# Water and Ethics

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*Mike Acreman*

UNESCO International Hydrological Programme

World Commission on the Ethics of Scientific Knowledge and Technology

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# Preface

This essay is one of a series on Water and Ethics published under the International Hydrological Programme of UNESCO. A Working Group on the Use of Fresh Water Resources was established under that programme in 1998. Preliminary drafts on fourteen aspects of this topic were prepared under the guidance of this Working Group.

An extended executive summary was prepared by J. Delli Priscoli and M. R. Llamas and was presented to the first session of the World Commission on the Ethics of Scientific Knowledge and Technology (COMEST) held in Oslo in April 1999. At the latter meeting, COMEST established a sub-commission on the Ethics of Fresh Water under the Chairmanship of Lord Selborne. The first meeting of this sub-commission was held at Aswan in October 1999. A 50-page survey by Lord Selborne on the Ethics of Fresh Water, based on the above meetings and documents, was published by UNESCO in November 2000.

Since then, the original draft working papers have been revised under the editorship of James Dooge and published on CD ROM as an input to the Third World Water Forum held in Kyoto in March 1993. These are now being published in printed form as the first fourteen titles in a series of Water and Ethics

These essays are written from the point of view of experts on different aspects of the occurrence and use of fresh water who are interested in the ethical aspects of this important subject. They do not purport to be authorative discussions of the basic ethical principles involved. Rather, they aim at providing a context for a wide-ranging dialogue on these issues between experts in diverse disciplines from the natural sciences and the social sciences.

James Dooge
John Selborne

This essay deals with some important linkages between ecology and water. It describes in outline the functioning of freshwater ecosystems and the resulting benefits of combining water management with ecological management.

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# Contents

# 1. Introduction

Water is the lifeblood of our planet. It is fundamental to the biochemistry of all living organisms. The Earth's ecosystems are linked and maintained by water, it drives plant growth and provides a permanent habitat for many species, including some 8,500 species of fish, and a breeding ground or temporary home for others, such as most of the world's 4,200 species of amphibians and reptiles described so far. These ecosystems offer environmental security (McCartney et al., 1999) to humankind by providing goods, such as fish, plants for food and medicines and timber products, services, such as flood protection and water quality improvement, and biodiversity.

Part of the success of the human species has been our ability to control the hydrological cycle, storing water for drinking, growing food and driving industrial processes, harnessing its power for generating energy, and reducing vulnerability to natural hazards, such as floods and droughts. However, this drive to overcome nature is now seen to have disadvantages. It has destroyed much of the Earth's natural beauty and degraded many of the vital ecological support systems that keep the planet fit for life. Degradation of the Aral Sea and destruction of the Amazon rainforest are high profile examples. Whilst no one wants to give up reliable water supplies and flood prevention infrastructure, a balance needs to be struck between allocating water directly for people – for industry, agriculture and public supply – and indirectly for people – through the good, services and attributes provided functioning ecosystems (Acreman, 1998). However, this requires a suitable way to allocate water to various uses in an objective and equitable manner. Economic value of water is often used to support such decisions. A stumbling block is that although environmental economists have developed techniques for valuing some ecosystem functions, there is no satisfactory method to measure the ethical values of, on one hand to conserve biodiversity, and on the other to provide food and water to starving thirsty people.

This paper describes some of the linkages between the ecology and water, expanding on previous publications by Acreman (1999, 2001*a*). It explores the hydrological functions of ecosystems and describes the benefits of combining ecological and water management. It also highlights how an optimum water allocation can be achieved through a trade-off between natural and highly managed systems.

# 2. The water crisis

Whilst water is created and destroyed in biochemical processes such as respiration and photosynthesis, the total amount of water on earth is stable at around 1.4 billion km$^3$. Of this, about 41,000 km$^3$ circulates through the hydrological cycle, the remaining being stored for long periods in the oceans, ice caps and aquifers. It only moves from place to place and changes in quality. Furthermore, the renewal rate provided by rainfall varies around the world. In the Atacama dessert in southern Peru it almost never rains, whilst 6,000 mm of rain per year is not uncommon in parts of New Zealand. In any one place rainfall also varies from year to year. In the early 1980s the world witnessed tragic scenes of drought and starvation in the Sahel, but by August 1988 floods ravaged the same region. Water availability also varies over a longer time scale. Some 10,000–20,000 years ago, during glacial phases in high latitudes, rainfall over the current Sahara desert and Middle East was much higher and percolation of water to underlying rocks led to the build up of substantial groundwater resources (Goudie, 1977). However, the recent drier climate in these regions means that recharge is much reduced and groundwater exploited is not being replaced at the same rate. Superimposed upon natural climate cycles are man-induced global changes. The consensus is that by 2050 global temperatures will rise by about 0.2°C per decade (IPCC, 1996), with some areas exceeding this rate and some areas cooling. The implications for water resources are not clear. However, for the Mediterranean region, Estrela et al. (1998) have estimated that a 1.5–2.0°C rise in temperature could result in 10% reduction in rainfall and a 40 to 70% reduction in renewable water resources.

The twentieth century has witnessed unprecedented rises in human populations, from 2.8 billion in 1955 to 5.3 billion in 1990 and is expected to reach between 7.9 and 9.1 billion by 2025 (Engleman and LeRoy, 1993). Consequently, human demands for water, for domestic, industrial and agricultural purposes, are also increasing rapidly (Gleick, 1993). The amount of water that people use varies, but tends to rise with living standards. In the United States of America, each individual typically uses 700 litres per day for domestic tasks (drinking, cooking and washing), whilst in Senegal, the average use is 29 litres per day. In general, 100 litres per person per day is considered a minimum threshold (Falkenmark and Widstrand, 1992) for personal use. However, when agricultural and industrial uses are included, countries with less than 1,700 m$^3$ per person per year (about 4,600 litres per day) are considered to experience water stress, those with less than 1,000 m$^3$, water scarcity (World Bank, 1992). Because of the spatial mismatch between water resources and people, it is predicted that by 2000, twelve African countries with a total population of approximately 250 million will suffer severe water stress. A further ten countries will be similarly stressed by the year 2025 containing some 1,100 million people, or two-thirds of Africa's population, while four (Kenya, Rwanda, Burundi and Malawi) will be facing an extreme water crisis (Falkenmark, 1989). At the Millennium World Summit in 2000, the states of the United Nations reaffirmed their commitment to eliminating poverty and sustaining development. Specific goals included the commitment to halve by 2015 the number of people unable to reach or to afford safe drinking water (World Bank, 2000).

In addition, the burden of insufficient water for domestic use is increasingly being borne disproportionately by women and children. Because they are the primary water collectors, longer collection times mean that women have less time for agricultural production and less time for child care. Water is vital to women for many small-scale food processing or craft activities, which are important sources of income (Serageldin, 1995). Women are also the main care providers, thus sickness in the family due to contaminated water impacts on women more severely than on men. In some households, children are involved in water collection and have insufficient time for school.

With such a water crisis facing many countries (DFID, 2001), it seems an immense task just to manage water so that there is enough for people to drink let alone for agricultural and industrial uses. Thus, providing water to other users, such as 'the environment' surely ought to be given a low priority. Indeed the situation is often presented as a conflict of competing demand, as though it was a matter of choice between water for people and water for wildlife. This ignores the indirect benefits to mankind of functioning ecosystems. Research by Sullivan et al. (2002) to develop a Water Poverty Index has shown that the link between water and poverty involves five elements: water resource (surface and groundwater availability), water use (demand for domestic use, agriculture or industry), access (distance to source and legal rights), institutional capacity (human and financial capacity to manage the system) and environment (hydrological functions of ecosystems including protection from floods, water quality improvement and provision of water resources). Some of the poorest people in the world are the most dependent on the environment because they rely on natural resources for food and building material and are most vulnerable to natural disasters, such as floods. Conserving the world's ecosystems is an essential component of addressing world poverty and thus an important ethical consideration for those concerned with overcoming the inequalities between rich and poor people.

# 3. Controlling water

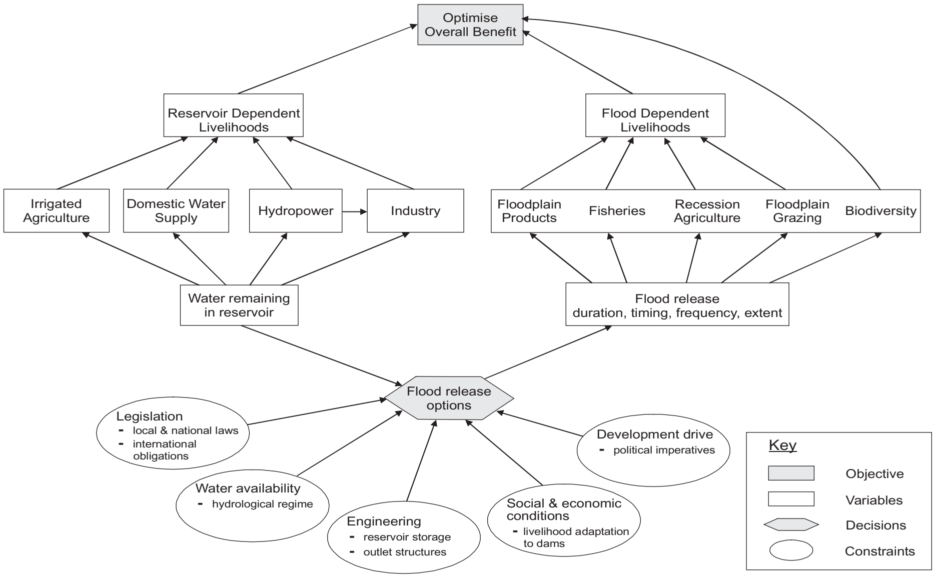
In an attempt to overcome the vagaries of the hydrological cycle, throughout human history water has been increasingly controlled to benefit mankind. As early as 6000 BC, the Egyptians manipulated water to irrigate crops and built the Sadd el-Kafar ('dam of the Pagans') around 2800 BC. Dams can store water during the wet season and release it during the dry season or when needed for irrigation or hydro-power generation. The Romans are noted for the huge aqueducts that they constructed (between 50 BC and 100 AD) to distribute water, such as the Pont du Gard, that supplies Nîmes (in southern France). These projects, including the Alicante dam (41 metres high), built in 1594, were considered as a miracle of modern engineering, reducing floods, improving agriculture and securing water supplies. More recent mega-hydrological projects include the pumping of water from wells 450 metres deep in the remote southern Libyan dessert and piping it 1,000 km to the coast to grow crops. During the eighteenth century, the River Guadalquivir in South-west Spain was straightened, reducing its lengths by 50 km (40%) to reduce flood risk. In the nineteenth century widespread floodplain reclamation began to improve agriculture, involving the construction of embankments along major rivers, such as the Rhone, to prevent flooding of this land. Intensification of agriculture and industrial and urban development continued during the twentieth century as the population increased and engineering techniques improved, culminating in 1950s and 1960s with the construction of major dams, such as the Hoover dam in the United States of America, led to the belief that man could control the environment totally.

During the past few decades, there has been an increasing realisation that the 'hard' engineering approach to water management has had its costs as well as its benefits. For example, installation of powerful pumps, whilst producing short-term economic benefits, has led to over-exploitation of groundwater in may parts of the Mediterranean, such as in the La Mancha region of Spain (Acreman, 2000). In addition, the Aswam dam in Egypt, at the same time as generating power and providing irrigation water, has led to the loss of fisheries, and led to coastal erosion and salt-water intrusion (Acreman, 1996). These problems have led to calls for more environmentally-based water management, which works with nature rather than against it. For this to be widely accepted, the benefits for people of maintaining ecosystem processes must be demonstrated.

In 1997, following many years of increasingly antagonistic debate between pro and anti dam lobbies, the World Bank and IUCN-The World Conservation Union held a meeting in Gland, Switzerland (Dorcey et al., 1997). Participants agreed unanimously that insufficient data were available to conclude unambiguously whether dams were achieving their development objectives. They recommended the establishment of an international independent commission with a clear and achievable mandate. The World Commission on Dams started work in August 1998 to produce a global review if the development effectiveness of dams, a framework for options assessment and decision-making processes and internationally acceptable criteria and guidelines for planning, construction, operation, monitoring and decommissioning of dams. The Commission's report (World Commission on Dams, 2000) concluded that dams have made an important and significant contribution to human development, but the social and environmental costs have, in too many cases, been unacceptable and often unnecessary. A key principle of the Commission was equity, i.e.. that decisions made concerning dams should not be biased towards any particular group, and all key stakeholders should perceive the process and outcomes to be fair and legitimate, which requires transparency in the procedures and decision making criteria. The report makes many recommendations including increased participation from stakeholders and provision of environmental flows downstream of dams. A detailed assessment of dams, ecosystem functions and environmental flow restoration was undertaken for the Commission (Bergkamp et al., 2000).

Whilst it was widely recognised that low flows downstream of dams need to be maintained to support instream ecology, less consideration had been given to the release of high flows for short periods to inundate downstream floodplain and deltaic ecosystems. When flooded periodically, these wetland ecosystems supply important products (e.g. arable land, fisheries, livestock grazing), functions (e.g. groundwater recharge, nutrient cycling) and attributes (e.g. biodiversity), which have contributed to the economic, social and environmental security of rural communities world-wide for many centuries. Floods are also very important for fish migration and sediment transport. Reduction in the frequency and magnitude of flooding by dams, whilst it will be beneficial in many locations to protect vulnerable urban areas, it alters the conditions to which ecosystems have adapted and may degrade the natural services that provide benefits to people. In some cases, the release of managed floods has been proposed, and in a few places implemented, as a mitigation measure to restore and conserve wetland ecosystems in order that traditional livelihood strategies may be maintained. There is clearly a trade-off associated with this action, as less water will remain in the reservoir for it's primary design purposes, such as hydropower, irrigation, domestic or industrial supply (Figure 1). The World Bank has adopted the idea of managed flood releases as best practice for dam operation (Acreman, 2002). Managed floods are not a panacea for downstream environmental problems of dams. Nevertheless, they may be appropriate in many cases where downstream wetland ecosystems support dependent livelihoods (particularly where alternative livelihood strategies are limited) or important biodiversity and bio-productivity.

**Figure 1. The trade-off between using water for managed flood releases and for reservoir based activities**




# 4. Water and the environment

The Bruntland Report, *Our Common Future* (WCED, 1987), *Caring for the Earth* (IUCN/UNEP/WWF, 1991) and *Agenda 21* from the UNCED Conference in Rio in 1992 marked a turning point in our thinking about water and ecosystems. A central principle that emerged was that the lives of people and the environment are profoundly inter-linked and that ecological processes keep the planet fit for life providing our food, air to breathe, medicines and much of what we call 'quality of life'. The immense biological, chemical and physical diversity of the Earth forms the essential building blocks of the ecosystem. The sustainable development of water was the focus of the Dublin Conference in 1991 (a preparatory meeting for UNCED). It concluded that 'since water sustains all life, effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems' (ICWE, 1992, Young et al., 1994). For example, upstream ecosystems need to be conserved if their vital role in regulating the hydrological cycle is to be maintained. Well-managed headwater grasslands and forests reduce runoff during wet periods, increase infiltration to the soil and aquifers and reducing soil erosion. Downstream ecosystems provide valuable resources, such as fish nurseries, floodplain forests or pasture, but these must be provided with freshwater and seen as a legitimate water user. At the UNCED Conference itself, it was agreed that 'in developing and using water resources priority has to be given to the satisfaction of basic needs and the safeguarding of ecosystems' (*Agenda 21*, chapter 18, 18.8). Thus whilst people need access to water directly to drink, irrigate crops or run industrial processes, providing water to the environment means using water indirectly for people. The declaration from the Second World Water Forum in The Hague 2000 highlighted the need to ensure the integrity of ecosystems through sustainable water resources management. The World Summit on Sustainable Development held in August 2002 in Johannesburg, reinforced the role of environmental protection as a key pillar of sustainable development. South Africa has taken a lead in implementing the concept. Principle 9 of the new water law of South Africa states that: 'the quantity, quality and reliability of water required to maintain the ecological functions on which humans depend shall be reserved so that the human use of water does not individually or cumulatively compromise the long term sustainability of aquatic and associated ecosystems'. Likewise, Tanzania is currently developing a new water policy that gives high priority to water allocation for ecosystems.

Many organisations have recognised the importance of understanding the links between water and ecosystems. The 1996–2001 Fifth International Hydrology Programme of UNESCO included an Ecohydrology theme that focused on two projects: (a) interactions between river systems, floodplains and wetlands and (b) a comprehensive assessment of surficial ecohydrological processes (Zalewski et al., 1997). A particular focus was the resilience and resistance of ecosystems and their role in management of water quality, such as the use of buffer strips to ameliorate the impacts of agricultural pollution on river systems. UNESCO has strong links with the Scientific Committee on Water Research (SCOWAR), which is part of the International Council for Scientific Unions (ICSU). SCOWAR has focused on hydrological impacts on ecological systems from different regions around the world (Naiman, 2000) and on forecasting the ecological consequences of changing water regimes. Similarly, the International Association of Hydrological Sciences has supported research on the links between hydrology and aquatic ecology (Acreman, 2001*b*).

# 5. Hydrological functions of natural ecosystems

Natural ecosystems, such as forests and wetlands can play a valuable role in managing the hydrological cycle. Vegetation encourages infiltration of water into the soil, aiding the recharge of underground aquifers, lowering flood risk and anchoring the soil, thus reducing erosion. In Honduras the La Tigra National Park, 7,500 hectares of cloud forest, sustains a high quality, well-regulated water flow throughout the year, yielding over 40% of the water supply of Tegucigalpa, the capital city (Acreman and Lahmann, 1995). Because of its value for watershed protection, La Tigra is today the focus of an investment programme involving a series of economic incentives for villagers living in the buffer zones. The value of these services is considerable. Rather than build water treatment facilities at a cost of US$7 billion, the New York City water department has spent a tenth of this sum to ensure the protection of the biological and hydrological processes of the highlands of the catchment (Abramovitz 1997). Evidence for the beneficial role of forests in reducing floods at a local scale has been extrapolated to the regional scale. Various reports (e.g. Agarwal and Chak, 1991) suggest that deforestation of the Himalayas has increased flood risk downstream in India and Bangladesh. However, Kaimowitz (2002) has raised questions concerning the evidence for large-scale impacts and contests that deforestation had limited influence on the impact of floods in central America caused by hurricane Mitch in October 1988.

Forests also take up water and release it into the atmosphere. A rain forest tree can pump 2.5 million gallons of water into the atmosphere during its lifetime (Gash et al., 1996) but much of this is recycled and not lost from the forest. In the Amazon rainforest, 50% of rainfall is derived from local evaporation. After forest cover is removed an area can become hotter and drier because water is no longer cycled between plants and the atmosphere. This can lead to a positive feedback cycle of desertification, with increasing loss of water resources in that area. Results of simulations using a global circulation model, in which the Amazon tropical forest and savannah was replaced by pasture land, predicted a weakened hydrological cycle with less precipitation and evaporation and an increase in surface temperate (Lean and Warrilow, 1989) due to changes in albedo and roughness. Rainfall was reduced by 26% for the year as a whole (Shukla et al., 1990). Similarly, modelling the removal of natural vegetation in the Sahelian region of Africa suggests that rainfall has been reduced by 22% between June and August and the rainy season has been delayed by half a month (Xue and Shukla, 1993). Therefore these ecosystems *function* as water cycling systems between the earth and the atmosphere and in return for the water they use provide *the service* of regulating both global and local climate and maintaining local water resources.

Acreman (1998) advocated ecosystem management as one of the main principles of water management for people and the environment. The ecosystem management approach (Maltby et al., 1999) aims to integrate all the important physical, chemical and biological components and processes which interact with social, economic and institutional factors. This requires integrated management of mountains, drylands, forests, agriculture, housing, industry, transport, waste disposal, aquifers, rivers, lakes, wetlands and anything which has an effect on the environment. The appropriate management scale depends upon the relative importance of the components in the system. The fundamental unit for water issues is normally the drainage basin, as this demarcates a hydrological system, in which components and processes are linked by water movement. Deforestation of headwater catchments can, for example, affect water yield and frequency of flooding downstream (Newson, 1992). Hence the term integrated river basin management has developed as a broad concept which takes a holistic approach. However, frequently the underlying aquifer does not coincide with the surface river basin. Thus, where groundwater plays a significant role, a group of basins overlying the aquifer may constitute the appropriate unit of water resource management. For issues where air quality is influential, such as acid rain, the 'airshed' (as apposed to the watershed) will be more appropriate implying the integrated management of source areas, which may be industries in the UK, with affected areas in Scandinavia.

Ecosystem conservation can be a cost-effective solution to water management. For example, Mackinson (1983) has shown that the cost of establishment of protected areas, reforestation where necessary and other measures to protect the catchments of 11 irrigation projects in Indonesia, ranging from less than 1 to 5% of the development costs of the individual irrigation projects. This compares very favourably with the estimated 30–40% loss in efficiency of the irrigation systems if catchments were not properly safeguarded.

Wetlands, such as floodplains, marshes and reed beds, can also perform important hydrological functions within a catchment including storage of water during floods, nutrient cycling and recharging groundwater. The value of utilising the natural functions of aquatic ecosystems, as an alternative to major engineering investment, was recognised as early as 1972 by the US Corps of Army Engineers (1972). They recommended that the most cost effective approach to flood control in the Charles River of Massachusetts lay in conserving the 3,800 hectares of mainstream wetlands which provide natural valley storage of flood waters. Serious flooding of cities in Germany and the Netherlands along the River Rhine during 1994 was made worse by the presence of embankments upstream. These had separated the river from the floodplain wetland, protecting agricultural land, but preventing access by the river to natural floodwater storage. In 1995 two large flood storage wetlands were created on the German bank of the Rhine as part of a programme to reduce flood damage downstream and restore degraded floodplain ecosystems (Schropp and Jans, 2000).

Hollis et al. (1993) have demonstrated that recharge to the aquifer which supplies well-water to some 100,000 people in the Komodugu-Yobe basin, Nigeria, occurs during flooding of the Hadejia-Nguru wetlands. However, dams constructed upstream, which stored water for intensive irrigation, have degraded the wetlands by starving them of water. Following presentation of research on the natural functions of the wetlands (HNWCP, 1993), the Nigerian authorities realised the benefits of conserving the wetlands and have been exploring the potential for releasing water from the reservoirs to augment flooding of the floodplain. This is consistent with the ideas of Scudder (1980) and Acreman (1994) who have promoted more widely the benefits of making managed flood releases from dams to conserve important ecosystems downstream as a cornerstone of integrated catchment and water resources management.

Wetlands also perform important water quality functions. The Nakivubo papyrus swamp in Uganda receives semi-treated effluent from the Kampala sewage works and highly polluted storm water from the city and its suburbs (Kansiime and Nalubega, 1999). During the passage of the effluent through the wetland, sewage is absorbed and the concentrations of pollutants are considerably reduced. Water flowing out of the wetland enters Murchison Bay about 2 km from the intakes of the two Kampala water supply works. Consequently, the National Sewerage and Water Corporation is supporting conservation of swamps and other wetlands near Kampala because they purify the water, serving as a low cost alternative to industrial sewage treatment. Likewise, Khan (1995) described the important functions of the 75,000 hectare North Selangor Peat Swamp forest, which borders one of the largest rice schemes in Malaysia. These wetlands mitigate floods and maintain high water quality. In recent years the forests have been cleared for agriculture and tin mining, reducing the buffering effect on pollution and releasing sediment. It is forecast that further clearance would result in significant water quality problems in rice scheme. Because of this valuable water purifying function, in many parts of the Europe and North America artificial wetlands have been created to treat polluted water, including sewage effluent and mine waste (Nuttal et al., 1997).

Meynell and Qureshi (1995) reported on the vital functions of the mangrove ecosystem in the delta at the mouth of the River Indus delta in Pakistan. By breaking the force of wind and waves, they protect the coast and Port Qasim from damage. Wave height can reach six metres in the open sea beyond the mangroves, but in the sheltered creeks the maximum recorded has been 0.5 metres. Mangroves also stabilise the creek banks which maintains channel width. This focuses the currents, reducing sedimentation by encouraging scouring of the channels bed. The creeks are thus self-cleaning and able to maintain their geometry naturally. Without mangroves Port Qasim would need expensive engineering works such as sea walls and constant dredging costing around US$ 1 per cubic metre and thus would not be economical.

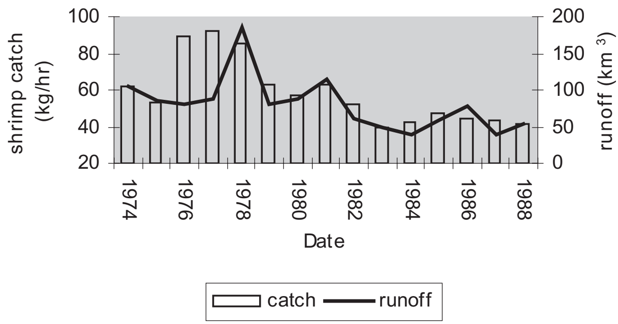
It is clear from the above examples that natural ecosystems can perform valuable hydrological functions. Clearly, not all ecosystems perform all functions, for example, not all wetlands reduce floods, recharge groundwater and improve water quality. Nevertheless, each has its own role to play in the natural processes of the catchment. Thus conservation of ecosystems should be a key element in sustainable water resource management.

## 6. Ecosystems and biodiversity

Many ecosystems support a wide range of species and large numbers of individuals. Water availability is often a key controlling factor in biodiversity. For example, in central Africa, Tchamba, Drijver and Njiforti (1995) describe how flood water from the River Logone inundates annually a large floodplain, originally around 6,000 $km^2$. This wetland has a high biodiversity with large herds of giraffe, elephant, lions and various ungulates (including topi, antelope, reedbuck, gazelle, kob). Part of the floodplain has been designated as the Waza National Park which attracts around 6,000 tourists per year, which bring direct financial benefit to the region. In the flood season, the entire floodplain becomes a vast fish nursery. Up to the 1960s, fishing was the primary economic activity amongst the local Kotoko people who could earn US$ 2,000 in four months. The floodplain is also an important dry season pasture for 300,000 cattle and 10,000 sheep and goats (Schrader, 1986). Since 1979, the area inundated has reduced, partly by climatic factors, but primarily due to construction of embankments and a barrage across the floodplain which created Lake Maga to supply water to an irrigation project. Flooding became insufficient in large areas to grow any floating rice and fish yields fall by 90%. The irrigation schemes which cover around 5,000 hectares were not making full use of water stored in Lake Maga and the potential to release water to rehabilitate the floodplain was identified (Wesseling and Drijver, 1993). To implement this, the embankments along the river were modified in 1994 to allow flood waters to reach the floodplain, which has revitalised the wetland ecosystem and extensive fishing and grazing have been rejuvenated.

Coastal ecosystems in particular have been neglected in water management. For most water engineers, any freshwater that reaches the sea is a waste. This ignores the fact that valuable ecosystems, along the river and in the coastal zone, rely on inputs of freshwater. For instance, freshwater from the Zambezi supports extensive inshore fisheries on the Sofala bank at the mouth of the river. This provides Mozambique with an important source of foreign income worth some US$ 50–60 million per year. Gamelsrød (1992) has shown that shrimp abundance is directly related to wet season freshwater runoff (Figure 2) and earnings could be increased by US$ 10 million per year by correctly releasing flood waters from the Cahora Bassa dam which are not currently utilised. Likewise, a positive relationship between freshwater runoff and

**Figure 2. Relationship between shrimp abundance and wet season freshwater runoff from the Zambezi**




*Source:* Gamelsrød, 1992.

shrimp production was found for the Tortugas grounds off the Florida peninsula of United States of America by Lugo and Snedaker (1973). These estuarine wetlands receive water from the Everglades National Parks and further demonstrate the close link between ecosystems through the hydrological cycle.

A similar situation occurred in the Nile delta following completion of the high dam at Aswam in Egypt in 1968. Nutrients brought to the sea by the river supported a rich sardine fishery, but fish catches declined from 22,618 million tonnes in 1968 to only 13,450 million tonnes in 1980 and rates are still falling. In lower Nile, fish populations have also declined. Of the 47 commercial species present in 1948, only 17 now exist. The reservoir behind Aswam has created new fishing opportunities and produced some 34,000 tonnes in 1987, but much is due to the increased fishing effort and it is unclear if this rate is sustainable.

Water control may not always be environmentally detrimental. Masundire (1995) reported that Lake Kariba, created by the construction of Kariba dam on the Zambezi River, supports an important inland fishery and the whole shoreline has been declared a ‘recreational park’ as the availability of water during the dry season attracts large herds of buffalo, eland and other species, enhancing the eco-tourism value of the area, which brings in foreign currency. However, the dam has had negative effects on the ecology downstream and on the health of local people as disease vectors such as snails have proliferated.

The above examples demonstrate that the products from many ecosystems can have a direct benefit to mankind. To maintain the valuable products and services they provide, they must be treated as legitimate water users and allocated sufficient water to remain healthy.

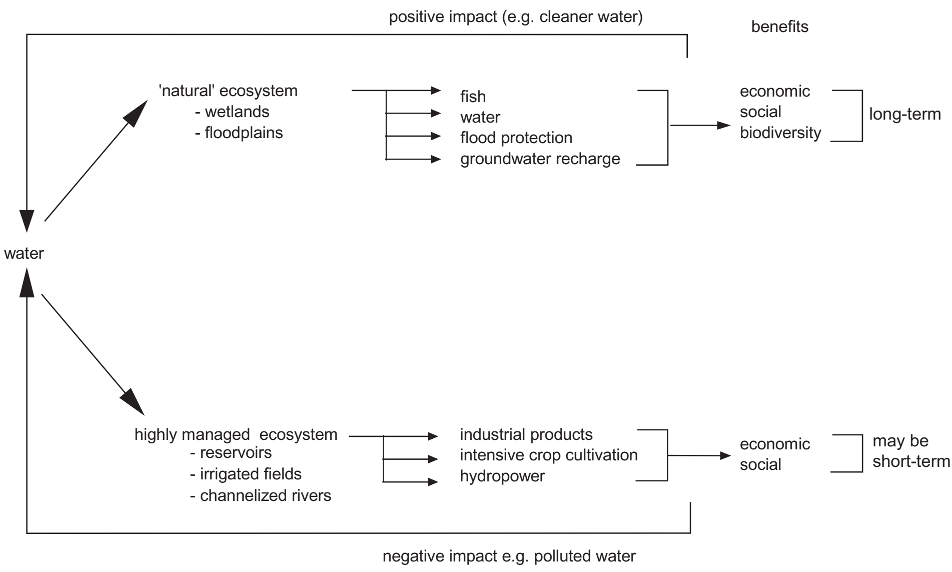
# 7. Water allocation, sustainability and ethics

In the water debate, it is useful to divide human needs into three areas:

- economic security, e.g. drinking water, shelter, food and other consumable goods;
- social security, e.g. protection from natural hazards, such as floods; and
- ethical security, e.g. upholding the rights of people and other species to water.

Figure 3 summarises the implications of allocating water to indirect human use, by supporting ecosystem processes and direct use. The upper part of Figure 3 shows the impact of allocating water to natural ecosystems, which in turn provide valuable goods (e.g. fish), services (e.g. water regulation) and amenity/touristic value (landscape and species). In this case the impact on the hydrological cycle is frequently positive, as, for example, ecosystems improve water quality. Additionally, it satisfies the growing belief amongst many people that humans have a moral duty to protect wildlife, through providing sufficient water to maintain flora and fauna. The idea that the natural environment has a right to water per se was taken up at UNCED in 1982, where the governments of the United Nations made an ethical commitment to the environment in the form of the World Charter for Nature. This expresses absolute support of the governments for the principle of conserving biodiversity. It recognises

**Figure 3. Natural and highly managed ecosystem benefits**

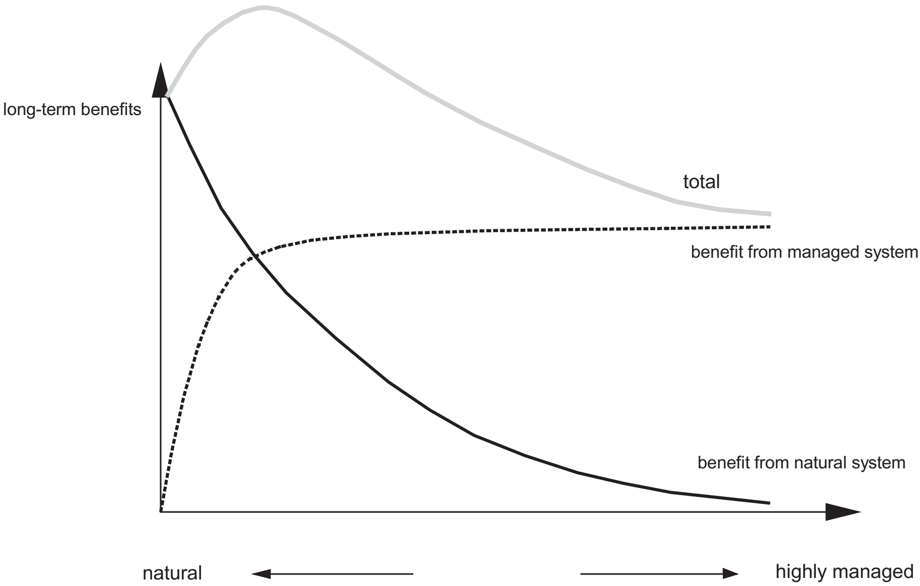


that every form of life is unique and warrants respect, regardless of its direct worth to humankind and that the lasting benefits of nature depend on maintenance of essential ecological processes and life-support systems and upon the diversity of life forms (McNeeley et al., 1990). It promotes conservation of ecosystems as a public good independent of their utility as a resource and hence water rights to species and ecosystems. Whilst we may all support this at a superficial level, especially when thinking of flagship species such the giant panda, few would want to extend this to include the small-pox virus. Indeed, human choice influences our objectives for the environment significantly. Many of the cherished landscapes of the world, from the terraced paddy fields of Bali to the rolling fields and hedgerows of rural England, are highly managed systems. Indeed, very little of the Earth is natural or completely unaffected by human influences; almost all is managed, intentionally or unintentionally, to a greater or lesser extent. It is unrealistic to expect to return much of the Earth to a natural ecosystem, and it is undesirable as many are classified as World Heritage Sites. The status of the ecosystems is as much a result of societal choice (Maltby et al., 1999)

The lower part of the Figure 3 shows the direct use of water through the development of highly managed systems, including reservoirs, intensive irrigation schemes, dams, river embankments and water purification plants. This has led to production of crops, industrial products, electricity, protection from floods and provision of clean water, thus improving economic and social security. However, this has often caused negative impacts in the form of pollution. To some extent economic and social security have been improved. In addition, through the provision of food and water to starving and thirsty people in drought stricken countries, technology has contributed to the ethical security of those who do not face this problem.

The important question is 'at what level to maintain the Earth's ecosystems?' The concept of sustainability suggest that we need to maintain the Earth's ecosystems so that they yield the greatest benefit to present generations, whilst maintaining the potential to meet the needs and aspirations of future generations. The problem is to decide how much water should be utilised directly for people for domestic use, agriculture and industry and how much water should be used indirectly by people to maintain ecosystems that provide environmental goods and elemental services. Figure 4 shows the problem conceptually as a trade-off between natural and highly managed systems. As natural systems are modified into highly managed systems, the benefits of the natural system obviously decline (solid line); e.g. hydrological functions, products and biodiversity are lost. At the same time, benefits from the highly managed system increase (dotted line); e.g. food production rises. It is suggested that the benefits from highly managed systems reaches a plateau, whilst the benefits of the natural system will decline to zero at some point. The total long-term benefits

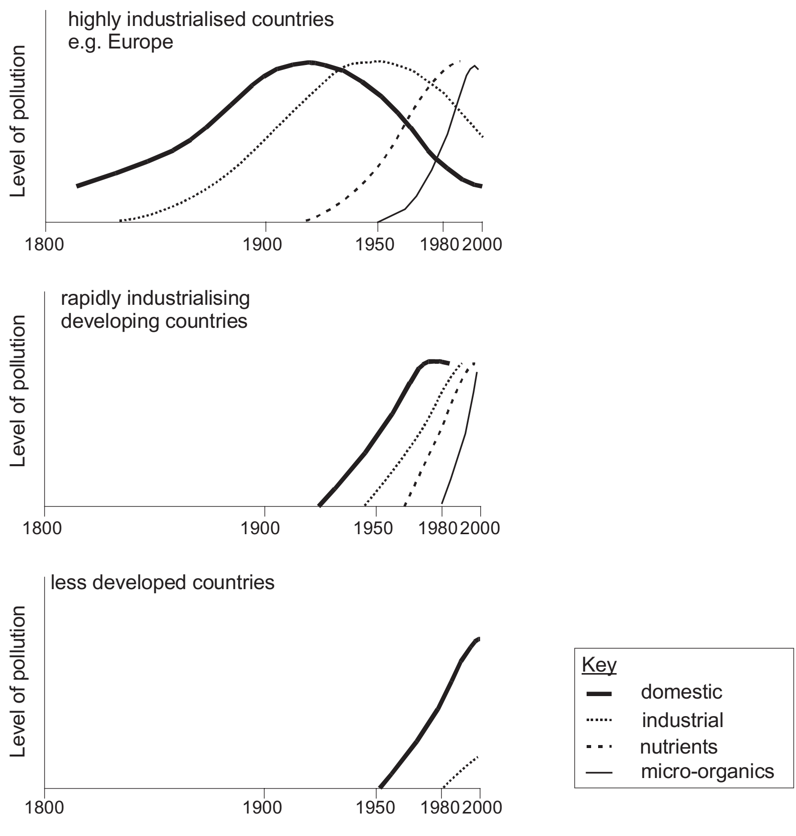
**Figure 4 . Maximising benefits from freshwater ecosystems**




(dashed line) can be calculated by adding the benefits of the natural and highly managed systems. The total rises to a maximum before declining. It is at this point that the balance between naturalness and high management is optimised. Obviously, the value that society places on goods and services and ethical considerations will determine the exact form of these curves. Indeed the perceived benefits will vary between different groups and individuals. It is essential therefore that the costs and benefits to society of allocating water alternatively to maintain ecosystems and to support direct use in the form of agricultural, industrial and domestic uses are quantified.

A major question is whether highly managed systems are sustainable. Developed countries have faced many problems over the past 200 years. However, humankind has been ingenious enough continually to find technological fixes to problems as they arise, such that, as a whole, the highly managed system is sustainable. The upper graph in Figure 5 shows the increase and subsequent decrease of different forms of pollution facing developed countries since 1800. For example, human waste increasingly polluted rivers up to the 1850s, when sewage treatment plants were developed to deal with the problem. Currently pesticide and fertiliser pollution in surface and groundwaters is causing considerable problems. Future issues, such as endocrine disrupters, which have created hermaphrodite fish in European rivers, may not be as easy to remedy as sewage (Williams et al., 2000). A further counter argument is that more reliance on technology makes us more vulnerable when the technology fails. People along the River Mississippi in the United States of America lived and farmed behind the embankments, which protected them from small-scale floods. However, when a large flood came in 1993, the impacts were worse because of intensive cultivation and embankments preventing the water from returning to the river. The central graph in Figure 5 shows that similar water quality problems are facing rapidly developing countries, but within a much more condensed period, which

**Figure 5. Water quality problems in developed, rapidly industrialising and developing countries**



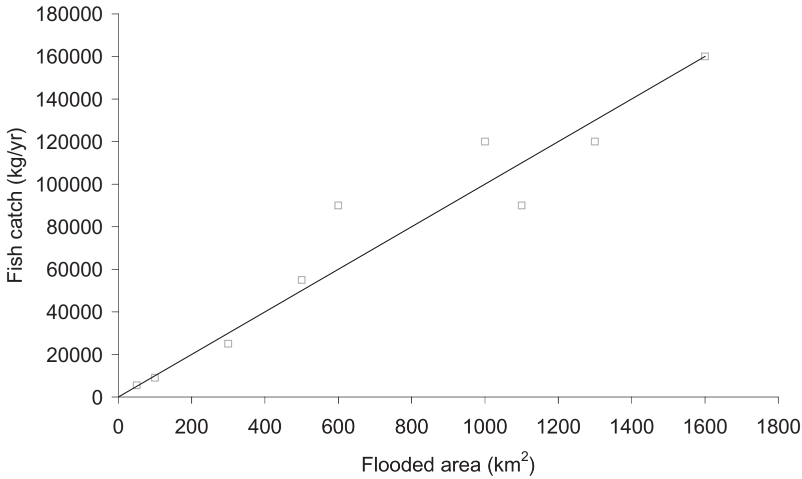
began in the early 1900s. In recent years the same problems are being faced by developing countries. The developed countries' technological fixes are available from developed countries (Figure 5, lower graph), but it not clear who would finance their implementation.

# 8. Quantifying water needs of ecosystems

The water needs of ecosystems and their various component species is a complex issue that has been the subject of considerable study world-wide. Much of the focus has been on minimum flow requirements, but many species rely on high flows and flooding. For example, the acacia trees in the riverine forests of the Indus river valley require inundation from flood water for their moisture, which also brings important nutrients. At least in their early stages of growth, the trees must be flooded for at least 10 days per year. Once acacias are about 8–10 years old their roots are normally able to reach the permanent water table. Some species have specific requirements during a particular life stage. Common reeds (*Phragmites australis*) on the other hand require permanent inundation of around 200 mm, but can tolerate short periods of drying (Newbold and Mountford, 1997). The Palla fish of Asia, for example, requires a minimum depth of 1.8 metres for breeding. Welcomme (1976) studied the fish catches in various floodplains in Africa as a surrogate for fish productivity. However, his data show a linear relationship between flooded area and fish catch (Figure 6). There is no clear threshold point below which the flooded area is insufficient to maintain the fish population. The water needs of such an ecosystem depend on how many fish people wish to catch.

The Environment Agency of England and Wales has developed a procedure called the Resource Assessment and Management (RAM) framework (Environment Agency, 2002) for defining the water needs of rivers in terms of a proportion of the flow duration curve (where the flow duration curve defines the relationship between flow and the percentage of the time this flow is equalled or exceeded, Figure 7). This is a default procedure when no other detailed method is available. The exact proportion is based on sensitivity of the river to removal of water and is determined though consideration of four elements: 1. Physical character; 2. Fisheries; 3. Macrophytes; 4. Macro-invertebrates. Each element is given a score from 1–5 based on its sensitivity to abstraction. For physical characterisation, rivers with steep gradients and/or wide shallow cross-sections score 5 (most sensitive). At the other extreme, deep lowland river reaches score 1 (least sensitive). Photographs of typical river reaches in each class are provided to aid scoring of physical character. Scoring for fisheries is determined by using expert opinion to interpret the available monitoring data and

**Figure 6. Relationship between flooded area and fish catch (after Welcomme, 1976)**




*Source:* Welcomme, 1976.

classify the river using common indicator species. In the case of macrophytic vegetation, various approaches are possible depending upon the availability and quality of the data. Once a score for each of the four elements has been defined, the scores are combined to categorise the river into one of five Environmental Weighting categories, ranging from Very High to Very Low. A look-up table is used to determine the percentage of the natural flow that can be taken at different flow percentiles (e.g. Table 1 gives figures for $Q_{95}$). In this way the ecological need can be derived based on the proportion of the flow percentiles not abstracted. The figures in the table are based largely on professional judgement of specialists, since critical levels have not been defined directly by scientific studies. Any such figures are open to revision, but with no clear alternative, this provides a pragmatic way forward.

As discussed above, the water allocation to a river ecosystem will depend upon the expectations (or objectives) that have been set for it. As part of the derivation of the environmental flows agreed for the South African Water Law, the Department of Water Affairs and Forestry (1999) produced a classification of rivers according to ecological management targets. There are four target classes, A-D (Table 2). Two additional classes, E and F may describe present ecological status but not a target. Water resources currently in category E or F must have a target class of D or above.

**Figure 7. Environmental and natural flow duration curves**

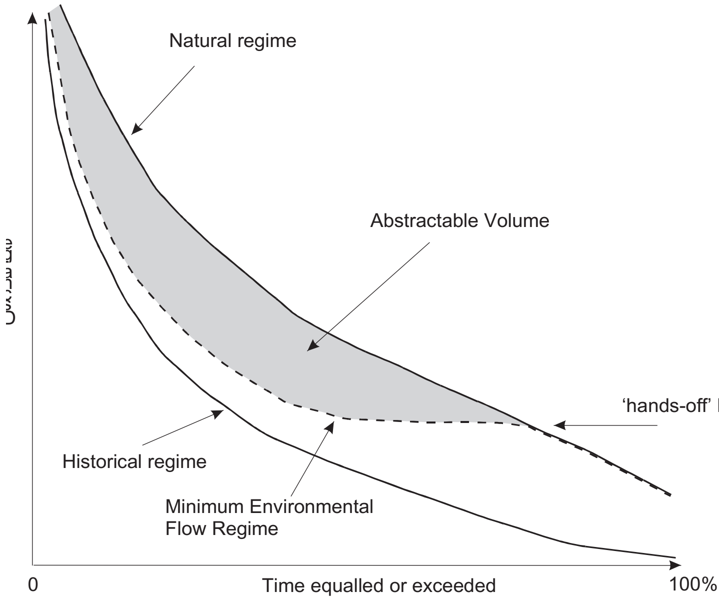



**Table 1. Percentages of $Q_{95}$ flow that can be abstracted for different environmental weighting bands**

| *Environmental weighting band* | *% of $Q_{95}$ that can be abstracted* |
|---|---|
| A | 0–5 |
| B | 5–10 |
| C | 10–15 |
| D | 15–25 |
| E | 25–30 |
| Others | Special treatment |

*Source:* Environment Agency, 2002.

Once the river has been assigned to a class, the ecological Reserve flow regime is defined using the Building Block approach (Tharme and King, 1998). This involves

**Table 2. Ecological management classes**

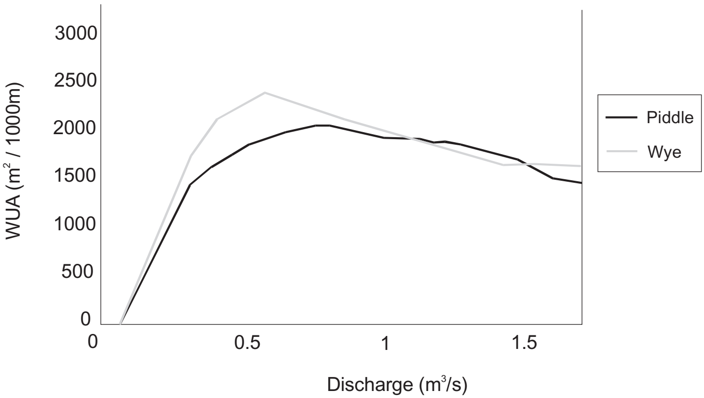
| *Class* | *Description* |
|---|---|
| A | Negligible modification from natural conditions. Negligible risk to sensitive species. |
| B | Slight modification from natural conditions. Slight risk to intolerant biota. |
| C | Moderate modification from natural conditions. Especially intolerant biota may be reduced in number and extent. |
| D | High degree of modification from natural conditions. Intolerant biota unlikely to be present. |

*Source:* DWAF, 1999.

an expert panel, including a geomorphologist, hydrologist and ecologists, undertake a field visit to the river and study available data to determine the various elements (building blocks) of the Reserve, such as low flows, average flows and small and large floods. As a rapid first approximation to setting the Reserve, which does not require the expert panel, Hughes and Münster (2000) have a devised a hydrological assessment method. This assumes that if the flow regime is highly variable, biota will be adjusted to a relative scarcity of water and will hence require a lower proportion of natural flow. Biota in less variable rivers are more sensitive to reductions in flow and a larger proportion of the mean will be required.

Research by the US Fish and Wildlife Service on the flow requirements of riverine species, including fish, invertebrates and plants, led to the development of a system called PHABSIM (Physical Habitat Simulation) that relates river flow to in-stream ecology. PHABSIM assumes that a given species has preferences for certain habitat characteristics, such as water depth or flow velocity. The graph in Figure 8 shows changes in in-stream physical habitat (indexed by weighted useable area - WUA) for the fry/juvenile life stage of brown trout in two contrasting UK rivers, the Piddle, a lowland groundwater-fed river, and the Wye, a upland river in an impermeable catchment (Elliott et al., 1996). PHABSIM has been used to determine the impacts of changing river flows on brown trout. This species is used because of it's sensitivity to river flows and it's acceptance by many stakeholders as a good indicator of river health. PHABSIM has also been used to estimate the ecological effects (in terms of available physical habitat) for historical or future anticipated changes in flow caused by abstraction or dam construction. The method has been adapted for use in many countries including UK, Canada, Austria and New Zealand. However, PHABSIM has been applied primarily to the physical habitat needs for species and has not normally

**Figure 8. Relationship between discharge and habitat availability (WUA - weighted usable area) for brown trout in two UK rivers**




considered indirect impacts, for example reduced river flows may increase concentrations of pollutants or may reduce dissolved oxygen.

Although the quantity of water flowing in a river is a key control over the health of the ecosystem, it is the interaction of the flow and the channel structure that defines the conditions that make it suitable for different species. One of the strengths of habitat approaches like PHABSIM is that they combine river flow and channel morphology. Acreman and Elliott (1996) used PHABSIM to show how straightening and deepening of the channel of the River Wey in the UK reduced its suitability for fish, even though the flow was unchanged. Subsequent restoration of the channel by narrowing and reinstatement of an irregular path improved conditions for fish. Booker et al. (2002) showed how both different levels of channel and flow modification in urban areas influenced the habitat for fish.

In some cases detailed local studies have revealed critical timing of water requirements for specific ecosystems. For example, the ecology of the Diawling National Park, in the delta of the River Senegal in Mauritania, is controlled by seasonal variations in water availability and salinity, which has generated particular vegetation types, such as mangroves with associated species, including penaeid shrimp and mullet. In the late 1980s, the delta was separated hydrologically from the river by construction of the Diama dam and right-bank embankment. These maintain water levels in the Senegal River for gravity irrigation and navigation, but caused degradation of biodiversity of Park and loss of natural resources, including grazing and fisheries, in the buffer zone, increasing poverty in local communities. Restoration of the Park involved releasing water through the embankment via a sluice gate. On 1 July initial releases are made to dampen the soil, simulating rainfall. On 1 August releases are increased so that the water level rises at maximum 1 cm per day, so that the growth of grasses, such as *Sporobolus robustus* and *Echinocloa colona* can keep pace. The grass provides habitat for fish that spawn on the floodplain and for the nesting of crowned cranes. Annual fish production increases with flooded area by around 100 kilograms per hectare. The flooded wetlands provide habitat for many thousands of migratory birds. After 45 days of inundation, salt has been leached from the soils and the water is allowed to drain off, to prevent colonisation by unwanted species such as *typha* and cypergrasses. In the dry season the *Sporobolus* is exploited for the production of mats, providing the main source of income for local women. The *Echinocloa* provides excellent grazing for the thousands of cattle visiting the delta.

In some cases it may be as important to ensure that hydrological conditions are unfavourable to nuisance species such as algae (Davis and Koop, 2001). As part of the development of the Senegal River basin, the Diama barrage was built across the river mouth. This allowed its use for irrigation, since periods of saline water intrusion into the river, which used to occur during the dry season, were replaced by a regime of continuous freshwater. This also led to increased survival of snails and mosquitoes which carry diseases. Before 1987, rift valley fever (a mosquito-borne viral disease) had never been recorded in West Africa and human intestinal schistosomiasis (an aquatic snail-borne worm parasite disease) was little recorded. Following construction of Diama dam, 200 human deaths from rift valley fever were recorded along with an 80% abortion rate among sheep and goats. In 1988, there was a 2% prevalence rate of schistosomiasis, by 1989 this had risen to 72% (Verhoef, 1996). The traditional approach to disease control has been to spray chemicals to control the mosquitoes and to inoculate local people. This clearly treats the symptom rather than the cause. However, the World Health Organisation's Panel of Experts on Environmental Management (PEEM) is now promoting environmental management as health control measure which treats the cause. In the case of the Senegal valley this might mean allowing irrigation areas to dry out or allowing saline water into the river periodically to mimic the natural system.

# 9. Economics as a framework for decision-making

Once the water requirements of an ecosystem are defined, they can be compared with allocation of the water to alternative uses. Many decisions about water allocation are made today on economic grounds. Thus the monetary value of one water use (say direct use for irrigation) must be compared with its value for an alternative use (e.g. to maintain an ecosystem). Such an economic analysis was made by Barbier et al. (1991) for water use in Northern Nigeria. Here the Hadejia and Jama'are rivers used to inundate annually a floodplain of around 2,000 square kilometres. The wetlands provided fertile naturally irrigated soils, fuelwood and fisheries for local people and grazing for migrant herds. Beginning in 1971, a series of dams was constructed on the main tributaries. These stored water for intensive cereal irrigation that would normally have flooded the wetlands. During recent years the area inundated has reduced, with only 300 square kilometres flooded in 1984 (Hollis et al., 1993). It is clear that the yields from intensive irrigation schemes are higher per hectare than from floodplain agriculture, although the high operational costs of the schemes reduce substantially the relative benefits. However, because the economy in this area is limited by water resources, it is more appropriate to express the benefits of various development options in terms of water use. Barbier et al. showed that the net economic benefits of the floodplain (agriculture, fishing, fuelwood ) were at least US$ 32 per 1,000 cubic metres of water (at 1989 exchange rates), whereas the returns from the crops grown on the Kano river project were only US$ 0.15 per 1,000 cubic metres (Table 3). When the operational costs are included, this drops to only US$ 0.0026 per 1,000 cubic metres. Furthermore, this analysis did not include the other of benefits of flooding, such as groundwater recharge or downstream flows to Lake Chad.

Barbier et al. (1997) extended this work to produced generic guidelines for the economic valuation of all types of wetland goods and services. Going a step further, Costanza et al. (1997) have attempted to calculate the economic value of 17 ecosys-

**Table 3. Comparison of productivity of the Hadejia-Nguru wetlands compared with an alternative use of water in the Kano River Project**

| | *Production (US$)* | |
|---|---|---|
| *Location* | *per hectare* | *per 1,000 $m^3$ water* |
| **Kano River Project** | | |
| crops | 115 | 0.15 |
| project (including operating costs) | 2.5 | 0.0026 |
| **Hadejia-Nguru wetlands** | | |
| agriculture, fishing, fuelwood | 58 | 50 |

tem services for 16 biomes. They used these estimates to determine a value of US$ 16–54 trillion per year (with an average of US$ 33 trillion per year) for the value of the entire biosphere. This is almost twice the global national product total of US$ 18 trillion.

In a further application of economics to make choices about water resources, Gren (1995) considered options for reducing nitrate pollution in groundwater supplies on the island of Gotland, Sweden. She compared the restoration of a wetland ecosystem to abate nitrate pollution to installing additional sewage treatment facilities. Nitrogen may originate from a number of sources but in the Swedish case it arises chiefly as leachate from drained marshes and as non-point source pollution from the use of fertiliser and manure by farmers. Table 4 brings together benefits and costs associated with restoring wetlands and with modern treatment. It is apparent that restoring wetlands to abate nitrogen pollution involves substantively higher benefits then the alternative. In addition, there are other benefits stemming from the restoration of wetlands, such as wildlife habitat provision, that are not included in these figures. Some care is required in interpreting the nitrogen abatement benefits. The differences in benefits result from assumptions about the trends in values over time. For the wetlands option, nitrogen abatement capacity is assumed to increase naturally over the first ten years after restoration, while sewage treatment capacity decays as a result of depreciation of the initial capital investment in plant expansion. Discounting annual values subjected to these time trends results in the divergence in values illustrated in Table 4. If there were no time trends to consider, values for the two options would be identical since they rely upon the same measurement of value per kg of nitrogen reduction.

One problem is that the economic value of water is distorted by subsides from national governments or regional bodies such as those paid to farmers by the European Union for growing certain crops. As these subsides change, so the value of water for different uses will change. Traditional cost-benefit analysis does not consider ethical, political, social, historical or ecological issues (such as biodiversity), which cannot be readily given a monetary value. Many people suggest that natural

**Table 4. Benefits and costs associated with nitrogen abatement in Gotland, Sweden (US$/kg N reduction, 1990 prices)**

| *Policy option* | *Benefits* | *Costs* | *Benefits-costs* |
|---|---|---|---|
| Restoration of wetlands | 34 | 16 | 18 |
| Expansion of sewage treatment facilities | 9.1 | 8.4–25 | 0.7–16 |

ecosystems and the living resources they contain may have an additional 'pre-eminent' value in themselves beyond their economic value Because of this ethical obligation, economic value should not be the only criterion used for decision making. Multi-criteria analysis (MCA), promoted by the World Commission on Dams (2000) provides a framework within which decisions can be made on the basis of many measures, not just economic value. In this method, a range of criteria, including social and ethical considerations, may be used to determine the most appropriate objectives. Criteria may be quantitative, such as economic value, semi-quantitative including the priorities for threatened species conservation or purely qualitative, for example, high or low ethical quality. In addition, weights may be assigned to each criterion to indicate their relative importance. MCA is thus more flexible than economic analysis for incorporating distribution effects (who gains and who loses) and sustainability objectives where natural resources use and social issues are important.

No method of assessment is 100% accurate. Although decision-making does not require total accuracy, it greatly enhanced if the accuracy of the scientific results used is known and incorporated in the decision-making process. This requires a decision-support system that handles probabilities of various outcomes. Bromley et al. (2002) reported the use of Bayesian Belief Networks (BBNs) for water resources planning. BBNs define linkages between specific parts of the system under study (e.g. climate, groundwater, surface water, instream ecology, economics, social issues) and expresses these links in probabilistic terms so that the optimum management strategy can be identified with explicit uncertainty despite imperfect knowledge

# 10. Conclusions

In many parts of the world, the limited availability of clean, fresh water is now seen as a major constraint to further social and economic development. In the Middle East many commentators argue that a future regional conflict may be sparked by the need for freshwater. In responding to this growing crisis, *Caring for the Earth* (IUCN/UNEP/WWF, 1991) has called for 'better awareness of how the water cycle works, the effect of land uses on the water cycle, the importance of wetlands and other key ecosystems and of how to use water and aquatic resources sustainable'.

In view of society's increasing need for water for domestic use and for basic goods provided through agriculture and industry, the idea that water should be used to support ecosystems rather than withdrawn directly to support people, may be seen as extravagant and wasteful. Allowing rainfall to 'run away' to the sea, or be taken-up and released into the atmosphere by forests, might appear as bad management of the water resource. Indeed as consumers of water, the landscape and plants and animals can appear as direct competitors with people for water use. However, although it is true that ecosystems, such as wetlands, may lock-up water and plants and animals consume water which can not then be used for direct use by people, 'expending' water in this way may in many cases, provide greater benefits to people than those provided by directly using it for agriculture, industry or domestic use. Making sound decisions about water allocation requires details of the water needs and of the value of ecosystem functions to people. The economic value of the costs and benefits of ecosystem (and their associated goods and services) and its comparison with alternative uses of water provides one framework for decision-making. However, this only considers the economic security provided by water allocations. Social and ethical security need also to be considered, requiring a multi-criteria framework. Uncertainty in water allocation decision-support tools may be handled by considering the probabilities of various outcomes within, for example, Bayesian Belief Networks.

Within water ethics there is also a dichotomy. Scenes of starving and thirsty people in Sahelian African remind us of a basic altruistic need to share resources within other members of the human race. At the same time we feel that other species have a right to freshwater and we should allocated sufficient resources to conserve the biodiversity of the planet for future generations. It is not easy to develop consistent measures of ethicism that can be used for deciding water allocations. But should we bother, since perhaps ethical security is merely a luxury that can only be afforded by those who have already achieved economic and social security.

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