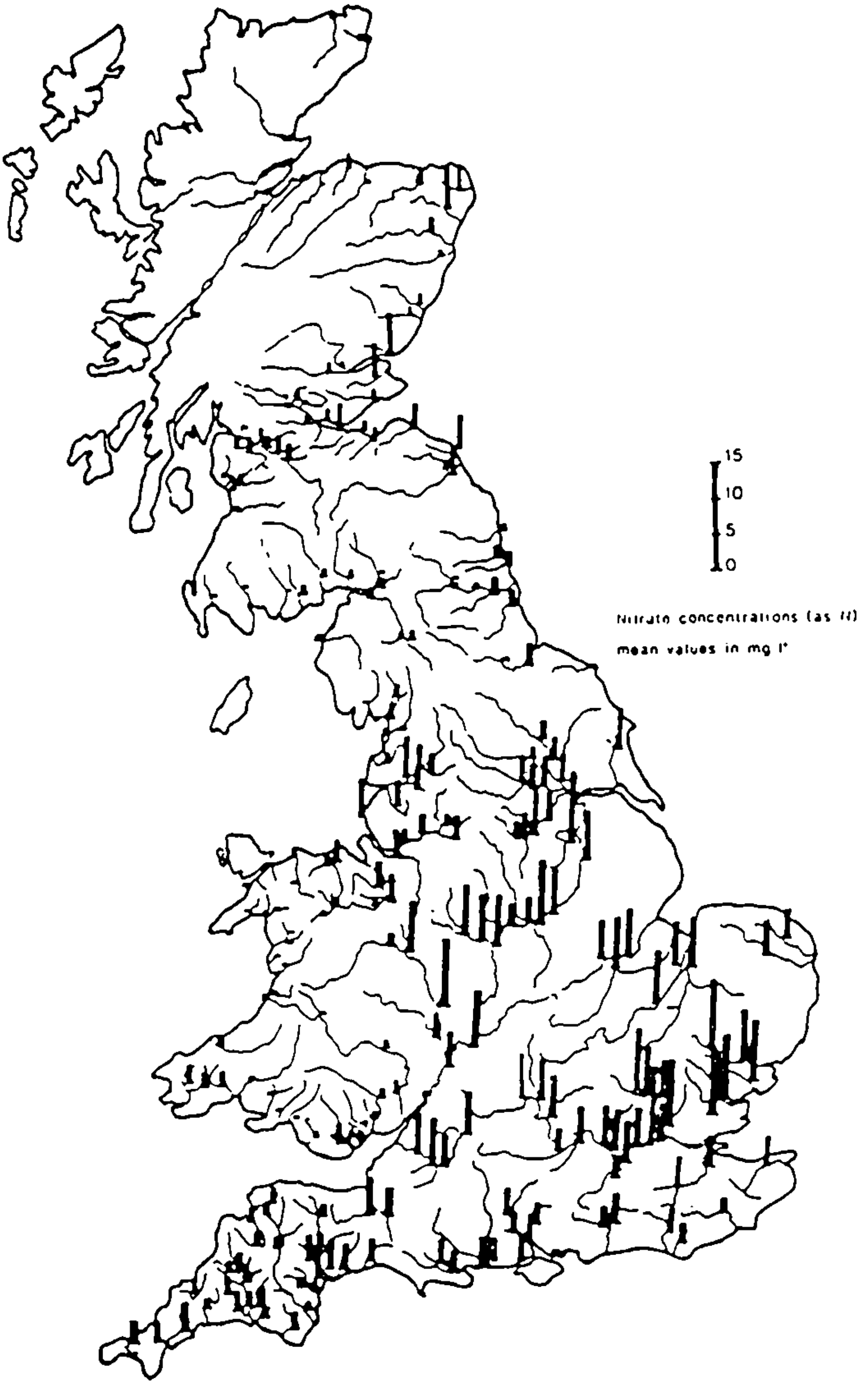

Figure 8   Spatial Distribution of Nitrates in Surface Waters

management of river and reservoir systems threatened by eutrophication and resulting biological problems such as algal blooms.

(ii) Biochemical Oxygen Demand and Dissolved Oxygen

These components of water quality are mainly controlled by the quantity and nature of point source pollutants. Treated sewage, oxidising agents and any other pollutant which consumes oxygen are important in this respect. Farm pollution incidents are serious since they involve the discharge of organic matter. As a consequence, the pattern of this pollution shows not just a between-river variation but also within-river and temporal variations closely linked to water temperature. Immediately downstream of an effluent discharge, there are major changes in stream chemistry and biology as indicated in Figure 9. For example, the DO reaches a minimum level associated with high BOD levels and then slowly recovers as oxygen is transferred via reaeration into the water column. Transformations also occur affecting nitrate, ammonia, bacterial and algal concentrations (see Whitehead and Lack, 1982). The chemical classification of water quality for pollution surveys is based on the concentration of DO and ammonia and BOD and the criteria are show in Table 2.

(iii) Pesticides

Pesticides and herbicides arrive in water courses predominantly as non-point source agricultural runoff. High concentrations of these agrochemicals have been reported in both surface and groundwaters, concentration being determined by temperature, rainfall and runoff generation mechanisms.

(iv) Suspended Sediment

Siltation of reservoirs and navigable waterways is not a major problem in the lowland UK but an increasing awareness of the role of suspended sediment in the transport of nutrients and contaminants in sediment-associated forms demands their inclusion. In particular, it is not uncommon for sediments to contain 10-30% organic matter and this, amongst other factors such as temperature, enhances microbial survival times in bottom sediments. Also metals, pesticides and radionuclides are often adsorbed onto sediment surfaces and transported along with sediments.

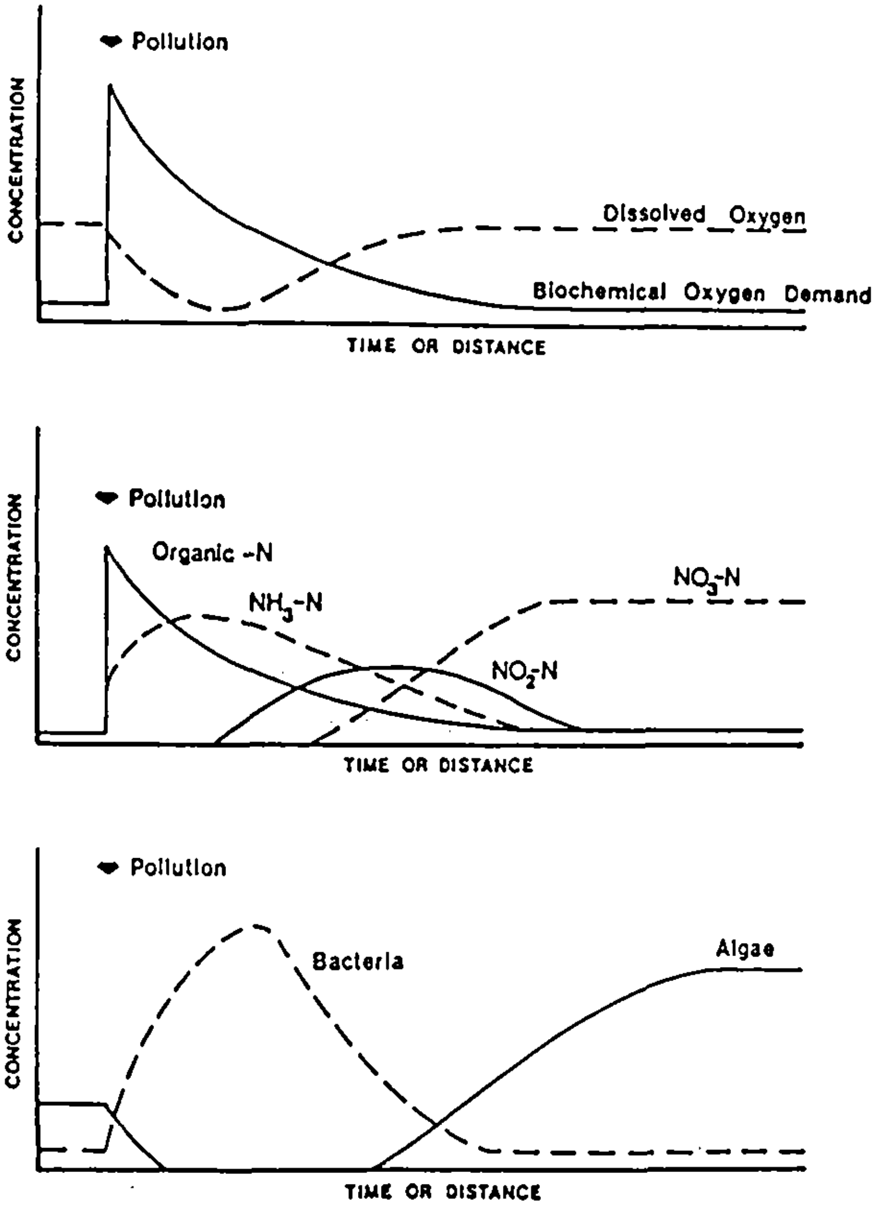

Figure 9 Changes in stream quality downstream of a waste outfall

TABLE 2 River Pollution Classification

(a) *Class*	*Description*
1	unpolluted and recovered from pollution
2	doubtful quality and needing improvement (fairly good in Scotland)
3	poor quality requiring improvement as a matter of some urgency
4	grossly polluted

(b)[*] *Class*	*Limiting criteria* (95 percentile)
1A unpolluted	DO saturation > 80%, BOD ≤ 3 mg l^{-1}, $NH_4 \leq 0.4$ mg l^{-1}, EEC A_2 category, non-toxic to fish
1B high quality	DO saturation > 60%, BOD ≤ 5 mg l^{-1}, $NH_4 \leq 0.9$ mg l^{-1}, EEC A_2 category, non-toxic to fish
2 doubtful quality	DO saturation > 40%, BOD ≤ 9 mg l^{-1}, EEC A_3 category, non-toxic to fish
3 poor quality	DO saturation > 10%, BOD ≤ 17 mg l^{-1}, not likely to be anaerobic
4 grossly polluted	inferior to Class 3 and likely to be anaerobic at times
X insignificant watercourses	DO saturation > 10%

5. THE IMPACT OF CLIMATE CHANGE ON WATER QUALITY

Under the scenario assumptions outlined in section 1, a wide range of water quality problems can be envisaged. These will consist of a general enhancement of the existing problems, outlined in section 4, and may introduce many new problems although these are difficult to identify. As stated earlier, the perception of water supply engineers, public health engineers and conservationists may be very different. As a result of these different outlooks it is convenient to assess the possible water quality changes induced by climate change in terms of water supply, effluent disposal and recreation/conservation concerns. In any case the conventional split between upland and lowland water resources may also be interpreted as depending on land use and this may also change as a consequence of climatic change. For example, the uplands are presently characterised by commercial forestry and unimproved grassland although a change in climatic regime might increase the economic viability, and introduce the need, for marginal land improvement. Clearly, such a change would introduce the problems of increased fertiliser and agrochemical application to upland areas. A further problem in assessing future river water quality on a national scale is that most 'lowland' rivers have their headwaters in 'upland' areas and so a change in water quality in the uplands will be reflected in the same river further downstream as an increase in 'background' concentration.

5.1 Water Supply Problems

In the UK, water for potable supply is obtained from surface reservoirs, groundwater aquifers and direct stream abstraction. In the north and west of the country, upland reservoirs and abstraction from small streams and wells predominate while the south and east of the country relies heavily on groundwater and river abstraction.

(i) The north and west UK

(a) The base scenario of increased rainfall, increased temperature and increased atmospheric carbon dioxide concentration will tend to enhance the existing acidification problem in upland streams and lakes. The overall effect of increased CO_2 will in itself be small (George, 1988) but the increased rainfall could substantially change flow pathways by concentrating more flow through preferential pathways (pipes and macropores), the near surface soil layers and over the surface. The neutralising capacity of these routeways is small or non-existent and may act as a source of hydrogen ions and hence acidity. Increased temperature will cause an increase in evapotranspiration thereby concentrating the acidifying effect of anthropogenic inputs. The pattern of deposition may also change as the possible increased cloud cover would lead to more filter deposition in the form of acidic mist and fog. The overall reaction of the system would be to demonstrate increased acidification and subsequently increased aluminium mobilisation. A quantitative study using a process-based modelling strategy demonstrates clearly how these effects will operate together and this is included in appendix A.

From the water supply viewpoint, many communities in upland areas rely on small surface water streams, springs or shallow groundwater aquifers and these coincide with groundwaters vulnerable to acidification (Kinniburgh and Edmunds 1984). Consequently, increased aluminium concentrations due to acidification could put the consumer at risk. Given the human health implications of increased aluminium concentrations it may be perceived that untreated rural supplies will require treatment facilities and existing 'older' treatment plants will need uprating.

(b) Nitrate problems in the uplands are less well understood than the sulphate problems associated with surface water acidification. If pressure for land use change in the uplands is a consequence of climate change, the increased use of nitrate fertiliser would undoubtedly cause in increase in streamwater concentrations. Clearly, runoff quality from improved grasslands would be unlikely to exceed present potable water standards, but may form a significant contribution to downstream quality deterioration, where it effectively constitutes the 'background' level. The effect of rising soil temperature will be to enhance microbial activity and hence mineralization of nitrogen in wet soils. This nitrogen could significantly affect upland water quality.

(c) Increases in nitrate and phosphate concentration in streams would increase the productivity of upland reservoirs. Eutrophication is not anticipated as being a problem but algal growth rates would accelerate and this may lead to operational problems. Furthermore, any change in land use and run-off regime will increase catchment erosion and reservoir sedimentation rates. The problem is, however, difficult to assess without a more detailed examination of the land use changes expected under the base scenario.

(d) Further problems could be considered, notably an increase in bacterial concentrations through enhanced survival ability, due to higher temperatures, and an increase in water colour, due to the marked seasonality of rainfall regime and the drying and subsequent resaturation of soils. Both problems would require substantial expenditure by water supply companies to maintain existing standards.

(ii) The south and east UK

The base scenario proposes a generally wetter and warmer climate for the south and east of the UK, although less wet than the north and east, with a much more intensely seasonal streamflow regime. This marked seasonality will have an important effect on water quality although the number of feedback mechanisms alone dictates a generalised overview here.

(a) Changes in flow paths on a seasonal basis will intensify non-point source pollution problems by generally increasing solute levels, notably nitrates. In autumn, winter and spring the higher rainfall will undoubtedly cause increased transport of fertilisers and agrochemicals into both surface and ground waters since these seasons represent the main periods of application. In some areas, dependant on soil and bedrock type, infiltration will increase (for example freely draining soils over chalk) causing direct contamination of groundwater, while in other areas increased saturation of soils will allow rapid surface runoff (for example, gleys or soils with impeded drainage over sand and clay mudstones) and direct pollution of surface water. In the summer months, that is the time of highest water demand, flows will be generally lower (although in catchments where the dominant streamflow contribution is from groundwater, flow could be maintained through the summer after the aquifer is fully charged following a wet winter) and so the concentration of solutes will be naturally increased through decreased flow dilution. This effect will be intensified as the increased temperature tends to increase evapotranspiration. This situation is demonstrated by the results of the computer simulation given in Appendix B.

(b) The warmer and wetter climate will lead to the increased use of pesticides and herbicides and by the same mechanisms as described in (a) an increase in surface and ground water concentrations can be expected.

(c) Given the current structure of water supply in these areas, groundwater and surface water pollution is likely to occur in tandem because of the natural water routing in catchments and also through management practice, such as the artificial recharge of aquifers with water pumped from river systems. In general the expected deterioration of water quality from all sources will require uprated treatment plants to maintain potable water standards.

(d) Other water quality problems affecting supply that could be identified are eutrophication of lowland impoundments, given the increase in solute levels, and the increased persistence of harmful bacteria and protozoa brought about through increased water temperatures. Protozoa are especially difficult to remove from a supply system (for example, note the recent problem in Oxfordshire with Cryptosporidium).

(e) Another potential problem arising from increased sea levels is saline intrusion of coastal aquifers. At present many coastal aquifers that supply fresh water, such as the Folkstone aquifer, maintain an equilibrium with sea water. In the event of sea level rise this equilibrium will be shifted such that the aquifer will be infiltrated by sea water. Quite modest sea level rises could result in saline intrusion and the loss of coastal aquifers as a source of potable supply.

5.2 Impacts on Effluent Disposal

(a) In the upland areas of the UK direct disposal of large volumes of effluent to waterways is not common and so no deterioration of water quality is expected. The increased rainfall, and as a consequence changing flow pathways, however, may call for a reappraisal of septic tank and soakaway systems used in unsewered areas.

(b) In the major river systems across the country where point source effluent disposal is common, the base scenario would provide for a general improvement in the quality of streams by increased dilution during autumn, winter and spring. Pollutant residence times would decrease and it is conceivable that dischargers will more easily be able to adhere to consent conditions imposed upon them. The generally increased river flow would also tend to increase the oxygenation of the water improving the dissolved oxygen content and biochemical oxygen demand.

(c) During the summer period, however, when flows are expected to be less than at present, pollutant residence times will increase and a generally higher BOD and lower dissolved oxygen content will result. In the extreme, water pollution controllers may find it necessary to impose seasonal discharge consents.

(d) While the increased temperature associated with climate change may be beneficial to the bacterial processes utilised in sewage treatment there are likely to be significant detrimental effects on sewerage systems and urban pollution.

The increase in rainfall and a change in rainfall intensity will affect the runoff quantities being handled in sewage works and transported by sewerage systems. Increased runoff from urban areas will increase wash-off of organic matter, heavy metals, herbicides, suspended solids and nutrients such as nitrogen and phosphorus. Since combined sewer overflows will divert more water, larger volumes of polluted water will be released directly to receiving waters. A recent analysis of the city of Lund in Sweden by Niemczynowicz (1988) indicates that pollution loads by stormwaters would increase by up to 32% and pollution loads by combined sewer overflows would be increased by up to 78%. These loading increases apply to suspended sediments, biochemical oxygen demand and heavy metals including copper, zinc and lead. It is highly likely that such increased loading figures would also apply to herbicides, pesticides, nitrogen and phosphorus. These large increases in urban pollutant loads result from sewage treatment plants being unable to handle the increased runoff in intense storm events and the subsequent direct release of polluted waters into rivers.

Most stormwater systems are designed to accommodate intense storms. However, if climate change alters the basis of the original design criteria, significant flooding of sewerage networks may occur leading to problems of bacterial pollution of fresh water supplies and degradation of urban streams and lakes. Moreover, sewerage works will be incapable of handling the larger volumes of polluted water. The costs of expanding sewage works and redesigning and rebuilding sewer networks would be extremely high but may be the price of ensuring the environmental damage does not occur.

5.1 Impacts on Recreation and Conservation

Many of the water quality effects discussed already will be perceived by some to have a serious effect on the ecology of lakes and streams and as possible health hazards. The base scenario contains no detail of the expected changes to streamflow regime, or to how this will vary, over small regions of the UK. It is apparent, however, that periods of good and poor water quality may occur on a seasonal basis, and infection of bathers by waterborne bacteria could be a problem during the summer months.

It is not possible to generalise about the expected conditions over large areas of the UK as regards the effect of water quality on ecosystem status. Undoubtedly, a number of site specific problems relating to particular habitats may occur. This aspect has been comprehensively covered in the FBA Desk Study (George 1988).

6. CONCLUSIONS AND PRIORITIES FOR RESEARCH

This review has raised more questions than answers. This is inevitable given that there are uncertainties associated with climate change and that water quality depends on so many different factors which are themselves subject to change. It could well be that many of the water quality problems outlined in this report will not be severe and that climate change will actually improve the situation in some respects. On balance, however, we conclude that climate change will adversely affect water quality. In order to fully investigate the potential impacts of climate change it is proposed that certain priorities for research be established.

6.1 Priorities for Research

(i) Monitoring Ecosystems

A network of catchments within the UK should be established covering a range of environmental conditions and pollution climates. These should provide a common baseline programme of monitoring and can provide the focus for more intensive programmes of research. The objective of such a network would be to identify indications of environmental change at different hierarchical levels within catchments suitable for analysis and prediction. The baseline data set should contain information along the lines suggested in Appendix C.

(ii) Techniques of Trend Analysis

A range of techniques are required for the identification and analysis of trends. This will need to include development of methods for handling incomplete and sparse data sets given that most long term data sets are of poor quality in the UK (DOE 1986). There is a need to know the timescales of change and different factors producing perturbations.

(iii) Modelling Studies

Models provide a means of assessing the complex interactions and feedback mechanisms occurring in the natural environment. There is need to review existing models, assess their suitability for climate change studies and apply them to a range of problems such as:

(a) Upland Water Quality Given changes in rainfall, runoff and temperature, assess the effects on water quality through changing dilution, changing atmospheric deposition, enhanced chemical reaction rates, altered biochemical behaviour, altered erosion pattern and altered land use.

(b) Lowland River Quality Management Assess effects of changing flow patterns on water quality variables in lowland rivers and investigate implications on water resources and water pollution levels. Investigate the effects of dry summers and hence low flows on operational problems, particularly, impacts of pollutants, travel times, growth of algae, etc.

c) River Reservoir Interactions Many rivers are regulated by reservoirs. Problems of water yield and release strategies affect river water quality in reservoirs and consequent effects on river quality and water supply.

(iv) Manipulation Experiments

Some consideration should be given to manipulation experiments to investigate aspects of climate change. For example, the RAINS project in NORWAY is *likely to be converted to a climate change experiment by introducing soil* heating and enhanced CO_2 concentrations. Similar experiments could be established in the UK. A network of similar experiments is being established across Europe and experiments are planned in North America.

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Appendix A

AN EXAMPLE OF HOW CLIMATE CHANGE MAY AFFECT UPLAND WATER QUALITY

Given the scenario that temperatures will rise by 3°C ± 1.5°C and that rainfall and hence cloud cover will also increase it is likely that several process interactions will affect water quality. Two of these are increased evaporation, and increased deposition. Beran and Arnell (1989) describe the likely increase in evaporation associated with temperature increases and increased deposition will occur following increased rainfall or, probably more significantly, by increased mist or cloud cover. These two effects can be simulated using the MAGIC model.

MAGIC (Model of Acidification of Groundwater In Catchments) is explicitly designed to perform long term simulations of change in soilwater and streamwater chemistry in response to changes in atmospheric deposition of pollutants. The processes on which the model is based are:

- anion retention by catchment soils (eg sulphate adsorption);
- adsorption and exchange of base cations and aluminium by soils;
- alkalinity generation by dissociation of carbonic acid (at high CO_2 partial pressures in the soil) with subsequent exchange of hydrogen ions for base cations;
- weathering of minerals in the soil to provide a source of base cations;

A sequence of atmospheric deposition and mineral weathering is assumed. Current deposition levels of base cations, sulphate, nitrate and chloride are needed along with some estimate of how these levels varied historically. Historical deposition variations may be scaled to emissions records or may be taken from other modelling studies of atmospheric transport into a region.

The MAGIC model has been applied extensively to a range of catchments and details of the model and its application are presented elsewhere by Cosby et al (1985,86), Wright et al (1986), Whitehead et al (1988) and Jenkins (1988).

The model is sufficiently flexible such that it is possible to vary evaporation rates, dry, wet and mist deposition, soil types, catchment characteristics, etc. In this study MAGIC has been used to assess the effects of increased evaporation and deposition rates on a sub-catchment of Loch Dee, the Dargall Lane.

Figure A1 shows the predicted pH for the Dargall Lane site given a supposed climate change over a 25 year period from 1990. The continuous line shows the expected trend in pH given constant deposition and climate into the future. The dotted lines show the expected change in pH given both the enhanced evaporation occurring and increased deposition. In fact the deposition of anions has been doubled producing a large effect in terms of pH. However, this may not be unrealistic given that, with soil temperature increases of the order of 4°C, there is likely to be a significant release of nitrate in the particularly wet region of Scotland which will act as a mobile anion acidifying the stream water. MAGIC provides a means of assessing the interactions between a whole range of processes and variables and, as such, could be particularly useful in assessing some of the effects of climate change.

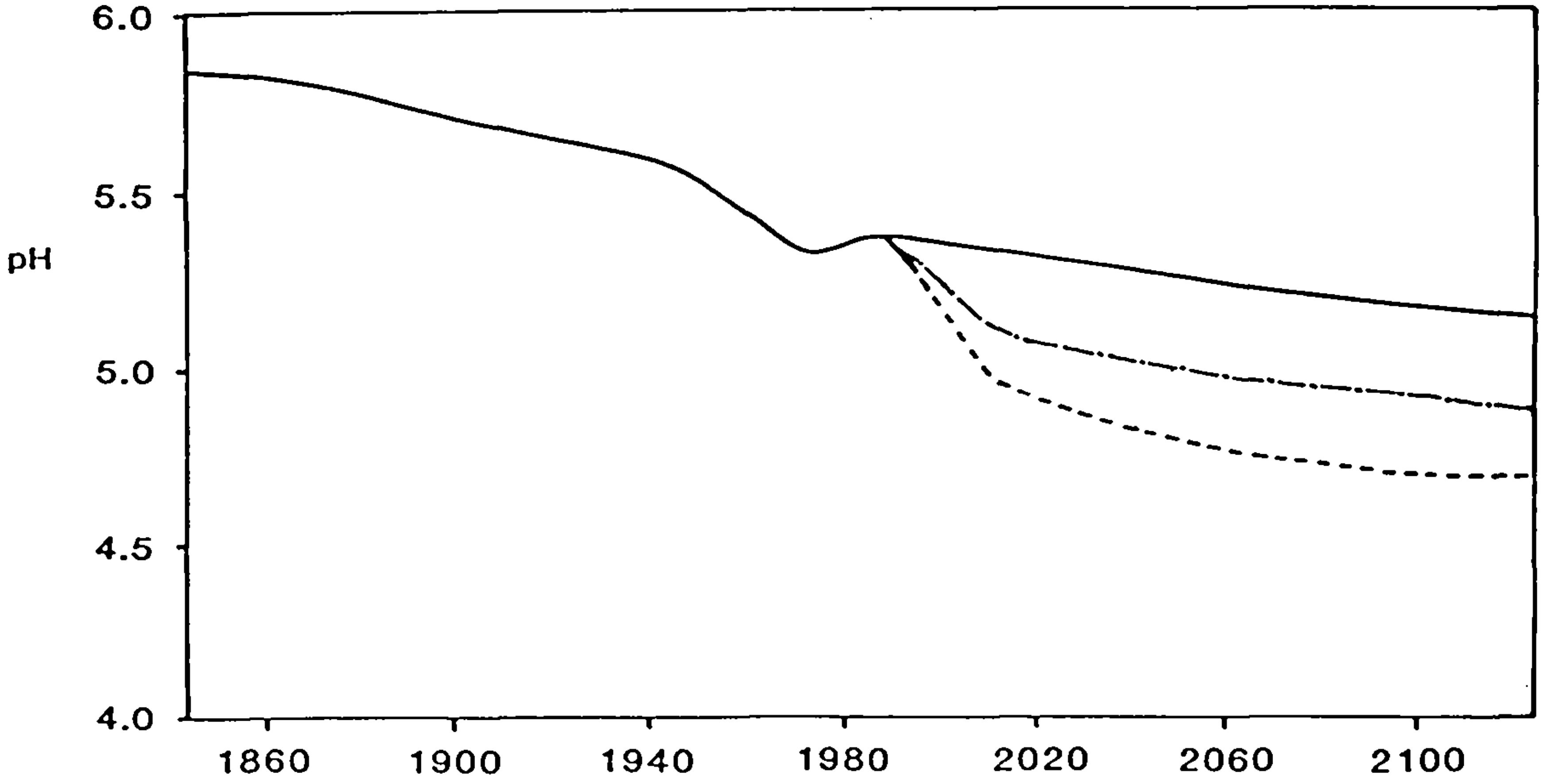

Figure A1 Simulated effects of increased temperature, evaporation and deposition on stream pH at Loch Dee, South West Scotland

Appendix B

ASSESSING THE IMPACT OF CLIMATE CHANGE OF RIVER POLLUTION USING QUASAR

The model QUASAR (Quality Simulation Along Rivers) has been designed at the Institute of Hydrology to assess the impact of pollutants on river systems. The model was originally developed as part of the Bedford Ouse Study, a DOE and Anglian Water Authority funded project initiated in 1972 (see Whitehead et al 1979, 81). The model has since been applied extensively in studies of the River Thames (Whitehead and Williams 1984) and more recently the River Tamar. A total of eight water quality variables are simulated in addition to flow, including:

dissolved oxygen
biochemical oxygen demand,
nitrate
ammonia
temperature
E.Coli, pH
and any conservative pollutant.

A wide range of inputs can be investigated including tributaries, groundwater inflows, direct runoff, effluents and storm water and the model can allow for abstractions for public supply or irrigation. A multi-reach approach is utilised so that the user specifies reach boundaries and locations of primary interest.

The model can be operated in two modes; a dynamic mode in which pulses of pollutant can be traced downstream, and a planning or design mode in which effluent consent conditions can be established given a river quality objective. Figure B1 shows a typical simulation in the dynamic mode for a 'theoretical' pulse of pollution in the River Thames. Figure B2 shows the type of information for a planning mode application in which the distribution of nitrate for the River Tamar is presented for a reach of the river downstream of an effluent discharge. River Quality Objectives are generally

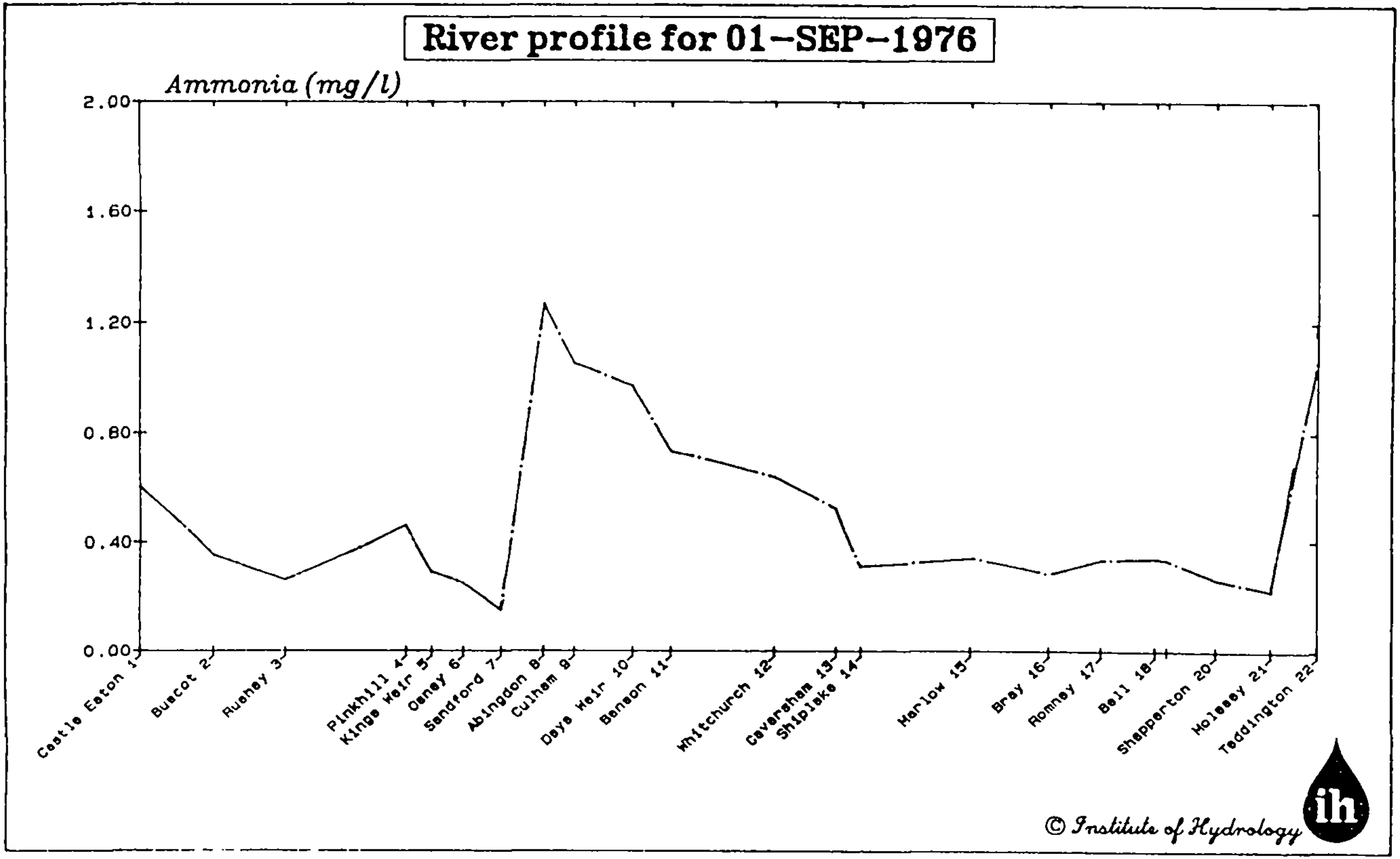

Figure B1 Simulated ammonia concentrations along the River Thames specified in terms of 95 percentile levels and therefore the distribution of quality at a site on the river provides direct information on the likely 95 percentile levels given a particular effluent consent level.

The QUASAR model has been used in a preliminary investigation of the impact of climate change or water quality. The change in rainfall patterns expected from climate change will alter the flow regime and thereby alter the residence time of water in rivers and the dilution factors. A set of runs using QUASAR provides information on likely nitrate distributions along the Tamar under different flow regimes. Three flow distributions have been assumed; the current flow distribution for the Tamar, and the current distribution increased and decreased by 20% to reflect two ranges of climate change effects. It is also assumed that effluent discharges are increased significantly on the Tamar. It should be emphasised that this is purely hypothetical but it does reflect the impact of effluent on other lowland rivers where major effluent sources exist, such as the Thames, the Bedford Ouse, etc. The nitrate distributions shown in Figure B2 reflect the differing flow regimes. Under decreased flow conditions the mean nitrate concentrations and 95 percentile level increase reflecting the decreased dilution effect. The reverse occurs for the increased flow levels which produce lower nitrate concentrations. Note that under the decreased flow scenario the 95 percentile concentration increases to 12.6 mg/l which is above the EEC guideline level.

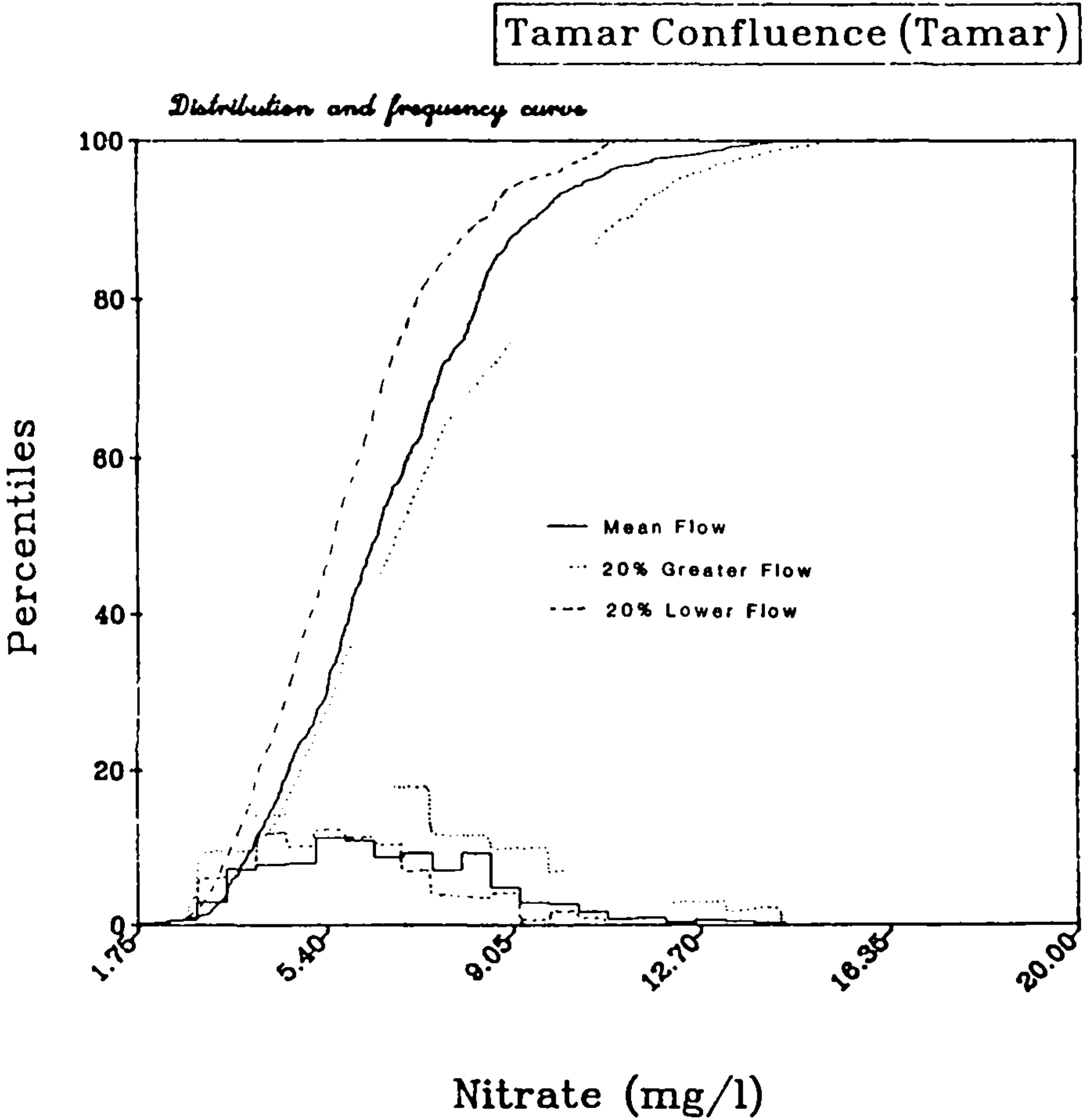

Figure B2 Distribution of Nitrates under three flow conditions

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Appendix C

MEASUREMENTS REQUIRED FOR A CATCHMENT MONITORING NETWORK

Measurements to be made at all catchments in the network.

Site data

Vegetation - main vegetation types and their spatial distribution; above ground biomass of the main vegetation types; leaf chemistry from main forest species at 3-year intervals - for total C, N, P, Na, K, Mg, Ca, S.

Soils description of main soil types and their distribution; for main soil horizons of main soil types cation exchange capacity, base saturation, exchangeable cations, organic matter content, total C, S and total N, SO_2 adsorbtion, texture. Parent material mineralogy if different from bedrock.
Geology - main rock types and spatial distribution.

Meteorological data

Mean monthly temperature; weekly bulk precipitation the number of gauges being determined by variation in altitude and aspect within the catchment.

Inputs

Bulk precipitation - weekly collections bulked for monthly analysis Throughfall - weekly collections for monthly analysis from each forest type within the catchment; several throughfall sites may be necessary if there is a large variation in aspect, altitude or age.

All samples to be analysed for pH, conductivity, calcium, magnesium, sodium, potassium, ammonium, nitrate, chloride, sulphate, filtered aluminium, alkalinity. Occasional samples to be evaluated for SiO_2, DOC, total P, Mn, organic N, Fe Al speciation.

Outputs

Daily mean flow. Weekly spot samples analysed in the same way as bulk precipitation and throughfall.

Biological Data

Fish Density; Invertebrate diversity, chlorophylla, algal species.

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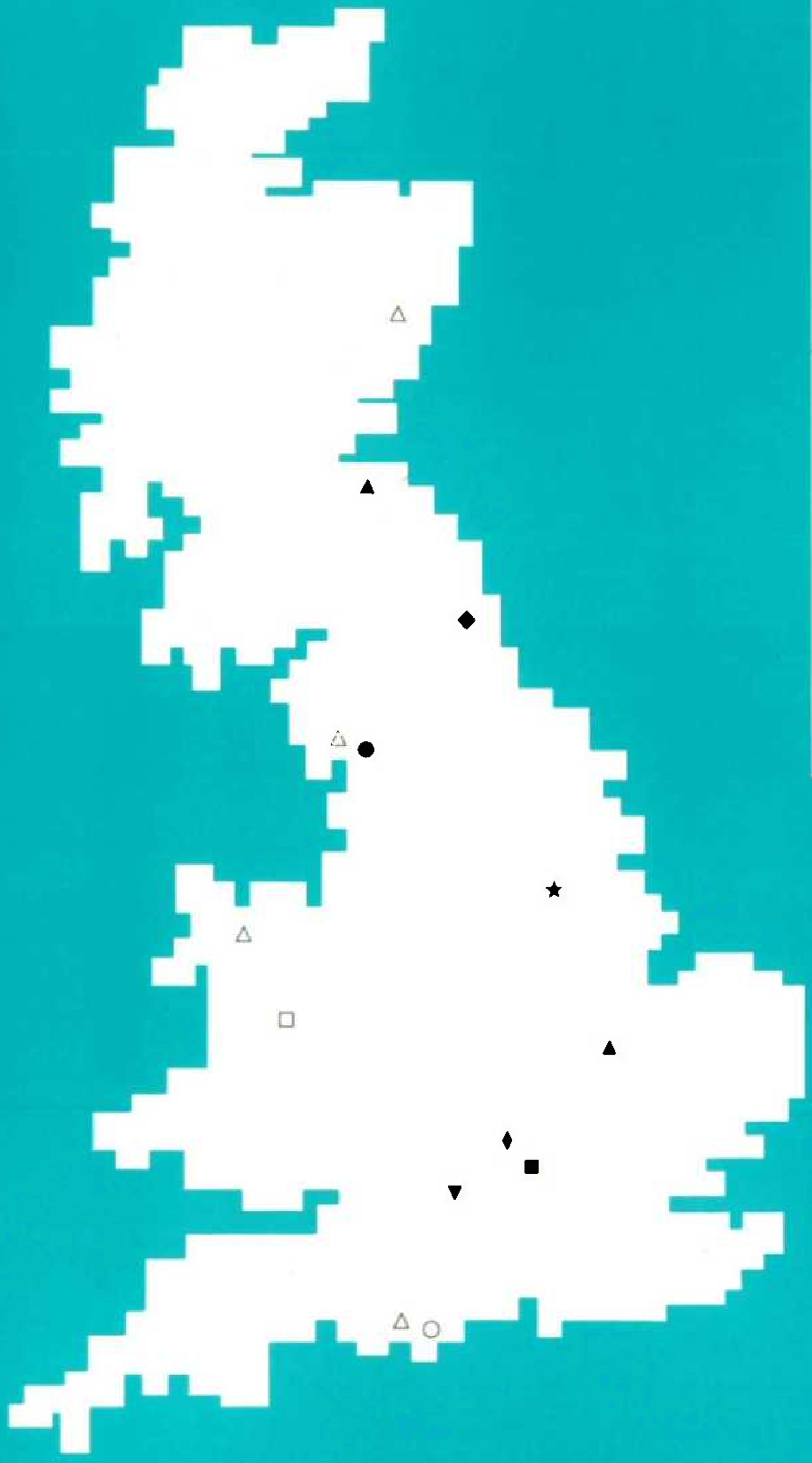

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