THE IMPORTANCE OF PERIODIC DROUGHTS FOR MAINTAINING DIVERSITY IN THE FRESHWATER ENVIRONMENT

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Disclaimer

This article represents the author's personal opinion and does not necessarily accord with the views of the Environment Agency. It briefly reviews the influences of drought upon freshwater ecosystems in the UK, and is not intended as a justification for irresponsible management of the freshwater environment.

Introduction

It is common knowledge that all living things rely upon water. It is also widely accepted that much of the biota native to Britain is adapted to aquatic or wetland conditions, including about one-third of our flora (Palmer & Newbold 1983), many groups of invertebrates, all native and introduced species of amphibians (Oldham 1996) and many birds and mammals (RSPB/NRA/RSNC 1994). Aquatic and wetland habitats may also play an important part in the life cycles or behaviour of other species generally considered as terrestrial (RSPB/NRA/RSNC 1994). Waterbodies and wetlands are therefore vital for the maintenance of biological and genetic diversity (Denny 1994). Mankind too is dependent upon water, and places growing demands upon aquatic environments as sources for potable supply and for waste disposal (Environment Agency 1996a), as well as recreation (Ferguson et al. 1996). Chronic environmental stresses, such as climate change, produce less obvious, though perhaps no less problematic, effects upon the aquatic environment.

Climatic conditions are inherently variable. At one extreme, the aquatic environment may be subject to severe flooding and elevated river discharge during years of above-average effective rainfall (the balance between rainfall and evapotranspiration). At the other extreme, lower than average rainfall can expose the water environment to periodic drought conditions. Drought has been variously defined as the lowest average effective rainfall in a 50-year return period (Environment Agency 1996a), by numbers of successive days none of which has recorded in excess of a minimum rainfall level (Shaw 1983), by more sophisticated statistical methods based on cumulative departures from the average rainfall (e.g. Herbst et al. 1966), and so forth. For the present purpose, drought is perhaps best defined qualitatively as *"a period in which the rainfall consistently falls short of the climatically expected amount, such that natural vegetation does not flourish and agricultural crops fair* (Shaw 1983).

Whilst the impacts of drought upon human uses of the water environment are widely publicised, the response of the aquatic ecosystem itself to drought conditions has received considerably less attention. At the time of writing, parts of England and Wales are in the midst of an extended period of drought, the socio-economic effects of which are generating considerable public and political interest. It is therefore opportune to briefly review the impacts of droughts upon aquatic ecosystems in the UK, and to draw attention to some beneficial aspects of droughts which are generally ignored.

The drought of 1995 and 1996

1995 and 1996 are perceived as years of drought in many parts of the UK (although not in Scotland). Falling reserves in reservoirs, rivers and groundwater, in addition to the formation of blooms of potentially toxic blue-green algae (cyanobacteria), have threatened the security of public drinking-water supplies throughout the summer months (Ferguson et al. 1996). Aside from threats to drinking-water supplies, the drought has also threatened fisheries - the National Rivers Authority (NRA) was active throughout the summer of 1995 in managing a large number of fish rescues in England and Wales - and reduced amenity access to water due to the formation of toxic blue-green algal blooms. During 1995 and 1996, Government has requested advice from the NRA, and subsequently from the Environment Agency (the "Agency"), on the overall state of water resources in England and Wales. The primary conclusions of this advice are that:

- despite a wet 1994/5 winter, dry weather throughout the summer of 1995 had made the April to August period drier in most parts of the country than the same period in the severe drought year of 1976 and, by the end of August 1995, over 50% of rivers were flowing at half their normal flow for the time of year (NRA 1995a);
- the onset of groundwater and surfacewater recharge during the 1995/6 winter was late (NRA 1995b) and the continued sluggish recharge during

the winter posed further threats of serious water shortage during 1996 (NRA 1995c);
- between April 1995 and 1996, accumulated rainfall deficiencies in the worst-affected areas of England and Wales were equivalent to 5-months average rainfall (Environment Agency 1996b);
- below-average flows in some groundwater rivers and aquifers continues in 1996 (Environment Agency 1996b); and
- drought conditions place the environment at risk (Environment Agency; 1996b).

In addition to these adverse impacts, the first toxic blooms of algae recorded in British rivers occurred in the Warwickshire Avon in 1995 and in the Thames and the Great Ouse in 1996, and the prevalent drought conditions were believed to be a major contributory factor (Ferguson, personal communication)

The drought of 1995 and 1996 is therefore undoubtedly problematic from a socio-economic point of view, and the press have given substantial coverage to its more alarmist implications. However, little coverage or consideration has been devoted to the natural variability in climate that contributes to drought conditions, and therefore an understanding of the role of drought within the context of ecological cycles is lacking. In the fervour of media interest and public concern, it is all too easy to make moral judgements about the impacts of drought without considering its role in the maintenance of aquatic and other ecosystems. This article seeks to redress this imbalance by exploring the major impacts, including some potential benefits, of drought conditions upon freshwater ecosystems in the UK. I shall deal first with the physicochemical environment and then with the biota

Physicochemical conditions

Reductions in river flows during low-flow conditions result in a smaller concentration of oxygen entering the watercourse through diffusion processes (Gordon et al. 1992) which, in conjunction with elevated temperatures during drought years, tend to give rise to an increased biochemical oxygen demand (BOD), resulting largely from increased algal growth but also from reduced dilution of effluent (NRA 1991). Microbial oxidation of the organic substances creating BOD tends to deplete the water of oxygen, and respiration by both macrophytes and planktonic algae also tends to suppress oxygen levels during periods of darkness. Both elevated water temperatures and decreased wind-generated turbulence, commonly associated with the prolonged periods of settled weather that occur during drought conditions, also result in lower concentrations of oxygen being present in waterbodies. Cumulatively, these conditions threaten wildlife including fish stocks and invertebrates with high oxygen demands.

In many of the rivers of England and Wales, nutrient concentrations are frequently higher in the summer than in the winter. Although one might expect diffuse inputs of nutrients to diminish during dry weather, much of the nutrient load of heavily populated river catchments derives from point sources and so increasing summer concentrations are generally attributed to reduced dilution during periods of low flow. During drought conditions, when river flow and hence dilution is unusually low, this effect will be magnified. It is probable that changes in redox potential at the sediment surface, brought about by fluctuating water levels during drought conditions, may play an important role in nutrient flux. Soluble phosphorus is immobilised by passive physicochemical processes at the sediment surface, although these reactions are considerably affected by the fluctuations in redox potential that accompany the drying and waterlogging of wetland sediments (Casey & Clarke 1986). The biological processes governing nitrogen metabolism, including nitrification in aerobic conditions and denitrification in anaerobic conditions, are also potentially modified by changes in water level. Salinity also tends to rise during drought conditions due to decreasing dilution (Gordon et al. 1992), and saline intrusion into coastal groundwaters and into the lower reaches of rivers also tends to occur during extended dry periods. During 1995, saline intrusion permitted marine invertebrates and fish to invade the lower reaches of many of the rivers of East Anglia, disrupting existing ecosystems (Ferguson, personal communication).

During drought conditions, various substances tend to be immobilised in soils and on the land surface, resulting in lower diffuse loads entering rivers and still waters. The first pulse of stormwater entering watercourses during the initial period of heavy rain at the end of a drought period tends to introduce a high load of suspended solids and associated pollutants into waterbodies. Interim conclusions from an ongoing study (Centre for Ecology and Hydrology 1996) suggest that a large peak in the concentration of suspended solids, heavy metals and nutrients occurred at selected sites in England and Wales following the first heavy rainfall in the autumn of 1995, and that drought therefore served to sequester pollutants during the dryer summer months.

Hydrology

Dwindling reserves of water and increased evapotranspiration during drought conditions lead to a variety of hydrological changes in waterbodies and in wetland habitats. Perhaps the most obvious of these changes are falling levels in both rivers and lakes, exposing a "toiche" zone (that part of the littoral zone which is seasonally or periodically exposed as water levels recede during prolonged dry conditions) at their margins. Groundwater levels also fall, contributing, together with receding surface water levels, to the drying of wetland habitats. The cessation of flow in normally perennial rivers, and the complete desiccation of temporary flowing and standing waters and wetland systems, also impose significant stress upon their ecosystems. Drying of toiche and wetland sediments influences the redox potential, which may switch from reducing to oxidising conditions as waterlogged conditions are replaced by drying.

The reduced flow rates in flowing-water systems are, as noted previously, a significant factor in various physicochemical processes such as the concentration of dissolved oxygen in the water. Declining streamflows may also result in lower loads of sediment being flushed into waterbodies, and a tendency to deposit out suspended fines in flowing waters. The influence of these effects on geomorphological processes is considered in the following section.

Geomorphological processes and habitat diversity

Rivers are unstable systems, subject to constant changes in discharge which in turn affect the formation of substrate-based or dynamic habitats through geomorphological processes (Harper 1996). The flow regime of the river, and particularly minimum acceptable flows, is therefore important to the maintenance of river structure (Harper et al. 1995; Harper 1996). Variations in water velocity result, through action on the substratum, in a diversity of microhabitats to which the benthic fauna is adapted (Armitage 1995; Newall 1995). The geomorphology of flowing waters depends to a large extent on degradation and aggradation processes, which are related to stream power, sediment size and sediment load (Gordon et al. 1992). As stream power declines with lower discharge, lower loads of sediment are flushed into flowing-water systems, and the remaining load of suspended sediment tends to be deposited. If low flows are prolonged, emergent vegetation tends to encroach into the river channel or open water of still waters, and may further encourage siltation by absorbing current-flow energy and stabilising the sediment by root growth (Hemphill & Bramley 1989; RSPB/NRA/RSNC 1994; Wade 1995). Falling flows also reduce the available habitat for key aquatic life forms in rivers (Bullock et al. 1991; Johnson et al. 1993).

Prolonged drying of waterside soils can ultimately enhance the mobility of river channels as, when dried soils wet-up again following rainfall, their physical cohesion can be substantially reduced leaving them increasingly vulnerable to erosion (NRA 1995d). Soil erosion from surrounding land is also elevated during storm events when the drought is broken. These processes are not only important in the sediment budget of the river system, but also play a key role in the formation of transitional habitats such as eroding cliffs and midchannel gravel bars, which are widely acknowledged in their importance to various aquatic species (RSPB/NRA/RSNC 1994; Harper 1996).

Not all waterbodies or watercourses are permanent. Temporary pools, which were once perhaps one of the commonest of waterbodies found in the British Isles (Biggs, personal communication), are now a relatively uncommon habitat but are nevertheless ones in which rare or notable species are more likely to be found (Collinson et al. 1995). Likewise, winterbournes dry periodically and contain characteristic biota adapted to their particular flow regimes. The hydrological regimes of both of these types of temporary waters are influenced substantially by climatic variations, which are therefore essential in the maintenance of their characteristic ecosystems.

Impacts of drought upon the biota

The biota present in fresh waters and wetland habitats reflects the environmental conditions to which they are adapted. Changing environmental conditions inevitably influence the ecosystem. We understand some of the environmental dependencies of aquatic organisms, and can speculate upon others. The likely impacts of drought-induced environmental changes on the biota are considered below.

Algae

The development of nuisance blooms of blue-green algae (cyanobacteria) during prolonged warm and stable conditions is well documented (NRA 1990). However, other types of algae - both planktonic and benthic - can also proliferate in the bright, warm conditions associated with droughts. In particular, the formation of potamoplankton in many of our river systems can only occur when flow rates fall below critical levels, beneath which algal reproduction can outpace the tendency for algal cells to be flushed out of the system. Algal blooms in rivers are believed to have contributed to EC Freshwater Fish Directive (CEC 1978) compliance failures in a number of rivers in England and Wales during 1995. Benthic algae, and other components of biofilms, can also build up in rivers during low-flow conditions when current shear is reduced (Gordon et al. 1992). During 1995, many rivers developed exceptional growths of "blanket weed" (predominantly *Vaucheria* and *Cladophora)* which smothered macrophyte growth and interfered with surveys of rooted plants (Nigel Holmes, personal communication). Where dense planktonic algal growths occur, they inevitably compete for light and dissolved nutrients with submerged macrophytes. Dominance of the phytoplankton, shading out submerged vegetation, is one of the adverse effects associated with eutrophication (Phillips et al. 1996); however, the role of environmental conditions in drought years, in "flipping" lake ecosystems from macrophyte-dominated to a plankton-dominated condition, is unknown.

Macrophytes

Wetland vegetation is highly dependent upon soil hydrology. Gowing & Spoor (1996) have recently summarised the responses of different lowland wet grassland species to water stress, and conclude that changing water levels may be highly significant in maintaining competitive effects. They found that the grass *Dactylis glomerata* tends to out-compete other lowland wet grassland species when subject to drought stress, and the sedge *Carex nigra* is rare where drought stress does not occur for at least part of the year. Conversely, *Eleocharis palustris* tends to dominate in grassland areas that are not subject to drying. The sedge *Carex hirta* has intermediate needs, competing most successfully where there is a balance between aeration and waterlogging. It is therefore clear that in lowland wet grasslands, and potentially also in other wetland habitats, the changing goalpost of varying hydrology plays a key role in preventing the formation of monocultures of single dominant species, thereby maintaining the biological diversity of the ecosystem.

The toiche zone, normally inundated but exposed during low-water conditions, is subject to waves of colonisation and subsequent extinction variously by terrestrial and aquatic macrophyte species (Palmer & Newbold 1983). Owing to the extreme variability of this zone, plants with opportunist dispersal strategies (for example, annual species of the Cruciferae) are favoured, but it also provides habitat for some specialised and tolerant plants. Muds and soils exposed at the margins of British waters are commonly exploited by plants such as *Rorippa palustris, Veronica* spp., *Bidens* spp., *Polygonum hydropiper, Nymphaea* spp. and *Potamogeton polygonifolius* (local conditions will determine the most successful species), whereas draining river-gravels are colonised by plants such as *Rorippa sylvestris, Sagina* spp., *Equisetum arvense* and *Mimulus* spp. (Newbold 1996; Nigel Holmes, personal communication). Drying of the toiche zone may also have positive competitive benefits for some species of predominantly aquatic plants, including for example the shoreweed *Littorella uniflora* which is not only tolerant of a limited amount of drying but is also stimulated into flowering when drying occurs (Nigel Holmes and Peter Hiley, personal communications). The bare mud of the toiche zone, formed by drying or geomorphology, provides the perfect habitat for plants to seed themselves. There is also evidence that the development of plants which are at the northerly extent of their range in the UK, and which are therefore generally adapted to climates more continental than ours, is favoured by hotter and dryer summers (Toogood 1995).

Holmes (1996) has demonstrated that a characteristic winterbourne flora develops according to the pattern and duration of inundation, particularly during the summer months (April to August), and this flora can be used as diagnostic for the pattern of inundation. Interruption of this pattern through drought results in non-aquatic species becoming dominant, but the winterbourne communities are resilient to such periodic environmental changes, as the characteristic flora is soon reinstated after inundation. A characteristic flora, with a significant representation of rare species, also tends to develop in temporary pools (Pond Action 1994; Collinson et al. 1995). It is however likely that total desiccation of a seasonal waterbody, as opposed to periodic drying of surface waters, will have adverse effects on the survival of primarily aquatic organisms.

Invertebrates

Owing to their rapid response to changing environmental conditions, invertebrate communities are excellent indicators of the health or characteristics of the freshwater environment (Wright et al. 1988). The differing tolerances of invertebrate groups to organic pollution and declining oxygen levels is well established (Wright et al. 1988). Daily and annual temperature rhythms also influence the development of animals (Edwards 1995), affecting both interspecific competitive success and the success of key life stages in a variety of invertebrate species (e.g. Brittain 1983; Elliott 1991, 1992; Wagner 1990). Nutrient-driven changes in aquatic ecosystems will also have knock-on effects on the invertebrate community, and the enhanced growth of encroaching emergent vegetation that occurs in low-flow rivers can enable the development of rich invertebrate communities, through the provision of habitat and by improving evasion from predators (Mills 1991). Changes in the invertebrate community are also likely to reflect other changes in food sources and habitats as they too adapt to changing environmental conditions.

In common with macrophytes, characteristic invertebrate communities develop in waterbodies or watercourses that are subject to periodic drying. Winterbournes are characterised by the presence of certain indicator species which, owing to their specialised colonisation or survival strategies, show a particular affinity with these habitats. From studies on brief cessations in discharge, Furse et al. (1977) concluded that the invertebrate population was resilient to short-term drought but that, after prolonged environmental change, stream fauna tends to change to reflect the next environmental conditions. Temporary and seasonal standing waters also develop a characteristic invertebrate fauna (Biggs et al. 1994), and drying out does not diminish their conservation value, species richness or the likely occurrence of rare species (Pond Action 1994; Collinson et al. 1995). Survival of the characteristic fauna of both types of temporary waters is brought about by their ability to retreat into moist areas of substrata (Larimore et al. 1959; Bevercombe et al. 1973), to persist in dry conditions or to disperse efficiently. However, in both cases it is clear that the characteristic fauna is rapidly displaced by more aggressive competitors or by predators if inundation persists.

The toiche zone of more permanent waterbodies also represents a temporarily exposed environment, and may provide important habitat for opportunist invertebrates (Newbold 1996). Many species of invertebrates utilise the toiche zone to bask, hunt, burrow or nest (Hawkins 1995), whereas transitional habitats, formed in active rivers by geomorphological processes, also provide essential habitat for invertebrates, many of which are of high conservation importance (Harper et al. 1992; Harper 1996). The geomorphology of rivers, and the plant growth that follows, give rise to a range of other "functional habitats" within rivers which provide essential habitat and therefore act as the building blocks of river invertebrate biodiversity (Harper et al. 1992, 1995; Harper 1996).

Fish

The water quality requirements of fish have been thoroughly studied and provide the basis for water quality standards used in England and Wales (NRA 1994). As noted previously, drought conditions frequently result in increased BOD and potentially suppressed oxygen levels, as well as elevated nutrient concentrations which may stimulate dense algal growth and an increased salinity due both to lack of dilution and to saline intrusion. It is therefore not uncommon for fish populations to become distressed in drought conditions, due to the drying up of waterbodies, loss of habitat and poor water quality.

Temperature also exerts a significant influence over the development and growth of younger life stages, including the eggs and juveniles of salmonids (Weatherley & Ormerod 1990; Crisp 1993) and coarse fish (Diamond 1985; Mann 1991). Temperature is one of the most important "driving forces" determining the competitive strength of fish year-classes (Mills & Mann 1985). Since only low current velocities are required to displace coarse fish larvae (Mills 1991; Mann 1995), lower river flow rates and the reduced turbulence that occurs during settled weather conditions may also contribute to the strength of fish year-classes in drought years. Enhanced growth of encroaching emergent vegetation may also be important in the development of rich invertebrate communities upon which fish growth depends and also in evasion from predators (Mills 1991). Conversely, habitat loss due to falling water levels may have an adverse impact on fry survival as the elimination of the littoral zone was believed to be a significant factor in the loss of larval and juvenile perch from a lowered reservoir (Prokes 1995), and habitat diversity is known to be important in fulfilling the food requirements of different stages in the life cycles of fish (Pratt 1975). Falling river flow rates may also interfere with migratory behaviour, as passive and active migration activity of the fry of some species of coarse and anadromous fish is triggered by rheotaxis, and swim-up behaviour may be modified by temperature (Pavlov 1994). Low flows may also impede or deter access of migratory salmonids into river systems (Atlantic Salmon Trust and Scottish Office Agriculture and Fisheries Department 1995). Impacts on invertebrate communities, which have been reviewed above, will also contribute to competitive success of fish.

Different species of fish have varying environmental requirements and so fish that can survive at relatively low concentrations of oxygen, e.g. bronze bream *Abramis brama* and carp *Cyprinus carpio,* will have a competitive advantage relative to fish favouring cooler water and higher oxygen levels, e.g. dace *Leuciscus leuciscus* or brown trout *Salmo trutta.* Drought-induced environmental changes such as retreating water levels and falling oxygen concentrations, whilst threatening adult fish, may provide younger life stages with a competitive advantage through influences upon growth rates, habitat, food availability, elimination of predators, flow regime and turbulence. It is apparent from the above considerations that drought exerts not only an inter-specific impact, but may also influence year-class structure within the population of any one fish species.

Other aquatic fauna

The influence of temperature on fish and other components of the aquatic ecosystem has already been considered, and it is highly likely that it will influence other aspects of the aquatic ecosystem directly through impacts on the food chain, and by affecting competition. Amphibians are a group of animals that benefit particularly from drought years, which reduce their predators and make the following year safer for their tadpoles (Hawkins 1995). The larvae of all native and introduced amphibian species are most successful where fish and other predators have been eliminated (Oldham 1996). It is however likely that waterfowl will be less able to forage in wetland soils hardened due to desiccation.

Ecosystem balance

Whereas some species may rely on periodic drought conditions for part of their life histories, or have life strategies suited to exploiting the habitat or changed environmental conditions that are created by drought, for others organisms it is a time of stress (Gordon et al. 1992). Some organisms - for example amphibians, fairy shrimps and dragonflies - are adapted to prosper in the absence of their predators. Others - like the Cruciferae or some groups of water beetles - can adapt rapidly to new or transitional habitats. As wet conditions return, and with them the aggressive competitors and predator groups, these opportunist or pioneer organisms are once again displaced.

Periodic drought conditions therefore generate a series of waves of colonisation and extinctions. Studies on lowland wet grassland, in winterbournes and in the toiche zone of both ponds and rivers, also demonstrate that different organisms are competitively favoured with changing hydrological conditions, and that this process prevents any one species from overwhelming its competitors. Competitive impacts may be inter- and intraspecific. It is therefore apparent that the death of organisms such as adult fish during severe drought conditions, though traumatic for human onlookers and commercial interests, may be merely a regular occurrence to which the ecosystem is adapted. The variability of climatic conditions thereby provides a direct influence on the maintenance of biological diversity, and it is this very biodiversity that provides the ecosystem with the resilience to respond to environmental changes in both the short and the longer term (so-called "white noise" and "red noise" trends).

The message is then clear. It is not only the environmental averages that are important to ecosystem protection. The natural variability of the environment also plays a crucial role in the protection of habitat and biological diversity.

Implications for the management of water resources

It is clear that aquatic ecosystems adapt to changing environmental conditions, and equally evident that a diverse biological community is essential to allow this adaptation to occur. Biological diversity is both enhanced by environmental change as well as essential to the adaptation of the ecosystem to change.

Regulatory practices generally aim to manage the environment to a norm. Water quality determinands are managed to comply with target concentrations, usually expressed as maxima, percentiles or means, whilst river flows and groundwater reserves are generally managed to exceed critical minima. Since 1989, the NRA has sought to curb or reverse the damage caused by excessive abstraction in high-priority rivers, largely through reducing or relocating abstractions, groundwater compensation, or the recycling of water within river systems (NRA 1993). In recent years, the Agency and its partners have collaborated in the development of Water Level Management Plans, a MAFF-led framework for consensus-building between operating authorities (statutory conservation agencies, the Environment Agency and Internal Drainage Boards) on the maintenance of ecologically beneficial water levels in sites identified for conservation benefit (MAFF et al. 1994). It is, however, clear from prior discussions in this article that alterations to the frequency and duration of inundation in temporary habitats, and changes in permanent water environments during drought conditions, may lead to successional changes in the ecosystem if the drought is prolonged. Equally, the absence of extremes of dryness may deprive aquatic systems of the perturbations that maintain their characteristic ecosystem. Interruptions in patterns of stream energy are also likely to influence geomorphological processes and thereby the diversity of habitats upon which aquatic organisms depend. Disruption of natural variability is therefore likely to lead to ecological change, and compensatory water management activities should therefore take particular account of the natural variability in hydrological regime.

Recognition of the role of drought in maintaining the diversity of aquatic environments therefore in no way makes a case for over-abstraction or irresponsible management of the freshwater environment. Over-abstraction results in loss of functional habitats, and with them the loss of biological quality and diversity (Harper et al. 1992; Harper 1996). In the short-term, aquatic ecosystems are resilient to the adverse effects of over-abstraction but, in the longer-term, will adapt to the changed environmental conditions with a loss of the former characteristic community (Furse et al. 1977). Prolonged perturbation of the water environment ultimately triggers successional changes in the ecosystem.

Traditional flood defence and land drainage practices in the UK over the past centuries have sought to remove water from land and river systems as rapidly as possible, drying out soils and increasing their utility value to man (Purseglove 1989). Changes in land cover and use have stressed our water resources, largely due to their reduced capability to store water and thereby to buffer flows throughout the year (NRA 1995d). Unsympathetic catchment management disrupts smooth patterns of river flow throughout the year, and may also interfere with interactions between the river channel, surrounding wetland and groundwater, thereby introducing an imbalance into the water cycle within the whole catchment (Everard 1996). It is inevitable that any reduction in the buffering capacity of the catchment will exacerbate stress induced by drought, and hence diminish the resilience of aquatic ecosystems to climatic extremes. The relatively recent trend towards the restoration of river channels and other aquatic habitats is therefore welcome for its contribution to restoring the natural hydrological regimes upon which ecosystem health and catchment sustainability may depend.

The maintenance of the environment in as natural a state as possible, in terms both of its norms and its variability, is of central importance in protecting healthy ecosystems, and in particular for the protection of those wetland habitats which, though largely controlled by their hydrology, are frequently omitted from management decisions. It is therefore essential that all aspects of likely ecological impacts, wrought by both changing the norms and the variability of aquatic ecosystems, are balanced in considerations about the allocation of scarce water resources between the needs of people and of aquatic ecosystems. It is recommended that a detailed environmental appraisal should be mandatory in all environmental assessments conducted to support applications for licences to abstract water, or to impound rivers or transfer water resources between river basins and subsequently regulate their flows through controlled releases. Furthermore, it will be important to develop a better understanding of the natural variability in hydrological regimes, thus providing a better basis for predicting likely ecological impacts of management decisions. Where possible, it would be advantageous to develop river flow objectives for all river systems to provide a framework for future management.

Concluding comments

Based purely upon security of potable supply, the drought of 1995 and 1996 has undoubtedly been problematic, and has placed fish populations and other components of aquatic ecosystems under threat. However, when viewed within the context of longer-term trends, periodic droughts contribute to maintaining the diversity of freshwater ecosystems. This phenomenon is paralleled in various other types of ecosystem, including for example the perturbation of periodic fires in maintaining *Calluna* heathland in the UK or gum-tree forests in Australia. The conservation of biological diversity in aquatic ecosystems is therefore crucial to preserving the resilience of the environment to exceptional conditions, such as drought, but may also provide the ecosystem with the resilience to adapt to longer-term trends of climate change. Protection of biological and genetic diversity is best served by protecting the variability, as well as the norms, experienced in environmental variables.

It is also clear that the pressures we place upon our freshwater resources impose substantial stresses upon the aquatic environment; never more so than during drought conditions. In formulating management decisions, it is therefore essential that we acknowledge the natural variability of environmental conditions and the importance of maintaining the extremes, as well as the norms, during management actions. The importance of preserving not only low flows but also the variability of flows has been recognised, although the mechanisms by which they can be protected are not yet developed (NRA 1995e). Although environmental impacts are unavoidable in densely-populated countries, it is strongly recommended that the potential environmental costs of changes to environmental variability, and the biological diversity that depends upon them, are taken into account in management decisions.

Growing evidence of over-exploitation and pollution of our water resources has led the Ramsar Commission recently to recognise that Water Management will be a crucial issue in the 21st century (Ramsar 1996). Perhaps the environmental problems associated with the severe droughts of 1995 and 1996 in the UK will help to reinforce in the public mind that water is indeed a finite and precious resource to be managed sensitively if we are to sustain our ecosystems and the quality of life that depends upon them.

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