Managing the environmental impact of dams

Matthew P. McCartney. International Water Management Institute. M.mccartney@cgiar.org
Hilmy Sally International Water Management Institute. H.sally@cgiar.org

Abstract
In its final report, published in November 2000, the World Commission on Dams concluded that the benefits derived from large dams have made a significant contribution to human development. However, in many cases the environmental and social costs have been unnecessary and, by present standards, unacceptable. Often negative impacts arise as a consequence of lack of foresight and because dams are planned and managed in isolation from other developments occurring in a catchment. Given the huge number of existing dams and the large number that may be built in the future, it is clear that humankind must live with the environmental and social impacts for many decades to come. Consequently, there is a need to improve environmental practices in the operation of both existing and new dams. This paper provides a brief review of the consequences for ecosystems and biodiversity resulting directly from the presence of dams on rivers. Strategies to protect the environment are described. A prerequisite for successful environmental protection is that dams are managed within the specific environmental, social and economic context of the catchment in which they are situated.

Key Words: biodiversity, ecosystems, environmental protection, large dams

Introduction

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. Where water is over-extracted, its quality degraded or hydrological regimes modified, the natural environment deteriorates, habitats are destroyed and ecological functions, many of which enhance peoples' well-being, are lost.

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 two 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).

Abiotic impacts of dams

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. 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.

Dams constitute obstacles for longitudinal exchanges along fluvial systems and so result in "discontinuities" in the river continuum (Ward and 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.

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. A consequence of reduced flood peaks is reduction in the frequency and extent of overbank flooding. 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 1000 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.

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. However, even without thermal stratification, water released from reservoirs is often thermally out of phase with the natural regime of the river.

Impacts on 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. 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.

Some reservoirs require many years for the development of stable water-quality regimes. 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 and 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). Hence catchment management has a key role to play in sustaining reservoir water quality.

The quality of water released from a reservoir is determined by the elevation of the outflow structure(s). Water released from near the surface is generally well-oxygenated, warm, nutrient-depleted water. In contrast, water released from near the bottom is often cold, oxygen-depleted, nutrient-rich water that may be high in hydrogen sulphide, iron and manganese.

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 that 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 Organizations recommended upper limit (i.e., 6 ppm by weight) as a consequence of eating fish from reservoirs (Dumont 1995).

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. 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. Reservoir flushing (i.e. the selective release of highly turbid waters) is a technique sometimes used to reduce in-reservoir sedimentation. Consequently, reservoir operations may periodically result in unnaturally high concentrations of sediment in downstream systems.

Impacts on organisms and biodiversity

Dams, through disruption of physiochemical and biological processes, modify the conditions to which ecosystems have adapted. The impacts of dams 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.

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. 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 and 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. Studies in Norway have shown that the presence of storage reservoirs permanently reduces the diversity of riparian vegetation (Nilsson *et al.* 1997).

Impacts on fish

Few fish are adapted to both lotic and lentic habitats. Consequently, the transformation of a river to a reservoir often results in the extirpation of resident riverine species. 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 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 (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 1998).

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. 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 and Van Reit 1998).

The most negative downstream consequence of river regulation on mammals and birds is the disruption of the seasonal flood regime along the river (Nilsson and 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 at risk the birds and animals that depend on it.

Environmental Protection

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. 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 1 and 2). For example, making environmental flow releases to sustain downstream ecosystems is increasingly common. However, 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. 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. In many situations integrated approaches that incorporate changes in catchment management are essential for success.

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.

Table 1: Measures upstream and within the reservoir to mitigate the impact of dams on ecosystems

Issue	Mitigation Measure	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 and Bendorf 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 natural 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 and 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 and Dynesius 1994).

Table 2: Measures to mitigate the downstream impact of dams on ecosystems

Issue	Mitigation measure	Example
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 increasing 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 mgl^{-1} increase in DO, without significantly impacting turbine performance (Sigmon *et al*. 2000).
Sedimentation	Addition of sediment to rivers. Managed flow releases. Shoreline stabilisation. Pumping offshore sediment to estuaries.	Gravel has been added to the River Rhine, since 1977 downstream of dams, to reduce erosion and maintain the channel morphology (Dister *et al*. 1990). On the Galuare River in France banks historically protected with rip-rap, are now being protected through the regeneration of a buffer zone of riparian woodland (Piėgay *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 and 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 and 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).

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 the International Commission on Large Dams (ICOLD) and the International Energy Agency (IEA), 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.
- Weak or non-existent recourse and appeals mechanisms.

To improve compliance requires incentives and sanctions as well as mechanisms for monitoring environmental performance. 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 Organisation for Standardisation) 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). 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.

Conclusion

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 may 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 all 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 by owners, operators, financial institutions and environmental managers.

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 basic understanding of the complex interactions between ecological and socio-economic systems. This is particularly true of environmental flow releases, where lack of hydro-ecological understanding remains a key constraint to successful implementation. There is an urgent need for further research to link abiotic processes and the impact of dams on these processes to ecological change and the socio-economic consequences.

References

Atkinson E., 1996. The feasibility of flushing sediment from reservoirs. Hydraulics Research, Wallingford.

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.

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, 682-691.

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

Chapman, M.A., 1996. Human impacts on the Waikato River System, New Zealand. Geojournal, 40, 85-99.

Chaterjee, P., 1998. Dam busting. New Scientist 34-37.

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.

Cowan, G.A., van Riet, W., 1998. A directory of South African wetlands. Department of Environmental Affairs and Tourism, Pretoria.

Daldorph P.W.G., 1998. Management and treatment of algae in lowland reservoirs in Eastern England. Water Science and Technology 37, 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 and Management 1, 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 and Management 5, 1-15.

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

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 727-736.

Hellesten, S., Marttunen, M., Palomaki, R., Riihimaki, J. Alasaarela, E. 1996. Towards an ecologically based regulation practice in Finnish Lakes. Regulated Rivers: Research and Management 12,: 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.

International Commission on Large Dams (ICOLD) 1997. Position paper on dams and the environment 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 92 pp.

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.

Lafitte R., 2001. Ethics and dam engineers. International Journal of Hydropower and Dams 4, 58-59.

Leibenthal, A., 1997. The World Banks experience with large dams: a preliminary review of impacts. The World Bank, Washington DC.

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 and Management 17, 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 and Management 17, 637-650.

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 389-397.

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

Nilsson, C., Dynesius, M., 1994. Ecological effects of river regulation on mammals and birds: a review. Regulated Rivers: Research and Management 9, 45-53.

Piégay, H., Cuaz, M., Javelle, E. Mandier, P. 1997. Bank erosion management based on geomorphoogical, ecological and economic criteria on the Galuaure River, France. Regulated Rivers: Research and Management 13, 433-448.

Putz, K., Benndorf, J. 1998. Importance of pre-reservoirs for the control of eutrophication of reservoirs. Water Science and Technology 37, 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 and Management 12, 509-522.

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.

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 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, 409-416.

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

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 and Management 15, 575-590.

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

World Commission on Dams (WCD) 2000. Dams and Development: a new framework for decision-making. Earthscan Publications Ltd., London.