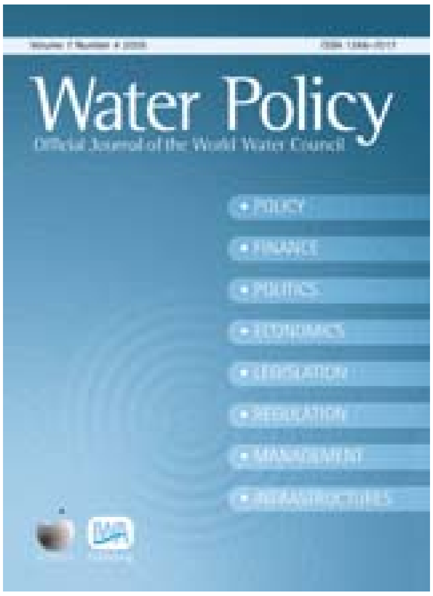

Water Policy 11 Supplement 1 (2009) 121–139

Living with dams: managing the environmental impacts

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Abstract

Dams, through disruption of physiochemical and biological processes, have water and associated environmental impacts that have far reaching social and economic consequences. The impact of each dam is unique. It depends not only on the dam structure and the attributes of local biota but also climatic and geomorphic conditions. Given the number of existing dams (over 45,000 large dams) and the large number that may be built in the near future, it is clear that humankind must live with the environmental and social consequences for many decades to come. This paper provides a review of the consequences for ecosystems and biodiversity resulting directly from the presence of dams on rivers, and of constraints and opportunities for environmental protection. It illustrates that a wide range of both technical and non-technical measures has been developed to ameliorate the negative impacts of dams. It argues that relatively few studies have been conducted to evaluate the success of these measures and that it is widely perceived that many interventions fail, either for technical reasons or as a consequence of a variety of socio-economic constraints. It discusses the constraints to successful implementation and mechanisms for promoting, funding and ensuring compliance. Finally, it contends that there is a need to improve environmental practices in the operation of both existing and new dams.

Keywords: Biodiversity; Ecosystems; Environmental Protection; Large dams

1. Introduction

Freshwater habitats comprise less than 0.01% of the Earth's water, but they contain exceptional concentrations of biodiversity. Although occupying a smaller area than land and oceans, freshwater ecosystems are home to a relatively high proportion of species, with more per unit area than other environments: 10% more than land and 150% more than the oceans (Millennium Ecosystem Assessment, 2005). About 45,000 species of freshwater animals, plants and micro-organisms have been scientifically described and named. However, scientists estimate that at least a million more species remain to be identified (McAllister *et al.*, 1997).

doi: 10.2166/wp.2009.108

Dams represent one of the most significant human interventions in the hydrological cycle. Through provision of water for drinking, irrigation and electricity, they have supported human socio-economic development, but simultaneously they have had a considerable impact on freshwater ecosystems. It is estimated that inter-basin transfers and water withdrawals for supply and irrigation have fragmented 60% of the world's rivers (Revenga *et al.*, 2000). For most of the world's existing stock of dams, environmental issues played little part in their design and operation. However, in the last three decades, an increase in environmental awareness has led to the recognition that the management of water resources includes a responsibility to protect the users of water (and the natural resources that depend on water) from over-utilisation or impacts that cause degradation. As a result, considerable effort has been invested in developing approaches to lessen the most damaging affects of dams. However, experience indicates that the success of these measures is extremely variable and far from assured (Bergkamp *et al.*, 2000).

This paper provides a review of the consequences for ecosystems and biodiversity resulting directly from the presence of dams on rivers, and of constraints and opportunities for environmental protection. It illustrates that a wide range of both technical and non-technical measures has been developed to ameliorate the negative impacts of dams. It argues that relatively few studies have been conducted to evaluate the success of these measures and that it is widely perceived that many interventions fail, either for technical reasons or as a consequence of a variety of socio-economic constraints. It discusses the constraints to successful implementation and mechanisms for promoting, funding and ensuring compliance. Finally, it contends that there is a need to improve environmental practices in the operation of both existing and new dams.

2. Impacts of dams on river flow, water quality and sedimentation

Rivers exist as a continuum of linked surface and groundwater flow paths and are important natural corridors for the flows of energy, matter and species. The spatial and temporal heterogeneity of river systems is responsible for a diverse array of dynamic aquatic habitats and hence biological diversity, all of which are maintained by the constantly changing flow regime.

Upstream and downstream linkages as well as lateral connections between the river and floodplain are encompassed within the "river continuum concept" (Vannote *et al.*, 1980) and the "flood pulse" concept (Junk *et al.*, 1989). These contend that natural changes in river flows, water quality and species, both within the river and on the floodplain, are all interlinked. Nutrients and sediment generated in the headwaters are recycled downstream driving plant growth and biotic productivity. Regular inundation of floodplains increases organic matter decomposition and nutrient cycling and has led to the evolution of adaptive strategies that are tightly coupled to the flood regime. In some places nutrients are returned upstream through the passage of migratory fish (e.g. salmon). When spawning is completed and the fish die, the carcasses floating downstream decompose releasing nutrients. This release leads to significant increases in primary and secondary production (i.e. phytoplankton and zooplankton). In some North American rivers, primary productivity and bacterial activity reach their annual peaks during carcass decomposition, even when spawning runs occur during the winter (Helfman *et al.*, 1997).

Dams constitute obstacles for longitudinal exchanges along fluvial systems. The construction of a dam results in "discontinuities" in the river continuum (Ward & Stanford, 1995). Post impoundment phenomena directly and indirectly influence a myriad of factors that affect natural processes and so, ultimately, alter the ecological structure of ecosystems, sometimes tens or even hundreds of kilometres downstream.

2.1. Impacts on flow regime

The most obvious impact of storage reservoirs is the upstream inundation of terrestrial ecosystems and, in the river channel, the conversion of lotic to lentic systems. Dams also alter the downstream flow regime. The effect of a dam and its reservoir on flow regimes depends on both the storage capacity of the reservoir relative to the volume of river flow and the way the dam is operated. The most common attribute of flow regulation is a decrease in the magnitude of flood peaks and an increase in low flows (Table 1). A consequence of reduced flood peaks is reduction in the frequency and extent of overbank flooding (McCartney & Acreman, 2001). For example, in the Hadejia–Nguru wetlands in Nigeria, annual flooding of about 3,000 km^2 prior to the building of dams was reduced to less than 1,000 km^2 after construction (Hollis *et al.*, 1993). In some circumstances, operational procedures can result in rapid flow fluctuations that occur at non-natural rates. Hydroelectric power and irrigation demands are the most usual causes, but short-duration high discharges are also utilised for navigational purposes and for recreation. For many purposes, so called "pulse releases" are made regularly. For example, daily releases through power turbines often reflect diurnal variation in power demand (Table 1).

2.2. Impacts on thermal regime

Water temperature influences many important ecological processes. Temperature is an important factor affecting growth in freshwater fish, both directly and indirectly, through feeding behaviour, food assimilation, and the production of food organisms. Under natural conditions the relatively small volume of water in a river section and turbulent mixing ensure that river water responds rapidly to changes in the prevailing meteorological conditions. In contrast, the relatively large mass of still water in reservoirs allows heat storage and produces a characteristic seasonal pattern of thermal behaviour. Depending on geographical location, water retained in deep reservoirs may become stratified. Releases of cold water from the hypolimnion (i.e. the deep cold layer) of a reservoir, is the greatest "non-natural" consequence of stratification. Even without thermal stratification, water released from reservoirs is often thermally out of phase with the natural regime of the river (Table 1).

2.3. Impacts on water chemistry

Water storage in reservoirs induces physical, chemical and biological changes, all of which affect water chemistry. Consequently, the water discharged often has a very different composition to that of inflowing rivers (Table 1). Nutrients, particularly phosphorous, are released biologically and leached from flooded vegetation and soil. Oxygen demand and nutrient levels generally decrease as the organic matter decays, but some reservoirs require many years for the development of stable water-quality regimes (Petts, 1984).

After maturation, reservoirs can, like natural lakes, act as nutrient sinks. For example, in comparison to the inflows, mean concentrations of orthophosphate in the outflows from the Callahan Reservoir, Missouri, USA, were reduced by 50% (Schreiber & Rausch, 1979). Eutrophication of reservoirs may occur as a consequence of large influxes of organic material and nutrients, often arising as a consequence of anthropogenic activity in the catchment (Chapman, 1996). The quality of water released from a stratified reservoir is determined by the elevation of the outflow structure(s) relative to the different

Table 1. Examples of the impacts of dams on abiotic variables.

Flow
Annual river flow at Wudil on the Hadejia River, Nigeria, has been reduced by 33% following construction of Challawa and Tiga dams (Goes, 2002)
Flow regulation by the Kariba dam reduces mean monthly flows in the Zambezi by in excess of 40% in the peak flooding months of March to May. Conversely, average dry season flows have more than tripled from 255 m^3 s^{-1} to 812 m^3 s^{-1} in October (Beilfuss & dos Santos, 2001)
Flow regulation in the Black Canyon of the Gunnison River, USA, results in altered flood magnitudes and stream flow durations. The 10-year flood has decreased from 422 to 198 m^3 s^{-1}, the five-year flood from 360 to 155 m^3 s^{-1} and the mean annual flood from 263 to 114 m^3 s^{-1}. Concurrently, the duration of flows between 32.3 and 85.0 m^3 s^{-1} has increased from 12% of the time (i.e. an average of 44 days per year) to 38% of the time (i.e. an average of 139 days per year) (Elliott & Hammack, 2000)
Downstream from the West Point hydropower dam (USA), flows may increase from 14.2 m^3 s^{-1} (at low power production) to 450 m^3 s^{-1} (at peak power production) within half an hour (Ashby *et al.*, 1995)
Thermal regime
Following impoundment, average water temperatures in the 270km long reach below the Danjiangkou dam on the Hanjiang River, China, have increased by 4 to 6°C from October to February, and decreased by 4 to 6°C from March to September. These changes in temperature are considered to be the biggest factor affecting the spawning, growth and the over-wintering of fish (Liu & Yu, 1992)
In the Surna River, Norway, summer (June to mid-August) water temperatures, downstream of a power station supplied by releases from the hypolimnion of a mountain reservoir, are typically 6–8°C lower than above the power station. This has a statistically significant impact on the growth of both Atlantic Salmon (*Salmo salar* L.) and trout (*Salmo trutta* L.) (Saltveit, 1990)
Below the Cow Green reservoir, UK, small changes in trout growth are attributed to lowered summer temperature peaks (by 1–2°C), reduced diel fluctuations, and the delayed rise in spring temperatures and fall in autumn temperatures (Crisp *et al.*, 1983)
The Hume dam on the Murray River, Australia, alters the thermal regime of the river and its effect is still discernible 200 km downstream (Walker, 1979)
Water chemistry
Lake Guiers, fills by flooding from the Senegal River. Since construction of the Diama and Manantali dams on the river, average salinity in the lake has reduced from 360 mg l^{-1} to 240 mg l^{-1}, and temporal variability is considerably reduced (Cogels *et al.*, 1997)
Increased salinity, across a wide range of flows, downstream of the Massingir dam on the Elefantes River, Mozambique, is attributed to high evaporation from the reservoir (Suschka, 1986)
Field and laboratory experiments suggest that, in the first 21 months after flooding, accumulated nutrient loads originating from the topsoil of the area (655 ha) inundated by the Nanhua reservoir, Taiwan, were 124 kg of nitrogen and 7.2 kg of phosphorous per hectare. Furthermore, if it had not been cleared, complete decay of the terrestrial vegetation (monsoon rain forest and farmland) would have contributed an additional 243 kg of nitrogen and 37 kg of phosphorous per hectare (Chang & Wen, 1998)
In the period immediately following impoundment, water abstracted from the Volta reservoir, Ghana, had to be treated with potassium permanganate to remove 'high' concentrations of iron and manganese, neither of which was present prior to dam construction (Kumi, 1973)
Sedimentation
Dams constructed on the Rhone River, France, have reduced the annual quantity of sediment transported to the Mediterranean from 12 million tons in the 19th Century to only 4 to 5 million tons today (Balland, 1991)
Prior to construction of the Aswan High Dam, floods deposited on average 12 million tonnes of silt on land along the Nile each year. The reduction in soil fertility due to the loss of the nitrogenous component of the silt has to be compensated for by the annual addition of 13,000 tonnes of lime-nitrate fertiliser (Biswas, 1992)
Between 1955 and 1982, sand beaches downstream of Hells Canyon dam on the Snake River, USA, decreased in area by 75% as a consequence of the trapping of approximately 5 million tons of sediment per year in upstream reservoirs (Collier *et al.*, 1996)
Ten years after construction, sediment accretion downstream of the Tiga Dam on the Kano River, Nigeria, reduced the effective channel width from 249 m to 34 m, and its depth from 2.01m to 1.44 m (Olofin, 1988)

layers within the reservoir. Water released from near the surface is generally well-oxygenated, warm, nutrient-depleted water. In contrast, water released from near the bottom is usually cold, oxygen-depleted, nutrient-rich water that may be high in hydrogen sulphide, iron and manganese (Zakova *et al.*, 1993).

Bacterial decomposition of material in reservoirs can transform inorganic mercury into methylmercury, a toxin of the central nervous system. Bioaccumulation results in levels of methylmercury in the tissues of fish at the top of the food-chain several times higher than in small organisms at the bottom of the food-chain (Bodaly *et al.*, 1984). This can have serious implications for people who depend on fish for a large proportion of their diet. For example, mercury levels in hair samples of Cree Indians, in the James Bay region of Quebec in Canada, were found to be above the World Health Organization's recommended upper limit (i.e., 6 ppm by weight) as a consequence of eating fish from reservoirs (Dumont, 1995).

In recent years the emission of greenhouse gases (i.e. carbon dioxide (CO_2) and methane (CH_4)) from reservoirs as a result of the submersion of biomass and organic soils has received attention. Studies undertaken have shown considerable variation. Emissions depend on a range of factors including reservoir depth, water residence times, temperature, the influx of organic matter from the catchment, age of the reservoir, primary production and the operating regime of the dam. The greatest gas emissions occur from shallow tropical reservoirs. Average fluxes of 3,500 mg $CO_2\,m^{-2}\,d^{-1}$ and 300 mg $CH_4\,m^{-2}\,d^{-1}$ have been reported for reservoirs in Brazil and French Guyana (St Louis *et al.*, 2000). When the power generated is less than 0.1 W per square metre of reservoir area, there is the chance that such emissions may exceed those that would be produced by an equivalent thermal power station (Fearnside, 2004). By comparison, studies in temperate climates indicate average fluxes of approximately 1,400 mg $CO_2\,m^{-2}\,d^{-1}$ and 20 mg $CH_4\,m^{-2}\,d^{-1}$ (St Louis *et al.*, 2000).

2.4. Impacts on sedimentation

Reservoirs reduce flow velocity and so enhance sedimentation. The rate at which sedimentation occurs within a reservoir depends on the physiographic features and land-use practices of the catchment, as well as the way the dam is operated. Large magnitude and frequent fluctuation in water levels in reservoirs can cause erosion of the shores and add to deposition. There are numerous studies that report sediment storage behind dams (Table 1). It is estimated that between 0.5% and 1% of the storage volume of the world's reservoirs is lost annually due to sediment deposition (Mahmood, 1987).

Downstream of a dam, reduction in sediment load in rivers can result in increased erosion of river-banks and beds, loss of floodplains (through erosion and decreased over-bank accretion) and degradation of coastal deltas. Removal of fine material may leave coarser sediments that 'armour' the riverbed, protecting it from further scour. In some circumstances, material entrained from tributaries cannot be moved through the channel system by regulated flows, resulting in aggradation (Table 1). Reservoir flushing (i.e. the selective release of highly turbid waters), is a technique sometimes used to reduce in-reservoir sedimentation (Atkinson, 1996). Consequently, reservoir operations may result in unnaturally high concentrations of sediment in downstream systems.

3. Impacts of dams on organisms and biodiversity

The impacts of dams, through disruption of physiochemical and biological processes, vary substantially from one geographical location to another and are dependent on the exact design and the way a dam is operated. Every dam has unique characteristics and, consequently, the scale and nature of environmental changes are highly site-specific. However, impacts invariably affect biota and can impact biodiversity.

3.1. Impacts on primary production

The introduction of a dam into a river system affects primary production. In freshwater ecosystems, phytoplankton, periphyton and macrophytes form the base of the foodweb. Upstream of a dam, the slow-moving water of the reservoir is often an ideal habitat for phytoplankton but, depending on depth, temperature, light penetration and the nature of the substrate, may be less suited for periphyton and rooted macrophytes. Downstream of a dam, primary production is affected by the changes to flow, water chemistry and thermal regimes, as well as current velocities and turbidity. In many temperate climates, increased summer flows, higher water temperatures in winter, reduction of turbidity, decreased scouring of the substrate and reduced effluent dilution often enhance primary production (Table 2). Modification of primary production may alter the aquatic environment directly. For example, blooms of phytoplankton and floating plants (e.g. water hyacinth) reduce light penetration and deplete oxygen when they decompose, and so have an adverse impact on other species (Joffe & Cooke, 1997).

Dams can also affect riverside and floodplain vegetation, the characteristics of which are often controlled by the dynamic interaction of flooding and sedimentation. By changing the magnitude and extent of floodplain inundation and land-water interaction, dams can disrupt plant reproduction and allow the encroachment of upland plants previously prevented by frequent flooding (Table 2). Studies in Norway have shown that the presence of storage reservoirs permanently reduces the diversity of riparian vegetation (Nilsson *et al.*, 1997).

3.2. Impacts on molluscs

Globally, it is estimated that there are between 80,000 and 135,000 species of mollusc (Seddon, 2000). In river ecosystems, molluscs occur in a wide array of lotic and lentic habitats and may exceed by an order of magnitude the biomass of all other benthic organisms (Layzer *et al.*, 1993). Although widely distributed, many freshwater mollusc species only occur over a relatively narrow range of habitat conditions. Consequently, dam construction can easily disturb the environmental conditions to which species are adapted. Alteration of sedimentation, and changes in flow and physiochemical regimes, may cause stress and ultimately undermine species survival. Conversely, the change in habitat may provide opportunities for non-native species (Table 2).

Many of the factors that influence molluscs will change immediately on dam closure. Others, such as channel morphology and substrate composition and stability, will change more slowly. Consequently, a progressive response in mollusc communities may occur over a period of many years. Some species have life cycles that exceed 100 years (Bauer, 1992). This can lead to the impression that populations are secure, when in fact no active recruitment is taking place and the populations are functionally extinct. In North America, studies indicate declines in species richness following dam construction of between 37% and 95% (Williams *et al.*, 1993).

3.3. Impacts on fish

Of the 24,600 species of fish presently described by science, about 10,000 (i.e. 40%) are found only in freshwater (Nelson, 1994). Few fish are adapted to both lotic and lentic habitats. Consequently,

Table 2. Examples of the impacts of dams on biota.

Primary productivity

The damming of the Niger River in Nigeria has more than doubled the peak phytoplankton density in the river downstream (El-Din El-Zarka, 1973)

Stabilisation of water levels and reduction in salinity in Lake Guiers, Senegal, following impoundment of the Senegal River has led to the rapid expansion of aquatic macrophytes (e.g. *Typha australis* and *Pistia stratiotes*) (Cogels *et al.*, 1997)

Growth of aquatic mosses (e.g. *Fontinalis dalecarlica*), filamentous algae (from the genera *Bulbochaete, Microspora, Muugeotia* and *Zygnema*) and aquatic vascular plants, following impoundment of the Suldalslågen River, Norway, impaired salmon spawning (Rørslett & Johansen, 1996)

Reduced flooding caused by upstream impoundment has resulted in substantial changes in the vegetation of the Zambezi Delta. On the alluvial floodplain, woody savanna and thicket species (e.g. *Hyphanae corciacea* and *Acacia robusta*) have increased in density, and drought tolerant grassland species (e.g. *Hyparrhenia rufa* and *Vetiveria nigritana*) have displaced flood-tolerant species (e.g. *Setaria spp.*) At the tidal margin, coastal mangrove has been replaced by saline grassland (e.g. *Erichloa borumensis* and *Hemarthria altissima*), and sandbars have become stabilised and colonised by grassland and woody species (Beilfuss *et al.*, 2001)

Molluscs

37 species of mussel have been extirpated from the Caney Fork River, USA, mainly as a result of the construction and operation of the Center Hill Dam. Included in the 37 are two now extinct species and five endangered species (Layzer *et al.*, 1993)

Abundance of *Bulinus truneatus*, a freshwater pulmonate, increased after construction of the Akasombo dam in Ghana, resulting in increased prevalence of urinary Schistosomiasis (Brown, 1994)

In the Murray–Darling River system, native gastropod species have declined from 18 to 1, due to changes in biofilms, predation by carp and flow regulation (Sheldon & Walker, 1993)

Reduced flow, increased transparency and less variable temperatures have resulted in a prolific increase in the population of the freshwater mussel *Limnoperna lacustris* downstream of the Danjiangkou dam on the Hanjiang River, China (Liu & Yu, 1992)

Fish

After construction of the Aswan High Dam on the Nile, total fish catch in the Mediterranean declined from 22,618 tonnes in 1968 to 10,300 tonnes in 1972, but had recovered to 13,450 tonnes in 1980 (Biswas, 1992)

Declines in the populations of *Gymnarchus niloticus, polypterus senegalus, Gnathonemus niger* and *Citharinus laticeps* followed construction of dams on the Niger River (Lae, 1995)

A decline from 54 to 37 species followed construction of the Petit Saut dam in French Guiana. There were 34 species common to both pre and post impoundment, 20 species present before the dam was constructed but not after, and 13 not found before but captured after (Merona & Albert, 1999)

In the Murray–Darling River system, Australia, flow regulation is believed to be an important factor contributing to the expansion in the range of exotic species (e.g. introduced carp, *Cyprinus carpio*) and concurrent decline of native fish, of which several previously abundant species (e.g. *Maccullochella peeli* and *Macquaria ambigua*) are now rare or threatened (Gehrke *et al.*, 1995)

Birds and Mammals

It is estimated that the population of wattled cranes (*Bugeranus carunculatus*) on the Kafue Flats declined by approximately 60% in the 1970s and 1980s, partly as a consequence of flow regulation, and disruption to the natural pattern of flooding, by the Itezhi-tezhi dam (Kamweneshe & Beilfuss, 2002)

Rutland Water, a reservoir (1350 ha) constructed in the UK is designated a Site of Special Scientific Interest, because winter wildfowl counts reach 20,000, with Internationally Important numbers (by Ramsar criteria) of widgeon (*Anas Penleope*), gadwall (*Anas strepera*) and shoveler (*Anas clypeata*) (Moore & Driver, 1989)

In Canada, reduced flows on the Eastmain and Opinaca rivers are associated with an increase in beaver populations (Hayeur, 2001)

Extirpation of river dolphins or Baiji (*Lipotes vexillifer*) occurred after construction of the Xinjiang dam on the Qiantangjiang River, China (Liu *et al.*, 1999) the transformation of a river to a reservoir often results in the extirpation of resident riverine species (Table 2). Downstream of dams, marked changes in fish populations occur as a consequence of blockage of migration routes, disconnection of the river and floodplain, and changes in flow regime, physiochemical conditions (e.g. temperature, turbidity and dissolved oxygen), primary production and channel morphology. These changes may benefit some species but they generally have an adverse effect on the majority of native species.

The 1996 International Union for Conservation of Nature (IUCN) Red List of Threatened Animals includes 617 freshwater fishes (i.e. about 6% of the known number of freshwater species). Other researchers have speculated that globally between 20% and 35% of all freshwater fish are threatened (Moyle & Leidy, 1992; Staissny, 1996). Although the loss of species is not solely a consequence of dams, they are one of the principal factors. It is estimated that half the fish stocks endemic to the Pacific coast of the USA have been lost in the past century, to a large extent because of dam construction (Chaterjee, 1997).

3.4. Impacts on birds and mammals

The importance of riparian corridors for birds and terrestrial animals has been demonstrated (e.g. Decamps *et al.*, 1987). The creation of reservoirs has both positive and negative effects for aquatic and terrestrial species (Table 2). The inundation of ecosystems inevitably leads to the loss of habitat and terrestrial wildlife. In tropical areas, flooding forests high in endemic species extirpates many and, in some circumstances, may result in species extinction. In contrast, in arid climates, reservoirs provide a permanent water resource that may benefit many species. In South Africa, the presence of reservoirs has greatly increased the availability of permanent water bodies, and has had a major effect on the distribution and numbers of waterfowl (Cowan & van Riet, 1998). In England and Wales, 174 water supply reservoirs are designated Sites of Special Scientific Interest because they provide habitat for birds and other water-associated organisms (Moore & Driver, 1989).

The most negative downstream consequence of river regulation on mammals and birds is the disruption of the seasonal flood regime along the river (Nilsson & Dynesius, 1994). In the long term, reduced flooding can alter vegetation communities that may be important for a wide range of mammal and bird species. In arid regions, riparian vegetation may be the only significant vegetation, and many animals will have adapted behavioural patterns to fit with seasonal flooding. If the flooding regime is altered, changes in vegetation may place the birds and animals that depend on it at risk.

4. Environmental protection

4.1. Factors promoting environmental protection

In many countries, particularly those with strong civil society, increased environmental awareness has fostered public demand (expressed largely through NGOs) for maintenance and improvements to environmental quality. As a consequence of public pressure, a number of factors now motivate the integration of environmental protection measures in dam projects. These are:

- Policies and legislation. At the highest political levels, there is an increasing consensus on the need to manage the environment and water-related processes in a sustainable manner. This is translated into international conventions (e.g. the Rio Declaration on Environment and Development, the Convention on Biological Diversity, the Convention on Wetlands of International Importance) and international and national policies and statutes (e.g. the European Union Water Framework Directive, the South African Water Law, the US National Environmental Policy Acts). These seek to protect the environment and recognise the "right" of ecosystems to adequate water. Although not relating specifically to dams, these agreements commit nations to enhance their environmental resources and use them sustainably, thereby providing the context and justification for environmental protection measures in dam projects.

- Conditions of financial support. The policies and requirements of many multilateral, bilateral and private investment institutions (e.g. World Bank, European Union, AusAid, USAID) promote the inclusion of environmental protection measures in large dam projects. Increasingly, loans will only be provided if developers of water resource schemes include measures to protect the environment. However, one of the constraints faced by financial institutions is that, once a dam is built and becomes operational, their ability to enforce the implementation of effective environmental programs is limited.
- Practitioner codes of conduct. The International Commission on Large Dams (ICOLD), the International Energy Agency (IEA) and the International Hydropower Association (IHA) have developed guidelines that encourage the highest standards in the planning and implementation of large dam projects. These guidelines include ways to protect the environment (ICOLD, 1997; IEA, 2000; IHA, 2006). At present, there is no way to enforce compliance, but many companies are wary of the negative publicity that may arise if they do not maintain the highest standards.

4.2. Options for environmental protection

Engineers, environmental scientists and ecologists have developed a broad range of technical and socio-economic interventions to ameliorate the most damaging impacts of dams (see Tables 3 and 4). For new dams, these can be conceptualised within a hierarchical framework comprising three types of measure:

- Avoidance measures result in no change to the existing environmental functioning of a particular area by avoiding anticipated adverse effects. For dams this means alternatives to dam construction such as demand management, water recycling, rainfall harvesting or alternatives to hydropower (e.g. solar, wind, thermal or nuclear). All alternatives have economic, social and environmental consequences that must be weighed against those arising from dam construction.
- Mitigation measures reduce the undesirable effects of a dam by modification of its structure or operation, or through changes to the management of the catchment within which the dam is situated. To date, mitigation is the most widely used approach to ameliorating the negative impacts of dams and a wide range of technical interventions has been developed (Tables 3 and 4). To be successful in a specific situation, mitigation measures require a great deal of understanding of complex processes and their interactions. Strategies are often of limited effectiveness, or may even result in undesirable effects, if detailed scientific and engineering studies are not conducted beforehand.
- Compensation measures compensate for effects that can neither be avoided nor sufficiently mitigated. Principal approaches include preservation of existing ecologically important areas (e.g.

Table 3. Measures taken upstream and within a reservoir to mitigate the impact of dams on ecosystems.

Issue	Mitigation measures	Examples
Thermal regime	Changes to inlet structure configuration Artificial mixing by mechanical mixer or compressed air Flushing to reduce residence times	Automatic aeration, controlled by temperature sensors, was installed at the Teddington dam in Australia in 1996. This maintains unstratified well-oxygenated conditions and prevents high manganese concentrations in the raw water supply (Burns, 1998)
Water quality	Catchment management Pre-impoundment clearing of reservoir Reservoir re-aeration Treatment of reservoir inflows Flushing to reduce residence times Construction of small 'pre-reservoirs'	To reduce eutrophication in the Cirata and Saguling reservoirs in Indonesia, a program of urban and industrial wastewater treatment within the upstream catchment has been proposed (Simeoni *et al.*, 2000) Five pre-reservoirs (i.e. small reservoirs with a retention time of a few days) have been constructed upstream of the main Eibenstock reservoir in Germany, to improve water quality and reduce sedimentation in the main reservoir (Putz & Benndorf, 1998) At Grafham Water in the UK, influent water was dosed with ferric sulphate to reduce reservoir phosphorous concentrations and so reduce algal concentrations (Daldorph, 1998)
Sedimentation	Catchment management Debris dams Shoreline erosion control Sediment flushing Utilisation of sediment density currents Dredging	At the Fortuna dam in Panama, a 10 km^2 reservoir is surrounded by a 160 km^2 nature reserve. This limits erosion and reduces sediment deposition in the reservoir (Leibenthal, 1997) Oulujarvi, a regulated lake in Finland, is drawn down to reduce the erosion of sandy shores caused by spring floods (Hellesten, 1996) Sediment flushing of the Hengshan reservoir in China, for a few weeks every 2–3 years, enables the long-term capacity of the reservoir to be maintained at 75% of the original capacity (Atkinson, 1996)
Weeds	Mechanical cutting Chemical control Biomanipulation	An integrated management strategy has been developed to control water hyacinth in the Yacyreta reservoir on the Parana River in Argentina. This includes biomass clearing, development of effective sewage treatment plants to reduce nutrient input to the reservoir and a program of water releases (Joffe & Cooke, 1997)
Fish	Man-made spawning areas Removal of sand bars across tributary mouths Construction of shallow water habitat Introduction of lake species into reservoir	New spawning grounds were successfully created in the upgrading of the Riviere-des-Prairies project in Canada (IEA, 2000) More than 1.5 million fish (i.e. salmon, rainbow trout and brook trout) were introduced into the Williston Reservoir in British Columbia, Canada (IEA, 2000)
Terrestrial wildlife	Wildlife rescue Enhancement of reservoir islands for conservation	10,000 animals were rescued from drowning prior to the filling of the Afokaba reservoir on the Surinam River in South America (Nilsson & Dynesius, 1994)

Table 4. Measures to mitigate the downstream impact of dams on ecosystems.

Issue	Mitigation measures	Examples
Flow regime	Managed flow releases	The Physical Habitat Simulation System (PHABSIM) has been used to compare options for minimising the in-stream ecological impacts of river regulation through compensation flow releases from the Derwent Valley Reservoir System in the UK (Maddock *et al.*, 2001)
Thermal regime	Multi-level outlet works	A multiple level outlet tower has been proposed for the Glen Canyon dam in the USA to mitigate the impact of cold water releases on trout (CGER, 1996)
Water quality	Outlet works aeration Multi-level outlet works Turbine venting	In the USA, Duke Power has experimented with various approaches to increase dissolved oxygen levels in turbine tailraces. At the Wateree Dam, turbine blades were modified to enable air to be drawn into the water through small holes in the turbine vanes. This produced a 3 mg l^{-1} increase in DO, without significantly impacting turbine performance (Sigmon *et al.*, 2000)
Sedimentation	Addition of sediment to rivers Managed flow releases Shoreline stabilisation	Since 1977, gravel has been added to the River Rhine downstream of dams, to reduce erosion and maintain the channel morphology (Dister *et al.*, 1990) On the Galaure River in France, banks historically protected with rip-rap, are now being protected through the regeneration of a buffer zone of riparian woodland (Pięgay *et al.*, 1997)
Weeds/algal blooms	Mechanical cutting Chemical control Biological control Flushing	Mechanical harvesting of aquatic macrophytes was attempted on the River Otra in southern Norway, to control *Juncus bulbosus*. The approach was largely ineffective because of high operational costs and inadequate removal of submergent vegetation (Rørslett & Johansen, 1996) Research has shown that algal blooms on the Murray River, Australia can be dispersed through a combination of flow management and reduction in water-levels behind weirs (Maier *et al.*, 2001)
Fish	Freshets to stimulate fish migration Improved design of turbine, spillways and overflows Fish passes Artificial spawning areas Hatcheries and fish stocking	A vertical slot fish pass has been shown to be effective in enabling 24 species of fish, including barramundi *(Lates calcarifer*) to move upstream of the Fitzroy barrage in Australia (Stuart & Mallen-Cooper, 1999) The hydropower dam in the Hunderfossen project in Norway was a barrier to migratory trout. A fish ladder was unsuccessful because the primary constraint to fish migration was reduced downstream flows. Trout restocking also proved to be less successful than expected. An increase in minimum downstream flows at certain times of year to trigger migration has improved the situation (IEA, 2000)
Terrestrial wildlife	Managed flow releases	High flow releases were designed into the operation of the Itezhi-tezhi dam in Zambia. One reason for this was to preserve, through annual flooding, the high biodiversity of the internationally important Kafue Flats (McCartney, 2002)

through the establishment of a national park) and rehabilitation of previously disturbed land, either around reservoirs or some distance from the development in question.

Ideally, environmental protection measures are identified through an Environmental Impact Assessment so that adverse affects are minimised from the outset of a project. For existing dams, amelioration measures also include restoration, which comprises attempts to return ecosystems to an approximation of pre-disturbance conditions. Within this context, dam decommissioning is increasingly being considered as a viable option (Shuman, 1995; Tucker, 2001).

4.3. Constraints to successful environmental protection

Measures to protect the environment are successful in some circumstances but are not effective in others (Bergkamp *et al.*, 2000; IEA, 2000). Constraints to successful environmental protection are not limited to technical deficiencies but also arise because of limitations in human, financial and institutional capacity.

At present, lack of scientific understanding is one of the primary constraints to successful environmental protection. Notwithstanding the research conducted to date, it is often impossible to predict, even with site-specific studies, what many of the precise impacts of a dam will be. There is still very little knowledge of the habitat requirements of many species. The relationships between biophysical and socio-economic aspects of systems are even less well understood and so often the social implications of the alteration of ecosystems cannot be foreseen. Developing the scientific and socio-economic knowledge base required to successfully ameliorate impacts requires comprehensive field investigations, necessitating significant time and financial resources. In many projects, funds for conducting environmental impact assessments and for post-project monitoring are insufficient.

The responsibilities for planning, monitoring and regulation of dams are often spread across a large number of institutions. Disparate organisation complicates management co-ordination and the identification of responsibility. This is a problem that is exacerbated in those countries where there is neither the necessary framework to ensure legal compliance, nor a civil society sufficiently empowered to insist that recommended measures to protect the environment are put into practice.

4.4. Mechanisms for funding environmental protection measures

On the basis of the “polluter pays principle”, the usual assumption for financing measures to protect the environment is that the organisation responsible for the development must fund them. The most common mechanism for financing environmental protection in new dams is to incorporate the costs into the capital finance package of the project. The measures that are most readily incorporated into the capital costs of a project are those that occur once, such as reservoir clearing or construction of fish passages or multi-level release structures. It is now standard practice for multilateral financial institutions (e.g. the World Bank and the Asian and African Development Banks) to include the costs for such measures in the financial packages that support dam development.

In some circumstances, other funding sources may be available to supplement the environmental protection measures undertaken by the dam developer or operator (Table 5). Such funds are most usually available for impacts unforeseen when the dam was planned, or for measures requiring financial support throughout the life of a project. These financial instruments can contribute significant revenues for environmental protection programs, provided the use of funds is specified at the outset. Often, acquisition of funding via these mechanisms is through third parties rather than directly by the dam owner. However, in the future, proponents of a water resource development, particularly when the owner is a government agency, may increasingly seek to utilise these sources to finance environmental protection programs.

4.5. Compliance with commitments for environmental protection

A broad body of regulation and guidelines applicable to the environmental impacts of large dams exists at national and international levels. In addition to those developed by ICOLD, the IEA and the IHA, most multilateral and bilateral development financing agencies now have comprehensive policies that cover environmental issues. However, incorporating environmental protection measures into large dam projects is made difficult by the failure of many developers and operators to fulfill voluntary and mandatory obligations. Principal causes for this have been identified (WCD, 2000) as:

- lack of, and incompleteness in, policy, legal and regulatory frameworks;
- difficulties in accurately defining environmental requirements and specifying these in the implementation agreements of projects;
- lack of human, financial and organisational capacity for project appraisal and to act on infringements of agreements;
- lack of transparency and accountability; and
- weak or non-existent recourse and appeals mechanisms.

To improve compliance requires incentives and sanctions as well as mechanisms for monitoring environmental performance (Chitan & Shrestha, 2005). Furthermore, there is need for greater consistency in the criteria and standards stipulated by different funding agencies, as well as increased transparency and accountability in the decision-making process. To deal with these issues, it has been proposed that the dam industry should adopt an ethical code of conduct to ensure that environmental concerns are adequately addressed and human rights respected. Such a code would provide guidance for environmental management, public participation and conflict resolution at each stage of project development and operation (Lafitte, 2001).

Regular environmental auditing, by independent bodies, leading to certification, has been proposed for both existing and new dams (WCD, 2000). Environmental management is a prerequisite for certification and the development of an ISO (International Organization for Standardization) standard for dam management is being contemplated (Giesecke *et al.*, 2000). Compliance plans that specify binding arrangements for specific social and environmental commitments are one way of encouraging developers and operators to implement environmental protection measures (WCD, 2000). Failure to implement or enforce arrangements could result in public exposure and possibly debarment of dam developers or operators from participation in future tenders and contracts. In North America, licensing of dams is an important mechanism for initiating environmental protection measures. Re-licensing (typically every 25 to 30 years) is now often made conditional on improved environmental protection, reflecting contemporary priorities. Although re-licensing agreements are constrained by the physical

Table 5. Approaches to financing environmental protection measures (adapted from Bizer, 2000).

Potential source	Description	Example
Government funding	In countries with ministries and agencies established for environmental management, the implementation of environmental protection programs may be integrated into their jurisdiction	In the USA, federal, state and local agencies establish and maintain parks and other recreational facilities along the margins of reservoirs. These include significant ecological areas managed through the National Park Service
Environmental taxes	The imposition of taxes specifically for environmental protection programs may be imposed directly on a water resource development simply as a fixed tax, or as a tax on revenues generated, or resources 'used'. Taxes may also be derived through general income taxes with funds allocated to environmental programs through the annual budgeting process	Recently, some countries (e.g. Belize) have imposed entry taxes for foreign visitors that are targeted for the development and maintenance of recreational facilities, and include environmental protection measures
Multilateral technical assistance	The coupling of environmental management programs with capital development projects can be an effective way of expanding the scope of an environmental program outside the specific area affected by a water resource development. Sources of funding include grants for program development offered by UN agencies (e.g. FAO)	The World Bank is at present considering an environmental management project in the Lao PDR that would complement the Bank's financing of the Nam Theun 2 hydropower scheme
Bilateral technical assistance	Bilateral agencies (e.g. AusAID, JICA, NORAD, USAID) provide funding packages to assist nations in developing the organisational framework for implementing resource management programs	In 1994, the governments of the riparian states of the Senegal River received financial assistance from the Dutch Development Aid Agency for a regional wetland development program. This aimed to restore the ecosystem of the lower delta by mitigating the impacts associated with the construction of dams (Vincke & Thiaw, 1996)
Global Environment Facility (GEF)	GEF finances projects supporting the objectives of international conventions, including reduction of greenhouse gases, protection of biological diversity and protection of international waters. Generally, funds are available for environmental protection, primarily when the affected habitats are of global significance. Funding may be limited for individual water resource schemes, but may be available for co-operative projects where incremental funding enables broader application of a management or development concept	An integrated management plan for the Volta Basin is presently being developed as a GEF funded project (GEF, 2008). This project will address water-related environmental and health 'problems', including those associated with dam construction in the basin

Continued

Table 5. (*Continued*)

Potential source	Description	Example
Debt for nature swaps	'Debt for nature' exchanges are a significant source of funding for environmental protection programs. In simple terms, the concept is that debtor nations trade high interest loans for loans with lower interest rates, on condition that the money saved is invested in environmental programs	Programs have been effective in Peru, Bulgaria and the Philippines (Kaiser & Lambert, 1996). Of the funds generated, no estimate is available of amounts specifically targeted for the amelioration of the negative impacts of dams, but it is likely that some funds were indirectly allocated through nature conservation and poverty alleviation funds
Rents	Rent allocations arise from benefits accrued to owners of facilities located downstream of projects. A reservoir built in the upper part of a basin can, through flow regulation, increase the benefits to downstream users. Consequently, the owners of the dam may receive a share of downstream project revenues	This mechanism is most commonly used within national boundaries, but may be imposed internationally (e.g. the Columbia River Basin Treaty between the USA and Canada) (Rothman, 1998)

configuration of the original scheme, many changes, particularly in relation to dam operation, are possible.

4.6. Contribution of research in enhancing environmental protection

The degradation of river ecosystems as a consequence of dam construction and river regulation can have profound economic and social implications. In the past, failure to take account of these consequences has resulted in human suffering and the benefits of many dams being overstated. Partly as a result of the concerns about the negative environmental and consequent social impacts, investment in large dams decreased substantially throughout the 1990s and into the early part of the 21st Century. More recently, there has been a re-evaluation of the role of large dams and although controversy remains, it is likely that investment in large dams, particularly in developing countries, will increase in the near future (World Bank, 2004).

An ongoing project of the Challenge Program for Water and Food, an initiative of the Consultative Group for International Agricultural Research (CGIAR), is conducting research into how to better incorporate environmental and social issues into the decision-making processes associated with large dam planning and operation (McCartney, 2007). The study, which is being conducted in the Nile Basin, with case studies in Ethiopia and Uganda, will increase understanding of innovative tools (e.g. decision support systems) and methods for improved decision making in relation to large dams in developing countries. Amongst other things, research is being conducted to determine the environmental concerns of different stakeholders, methods for assessment of environmental flow requirements in situations of data scarcity, and how to strengthen follow-up mechanisms for environmental impact assessments. The project will develop guidelines which it is hoped will contribute to improved decision-making processes.

5. Conclusions and implications

The management of natural resources and particularly freshwater will be a key human endeavour in the 21st Century. Given the large number of existing dams and those that are likely to be built in the future, it is clear that humankind must live with the environmental and social consequences for many decades to come. Most dams are built with the best of intentions: to provide water supplies and power at times when water is naturally scarce and to reduce the devastating effects of floods. These are worthy reasons for river regulation. However, it is now recognised that if development is to be sustainable, the effects of impoundment on ecosystems and other species cannot be neglected. Minimising the negative environmental effects of dams must become a prime focus of attention for owners, operators, financial institutions and environmental managers. Innovative approaches for financing environmental protection measures must be devised.

A prerequisite for sustainable development is that future dam planning, construction and operation must become part of an integrated management effort that gives prominence to environmental protection. All the environmental impacts of a dam should be evaluated within the specific environmental, social and economic context of the catchment in which it is located. This requires inter-disciplinary thinking and a basic understanding of the complex interactions between ecological and socio-economic systems. Lack of hydro-ecological understanding remains a key constraint to successful environmental protection.

References

Ashby, S. L., Kennedy, R. H. & Jabour, W. E. (1995). Water quality dynamics in the discharge of a southeastern hydropower reservoir: response to peaking generation operation. *Lake and Reservoir Management*, *11*, 209–215.

Atkinson, E. (1996). *The Feasibility of Flushing Sediment from Reservoirs*. Hydraulics Research, Wallingford.

Balland, P. (1991). *Le littoral mediterraneen francais. Evolution physique—qualite generale*. Agence de l'Eau Rhone-Mediterranee-Corse, Lyon.

Bauer, G. (1992). Variation in the life span and size of the freshwater pearl mussel. *Journal of Animal Ecology*, *61*(2), 425–436.

Beilfuss, R. & dos Santos, D. (2001). *Patterns of hydrological change in the Zambezi Delta, Mozambique*. Working Paper No. 2, Zambezi Basin Crane and Wetland Conservation Program, Baraboo.

Beilfuss, R., Moore, D., Bento, C. & Dutton, P. (2001). *Patterns of vegetation change in the Zambezi Delta, Mozambique*. Working Paper No. 3, Zambezi Basin Crane and Wetland Conservation Program, Baraboo.

Bergkamp G., McCartney, M., Dugan, P., McNeely, J. & Acreman, M. (2000). *Dams, ecosystem functions and environmental restoration: Thematic Review II.1*. World Commission on Dams, Cape Town.

Biswas, A. K. (1992). The Aswan High Dam revisited. *Ecodecision*, September. 67–69.

Bizer, J. R. (2000). *Avoiding, Minimizing, Mitigating and Compensating the Environmental Impacts of Large Dams*. IUCN, Gland, Switzerland.

Bodaly, R. A., Hecky, R. E. & Fudge, R. J. P. (1984). Increases in fish mercury levels in lakes flooded by the Churchill River diversion, northern Manitoba. *Canadian Journal of Fisheries and Aquatic Sciences*, *41*(4), 682–691.

Brown, D. S. (1994). *Freshwater Snails of Africa and Their Medical Importance*. Taylor & Francis, London.

Burns, F. L. (1998). Case study: automatic reservoir aeration to control manganese in raw water-Maryborough town water supply Queensland, Australia. *Water Science & Technology*, *37*(2), 301–308.

Chang, S. P. & Wen, C. G. (1998). Nutrient release from inundated land of a tropical reservoir (Nanhua reservoir, Taiwan). *Water Science & Technology*, *37*(2), 325–332.

Chapman, M. A. (1996). Human impacts on the Waikato river system, New Zealand. *Geojournal*, *40*(1–2), 85–99.

Chaterjee, P. (1997). Dam busting. *New Scientist*, *2082*, 34–37.

Chitan, G. S. & Shrestha, N. (2005). *Dams in Nepal: Ensuring compliance*. IUCN Nepal and Water and Energy Users' Federation, Nepal.

Cogels, F. X., Coly, A. & Niang, A. (1997). Impact of dam construction on the hydrological regime and quality of a Sahelian Lake in the River Senegal Basin. *Regulated Rivers: Research & Management*, *13*(1), 27–41.

Collier, M., Webb, R. H. & Schmidt, J. C. (1996). *Dams and Rivers: A Primer on the Downstream Effects of Dams*. US Geological Survey Circular 1126. Tuscon.

Commission on Geosciences, Environment and Resources (CGER) (1996). *River Resource Management in the Grand Canyon. Report of the Committee to Review the Glen Canyon Environmental Studies*. National Academy Press, Washington, DC.

Cowan, G. A. & van Riet, W. (1998). *A Directory of South African Wetlands*. Department of Environmental Affairs and Tourism, Pretoria.

Crisp, D. T., Mann, R. H. K. & Cubby, P. R. (1983). Effects of regulation of the River Tess upon fish populations below Cow Green Reservoir. *Journal of Applied Ecology*, *20*(2), 371–386.

Daldorph, P. W. G. (1998). Management and treatment of algae in lowland reservoirs in Eastern England. *Water Science & Technology*, *37*(2), 57–63.

Decamps, H., Joachim, J. & Lauga, J. (1987). The importance for birds of the riparian woodlands within the alluvial corridor of the river Garonne, S.W. France. *Regulated Rivers: Research & Management*, *1*(4), 301–316.

Dister, E., Gomer, D., Obrdlik, P., Petermann, P. & Schneider, E. (1990). Water management and ecological perspectives of the Upper Rhine's floodplains. *Regulated Rivers: Research & Management*, *5*(1), 1–15.

Dumont, C. (1995). Mercury and health: The James Bay Cree experience. *Proceedings of the Canadian Mercury Network Workshop, 1995*. Cree Board of Health and Social Services, Montreal.

Elliott, J. G. & Hammack, L. A. (2000). Entrainment of riparian gravel and cobbles in an alluvial reach of a regulated canyon river. *Regulated Rivers: Research & Management*, *16*(1), 37–50.

El-Din El-Zarka, S. (1973). Kainji Lake, Nigeria. In *Man-made Lakes: Their Problems and Environmental Effects*. Ackermann, W. C., White, G. F. & Worthington, E. B. (eds). (Geophysical Monograph 17). American Geophysical Union, Washington, DC, pp. 197–219.

Fearnside, P. M. (2004). Greenhouse gas emissions from hydroelectric dams: controversies provide a springboard for rethinking a supposedly "clean" energy source. Editorial comment. *Climatic Change*, *66*(1–2), 1–2.

Gehrke, P. C., Brown, P., Schiller, C. B., Moffatt, D. B. & Bruce, A. M. (1995). River regulation and fish communities in the Murray–Darling River system, Australia. *Regulated Rivers: Research & Management*, *11*(3–4), 363–375.

Giesecke, J., Heimerl, S., Markard, J. & Keifer, B. (2000). Environmental certification systems for hydropower: ISO 14001, EMAS and third party ecolabelling schemes. In *Hydro 2000: Conference Proceedings. International Journal of Hydropower and Dams*. pp. 727–736

Global Environment Facility (GEF) (2008). *Regional—Addressing Transboundary Concerns in the Volta River Basin and its Downstream Coastal Area*. See: http://www.gefonline.org/projectDetails.cfm?projID=1111 (accessed 6 March 2009).

Goes, B. J. M. (2002). Effects of river regulation on aquatic macrophyte growth and floods in the Hadejia-Nguru wetlands and flow in the Yobe river, Northern Nigeria: Implications for future water management. *River Research and Applications*, *18*(1), 81–95.

Hayeur, G. (2001). *Summary of knowledge Acquired in Northern Environments from 1970 to 2000*. Hydro-Quebec, Montreal.

Helfman, G. S., Collette, B. B. & Facey, D. E. (1997). *The Diversity of Fishes*. Blackwell Science, Massachusetts.

Hellesten, S., Marttunen, M., Palomaki, R., Riihimaki, J. & Alasaarela, E. (1996). Towards an ecologically based regulation practice in Finnish Lakes. *Regulated Rivers: Research & Management*, *12*(4–5), 535–541.

Hollis, G. E., Adams, W. M. & Kano, M. A. (1993). *The Hadejia–Nguru Wetlands: Environment, Economy and Sustainable Development of a Sahelian Floodplain Wetland*. IUCN, Gland, Switzerland.

International Commission on Large Dams (ICOLD) (1997). Position paper on dams and the environment. Available at: http://genepi.louis-jean.com/cigb/chartean.html

International Energy Agency (IEA) (2000). *Survey of the Environmental and Social Impacts and the Effectiveness of Mitigation Measures in Hydropower Development*. IEA, Paris.

International Hydropower Association (IHA) (2006). *Sustainabilty Assessment Protocol*. IHA, London.

Joffe, S. & Cooke, S. (1997). *Management of the Water Hyacinth and Other Invasive Aquatic Weeds: Issues for the World Bank*. The World Bank, Washington, DC.

Junk, W. J., Bayley, P. B. & Sparks, R. E. (1989). The flood pulse concept in river-floodplain systems. In *Proceedings of the International Large River Symposium (LARS)*, Doge, D. P. (ed). *Canadian Journal of Fisheries and Aquatic Sciences*. *106*(1), 110–127.

Kaiser, J. & Lambert, A. (1996). *Debt Swaps for Sustainable Development: A Practical Guide for NGOs*. IUCN, Gland, Switzerland.

Kamweneshe, B. & Beilfuss, R. (2002). *Population and distribution of wattle crane and other large waterbirds on the Kafue Flats, Zambia*. Working Paper No. 5, Zambezi Basin Crane and Wetland Conservation Program, Baraboo.

Kumi, E. N. (1973). Environmental effects of the Volta River project. *Onzieme Congres des Grands Barrages, Madrid, 11–15 June 1973*. Paris Commission Internationale Des Grands Barrages, Paris, pp. 907–920.

Lae, R. (1995). Climatic and anthropogenic effects on fish diversity and fish yields in the central delta of the Niger River. *Aquatic Living Resources*, *8*, 43–58.

Lafitte, R. (2001). Ethics and dam engineers. *International Journal of Hydropower and Dams*, *4*, 58–59.

Layzer, J. B., Gordon, M. E. & Anderson, R. M. (1993). Mussels: the forgotten fauna of regulated rivers—a case study of the Caney Fork River. *Regulated Rivers: Research & Management*, *8*(1–2), 63–71.

Leibenthal, A. (1997). *The World Bank's Experience with Large Dams: a Preliminary Review of Impacts*. The World Bank, Washington, DC.

Liu, J. K. & Yu, Z. T. (1992). Water quality changes and effects on fish populations in the Hanjiang River, China, following hydroelectric dam construction. *Regulated Rivers: Research & Management*, *7*(4), 359–368.

Liu, R., Wang, D. & Zhou, K. (1999). Effects of water development on river cetaceans in China. In: *Biology and Conservation of Freshwater Cetaceans in Asia*, Randall, R. R., Smith, B. D. & Kasuya, T. (eds). Occasional Paper No. 23, ICUN, Cambridge, UK, pp. 40–42.

Maddock, I. P., Bickerton, M. A., Spence, R. & Pickering, T. (2001). Reallocation of compensation releases to restore river flows and improve instream habitat availability in the Upper Derwent catchment, Derbyshire, UK. *Regulated Rivers: Research & Management*, *17*(4–5), 417–441.

Mahmood, K. (1987). *Reservoir Sedimentation—Impact, extent and mitigation*. World Bank Technical Paper No. 71. World Bank, Washington, DC.

Maier, H. R., Burch, M. D. & Bormans, M. (2001). Flow management strategies to control blooms of the cyanobacterium, *Anabaena circinalis*, in the River Murray at Morgan, South Australia. *Regulated Rivers: Research & Management*, *17*(6), 637–650.

McAllister, D. E., Hamilton, A. L. & Harvey, B. (1997). Global freshwater biodiversity: striving for the integrity of freshwater ecosystems. *Sea-Wind Bulletin of Ocean Voice International*, *11*(3), 1–140.

McCartney, M. P. (2007). *Decision support systems for large dam planning and operation in Africa. Working Paper 119*. International Water Management Institute, Colombo.

McCartney, M. P. (2002). Large dams and integrated water resources management, with reference to the Kafue hydroelectric scheme. In *Hydro 2002: Conference Proceedings*. International Journal of Hydropower and Dams, Aqua-Media International (Hydropower & Dams), Wallington, pp. 389–397.

McCartney, M. P. & Acreman, M. C. (2001). Managed flood releases as an environmental mitigation option. *International Journal of Hydropower and Dams*, *8*(1), 74–80.

Merona, B. & Albert, P. (1999). Ecological monitoring of fish assemblages downstream of a hydroelectric dam in French Guiana (South America). *Regulated Rivers: Research & Management*, *15*(4), 339–351.

Millennium Ecosystem Assessment (MEA) (2005). *Ecosystem Services and Human Well-being: Wetlands and Water Synthesis*. World Resources Institute, Washington, DC.

Moore, D. & Driver, A. (1989). The conservation value of water supply reservoirs. *Regulated Rivers: Research & Management*, *4*(2), 203–212.

Moyle, P. B. & Leidy, R. A. (1992). Loss of biodiversity in aquatic ecosystems: evidence from fish faunas. In *Conservation Biology*. Fielder, P. L. & Jain, S. K. (eds). Routledge, New York, pp. 129–169.

Nelson, J. S. (1994). *Fishes of the World*. John Wiley & Sons, Inc, New York.

Nilsson, C. & Dynesius, M. (1994). Ecological effects of river regulation on mammals and birds: a review. *Regulated Rivers: Research & Management*, *9*(1), 45–53.

Nilsson, C., Jansson, R. & Zinko, U. (1997). Long-term responses of river-margin vegetation to water-level regulation. *Science*, *276*(5313), 798–800.

Olofin, E. A. (1988). Monitoring the impacts of dam on the downstream physical environment in the tropics. *Regulated Rivers: Research & Management*, *2*(2), 167–174.

Petts, G. E. (1984). *Impounded Rivers: Perspectives for Ecological Management*. John Wiley & Sons, Chichester.

Piégay, H., Cuaz, M., Javelle, E. & Mandier, P. (1997). Bank erosion management based on geomorphological, ecological and economic criteria on the Galaure River, France. *Regulated Rivers: Research & Management*, *13*(5), 433–448.

Putz, K. & Benndorf, J. (1998). Importance of pre-reservoirs for the control of eutrophication of reservoirs. *Water Science & Technology*, *37*(2), 317–324.

Revenga, C., Brunner, J., Henninger, N., Kassem, K. & Payne, R. (2000). *Pilot Analysis of Global Ecosystems: Freshwater Systems*. World Resources Institute, Washington, DC.

Rørslett, B. & Johansen, S. W. (1996). Remedial measures connected with aquatic macrophytes in Norwegian regulated rivers and reservoirs. *Regulated Rivers: Research & Management*, *12*(4–5), 509–522.

Rothman, M. (1998). *Measuring and Apportioning Rents from Hydro-Electric Power Developments*. The World Bank, Washington, DC.

Saltveit, S. V. (1990). Effect of decreased temperature on growth and smoltification of juvenile Atlantic Salmon (*Salmo Salar*) and brown trout (*Salmo Trutta*) in a Norwegian regulated river. *Regulated Rivers: Research & Management*, *5*(4), 295–303.

Schreiber, J. D. & Rausch, D. L. (1979). Suspended sediment - phosphorous relationships for the inflow and outflow of a flood detention reservoir. *Journal of Environmental Quality*, *8*, 510–514.

Seddon, M. B. (2000). *Molluscan Biodiversity and the Impact of Large Dams*. IUCN, Gland, Switzerland.

Sheldon, F. & Walker, K. F. (1993). Pipelines as a refuge for freshwater snails. *Regulated Rivers: Research & Management*, *8*(3), 295–300.

Shuman, J. R. (1995). Environmental considerations for assessing dam removal alternatives for river restoration. *Regulated Rivers: Research & Management*, *11*(3–4), 249–261.

Sigmon, J. C., Lewis, G. D., Snyder, G. A. & Beyer, J. R. (2000). Improving water quality by application of turbine aeration—a case study. In *Hydro 2000: Conference Proceedings, International Journal of Hydropower and Dams*. Aqua-Media International (Hydropower & Dams), Wallington. pp. 417–425.

Simeoni, G., Hanselmaan, K., Harnanto, M. & Semiawan, A. (2000). Trends of pollutant indicators and mass balances in tropical hydropower reservoirs. In *Hydro 2000: Conference Proceedings, International Journal of Hydropower and Dams 2000* Aqua-Media International (Hydropower & Dams), Wallington. pp. 409–416.

Staissny, M. L. J. (1996). An overview of freshwater biodiversity: with some lessons from African fishes. *Fisheries*, *21*(9), 7–13.

St Louis, V. L., Kelly, C. A., Duchemin, E., Rudd, J. W. M. & Rosenburg, D. M. (2000). Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate. *BioScience*, *50*(9), 766–775.

Stuart, I. G. & Mallen-Cooper, M. (1999). An assessment of the effectiveness of a vertical-slot fishway for non-salmonid fish at a tidal barrier on a large tropical/subtropical river. *Regulated Rivers: Research & Management*, *15*(6), 575–590.

Suschka, J. (1986). Considerations about water mineralization of some Mozambican rivers. *Aqua*, *1*, 19–24.

Tucker, M. (2001). The Northwest US dam breaching decision: factors, costs and benefits. *Environment, Development and Sustainability*, *3*(3), 217–227.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sede, J. R. & Cushin, C. E. (1980). The river continuum concept. *Canadian Journal of Fisheries and Aquatic Science*, *37*, 130–137.

Vincke, P. P. & Thiaw, I. (1996). Protected areas and dams: the case of the Senegal River delta. *Parks*, *5*(1), 32–38.

Walker, K. F. (1979). Regulated streams in Australia: the Murray–Darling River system. In *The Ecology of Regulated Streams*. Ward, J. V. & Stanford, J. A. (eds). Pelnum Press, New York.

Ward, J. V. & Stanford, J. A. (1995). Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers: Research & Management*, *11*(1), 105–119.

Williams, J. D., Warren, M. L., Cummings, K. S., Harris, J. L. & Neves, R. J. (1993). Conservation status of fresh-water mussels of the United States and Canada. *Fisheries*, *18*(9), 6–22.

World Bank (2004). *The Water Resources Sector Strategy: an Overview*. The World Bank, Washington, DC.

World Commission on Dams (WCD) (2000). *Dams and Development: A New Framework for Decision-making*. Earthscan Publications Ltd, London.

Zakova, Z., Berankova, D., Kockova, E., Kriz, P., Mlejnkova, H. & Lind, O. T. (1993). Investigation of the development of biological and chemical conditions in the Vir reservoir 30 years after impoundment. *Water Science & Technology*, *28*(1), 65–74.

Received 13 November 2007; accepted in revised form 23 August 2008