FRESHWATER BIOLOGICAL ASSOCIATION

The Ferry House, Ambleside, Cumbria, LA22 OLP

BLOOMING WEATHER:
Predicting the Incidence of Summers with high-risk of Cyanobacterial blooms

A Report to Wallace Evans & Partners
April 1988

Sirs,

This report is submitted for your approval, in response to the requirements set out in your letter of 23 March 1988. The nature of at least part of the information required is outside the normal remit of the Association and in a field where we have little first hand experience. In effect we have collected, marshalled and presented relevant information on river flows and climatic trends, gleaned from the literature available to us and we have attempted to apply and interpret this information to the current problem. Whilst every effort has been made to maintain a strictly factual approach, save where opinions are clearly stated to be such, we cannot be certain that we have used either the most appropriate or recent literature in preparing the report, or that other conclusions could not be drawn.

C.S. Reynolds, April 1988
for and on behalf of the Association

INTRODUCTION

This report addresses questions about the occurrence of bloom-forming cyanobacteria (or blue-green algae) that, at times, accumulate at the surfaces of the lakes or reservoirs in which they grow. In particular, it probes the likely incidence of such blooms in the lake to be formed behind the proposed Cardiff Bay Barrage, given that earlier modelled predictions (1-3) indicated a strong dependence upon hydrological conditions obtaining during the growth period. Indeed, it has been argued (2) that hydraulic throughput of the fluvial flow emanating from the Taff and Elai inflows remains the major environmental constraint upon the growth of all planktonic algae in the lake. The various model runs in (2, 3) regularly reveal the clear response of algal biomass to reduction in inflowing discharges during spring, its sensitivity to flushing episodes in summer and autumn and the dependence of the intermediate periods of high biomass upon the length of time separating the relevant events.

Given that these biological responses are closely regulated by the general weather patterns experienced in any one year, then the question is immediately posed "How predictable are the weather events?" In particular, how strong is the seasonality of precipitation which leads flood events? What is the between-year variability, in amount, phasing and duration? And what level of probability can be placed upon the conditions conducive, either to bloom-formation or to high algal biomass per se, being satisfied in any one year?

These questions bring together the sciences of climatology, hydrology and biology in a rarely precedented fashion. Their answers are nevertheless approached not through the analytical process but, rather, the reverse: we begin by defining the biological responses of concern and the hydrological dimensions critical to their onset: then to distinguish the weather events which are likely to generate the relevant hydrological conditions; next, to review the present knowledge of national and regional patterns of past variability in weather; and, finally, to extrapolate trends in the weather which would influence the future extent and frequency of blooms in the Cardiff Bay Barrage.

DEFINING THE RELEVANT HYDROLOGICAL SCALES

The first requirement is to summarize the prescribed conditions conducive to plankton development in the barrage lake. These were examined in detail in the previous reports (1-3), paying particular attention to the scale, temporal phasing and species composition of large algal biomasses simulated through twelve consecutive years (1976-1987 inclusive), assuming the lake had been constructed as presently proposed and was subject to the actual fluvial loadings from the Taff and Elai inflows. These reports are taken here as read and their findings are not repeated. It is, however, important to distinguish among the terms 'capacity', 'development rate' and 'duration' of large planktonic populations in the lake.

'Capacity' is a property of the lake itself, referring to the plankton biomass that can be supported within the limits imposed by the supply-side resources. In the majority of lakes, the limitation is imposed by the available nutrients (of which phosphorus is generally regarded to be most commonly limiting; nitrogen to be so at times, and more enduringly so in certain classes of lakes; soluble silicon is also sometimes critical in the case of one group of planktonic algae, the diatoms); the limit is when the entire available resource is incorporated within living biomass. Where nutrients are not found to be limiting, the capacity will be determined by the light energy available. This is reached when the photosynthetic carbon fixation is balanced by the respirational losses of carbon dioxide. This occurs when the light penetration is so restricted by suspended material (of which planktonic algae may make up the largest fraction) that the effective mean period that algae are exposed to daylight is reduced to a few hours in any twenty-four. The exact limit is species-variable, so that low average light becomes an important selective factor influencing species composition of the biomass. As conceived, the Cardiff Bay barrage lake will receive supraoptimal nutrient supplies and its carrying capacity will be light-controlled: some 600 mg m^{-3} of chlorophyll a at the summer solstice: and about 100 mg m^{-3} in winter.

'Development Rate' is a property determined by the ability of algae to respond to the capacity conditions set by environmental factors. When spare carrying capacity exists and planktonic algae are present to exploit it, they can be expected to increase their biomass at rates determined by the rate of supply of the resources; where resources are saturating (or as near-saturating as day-night alternation will permit), the developmental rate is potentially rapid, equivalent to a doubling or two each day in the case of some small-celled unicellular species at 20C, a little less than half as fast at 10C. As the spare capacity is taken up, so the growth rate slows towards zero as the ultimate capacity is approached. In the case of the bloom-forming Cyanobacterium, Microcystis, the maximal rates of increase are relatively slower: calculations in (1) showed that less than one doubling per day could be achieved at 25C, given optimal conditions of high clarity at a summer-solstice day-length of 16 h; at 20C, an inferred maximal rate increase of 0.24 per day was derived: at 15C, only 0.19 d^{-1}. Natural development rates also respond to processes removing biomass - settling out, consumption by grazers and losses through outflow. Whereas the sedimentation- and grazing-losses are experienced more by certain groups than others, outwash is largely unselective. If in concert, removal (attrition) rate balances the rate of gain by growth, then the development rate is zero. Thus it is that the model simulations (2, 3) achieve a quasi-steady state below the theoretical carrying capacity, in the range 400-500 mg m^{-3} as chlorophyll a. Moreover, of the species introduced with inflow in the simulations, the development is initially dominated by species with the fastest rates of growth: later by the larger, buoyant species resistant to attention by grazing and sedimentation. All the three cyanobacteria introduced are in the latter category: Oscillatoria, which has the least capacity of the three to form surface aggregations, is best-adapted to use low levels of light: in the simulations, it consistently becomes the dominant.

One unrealistic assumption of the simulations was the continuous introduction of all algae in equal or near-equal amounts in the inflows. In fact, inflows will be sparsely populated by those species adapted to survive in flowing systems - Chlorella, Ankistrodesmus, Stephanodiscus; Microcystis and Oscillatoria will surely be supplied in this fashion but they are relatively very rare. Preliminary collections from the Taff and Elai confirm this view. This necessarily biasses the development of plankton in the lake in favour of just those algae which the simulations show to be favoured anyway. Equally, it biasses against the predominance of cyanobacteria, until such time that they develop a significant presence within the lake. This makes doubly important the definition of the conditions favouring their eventual development.

'Duration'. High biomasses can be maintained for as long as growth processes can make up the loss processes. For all algae, the ultimate loss process must be elevated discharge rates of sufficient magnitude to exceed growth rates corrected for other attritional losses. Thus, the typical duration time in the lake will be from shortly after attainment of high net development until rapid depletion in elevated throughflow. Each flood event will be followed by the re-establishment of conditions for growth but the new capacity may well be altered with respect to the earlier development, especially if the growth phases are separated by some months.

Quantitative patterns of development and control in the lake

It will be apparent that the most likely pattern of development in the lake will depend upon the combination of good growth conditions (warm, clear water, charged with nutrients) and minimal discharges. High biomasses will then be possible, within the capacity set by the resources, as modified by consumption in development. As the community matures, so selective processes will move towards the dominance of the biomass by cyanobacteria. High biomass will persist until washout becomes critical, though this may well happen at anytime prior to the eventual emergence of cyanobacterial dominance.

Quantitative criteria Against such given criteria as the lake volume, the predictable seasonal variations in light income and known variabilities in the fluvial discharges of the Taff and Elai, it is possible to define quantitative evaluations of the behaviour of algal biomass in the lake. Table 1 postulates a number of relevant scenarios concerning the growth rates of selected algae, the discharge rates necessary to meet the balancing attrition rate alone and the frequency with which the critical discharges have been exceeded during the period 1976-1987, inclusive, according to Welsh Water records analysed in (4). The assumptions are that the lake is uniformly well-mixed throughout its volume (7.58×10^6 m^3) and that the displacement volume is shared by the Taff and Elai inflows in the proportions at the given total exceedence frequency.

From these data, it will be apparent that at flow rates less than the critical rate, algae will be able to show net increase. We can now turn the equation around and set the times taken to achieve populations equivalent to the threshold levels of acceptability proposed by Welsh Water (3) (viz. 5 mg m^{-3} for Microcystis, 10 mg m^{-3} for Anabaena and 100 mg m^{-3} for other species) and to a notional limit of 400 mg m^{-3}, under specified flows (5 and 10 percentile flows). This is done in Table 2, for the same growth conditions

TABLE 1 : Potential development times of selected algae and the hydrological throughput rates required to prevent them.

	Microcystis	*Anabaena*	*Oscillatoria*	*Chlorella*
Growth rate when temperature is 10° daylength is 12h $\epsilon = 0.2\ m^{-1}$	0.025	0.085	0.148	0.290 d^{-1}
Compensatory flow	2.2	7.5	13.0	25.4 m^3s^{-1}
% Exceedence	>99	74	54	27
Growth rate when temperature is 20° daylength is 16h $\epsilon = 0.2\ m^{-1}$	0.243	0.461	0.616	0.872 d^{-1}
Compensatory flow	21.3	40.4	54.0	76.5 $m^{-3}s^{-1}$
% Exceedence	34	15	10	6
Growth rate when temperature is 20° daylength is 16h $\epsilon = 2.2\ m^{-1}$	0.215	0.393	0.616	0.627 d^{-1}
Compensatory flow	18.9	34.5	54.0	55.0 m^3s^{-1}
% Exceedence	38	21	10	9

visualized in Table 1, assuming a single inoculum of 1 mg m^{-3} chlorophyll on Day 0. Literal interpretation must be judged in relation to the caveats already advanced (i.e. inocula may well be smaller; growth slows as light becomes limiting: and the Cyanobacteria may be seriously limited competitively by the 'shade' imposed by the development of other algae. Nevertheless it is clear that the opportunities for increase after the equinox will fall mainly to small-celled algae other than Cyanobacteria and that no only will they dominate but are always likely to reassert themselves later in the summer after any flood event. Even at the summer solstice, these algae will grow to the 100 mg chlorophyll m^{-3} threshold before _Microcystis_ or even _Anabaena_ could reach theirs (5, 10 mg chlorophyll m^{-3}, respectively).

Frequency of conditions conducive to threshold concentrations

It follows that quite long periods of low flows (say < 4.7 m^3 s^{-1}, the 10 percentile) are necessary to the development of bloom-forming Cyanobacteria as opposed to the small greens and diatoms. Table 2 suggests some 7-10 days minimum, assuming that other algae simultaneously achieve _their_ maximal growth rates to exceed the equivalent of 100 mg m^{-3} chlorophyll in the same time span. The deduction may be compared with the actual time periods over which 4.7 m^3 s^{-1} obtained in recent years, listed in Table 3; by analogy, the years with substantial summer drought periods are those carrying a high risk of development of bloom-forming populations of cyanobacteria. On the other hand, _Chlorella_ and _Oscillatoria_ may be expected to develop every year; the risk is close to 100%!

This outcome is substantially confirmed by the model runs for each of the years concerned (see esp. 3). These showed: major growths of chlorophyceae (exemplified by _Ankistrodesmus_) > 250 mg chlorophyll m^{-1} every spring

TABLE 2 : Development times (in days) for various algal populations from initial inocula of 1 mg m^{-3}, at 5 (≡ 3.9 $m^{3}s^{-1}$), 10 (≡ 4.7 $m^{-3}s^{-1}$) and 50 (≡ 13.8 $m^{-3}s^{-1}$) percentile flows, under defined growth conditions

Temperature	10°			20°			20°		
Daylength	12h			16h			16h		
ε	0.2 m^{-1}			0.2 m^{-1}			2.2 m^{-1}		
Flow	5%	10%	50%	5%	10%	50%	5%	10%	50%
Microcystis: 5 mg m^{-3}	.	.	.	8.1	8.5	18.7	9.5	9.9	27.8
10 mg m^{-3}	.	.	.	11.6	12.1	26.7	13.5	14.2	39.7
100 mg m^{-3}	.	.	.	23.3	24.2	53.5	27.1	28.4	79.4
400 mg m^{-3}	.	.	.	30.3	31.5	69.7	35.2	37.0	103
Anabaena: 10 mg m^{-3}	57.5	71.9	.	5.5	5.6	7.6	6.6	6.7	9.8
100 mg m^{-3}	115	144	.	11.1	11.3	15.1	13.2	13.5	19.5
400 mg m^{-3}	150	187	.	14.4	14.7	19.7	17.2	17.6	25.4
Oscillatoria: 100 mg m^{-3}	44.7	48.5	.	8.2	8.2	10.0	8.1	8.2	10.0
400 mg m^{-3}	58.1	63.1	.	10.6	10.6	13.1	10.5	10.6	13.1
Chlorella 100 mg m^{-3}	18.7	19.4	34.6	5.6	5.6	6.4	7.9	8.0	9.8
400 mg m^{-3}	24.5	25.3	45.0	7.2	7.3	8.4	10.3	10.4	12.8

TABLE 3 : The maximum number of consecutive days when flow in the Taff remained $< 4.1\ m^3\ s^{-1}$ (corresponding to the combined 10-percentile level of Taff & Elai inputs of $4.7\ m^3\ s^{-1}$) and $< 3.5\ m^3 s^{-1}$ (≡ 5 percentile level) and the total such days in the calender years noted: data from (4)

Year	Days when flow $< 4.1\ m^3 s^{-1}$ consecutive	(10%) Total	$< 3.5\ m^3 s^{-1}$ Consecutive	(5%) Total	Risk of exceeding threshold
1976	41	94	39	69	*** for all species
1977	16	79	11	11	*Microcystis ** Anabaena
1978	27	107	14	34	**Microcystis *** all other species
1979	31	42	1	1	*Microcystis ** Anabaena *** others
1980	0	0	0	0	**other species only
1981	17	41	12	12	*Microcystis **Anabaena
1982	8	20	0	0	*Anabaena
1983	24	27	12	15	**Microcystis *** all other species
1984	32	96	29	62	***all species
1985	6	22	5	16	*Anabaena
1986	16	16	0	0	*Anabaena
1987*	4	4	1	1	**other species only

*Incomplete record, to end of August only between 1976 and 1987, of Oscillatoria > 300 mg chlorophyll m^{-3} in 1976 and 1984 and between 100-200 mg chlorophyll m^{-3} in each of the years 1977-1982 inclusive, but > 30 in 1976 and > 20 in 1984. Microcystis exceeded 5 mg m^{-3} chlorophyll only in 1976.

It is not so much either low flows per se or even long runs of consecutive days when flow is low that will necessarily be conducive to the growth of bloom-forming populations in the barrage but rather that such dry periods occur when temperatures are elevated and the days are long. On the evidence of the present data, two summers out of twelve satisfied this condition, with periods of two months or more giving low flow and high water temperatures.

FREQUENCY OF SUMMER DROUGHTS

The flow record for the Taff is not sufficiently long to predict with any great confidence whether 2 out of 12 is a reasonable probability for dry summers, neither is it reasonable to regard the seasonal fluctuations in flow in that river as being typical for the region. A 30-year data set of daily flow records, published in Hydrological data UK by the Institute of Hydrology (continuing The Surface Water Year Book of Great Britain of the former Water Resources Board), is available for the River Usk at Chain Bridge (NGR SO 345056). This record is summarized in Fig. 1 which shows the mean annual discharge rate as a proportion of the mean over the full time series (27.64 $m^3 s^{-1}$) and the number of days in each year that flow failed to exceed the mean 5 percentile flow over the full series (4.29 $m^3 s^{-1}$). It is interesting to note that the two plots are not closely comparable: while year-to-year fluctuations in low flow days in the Usk closely resemble those of the Taff (also included in Fig. 1: coefficient of correlation = + 0.94) it is quite clear low mean discharge is not a good predictor of long summer droughts (see entries for 1964 and 1973), neither is a high mean discharge a guarantee against the possibility of a moderate drought (1959, 1981); the coefficient of correlation is - 0.31). What is of greater relevance is the distribution of the wet periods through the year: an average mean annual flow distributed in only six months of the year would nevertheless represent a serious flow deficit during most of the other six months. In the plot of low flow days versus mean annual flow (Fig. 2), the years when there was either a prolonged drought period and/or a low mean flow throughout the year are separately identified. These "flow deficit years" (or FDYs), already identified as those being the more likely to support populations of bloom-forming algae, should be influenced in turn by the intensity and periodicity of rainfall in those years. This will be important in a later section when we look for long-term patterns of weather variation.

Before going on to consider these longer time-series of proximal events, it is desirable to estimate the probability of incidence of FDYs over the period of direct measurements. It is possible to extend tentatively the time series by adding a run of data for the Taf Fawr intake at Llwynon Reservoir, covering the period Oct 1937 - Sept 1945. By expressing the mean annual flow in each year, relative to the entire period and determining the periods of < 5 percentile flow, the data are rendered comparable (Fig. 1b) with the 1957-1986 sequence for the Usk (caution is still required owing to the different smaller, upland character of the river). The additional data are also shown (separately) on Fig. 2, with a scatter which suggests that three (1938, 1942 and 1944) might be classified as FDYs. If we arrange the 36 years in ascending order of days of < 5 percentile flow and, again, in descending order of daily mean discharge, some idea of the probability of any given year having been flow deficient emerges (Fig. 3, 4). In the former, the plot shows that the 50-50 mode is approximately 7 days of each year and that in one in 3 years it can be expected to exceed 15 days. Moreover, the risk of thresholds for Anabaena and Microcystis being exceeded becomes severe in 1 in 5 years. On the basis of annual mean discharges (Fig. 4), the risk of severe FDYs (< 0.9 mean flow) is also about 1 in 5.

PERIODICITY OF DROUGHT YEARS

So far as it is possible to judge from a time series of less than 30 years, it seems unlikely that the possibility of FDYs is realized on a regular basis: several consecutive incidences of low mean discharge occurred in the early sixties whereas towards the end of the following decade, uneven distribution of annual flows contributed relatively more to a cluster of drier years. These periods were separated by several rather 'wetter' years, 1965-1972. The period 1938-45 also included several FDYs (1938, 1942, 1944). In order to gain enhanced resolution of cyclical variability in fluvial flows it is necessary to look for longer time-series of proximal criteria. Fluvial flows are, of course, generated by catchment run-off which is, in turn, related to precipitation as modified by evapotranspiration, by storage in vegetation and soils and by the store of relative saturation or water-deficit of the soils prior to rainfall events. Nevertheless, some reasonable correlation may be expected between seasonal rainfall averages and typical fluvial flows. Some rainfall records extend back over 200 years, and the comprehensiveness and accuracy of the data collected has improved steadily to the present century. Several very thorough analyses of the records over the last 50-60 years have been undertaken and two of these in particular may be referred to here. One is the recently published update of precipitation variability since 1931 by Wigley & Jones (5): the other is a more detailed analysis of patterns of variability in rainfall and run-off, undertaken by the Climatic Research Unit, UEA (6). In both cases, the country is divided into hydrological regions: data for the "south-west region", which includes South Wales and the south-western peninsula of England, is pertinent to the present discussion.

Several relevant conclusions are drawn in these studies. The popular belief that the distribution of rainfall is not markedly seasonal in England

and Wales is shown not to apply universally: there is typically a strong seasonal cycle in the SW region with an autumnal peak and a late Spring period of relatively low precipitation. This statement applies over the thirty years, without overall change but there is superimposed variability in the levels of spring precipitation at the order of decades; these were higher on average in the period 1956-1969 and picked up again between 1979 and 1983. Variations in summer precipitation showed only a weak trend, being slightly wetter in the mid-forties, late fifties and late sixties, becoming a little drier on average since the mid-seventies. The February-March period was unusually wetter between 1977 and 1982. Both wet- and dry-spells tended to be longer in the SW region than elsewhere and, in the last 10 years or so the frequency of extreme wet springs and extreme dry summers has increased perceptibly. Variations in annual precipitation (Fig. 5a) integrate these features to show a distinct circa-decadian cycle of wetter-drier alternations.

The effects of contrasting increases in the frequencies of wet springs and dry summers generate some of the variability about these trends that is evident in interannual variations in run-off (Fig. 5b). Years of extreme low runoff (FDYs) include 1934 and 1949 as well as 1938, 1944, 1959, 1964, 1973 and 1976 (as shown in Fig. 1); 1984 is less extreme over the year, due to its wet start.

There is an encouraging similarity between run-off and rainfall trends in the South-west region evident in Fig. 5. This simple fact enables a more confident application of the 200-year series of high rainfall and drought fluctuations to the extrapolation of trends in the incidence of FDYs. In Fig. 6, the incidence and relative intensity of drought years, being those defined here with a below-average annual rainfall over England and Wales as a whole and one or more very dry seasons. The derivation of the plotted data is extremely complex: Fig. 6 is redrawn from analyses published by the Institute of Hydrology (7). Taking national averages obscures local extremes, which are not necessarily well predicted in the SW region: for instance, the 1976 drought was widespread across the country but was most intense in southern England and South Wales (< 50% of January-August mean): the 1984 drought was more severe in northern and western districts but the counter balancing of near average rainfalls in southern and eastern districts, together with the higher autumnal rainfalls that year, moderates its intensity when considered countrywide.

This phenomenon makes it difficult to compare interannual differences of intensity between drought years but their frequency is hardly affected. Inspection of Fig. 6 reveals evident clustering of drought years, especially between 1800-1810, 1850-1870, 1890-1911 and 1940-1964, conforming to a cycle of about every 40-50 years durations. The drought of 1976 is still the most prominent in this time series but the years 1785, 1844, 1887 and 1921 rank as among the more severe instances: 1826, 1854, 1864, 1870, 1911, 1929, 1949, 1959 and 1984 are all remarkable for extended drought periods. Subject to the difficulties of making reliable comparisons of drought intensity, Fig. 6 nevertheless suggests a significant trend in intensity fluctuations with a frequency of some 35-60 years.

Whether the intensity and frequency fluctuations are part of the same time-series or whether they are merely coincidentally similar is not clear. On the evidence of the two-hundred year series in Fig. 6 and discounting the extreme droughts, there may be a further trend in the distribution of moderate-intensity droughts which has a periodicity of about 60 years. No explanation is offered but the influence of this trend provides a further clue to cyclical behaviour in rainfall.

To summarise these interacting patterns we can suggest that the discharges to the proposed Cardiff Bay Barrage during the simulation period 1976–1987 have been responding to the following trends:

(i) a near-complete circadecadian cycle in alternations between wetter to drier groups of years

(ii) an underlying trend towards increased frequency of wet springs and dry summers, which must increase the frequency of FD periods through the years.

(iii) an ascendant risk of extreme-intensity drought, perhaps as a result of a major failure in rainfall in one of the statistically wetter seasons.

FORECASTING THE LIKELIHOOD OF BLOOM YEARS IN CARDIFF BAY

The essential problem may be now finally addressed. The previous sections have shown how the likely incidence of cyanobacterial blooms in the proposed lake is controlled by the growth dynamics of the species concerned and by their relatively high sensitivity to hydrological washout; it has been shown that the discharges are in any case strongly seasonal in South Wales and that there are apparently cyclical trends for these seasonal differences to intensify or ease. These patterns are in turn related to trends in both the frequency and intensity of periods of low rainfall run-off, for which there is a long time-series of reasonable data. Each trend has a detectible cycle of variability and which is, therefore, potentially extrapolable. Predictions vary in the confidence margin to which they are subject, according to the level of accuracy required. Statements about the future incidence of weather likely to be conducive to cyanobacteria in a lake yet to be constructed are necessarily very imprecise, verging upon the speculative. More confidence may be attached to general statements of risk based entirely upon the trends of the hindcasts. The following are ventured:

- At the scale of decades, the trend of fluctuation between wetter- and drier-groups of years would suggest an increasingly 'wet' period until the early 1990's, after which there will be a significant phase of drying until the end of the decade.
- At the scale of half-centuries, the supposed present trend towards a greater incidence of FDYs (Fig. 6) may be now approaching a peak and would be expected to decline during the next two-to-three decades. However, the intensity of the droughts seems set to increase slightly between now and the end of the century.

- The above statements are compatible only if the distribution of rainfall remains strongly seasonal. If it is the condition to the increased frequency of drought years, the intensity of which is increased after 'failure' of rainfall in one of the otherwise wetter seasons, we may expect to see this sharpened difference in seasonal extremes to retreat a little in the next decade or so.

Superimposing the predictions, the likely trend then is for relatively wet springs to alternate with relatively dry summers to continue but to weaken towards the year 2000. Mean flows will probably increase for the next 4-5 years (accentuating the risk of summer FD periods) before reducing somewhat with the slightly more equitable rainfall distribution, exemplified by the early 1960s. While a drought as severe as that of 1976 has a statistical return period of some 200-250 years, there is a heightened risk of one or more exceptionally dry seasons.

Over the next 10-12 years, we may therefore expect mean annual discharge into Cardiff Bay Barrage to be exceeded in 2 out of 3 years in the first half of the period, but towards its end, only in 1 out of 5 years. We may also expect this trend to be accompanied first by a rising incidence of long spells of either dry or wet weather and then by one towards more even seasonal distribution of the rain. 5-percentile flow days might move from an average of 12-15 days per year to less than 7 per year after 1992. However three or four years in the next twelve are likely to include rather longer low-flow periods in the order of 20-40 days.

By summation, 5 years should be above average in wetness and should not experience periods of consecutive $<$ 5 percentile flows for more than a few days at a time; 'Bloom risk' : very low.

3 or 4 years will experience below-average flows due to below average mean rainfall: 'Bloom risk' : moderate

3 or 4 years will experience appreciable summer droughts, with consecutive 5-percentile flow periods of > 20 days. 'Bloom risk' : proportionately high.

One caveat must be added to these tentative predictions. It is that anthropogenic changes to the atmosphere are known to be taking place, the effects of which are exercising the minds of expert climatologists. Their impact upon daily weather patterns and upon longer term trends in rainfall and its distribution are also a subject of research. It is not possible to say how the above 'predictions' would be modified since there is, as yet, no clear evidence of a newly emerging pattern. We consulted three authorities for an opinion about how they expected our climate to react - all gave very guarded responses and even these did not coincide exactly. They were all adamant that any changing pattern would have to be measured against the forward extrapolations of the hindcast-data. So far as the present exercise is concerned, the changes such as they might be will be superimposed upon an analysis which suggests that the next decade already offers significant opportunities (5 to 8 years in 12) of bloom-forming populations of cyanobacteria developing in the proposed Cardiff Bay Barrage, at least to the threshold levels proposed by Welsh Water.

SUMMARY

The report assesses the dynamic performance of planktonic cyanobacteria and algae in relation to the hydrology of a lake flushed rapidly by fluvial flow and, in turn, to inter-annual variability in the catchment run-off that generates the flow. Weather conditions conducive to the development of Cyanobacteria population, to the threshold levels proposed by Welsh Water are predicted to obtain in perhaps 5 to 8 of the next 12 calender years.

ACKNOWLEDGEMENTS

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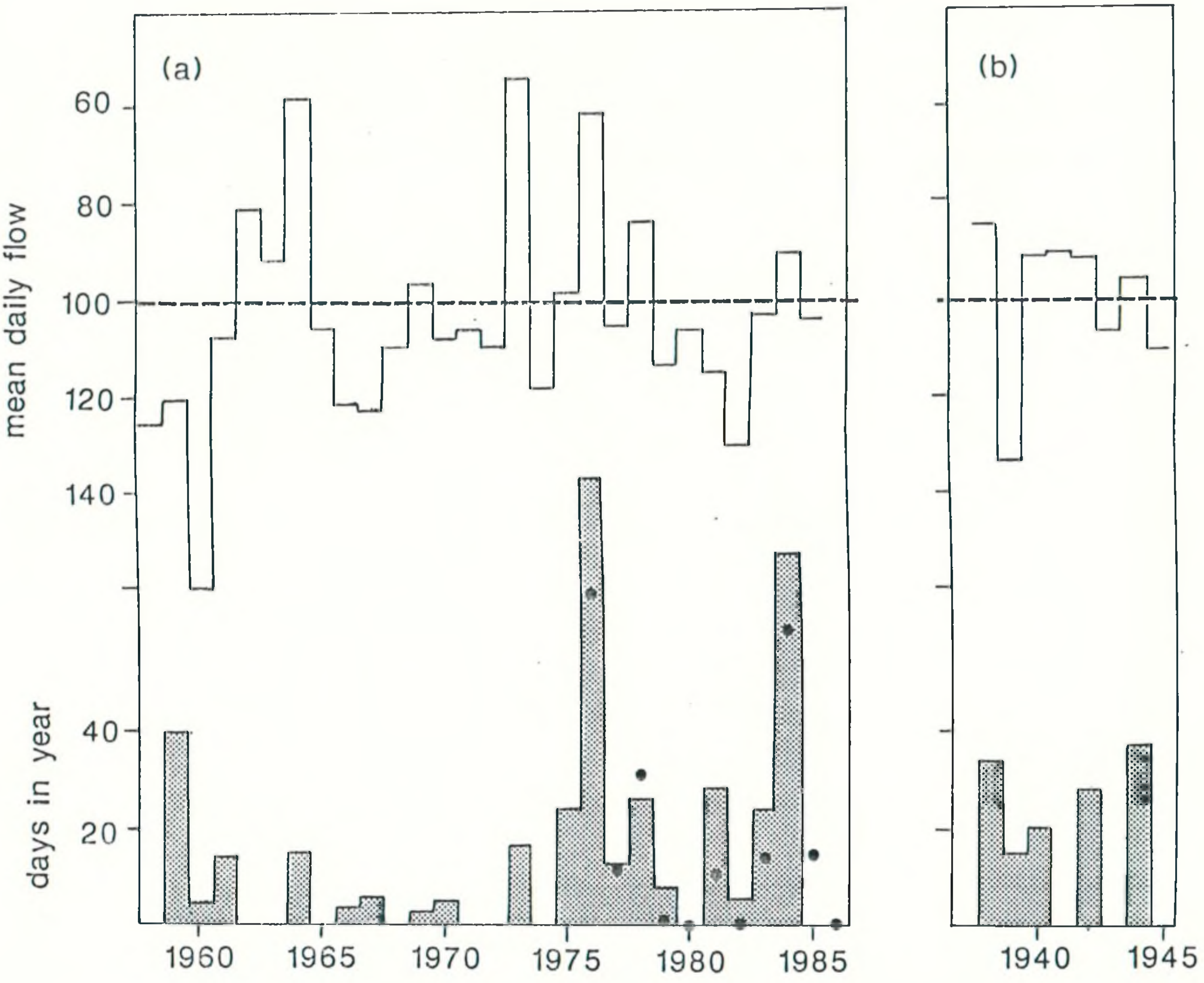

Fig. 1(a) The annual mean daily flow in the River Usk at Chain Bridge for each of the years 1958-1985, expressed as a percentage of the mean for the entire period (100%), and the number of days in each year that the flow fell below the 5-percentile level for the entire period (shaded histograms). (b) ditto for the Taf Fawr, 1938-1945. The closed circles inserted in 1(a) are the days of sub-5 percentile flow in the Taff, 1976-1984.

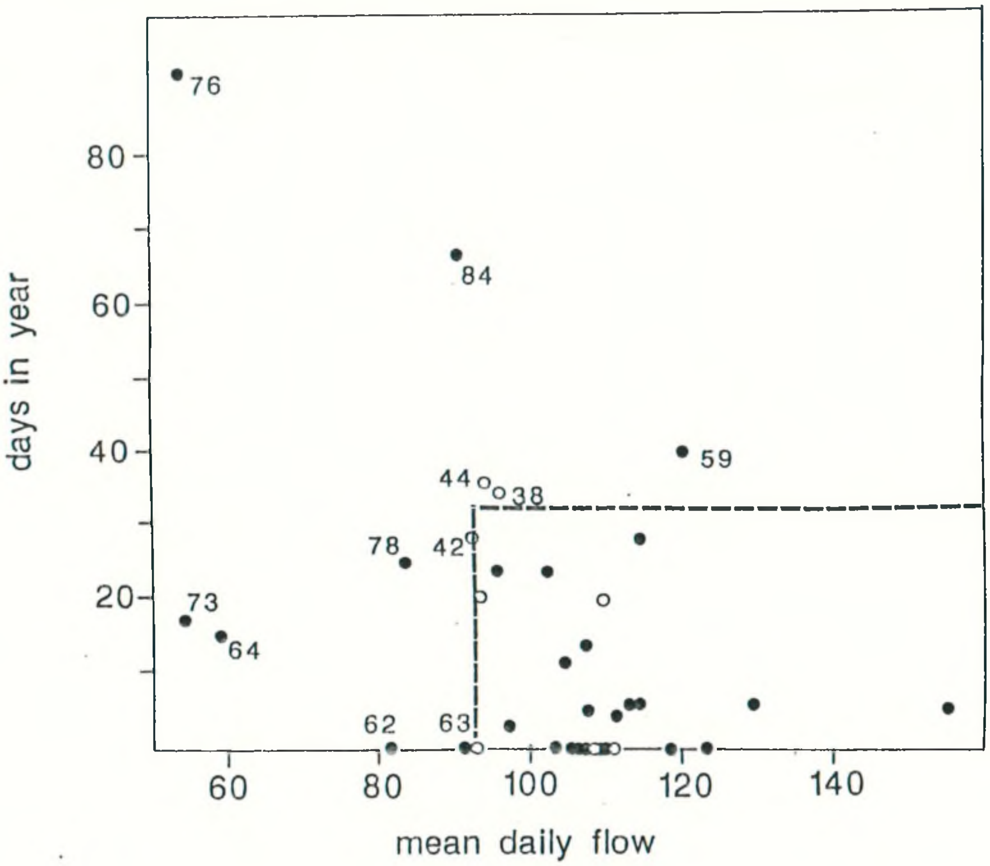

Fig. 2 Plot of the number of days of sub 5-percentile flow in South Wales rivers against the annual mean discharge expressed as a percentage of the overall mean; ● R. Usk 1958-1985 incl.; o Taf Fawr 1938-1945. The points above and to the left of the broken line represent years with a potential flow-deficiency.

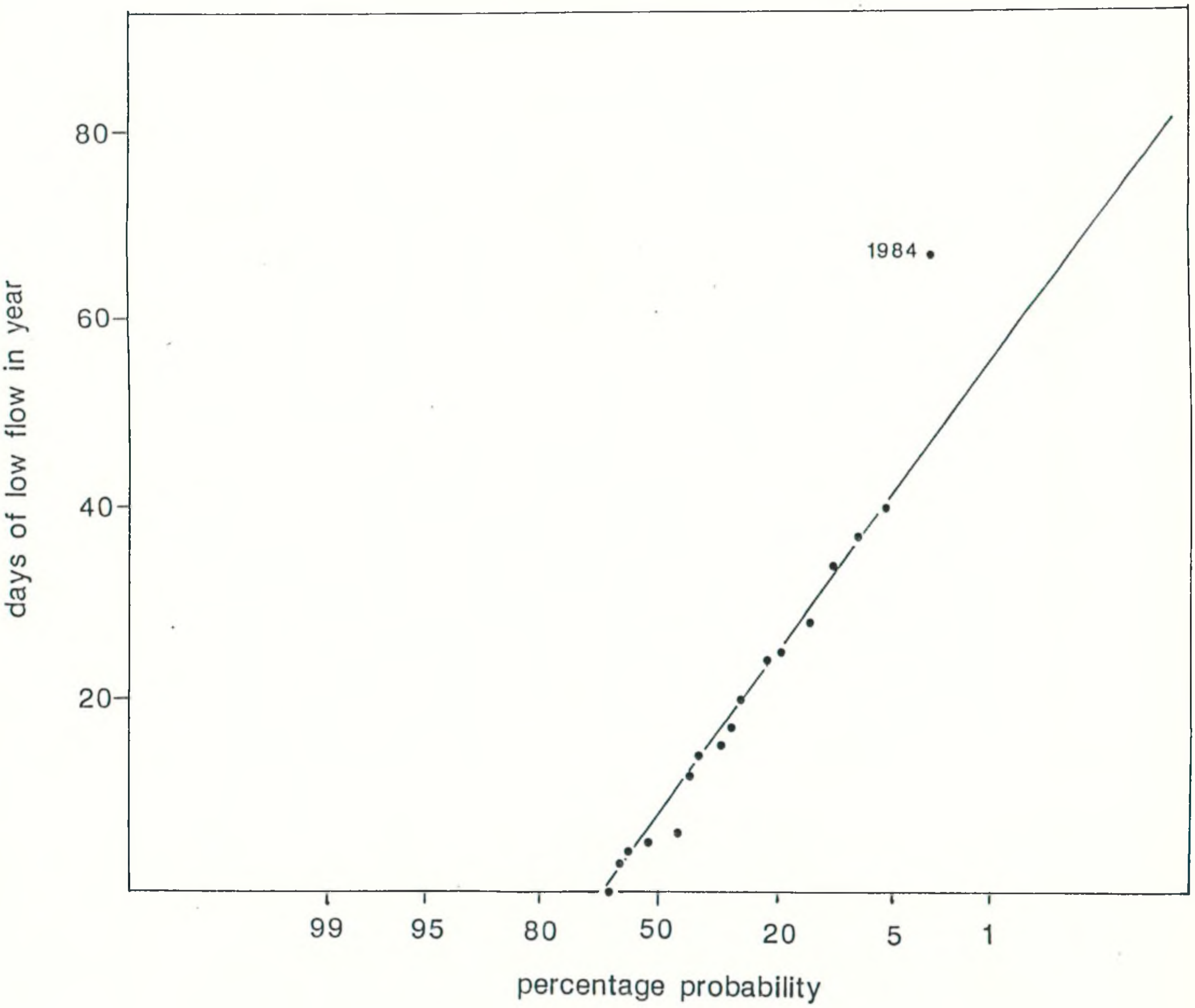

Fig. 3 Probability distribution of the annual number of days of flow below the 5 percentile level. The graph should be read as the percentage probability (x axis) that the number of low flow days in any one year will be greater than the corresponding value of the y axis.

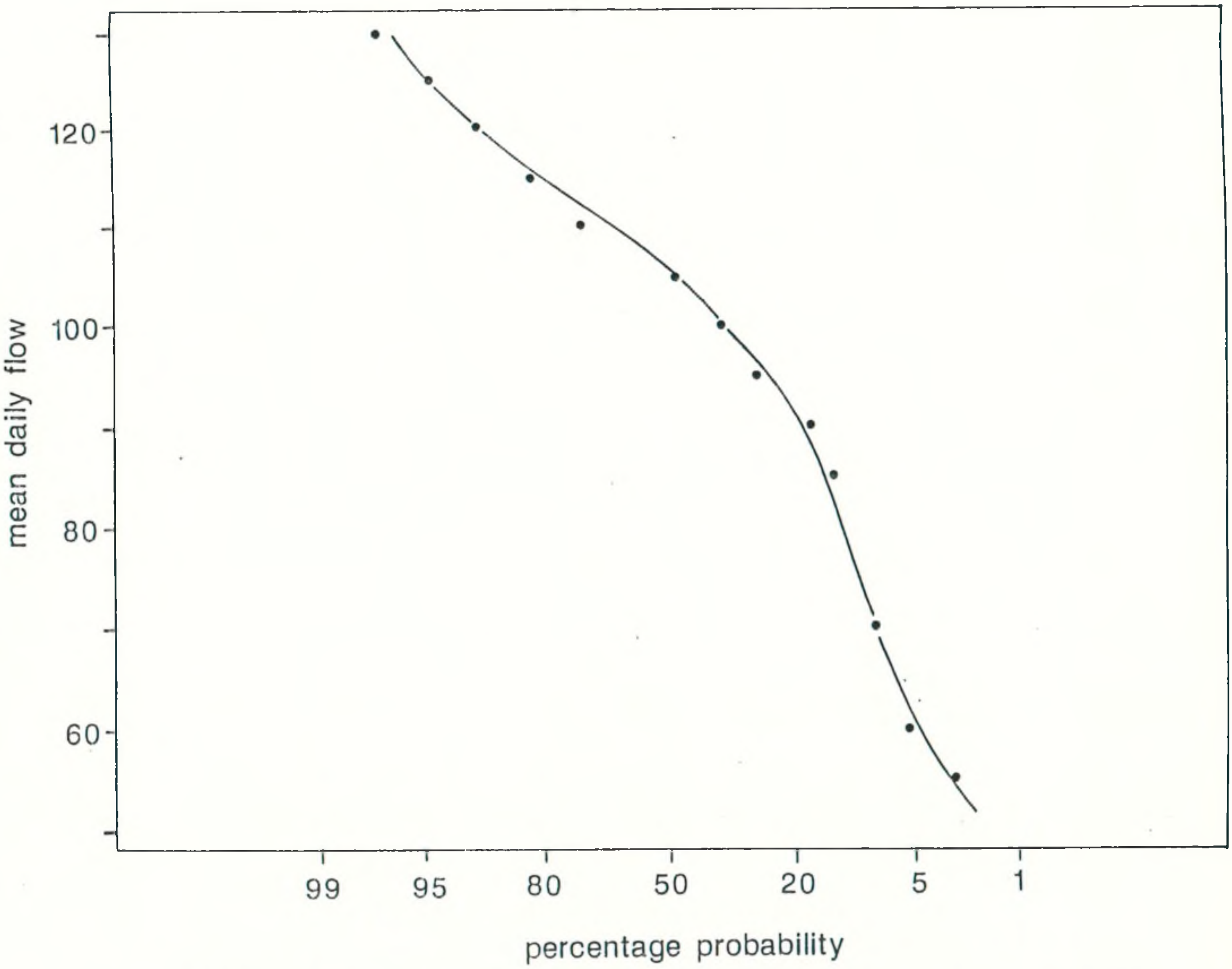

Fig. 4 Probability distribution of mean annual daily flow as a percentage of the mean over several decades. The graph should be read as the percentage probability (x axis) that the mean annual discharge in any one year will be less than the corresponding value on the y axis. The shape of the line shows that the distribution is not normal, but 'skewed' and 'tailed' at its extremes.

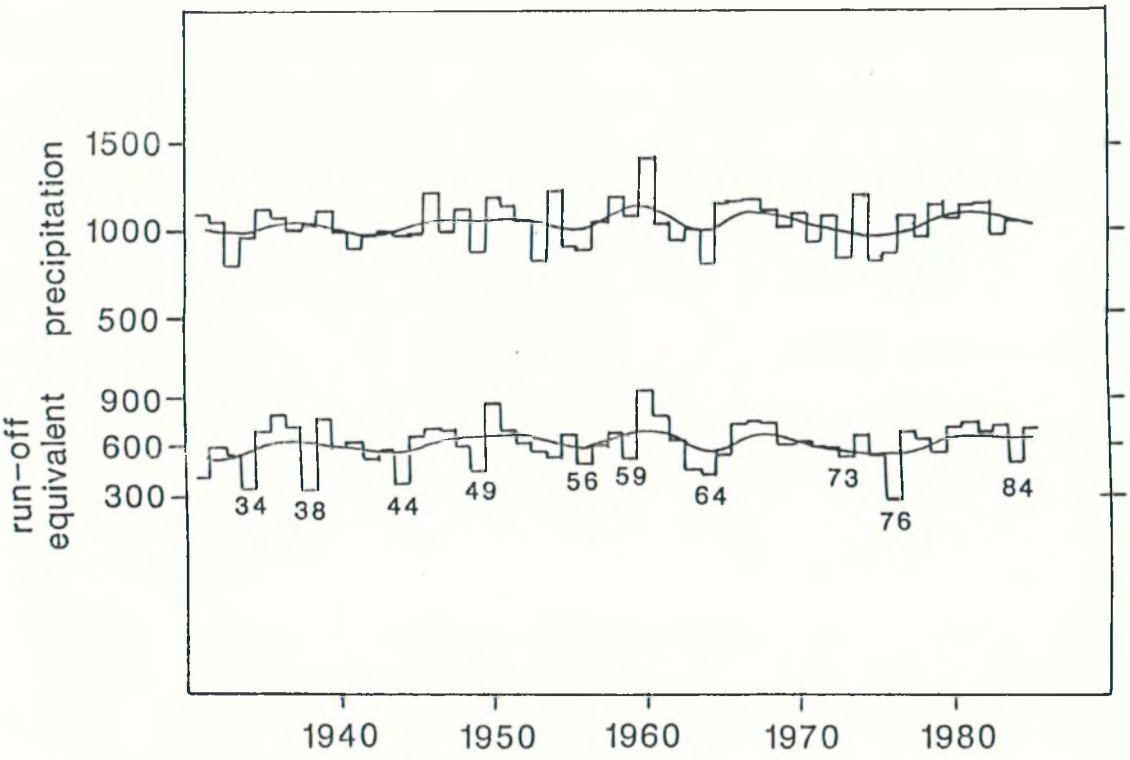

Fig. 5 55-year trends in variability in (above) annual precipitation (in mm year^{-1}) over the south-western region of England and Wales and in (below) the equivalent run-off (in mm year^{-1}) after correcting for evapotranspirational losses in the years concerned. FDYs are identified. Compounded and redrawn from several figures in (6).