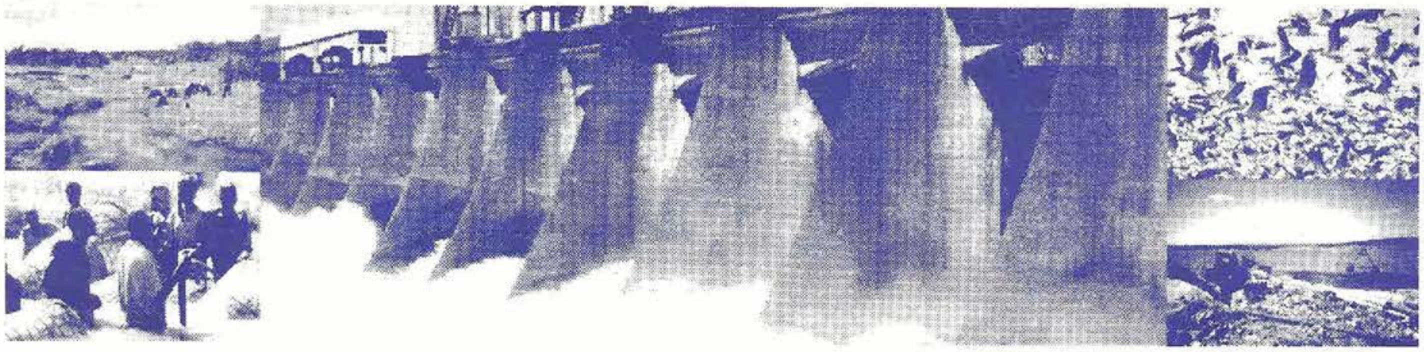
Improving the Environmental Performance of Dams



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Preface

Last year, the World Commission on Dams (WCD) produced its final report: *Dams and development - A new framework for decision-making*. Based on its three year long review, the Commission concluded that dams, whilst undoubtedly bringing benefits to many millions of people, have had some positive but largely negative impacts on ecosystems and species. They also stated that much effort needs to be put into rectifying the legacy of the past and putting in place sound planning and management systems that build on the recognition of rights and the assessment of risks.

Over the last three years, IUCN and UNEP have made a large contribution to the work of the World Commission on Dams. Funded by the United Nations Foundation through the United Nations Fund for International Partnerships (UNFIP), the two organisations commissioned a series of three contributing reports that, together with other major contributions, laid the basis for the WCD Thematic Study II.1: *Dams, ecosystem functions and environmental restoration*.

This document, summaries the three IUCN/UNEP submissions to the World Commission on Dams. The current report focus on summarising the specific aspect of environmental and ecosystem impacts of large dams. It is not intended to provide the wider scope or analysis of large dam issues. The document does not present a specific framework of action, but rather provides a benchmark of current status. It provides an overview of present understanding of the impact of dams on ecosystems and biodiversity. It describes measures for ameliorating the negative environmental impacts and outlines mechanisms that historically have promoted approaches to avoid, mitigate and compensate negative environmental impacts. Mechanisms for funding amelioration interventions and ensuring developer compliance with such measures are presented.

Management of freshwater will be a key human endeavour in the 21st century. Given the huge number of existing dams and the large numbers presently planned, no matter what the outcome of he present debate about the future role of dams in development, it is certain that we must live with the environmental and social consequences for the foreseeable future. There is a need to improve environmental practices relating to the operation of existing as well as new dams.

It is hoped that this report will contribute in a small way to the implementation of the recommendations of the World Commission on Dams.

Acknowledgements

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A workshop held in gland in December 1999 to review the potential measures for ameliorating the environmental impacts of large dams provided a valuable input to the project. The participants to this workshop: M. Acreman; B. Aylward; J.R. Bizer; Ch. Carey; J. Gamperl; G. Guertin; B. Gujja; M. Halle; Ch. Manab; J. Skinner; B. Svensson; A. Wüest; T. Ziegler; R. Zwahlen. IUCN Staff: G. Bergkamp; E. Bos; P. Dugan; M. Koch-Weser; J. McNeely; J.-Y. Pirot; S. Stuart; F. Vorhies; T. Young; are kindly acknowledged for their contribution.

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Executive Summary

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). About 45,000 species of freshwater animals, plants and micro-organisms have been scientifically described and named, but scientists estimate that at least a million more species remain to be identified.

The interaction of both living and non-living components of river ecosystems provide a wide range of services that nourish humanity, save lives and enhance people's well being. Globally, dam construction has had an enormous affect on river ecosystems. It is estimated that there are at least 45,000 large dams throughout the world and inter-basin transfers and water withdrawals for irrigation have fragmented 60% of the world's rivers.

Dams constitute obstacles for longitudinal exchange along rivers and disrupt many natural processes. They have impacts on both upstream and downstream, terrestrial and aquatic ecosystems. Flooding upstream of dams results in the permanent destruction of terrestrial tecosystems through inundation. All terrestrial plants and animals disappear from the submerged area. Reservoirs trap waterborne materials including sediment and obstruct migration pathways for some aquatic species. Downstream there are changes in flow regime, sediment transport, and water temperature and quality that may persist for considerable distances. Many of these changes are immediate and obvious. Others are gradual. For example, changes in thermal regime, water quality and land-water interactions result in changes in primary production, which in turn has long-term implications for fish and other fauna.

The complex inter-relationship between dams and their environment make it extremely difficult to predict all the consequences that dam construction will have for any particular river ecosystem. The impact of each dam is unique and dependent not only on the dam structure, but also on local sediment supplies, geomorphic constraints, climate and the key attributes of the local biota. Changes in habitat favour some species and have a derogatory impact on others. Research has shown that the most common result of habitat change produced by dams is a decrease in native biodiversity and a proliferation of non-native species.

It is estimated that at least 636 species of freshwater mollusc and 617 species of freshwater fish are currently extinct, endangered or threatened. Although the loss of species is not solely a consequence of dams they are one of the principal factors. Relatively few studies have been conducted on the impact of dams on birds and mammals. Those that have been done indicate that while waterfowl may benefit from the creation of new water bodies, many other species suffer, primarily through modification of flow and sediment regimes that disrupt the growth of riparian vegetation on which they depend, and obstruction of migratory paths especially for mamals.

Approaches to ameliorate the negative environmental impacts of dams fall into four categories: avoidance, mitigation, compensation and restoration. Avoidance encompasses both alternatives to dam construction and modification of dam design to preclude negative impacts. Mitigation comprises modifications to the structure or operation of a dam to reduce those negative impacts that cannot be avoided. Compensation consists primarily of measures to set-aside habitat to substitute for that lost or damaged through the construction of a dam. Restoration or rehabilitation comprises methods to return river ecosystems degraded as a consequence of dam construction back to an approximation of their pre-disturbance state.

Case studies show that amelioration interventions are successful in specific circumstances but are not effective in all cases. Constraints to successful implementation of amelioration measures arise for technical reasons and because of limitations in human, financial and institutional capacity. Lack of

scientific knowledge is at present the primary constraint to successful amelioration in both the developed and developing world.

The principle force driving the incorporation of amelioration measures in the construction and operation of dams is public pressure for sustainable and "environmentally friendly" development. This pressure has resulted in:

- international conventions and national environmental laws and regulations;
- policies of the major financial institutions that require developers and dam owners to incorporate mitigation and compensation measures into the overall plans for the dam as a condition of the loan agreement;
- environmentally friendly policies of companies that believe it will provide a commercial benefit

A major constraint to integrating effective mitigation and compensation measures into dams is the added costs. For many mitigation and compensation measures, these costs are significant and may affect the financial viability of the dam. Funds for mitigation and compensation measures can be incorporated into the financial package or can be provided through a portion of the revenues generated by the facility. In cases where the developer/owner is not able to fully fund such measures, other sources of funding are being identified. Such sources include international agencies such as the Global Environment Facility, debt-for-nature swaps, royalties, rents, taxes, and user fees that can be assessed at the national or regional levels. Additional sources of funding, particularly for establishing and managing compensation programs, include grants and proceeds from trusts.

Based on the presented analysis of the environment impacts of dams and opportunities for amelioration, key recommendations are made to:

- Improve dam planning, development and operation to minimise environmental impacts;
- Increase financial support for avoidance, mitigation and compensation of such impacts;
- Enhance information, knowledge and impact predictions on these impacts;
- Improve performance of dams and compliance with agreed policies.

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1. Introduction

Dams are one of the most significant human interventions in the hydrological cycle. Dams disrupt natural ecological processes, both upstream where the river and surrounding valley is inundated and downstream where hydrological, thermal, chemical and sediment regimes may be substantially altered.

It is estimated that there are at least 45,000 "large" dams (Box 1.1) and possibly 800,000 smaller dams throughout the world. For most of the world's existing stock of dams, environmental issues have played little part in their design and operation. Most dams have been constructed with the emphasis on maximising the economic use of water with little or no understanding of the long-term environmental consequences.

> **Box 1.1 Definition of Large Dams**
> According to the criteria used by the International Committee On Large Dams (ICOLD) a large dam is one that fulfils at least one of the following criteria:
> - Higher than 15 m
> - Higher than 10 m but with a crest length of more than 500 m
> - has more than 1 Mm^3 storage capacity
> - has more than 2000 m^3s^{-1} spilling capacity
> - has special foundation problems or is of unusual design.
>
> Thus, the demarcation between large and small dams, made by ICOLD, is based purely on engineering criteria. It is important to recognise that the differentiation does not represent a critical parameter in assessing the ecosystem impact of dams.

Over the last two decades, the multiple benefits of natural ecosystems to human society have become more widely understood. All dams have some undesirable environmental consequences. In certain circumstances these have profound economic and social consequences particularly for rural populations dependent on natural river ecosystems for their livelihoods.

Since the mid-1980s, opponents of dams have argued that, in many instances, the environmental and social costs outweigh the benefits gained (by some) from dam construction (IEA, 2000; ICOLD, 1997). Dam proponents maintain that large dams are essential to the well-being of many millions of humans and have played an important role in the social and economic development of modern societies.

The key issues are whether or not, in the long-term, most dams will provide a net benefit to humankind, and the extent to which the more negative aspects of construction may be avoided, minimised, mitigated or compensated. An increase in environmental awareness has led to heightened concern to minimise the negative impacts of dams. Considerable effort has been invested in developing approaches to ameliorate the worst impacts. However, as with many aspects of human development, it is not possible to avoid all adverse repercussions.

In the past dams have been built largely to provide water supplies for agriculture, industrial and household uses, to provide power and to reduce the devastating effects of floods. These are all worthy reasons for river regulation but the effects of impoundment for natural ecosystems cannot be ascribed secondary status without dire long-term consequences for human well-being. There is a need to balance economic development and environmental management in order to achieve sustainability of human development.

This report summarises present understanding of the environmental impacts of dams, focusing on the direct and indirect consequences of dams for ecosystems and species. Amelioration strategies to address negative environmental impacts are described, and constraints to their successful implementation are discussed. Finally, mechanisms for promoting and environmental impact amelioration strategies are resented together with strategies to ensure compliance.

2. Rivers: natural corridors of life

Water, species and nutrient movement along river and between river and floodplain are essential to keep rivers clean and healthy.

Rivers are central elements in most landscapes. They are important natural corridors for the flows of energy, matter and species, and are often key elements in the regulation and maintenance of biodiversity. Although occupying a smaller area than land and oceans, freshwater habitats are home to a relatively high proportion of species, with more animals and plants per unit area than other environments. Rivers are also essential for many terrestrial species.

2.1 River ecosystems

River ecosystems are inherently complex, comprising many interdependent components, including for example main channels, river anks and floodplains. The ecosystem of a particular river comprises all the biotic (living) and abiotic (non-living) elementsof the environment linked to the river. These not only includes a range of animals and plants but also the nutrients and other chemical and biological elements essential for ecosystem functioning. The river ecosystem extends from the headwaters to the sea and includes riparian areas; associated groundwater in the channel/banks and floodplains; wetlands; the estuary and any near shore environment dependent on freshwater inputs.

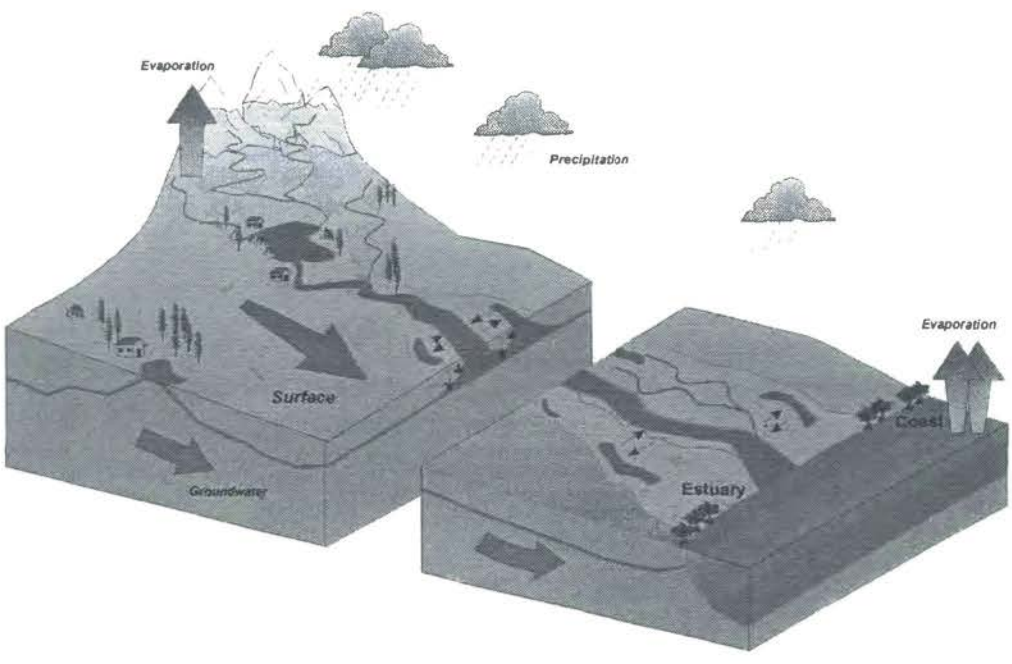

Figure 2.1 River ecosystems depend on lateral, longitudinal and vertical fluxes of water. Within a catchment all environments are dependent to a greater or lesser degree on connectivity with the active river channel. The ecological biological and chemical character of the river depends on the interactions with those environments

Box 2.1 The link between fish migration and nutrients in river ecosystems (source McAllister *et al.*, 2000)
Conventionally, rivers have been regarded as the one-way transfer of matter downstream. Recently there has been greater appreciation that migrating fish species carry nutrients upstream. Reimchen (1995) proposed that intensive coastal catches of Atlantic salmon (*Oncorhyncus* spp.) in the Queen Charlottes, (Canada) reduce the nutrients in adjacent stream riparian zones and estuaries. The contribution of nutrients from both Atlantic and Pacific salmon carcasses has been linked to riparian tree growth (Kavanagh, 1999). Data from 45 watersheds in British Columbia, Canada suggests that up to half the nitrogen stored in giant old-growth trees originates from salmon. Anadromous fishes carry nutrients in their bodies as well as gametes up river. The fishes and their eggs are used for food by a variety of aquatic and terrestrial predators, scavengers and detritivores. Decaying bodies, eggs and faeces of the consumers provide nutrients for algae and other plants scientists. [Cederholm *et al.* (1999)] calculated that in the Columbia River, USA prior to dam construction, spawning salmon contributed to 45,150 metric tonnes of fish bodies to the aquatic and terrestrial ecosystems. By 1997, following construction of multiple dams and impacts of other human activities, only 3,400 metric tonnes were contributed, this is only 8% of the pre-dam level.

Central to understanding the functioning of river systems has been the "river continuum concept" encompassing the linkages upstream and downstream from a river's source to the coastal zone, including any deltas or lagoon systems. This concept includes the gradual natural changes in river flows, water quality and species, that occur along the rivers length. Nutrients and sediment generated in the headwaters are recycled downstream driving plant growth and biotic productivity. One characteristic of the river continuum concept, that illustrates the high degree to which biotic and abiotic components of river ecosystems are interwoven, is the link between the movement of fish and the transfer of nutrients within the river ecosystem (Box 2.1).

2.2 The dynamic role of water

River ecosystems are adapted to the natural hydrological regime (Figure 2.1). The spatial and temporal heterogeneity of river systems is responsible for a diverse array of dynamic aquatic habitats and hence biological diversity (Box 2.2), all of which is maintained by the constantly changing flow regime. The frequency of flow extremes exerts important controls upon every physical, chemical and biological attribute of the river ecosystem (Box 2.3).

Floods are important in determining the composition of biotic communities within the channel, the riparian zone and the floodplain. The "flood pulse" concept (Junk *et al.*, 1989) is based on the importance of lateral connectivity between rivers and their floodplains. Rivers provide the floodplain with nutrients and sediment, whilst the floodplain provides a breeding and feeding ground for river species. Flooding and the consequent transfer of material make rivers and floodplains amongst the most fertile, productive and diverse ecosystems in the world.

Many coastal and marine ecosystems depend on inputs of freshwater and associated nutrients and sediments from rivers. The gradual and dynamic boundaries between salt, brackish and freshwater influence not only vegetation, but also animal behaviour and result in ecologically diverse environments.

Box 2.2 Biological Diversity
Biological diversity, or biodiversity, is a measure of the variability at four levels: genetic, species, ecosystem and ecological function. At the species level, mostly it is the indigenous or native components are examined. Exotic or alien species are considered a separate component, that interacts with native species. Many species are yet to be discovered, scientifically named and classified, especially in tropical regions and in some taxonomic groups that are poorly studied, for example the nematodes, algae, bacteria and fungi.

2.3 River ecosystems and people

People depend on functioning ecosystems to survive; ecological processes supply societies with required resources. In many places, particularly in developing countries, rural communities are highly dependent on the natural functions of river ecosystems and the resources supplied by them. For such communities, the biological resources of river ecosystems often provide the single most important contribution to their livelihoods (Box 2.4) in the form of food supplies, shelter, medicines, income, employment and cultural integrity.

River ecosystems are valuable to people because the processes that occur between different components of the ecosystem may provide beneficial functions (e.g. waste assimilation, flood control) and generate useful products (e.g. wildlife, fish and wood). Other ecosystem attributes such as biological diversity and cultural/heritage also have value either because they induce certain uses or because they are valued themselves. It is the combination of these functions, products and attributes that make river ecosystems important and valuable to society.

Box 2.3 The role of water in river ecology
Unregulated rivers exist as a continuum of linked surface and groundwater flow paths. Channel shapes are determined by flooding. Big floods fill channels with inorganic and organic materials eroded from the catchment and at upstream locations, thereby producing instream structures (e.g. pools, riffles, gravel bars, islands) and floodplain terraces in many shapes and sizes. Between big floods, flow dynamics gradually and subtly reconfigure channel features. Plants and animals must adapt to the physical forces of water movement and constant change in the distribution of the resources that they require. A river, thus, represents a complex array of habitat types ranging from headwaters to the river mouth. Flora and fauna are usually distributed along the river according to the resource requirements needed by each stage in their life-cycle. Each species is most abundant where the resources they require to sustain growth and reproduction are most abundant and/or can be most efficiently obtained. Some species can obtain all they require without much movement and so they will occur in a particular zone along the river. Others must move long distances in search of resources.

2.4 Dams and people

Dams have been an influential part of human development for thousands of years. However, only in the last century, and increasingly in the last 50 years, have technological advances enabled the construction of large dams. In the period 1900 to 1949 less than 1,000 large dams were constructed world-wide every 10 years. Since 1950, there has been an upsurge in the construction of large dams with more than 5,000 being built in a decade. The greatest proportion of large dams have been built in Asia, mostly China, North America and Europe.

Dams are built to impound water in a reservoir so that it can be released during the times that natural flows are inadequate to meet human water requirements. The water stored may be used for a variety of purposes including public and industrial supply, irrigation and hydropower. Dams are also used for flood control. There is no doubt that dams have enabled people to live in places where it would not otherwise be possible and have brought real benefits to many millions of people worldwide.

Today, it is estimated that more than 400,000 km^2 (i.e. 0.3% of the global land surface) have been inundated by reservoirs (McCully, 1996). The aggregate storage of about 6,000 km^3 represents a seven-fold increase in the standing supply of natural river water (Vorosmarty *et al.*, 1997). Globally it is estimated that dams, interbasin transfers and water withdrawals for irrigation have fragmented 60% of the world's rivers (Revenga *et al.*, 2000). In the northern hemisphere, only about 23% of the total water discharge of the 139 largest river systems in North America, in Europe and in the republics of the former Soviet Union is unregulated. All remaining free flowing large river systems are relatively small with a length less than 150 km. (Dynesius and Nilsson, 1994).

The review of the World Commission on Dams confirms that dams have brought benefits to many millions of people worldwide (WCO, 2000). However, very often they have also, through disruption of riverine ecological processes, reduced the opportunities for people who depend on the natural functions, resources and attributes of river ecosystem to sustain their livelihoods. In many cases the rural communities living in the vicinity of reservoirs, or downstream of dams, have gained little advantages from the water stored behind the dam.. Instead, the benefits they previously derived from ecosystem resources and functions may be seriously undermined.

Box 2.4 Definition of livelihoods
A livelihood comprises the capabilities, assets (including both material and social resources) and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance it capabilities and assets both now and in the future, while not undermining the natural resource base.

3. Impacts of dams on river flow and water quality

Dams constitute obstacles for longitudinal exchanges along river systems and tend to regulate natural flow processes. As such, they disrupt the hydrology of river ecosystems; replacing the natural open, dynamic system with one that is, in most cases, more closed and attenuated. The construction of a storage dam results in post impoundment phenomena that are unique to reservoirs and do not occur in natural lakes. The exact impact of an impoundment depends on site specific conditions, the type of storage dam and the way it is operated.

3.1 Effects 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 running water (lotic systems) into still water (lentic systems). Riverine flow patterns are replaced with lake (lacustrine) water circulations.

All dams are constructed to regulate flows and so they alter the downstream flow regime (i.e. intensity, timing and frequency). The effect of a dam and a 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 aspect of flow regulation is a decrease in the magnitude of flood peaks and an increase in low flows (Figure 3.1). In some instances 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 peak-discharge waves are also utilised for navigational purposes and to meet recreational needs.

As well as altering the flow regime, dams reduce the total annual volume of flow. In all cases there is a temporary reduction, when the reservoir first fills. When reservoir storage greatly exceeds the mean

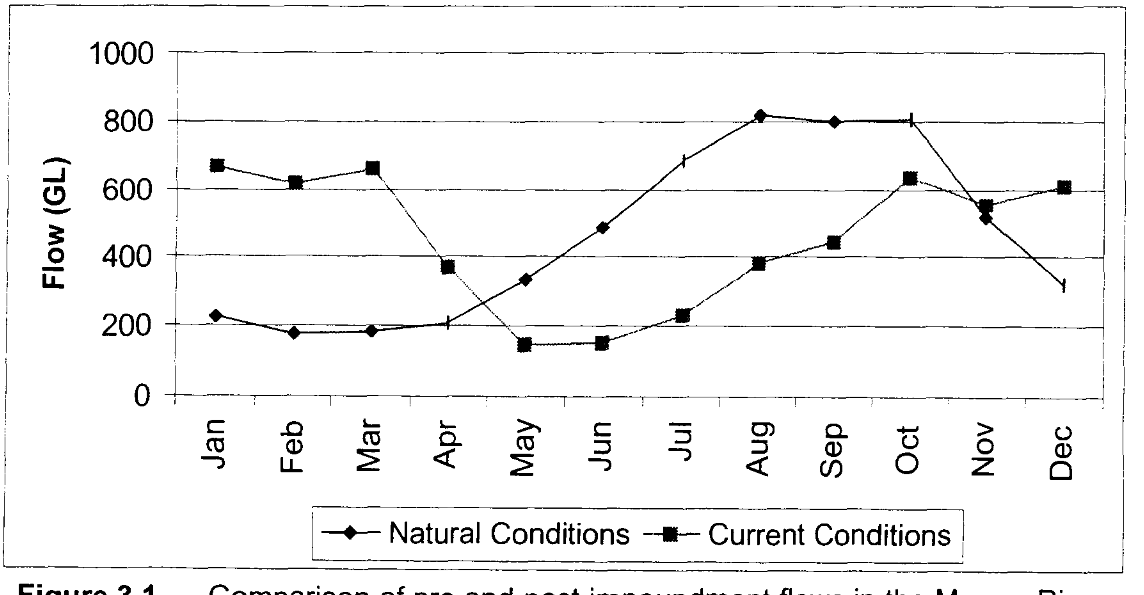

Figure 3.1 Comparison of pre and post impoundment flows in the Murray River, Australia: variation in the average monthly flow at Albury (2225 km from the mouth). Source: Murray-Darling Basin Ministerial Council, 1995.

annual runoff of a catchment this may take several years. In many cases permanent reductions occur because the presence of reservoirs increases evaporation from a catchment. In addition water abstraction for purposes such as irrigation and water supply may further reduce the total flow in a river basin.

3.2 Effects on thermal regime

Reservoirs act as thermal regulators so that seasonal and short-term fluctuations in temperature are changed. These fluctuations are often essential for ecological processes. 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, with warm well-mixed water at the surface (i.e. the epilimnion) and cold, dense water at the bottom (i.e. the hypolimnion).

Water temperature influences many important physical, chemical and biological processes. It has been postulated that thermal changes caused by water storage have the most significant effect on in-stream habitats and hence biota (Petts, 1984). Releases from the cold, dense botton waters of a reservoir is the greatest "non-natural" consequence of stratification. In natural lakes stratification, also occurs but there, hypolimnion waters remain in the lake and do not affect down stream river temperature. Currents generated by large water level fluctuations in reservoirs, resulting from water releases, sometimes prevent thermal stratification. However, even without thermal stratification, water released from reservoirs may be thermally out of phase with the natural temperature regime of the river.

3.3 Effects on water chemistry

Water storage in reservoirs induces physical, chemical and biological changes all of which affect water quality. Increased evaporation from reservoirs may increase water salinity. In the hypolimnion, the process of decay of organic matter submerged when the dam was constructed may become anaerobic. Then carbon dioxide, methane and hydrogen sulphide (H_2S) are released; pH decreases and the solution of iron and manganese occurs from the bottom sediments.

These changes mean that the water discharged from a reservoir often has a very different chemical composition to that of in-flowing rivers. The quality of water released from a stratified reservoir is determined by the elevation of the outflow structure(s) relative to the different layers within the reservoir. Water released from near the surface is well-oxygenated, warm and nutrient-depleted water. In contrast, water released from near the bottom is cold, oxygen-depleted, and nutrient-rich. It may be high in hydrogen sulphide, iron and/or manganese.

Although oxygen demand and nutrient levels generally decrease over time as the organic matter decreases, some reservoirs require a period of more than 20 years for the development of stable water-quality regimes (Petts, 1984). After maturation reservoirs, like natural lakes, can act as nutrient sinks particularly for nutrients associated with sediments. These nutrients, are released biologically and leached from flooded vegetation and soil nutrient enrichment, or Eutrophication of reservoirs may also occur as a consequence of large influxes of organic loading and nutrients. In many cases these are a consequence of anthropogenic influences in the catchment, for example, eutrophication of the heavily regulated Waikato River system in New Zealand was enhanced by sewage and stormwater discharges (Chapman, 1996). Eutrophication can result in blooms of blue-green algae (cyanobacteria) which in the basin upstream of the reservoir can cause oxygen depletion and increased concentrations of iron and manganese in the bottom layer and increased pH and oxygen in the upper layers of stratified reservoirs (Zakova *et al.*, 1993).

Sources for trace metals (e.g. zinc, lead, copper, cadmium and mercury) in reservoirs are atmospheric and riverine inputs and human waste discharges. Metals are introduced both in solution and in particulate form. The particles will partially settle to the bottom, but the dissolved trace metals are subject to adsorption, and uptake by biota in the water at the surface, for example in algaea.

Recent research has shown that, all reservoirs release some greenhouse gases such carbon-dioxide and methane. This contrast some of the earlier assumptions used for the Intergovernmental Panel on climate change scenarios. To date very few studies have been conducted but research indicates that gross emissions of greenhouse gases from some shallow tropical reservoirs may, in terms of global warming potential, approach those of thermal energy power stations (Rosa and dos Santos, 1997). The gas emitted by reservoirs originates from the decomposition of material from three sources:

The original biomass flooded by the reservoir, primary production, and organic matter washed into the reservoir.

Box 3.1 Methylmercury – the implication for human populations (source: Dumont, 1995)
Increased mercury in fish may have serious consequences for populations that depend on them for a large proportion of their diet. The Crees of the James Bay region of Quebec, Canada are an example. The natural lakes from which they obtained their fish were converted to reservoirs in the course of developing the La Grande River hydroelectric complex. After conversion, mercury levels in the fish rose steeply. It increased five fold in samples of northern pike, which brought it to six times the legal maximum concentration for commercial fish in Canada. At the same time, the mercury level in hair samples from many of the local Cree rose above the 6 ppm (by weight) recommended as an upper limit of the World Health Organisation. Bacterial breakdown and transformation of inorganic mercury into methylmercury in the reservoirs has been suggested to be responsible for the higher mercury levels.

To understand the potential role of dams and reservoirs in greenhouse gas production or reduction, it is important to assess the difference between reservoir emissions and emissions that would have *occurred if the dam had not been built. Hence, a full assessment of the impact of a reservoir requires* an evaluation of the difference between the pre dam emissions and the post dam emissions. Quantification of these changes requires understanding of the carbon cycle at the level of the whole catchment.

Mercury contamination of water courses has recently been highlighted as a major problem originating from reservoirs. In some circumstances, bacteria breaking down organic matter in a reservoir transform harmless inorganic mercury into methylmercury, a toxin of the central nervous system. Bio-accumulation results in levels of methylmercury in the tissues of fish at the top of the food-chain several times higher than in the small organisms at the bottom of the chain. This can have serious implications for communities for whom the fish are an important part of their diet (Box 3.1).

3.4 Effects on sedimentation

Reservoirs reduce flow velocity and so enhance sedimentation. Consequently, over time they fill with sediment. The rate at which a reservoir fills with sediment depends on characteristics of the catchment in which the dam is located, land-use practices within the catchment and the operation of the dam. Sedimentation is important ecologically because it alters the reservoir substrate and the progressive loss of storage influences both the character of discharges and the suspended loads passing the dam.

Box 3.2 Alteration of the Green River Morphology by Flaming Gorge Dam, USA (source Collier *et al.*, 1996)
The Flaming Gorge reservoir, located on the Green River in Colorado, USA, traps almost all the sediment that enters it. Downstream, between the dam and the confluence with its first major tributary, the Yampa, the channel is being actively; erosed. The Yampa, located 110 km downstream of the dam, is essentially unregulated and delivers an annual sediment load of 3.2 million tons to the Green River. Below the confluence with the Yampa, the sediment budget of the Green River remains in equilibrium with aggradation and degradation occurring in approximately equal amounts. However, approximately 160 km further downstream, desert tributaries with high sediment loads, contribute even more sediment to the Green River. The dam prevents the annual spring flood, which once moved this sediment, so here the Green River is aggrading. This aggradation has caused narrowing of the channel, infilling of secondary channels and attachment of mid-channel bars to the river banks. Since 1985, releases from the Flaming Gorge Dam have been modified in an attempt to simulate the more natural flow regime.

The reduction in sediment load in rivers downstream of dams can result in the increased erosion of river banks and beds, the loss of floodplains and the degradation of deltas and coastal areas. (Box 3.2). Removal of fine material from the river bed may leave coarser sediment behind that form an 'armour' and protects it from further scour. In some circumstances, increased sedimentation occurs because material entrained from tributary streamscannot be moved through the channel system due to the reduced and regulated flows released from the reservoir.

Sometimes large magnitude and frequent fluctuation in water levels in reservoirs causes erosion of the shores and adds to the turbidity of reservoir discharge. Furthermore, the selective release of highly turbid waters (i.e. reservoir sluicing) is a technique often used to reduce reservoir sedimentation. Consequently, even though reservoirs generally trap sediments, reservoir operations can result in extreme and unnaturally high, concentrations of sediment, which may cause major stress to animals and plants downstream.

4. Impact of dams on organisms and biodiversity

As with terrestrial biodiversity, freshwater biodiversity is unevenly distributed around the globe. It tends to be highest nearest the equator and decreases with increasing latitude. In addition there are so called "hot spots" which contain particularly high numbers of endemic species. Freshwater hot spots include the Amazon, Congo, Nile and Mekong basins.

Human uses of freshwater threaten the survival of freshwater, brackish, coastal and terrestrial biodiversity. Freshwater species are particularly threatened. Dams impact biodiversity by:

- blocking movement of migratory species up and down rivers, causing extirpation or extinction of genetically distinct stocks or species.
- changing river turbidity/ and sediment levels to which species and ecosystems are adapted;
- Trapping silt in reservoirs thereby depriving downstream deltas, estuaries and coastal areas of materials and nutrients that help make them productive ecosystems;
- filtering out of woody debris and thereby removing habitat and a source of food;
- changing the upstream habitat: from running water into still, waters, depositing, silt and creating deepwater zones, temperature and oxygen conditions that are unsuitable for riverine species;
- providing new habitats for waterfowl in particular in (semi) arid regions.
- fostering exotic species. tending to displace indigenous species.
- reducing accessibility to floodplain habitat for aquatic species that utilise the floodplain during periods of high flow;
- modifying downstream habitats through modification of flow, sediment dynamics and water temperature, quantity and and quality regimes;
- through provision of water, modifying human activities, such as agriculture, forestry, urbanisation and fishing, affecting plants and animals.

Conserving habitats and ecosystems is the key to species conservation. Here habitat may be defined as the place where an organism lives and an ecosystem as the interaction or functioning between a community of organisms and their nonliving environment (Odum 1963). The earth can be divided into a series of biogeographical regions, or biomes and ecological communities where certain species of organisms co-exist within particular climatic conditions. Within a biome there are several local factors which affect the distribution of species. Degradation of habitat leads to lowered population and sometimes. loss of a population (i.e. extirpation) or even loss of the entire species (i.e.extinction). Humans mainly induce extinctions by causing habitat loss (Wilcove *et al.* 1998). The importance of all components of the ecosystem including primary producers, herbivores, carnivores, detritivores and recyclers and their ecological function (Mosquin 1994) should be considered in the design of dams. In addition there are certain special linkages between species, that need to be considered for maintaining a fuction ecosystem and preserving species for example, freshwater mussel larvae (glochidia) are parasitic on the gills of fishes for part of their life cycle. Loss of the host fish by dam blockage of its migration route will affect the mussel population and ultimately their capacity to filter the river's waters. In many cases specific fish hosts are required.

4.1 Impacts on primary production

In freshwater ecosystems, free floating algae (i.e. phytoplankton), algae attached to substrate (i.e. periphyton) and plants (i.e. macrophytes) form the base of the foodweb. They are the main drivers of primary production by converting sunlight into chemical energy and protoplasm through photosynthesis.

Anything that alters the conditions for primary production will have an effect throughout the rest of the foodweb.

In natural rivers, phytoplankton tend to be found only in large, slow-moving rivers where nutrient availability does not limit development. Populations are often derived in natural lakes. The introduction of a reservoir into a river system affects phytoplankton populations in two ways. Firstly, by providing an, often ideal, habitat for their production and augmenting the supply into downstream systems. Secondly, by enhancing downstream phytoplankton development through flow regulation, temperature moderation, reduction of turbidity and reduction of effluent dilution. Eutrophication of reservoirs and consequent blooms in cyanobacteria (section 3.3) may further affect primary production in river systems.

Algae attached to submerged objects, including plants, are found where their growth is not limited by light penetration through the water. Different species have definite ecological requirements tolerances and sensitivities for example to flow and water quality changes. Within impounded rivers in temperate climates, the maintenance of higher summer discharges, the reduction of flood magnitude and frequency, the reduced turbidities and the higher winter temperatures due to water regulation often promotes periphyton growth.

Water depth, light penetration, current velocity and the susceptibility of the substrate to scouring are the dominant controls on rooted plant distribution within river ecosystems. Thus it is the influence of dams on these factors that tends to dominate their impact on aquatic plants. In those circumstances where flow regulation induces the deposition of fine nutrient rich sediments (e.g. from tributary or effluent sources) the area of suitable channel habitat may increase and this can have a marked effect on plant distributions.

Flow regulation by dams can affect the distribution of floating plants particularly in the tropics. The infestation of reservoirs by invasive aquatic weeds, for example, water hyacinth *(Eichornia crassipes)*, is a major constraint on water resource management in many tropical countries. The weeds propagate rapidly, and flow regulation can cause the clogging up of river channels. Weed proliferation can alter the aquatic environment by reducing light penetration and depleting oxygen when they die and decompose. They also adversely affect native species and impact on people (Box 4.1).

The characteristics of riverside and floodplain vegetation are largely controlled by the dynamic interaction of flooding and sedimentation. Many species have evolved with, and become dependent on, the natural flood regime. Flow regulation can allow the encroachment of true upland plants, previously prevented by frequent flooding. Studies in Norway indicated that the presence of storage reservoirs permanently reduces the diversity of riparian vegetation. In comparison to natural river reaches one-third fewer species were found downstream of storage reservoirs (Nilsson *et al.*, 1997).

4.2 Impacts on molluscs

Molluscs include all snails, clams, mussels, slugs, octupuses and squid, as well as a range of less known species. Globally there may be anywhere between 80,000 and 135,000 species. In river ecosystems, molluscs may exceed by an order of magnitude the biomass of all other benthic (i.e. bottom living) organisms. They occur on all continents and in a wide array of both running and still water habitats.

Of the 731 species of freshwater mollusc listed in the 2000 IUCN Red List of Threatened Species, 193 species are extinct, 434 species are endangered or threatened and data are deficient for 95 species. In the USA federal register of threatened North American species, of the total 901 mollusc species listed, 77 are listed as extinct, 71 are threatened or endangered and 244 are listed as "candidate" taxa. In Australia of the 176 endemic freshwater molluscspecies 88 are threatened (Mc Allister *et al.*, 2000). Although the loss of species is not solely a consequence of dams it is one of the principal factors. In the USA, studies indicate declines in species richness following dam construction of between 37% and 95% (Mc Allister *et al.*,2000).

Although widely distributed, many freshwater mollusc species occur only over a relatively narrow range of habitat conditions. Consequently, dam construction can easily disturb the environmental conditions to which species are adapted, often resulting in extirpation or extinction. For example, alteration of sedimentation and changes in flow, thermal and chemical regimes may cause stress and ultimately undermine species survival. Conversely, the change in habitat, in some circumstances, provides opportunities for other species, including non-native species.

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 (Table 4.1). Consequently, a progressive response in mollusc communities may occur over a period of many years. Some species have extended life cycles, sometimes over 100 years. 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.

One type of mollusc, freshwater mussels, play a particularly important role in the ecology of many river ecosystems. Freshwater mussels are filter feeders and consequently declining mussel populations may have negative effects on the self-purification of river ecosystem. They are often found in riffle areas, precisely the habitats most affected by dams. The larvae of most North American mussels are parasites on fish and so the life cycles of most is inextricably tied to the presence and well being of their host fish. Indeed, dams have destroyed mussel populations by affecting the host fish population rather than directly affecting the mussels.

4.3 Impacts on fish

It is estimated that there are approximately 10,000 species of freshwater fish. They are usually the best-known faunal components in freshwater ecosystems and so must often serve as indicators of the condition of these systems. Many environmental factors influence the presence or absence of fish species. The diversity of the fish community depends on an equivalent diversity of habitat.

The 2000 Red List of Threatened Animals list 617 freshwater fishes; about 6% of the known number of freshwater species. This is almost certainly an underestimate. Through the Red List is the most objective assessment of the current status of globally threatened species, it is acknowledged that many species are not yet been discovered or described. Other researchers have speculated that globally up to 35% of all freshwater fish are threatened (Stiassny, 1996). Although the loss of species is not solely a consequence of dams they are one of the principal factors.

Fishes in rivers are well adapted to conditions of flowing water. In eastern Canada, lakes and rivers that have emerged relatively recently from glaciation contain a number of fish species that are able to dwell in both habitats, but this is rarely the case. Consequently, the transformation of a river to a reservoir usually results in the extirpation of resident riverine fishes.

Dams may benefit fishes species that prefer deep still waters. In some places, particularly in the tropics, the overall number of fish species may increase. For example, in the ten years after closure of the Kariba dam, on the Zambezi, some species have been extirpated, but overall the number of species in the lake has increased from 28 to 40 (McAllister *et al*, 2000).

Increased fisheries, often through the introduction of alien species, is one of the frequently cited socio-

Box 4.1 Water hyacinth in the Niger Delta, Nigeria (source: Joffe and Cooke, 1997)
The Niger delta is a vast and ecologically complex area including the most extensive freshwater swamp forest in Africa. The delta is home to more than 6 million people, most of whose livelihoods depend on fishing, subsistence agriculture and the selling of forest products. The delta ecosystem is maintained through a dynamic equilibrium between flooding, erosion and sediment deposition. During the last decades, construction of dams along the Niger river has disrupted the natural hydrological Regime, significantly modifying water flows and sediment dynamics. Due to these changes the water hyacinth (*Eichornia Crassispes*) has sread over a disance of 800 km from near Lagos in just 7 years. The negative effects on fishing, navigation, irrigation, fish ponds and human are estimated to effect 5 million people. At current rates of expansion the plant will cover a large proportion of the freshwater streams and rivers in the delta within the next years.

economic benefits of reservoirs. The catches in new reservoirs often go through a boom and bust cycle with catches initially increasing following filling, due to nutrient leakage, and then declining as the reservoir matures. Fish species that benefit from reservoirs remain sensitive to pollution, eutrophication, and over-fishing.

Downstream of dams changes in flow regime, temperature, water chemistry and turbidity may benefit some species but will generally have an adverse effect on the majority of native species. Many fish in riverine systems associated with floodplains are adapted to utilise the floodplain habitat for feeding and reproduction. Suppression of habitat, as a consequence of reduced flooding, often results in the decline or even disappearance of species that depend on it. Some fish species may require several habitats during various life stages and it is sufficient to remove one of these to threaten their survival. Reduced freshwater flows and nutrient inputs at the coast may have a negative impact on some marine fish species, particularly those that utilise estuaries as nursery areas.

The class of species most sensitive to the fragmentation of river systems by dams are those which migrate long distances within the main channel. Dams block migratory pathways and interfere with their life cycle. Sturgeon populations in the Caspian Sea, nowadays rely mainly on hatcheries in Iran since Russian dams block natural spawning migrations.

It is often difficult to isolate a single causal variable in changes to fish populations. A characteristic sequence is often: elimination of major migratory species; progressive elimination of the larger elements of the community; reduction in mean size and reduction in quality of catch; substitution of native species with introduced species; fluctuations in catch and increasing need for human intervention to maintain the system. In most instances, dam construction results in a net decrease in fish diversity within a catchment.

Box 4.2 Evidence of Freshwater mussel extinction in the USA due to dam construction (source: McAllister *et al.*, 2000)

In the tennessee river basin, (USA), several molluscs are under threat of extinction following the construction of dams and the subsequent regulation of flow. A number of gastropods of the family *Pleurocercidae* are under threat and three other species have been extirpated as they persist on clean-swept riffle areas. Over 85 mussel species were known in the Cumberland River of the upper Ohio-Tennessee river basin prior to the construction of dams and locks between 1916 and 1923 (Blaock and Sieckel 1996). In Kentucky, a portion of the lower Cumberland river, for example, contained 25 species in 1911, 15 in 1981 and only 4 in 1994. A total of 21 extirpations were registered.

4.4 Impacts on birds and mammals

For freshwater species impacts of dams are mainly negative. Waterfowl the situation can be different. In several occasions, reservoirs provided new habitats for waterfowl over-wintering, in cool regions and for birds resident in (semi) arid regions that have few natural water bodies. Their diversity is, however, not likely to be as high as in natural lakes.

The impounding of rivers has impacts on terrestrial biodiversity. The biodiversity of land flooded by reservoirs, and floodplains, wetlands, oxbows and other river valley aquatic ecosystems deprived of normal flooding may be diminished or lost. River catchments provide habitat for many different species of birds and mammals. Many species have territories, home ranges and feeding circuits associated with rivers and their tributaries. Although there have been numerous studies on the effects of regulation on aquatic species, there have been relatively few studies into the effects of river regulation on birds and mammals.

Reservoirs inundate terrestrial ecosystems with the loss of much natural habitat and wildlife. Particularly in tropical areas, flooding native forests, high in endemic species with limited ranges, can extirpate many species and in some circumstances may result in species extinction. However, such losses documented very rarely because of the lack of scientific data.

In arid climates reservoirs provide a permanent water resource that may benefit many species. Reservoirs can aid migrating birds by providing stop over sites. However, many species of waterfowl nest close to the ground and large and irregular fluctuations of reservoir levels can cause damage to their nests and eggs.

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. In England and Wales there are over 500 water supply reservoirs. These provide habitat for birds and other water-associated organisms and are particularly valuable because extensive areas of wetland have been drained. The general importance of these reservoirs to wildlife conservation is indicated by the designation of 174 as Sites of Special Scientific Interest (Moore and 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. In the long term, reduced flooding can alter vegetation communities (section 4.1) which are very important for a wide range of mammal and bird species. In arid regions, near river vegetation may be the only significant vegetation and many animals will have adapted behavioural patterns to fit with seasonal flooding. Sufficiently wide continuous ribbons of river woodland may also be necessary for the maintenance of diverse bird assemblages. If the flooding regime is altered, changes in vegetation may place at risk the birds and animals that depend on it (Box 4.3).

4.5 Cumulative Impacts

River impoundment affects the downstream environment so dams built in the same catchment, either in series along the same river or in parallel on different tributaries inevitably result in cumulative impacts. An individually insignificant impact may, when combined with others, produce a major change within a river ecosystem. The total effect on a river ecosystem of cumulative impacts can in some circumstances be greater than the sum of each individual impact.

The addition of each new dam in a river contributes to the fragmentation of habitat and separation of populations. Gene flow, hitherto bidirectional, becomes unidirectional, downstream, reducing genetic diversity. Each new dam also prevents natural restoration of upstream populations lost through natural or anthropogenic causes. One of the biggest cumulative impacts may be that a greater proportion of running water is converted to still reservoirs habitat.

5. Avoiding and minimising environmental impacts of dams

Dams alter river ecosystems and can have a negative impact on biodiversity. Engineers, environmental scientists and ecologists have striven to understand how dams affect the ecology of running water and to determine how the adverse effects may be rectified or prevented (IEA, 2000). These efforts have resulted in the development of a broad range of mitigation technologies. Some of the early efforts to comply with the environmental protection statutes were devised to mitigate continuing impacts of existing dams. Many of these mitigation measures were developed for and implemented at some of the major dams in countries such as USA, Australia, France, Norway and Switzerland. The integration of environmental considerations into the planning and operation of large dams has increasingly been developed in many industrialised nations but is far less common in developing countries.

5.1 Ameliorating negative dam impacts

Box 4.3 Impacts of changing flood dynamics on wildlife in Mana Pools National park, Zimbabwe (source: Petts, 1984)

The construction of the Kariba Dam on the Zambezi River has had a significant impact on the ecology of the Mana Pools Game Reserve, located 130 km below the dam. Prior to construction of the dam, the foodplain was inundated in most years. Floods, which persisted for 3 months or more, supplied silts and nutrients and flushed stagnant pools. At the same time, large herbivores were driven off so that the vegetation could recover from the intense grazing pressure it was subjected to during the dry season. River regulation has reduced the ecological dynamism of the floodplain, resulting in reduced productivity. Flood control during the wet season has induced a response in the vegetation's composition to one favouring drier conditions. Floodplain pools have become infested with emergent rooted aquatics and water fern. Furthermore, the reduced flooding has allowed grazing to continue for much longer periods. Some herbivores now spend virtually all year on the floodplain. Consequently, the floodplain habitat is placed under stress. Overgrazing has resulted in habitat reduction and is believed to be the cause of reduced populations of some species.

A range of technical and socio-economic interventions has been devised to ameliorate the most damaging impacts of dams. These can be classified into four types of strategies:

- those that avoid anticipated adverse effects;
- those that mitigate or reduce those undesirable effects that cannot be completely avoided;
- those that compensate for effects that can neither be avoided nor sufficiently mitigated;
- those that, for existing dams, attempt to restore ecosystems to an approximation of pre-disturbance conditions.

The development and implementation of an amelioration strategy has technical, economic, social and political implications. Questions such as: What can be mitigated at a reasonable cost? How much impact must be mitigated to make the project socially and politically ac...... Below description is given of the four types of strategies together with examples and some of their implications.

Measures to avoid impacts

The best way to manage negative environmental impacts is to avoid them in the first place. The implementation of an avoidance strategiy maintains the unchanged functioning of a particular ecological area or resource.

The most obvious option for avoiding the impacts to aquatic and terrestrial ecosystems arising from the construction of a new dam is not to build it (Box 5.1). There are a variety of alternatives to constructing a water supply reservoir that should always be considered in the planning phase. Discussion of these is beyond the scope of this document, but they include, for example, water demand management, water recycling and rainfall harvesting. In addition, increasing efficiency of energy use or electricity production from alternative sources (e.g. solar, wind, thermal or nuclear) are all approaches that reduce the need for dam construction for hydropower. All alternatives have economic, social and environmental consequences that need to be weighed against those arising from dam construction.

An effective way to avoid widespread adverse effects to environmental resources at the national or regional level is to initiate a development strategy that commits a single river basin to development while limiting development in other river basins. By adopting a strategy whereby multiple water resource developments are concentrated in a relatively few basins, the ecological resources located in the other basins may be conserved. Implementation of such a strategy however, can most likely be implemented only at a national or regional level. Currently, the national hydropower strategies of Switzerland (Truffer, 1999a, b) and Norway (Larsen, 1999; Flatby and Konow, 1999) involve the "set aside" of particular river basins for the purpose of environmental protection.

Implementation of a strategy to set aside river basins with unique and relatively undisturbed ecosystems might be possible in some of the developing nations. Also, hydropower development strategy studies are currently developed Lao PDR and Vietnam, with assistance of the World Bank and the Asian Development Bank. The adoption of such a strategy may be of significant value in these countries where biological diversity is significant and interest in minimising cumulative effects of hydropower projects is high.

The concentration of dams in a single basin has important social and economic implications. Building all dams in one catchment increases the risk that water resources will be insufficient during extended periods of low flow. For example, the hydropower dams in Kenya are concentrated in a single catchment (the Tana River) that has recently experienced a serious drought. In the past the Tana river hydropower scheme produced up to 80% of Kenya's electric power. As a result of the drought the whole country has suffered from severe shortages in electricity (UNEP and Government of Kenya 2000).

Avoidance of adverse impacts to ecological resources may lead to conflict with other policy objectives in the decision-making process. According to World Bank Policies regarding environmental impacts (OP/GP/BP 4.01, 1999) a main objective in project planning is to avoid ecological impacts to the extent possible. Similarly, World Bank ODs 4.20 and 4.30 require involuntary relocation requirements to be minimised. The conflict here is that in many instances, significant ecological resources frequently occur where population density is low and damaged areas occur where population densities are great.

Assuming that ample justification and rationale is presented for continuing with development within a particular river basin, the second most obvious opportunity to avoid impacts to ecosystems is to select a location where significant ecological resources do not occur or significant adverse effects are not anticipated. Geological, hydrological and topographic conditions within a river basin will usually dictate suitable alternatives for the development. In many cases alternative locations within a basin are available and the selection of an alternative location may avoid impacts to significant ecological areas or resources.

Beyond the actual selection of a site, adjustments to the alignment of a dam is configuration may be made on the basis of environmental criteria. Factors that may be considered in developing the configuration of the project include dam height (maximum elevation of the water surface of the impoundment) and dam alignment. In many cases, constructing the dam to a lower elevation may avoid inundation of ecologically sensitive areas, for example those that provide habitat for rare, endangered or endemic species. Such adjustments must be based on an adequate understanding of the environmental conditions within the river basin as well as outside the project area.

Measures to mitigate impacts

Mitigation measures are modifications to the structure or operation of a dam to reduce negative environmental impacts. Ideally, mitigation measures are identified through an Environmental Impact Assessment (EIA) so that adverse effects are minimised from the outset of a project. However, present understanding of natural ecosystems means that almost always some negative impacts are not foreseen prior to dam construction (Box 5.2). Consequently, there is a need for a regular re-evaluation for the necessity of new and effectiveness of existing mitigation measures throughout the life of a dam. Measures should be introduced retrospectively when necessary.

A wide range of technical mitigation measures has been developed. These are applied either in the upstream catchment area, in the reservoir itself or downstream of the dam (Table 5.1). To be successful in a specific situation mitigation actions require a great deal of understanding of complex processes and their interactions. Any strategy will be of limited effectiveness, or may even have undesirable effects, if scientific and engineering studies are not conducted beforehand.

A mitigation measure, that often receives wide publicity, is the pre-impoundment rescue of large terrestrial animals from the area to be flooded. For example, 10,000 animals were rescued from drowning prior to the filling of the Afokaba reservoir on the Surinam River in South America (Dynesius and Nilsson, 1994). However, often the rescued animals are relocated in areas where there is insufficient carrying capacity to support the influx of new animals and it is rarely a success.

Mitigation measures, upstream and within reservoirs, generally focus on the maintenance of water quality, prevention of thermal stratification and reduction of sedimentation. Removal of vegetation prior to reservoir filling can reduce problems associated with biomass decomposition. However, unless leaves, twigs and litter are removed the benefits may be limited.

Mechanisms to control water temperature and dissolved gases, particularly oxygen frequently resolve other water quality problems. Water column mixing methods have been developed to prevent stratification and maintain aerobic conditions in the bottom waters. Building water treatment systems for water flowing into the reservoir or introducing catchment strategies that reduce the inflow of domestic sewage and runoff from agricultural or industrial areas can be effective means of reducing water quality problems.

Appropriate measures that reduce erosion in the catchment such as improved tillage or conservation of forests, can reduce sedimentation. Measures to minimise shoreline erosion in the draw-down zone of a reservoir include appropriate management of levels and flows and the use of vegetation resistant to the prevailing filling and draw-down regime. Removing sediment once it is in the reservoir, for example by flushing or dredging is difficult and costly and ca have severe environmental impacts down stream..

Downstream of dams it is the modification of the hydrological regime and associated changes that most damages aquatic ecosystems. One measure that is now increasingly common practice is the maintenance of so called "environmental flows". This is water that is left in a river system, or released into it, to manage the health of the channel, banks, wetlands, floodplains or estuaries. They are used as a management tool for conserving aquatic and terrestrial habitats and species, as well as the natural resources used by people. Increasingly, release regimes are planned to mimic the natural seasonal variation in flow. In some situations where rivers would naturally dry up at certain times of year, this may mean very small or even zero release. Increasingly, consideration is being given to the release of flood flows to maintain floodplain and delta ecosystems. High flow releases may also be made to stimulate fish migrations and flush aquatic weeds from rivers.

Environmental flow releases may reduce the revenues that can be generated from a project. The effect of environmental flow releases on the "feasibility" of a project may range from 5 to 20% of the realised or anticipated revenues from a project (Onta, 1999; MHSP, 1998;). In effect, the environmental flow requirement becomes a component of the operating expenditure for the project (Hagler-Bailly Canada, 1998).

Managed floods can partly mitigate for geomorphological changes that may occur downstream of dams by preventing aggradation. Approaches to mitigate the problems of downstream erosion, arising because of sedimentation in the reservoir, include the artificial addition of sediment, so called river feeding. However, this is costly and has not been widely attempted. More common are a variety of channel stabilisation methods, including the planting of appropriate riverside vegetation and the construction of retaining walls or the placement of rip-rap along the river banks. Mechanisms for rejuvenating estuaries include the planting of mangroves and pumping sediment washed offshore back into the estuary.

Reducing the impact of dams on fish migration has in some circumstances been achieved by installation of various types of fish pass and through improvement of turbine, spillway and overflow design to reduce fish injury and mortality. The effectiveness of fish passes have proved to be varied. Some of the problems are attributed to navigational difficulties for migrating fish, inappropriate dimensions, clogging of the facility and increased predation in the still waters along fish ladders. Such difficulties highlight the need for extreme care in the design and operation of mitigation measures.

Measures to compensate

No scheme will ever fully compensate for the natural resources and functions that are lost as a consequence of dam construction. Compensation can be viewed as a form of repayment for anticipated or realised negative dam impacts (both upstream and downstream) that can neither be avoided nor mitigated to an acceptable level. Principle approaches include preservation of existing ecologically important areas rehabilitation of previously disturbed land around impoundments (Box 5.2).

Dam decommissioning and river restoration

In industrialised countries, some rivers or river stretches on which dams are constructed are being restored, to an approximation of pre-disturbance conditions. Within this context dam removal is increasingly being considered as a viable option for the potential restoration of river ecosystems. In the USA 465 dams have been removed. The majority are small (i.e. < 5 m) and medium (i.e. 5 to 15 m) dams (American Rivers, 2000). To date very few dams greater than 20 m high have been decommissioned. The removal of dams in part indicates changing societal standards and in part reflects simple economic considerations. Increasingly society is placing greater value on "natural" systems and in many cases environmental enhancement is the primary consideration in dam removal (Box 5.4). In other cases dams reach the end of their design life or have become a safety hazard and decommissioning is considered the least expensive alternative option.

To date there has been very little research into the environmental impacts associated with dam removal. The primary concern in most dam decommissioning cases is the fate of sediment stored in the reservoir. The rapid washing of this sediment downstream, immediately following dam removal, can result in drastic changes to channel geometry and substrate conditions and may have a derogatory effect on fish and other river organisms. The problem is compounded if the sediment is polluted.

Following dam decommissioning the rate of recovery of ecosystems is unclear. It is postulated that in some circumstances decades or even centuries will be required for complete recovery of areas inundated by a reservoir. There are methods of mitigating the worst negative environmental impacts of dam decommissioning. These include removal of sediment prior to dam removal and active management upstream of the former dam site to stabilise sediments and encourage the return of naturally occurring plant assemblages.

Box 5.1 Avoiding impacts: Sugarloaf dam complex, Australia
(source Casinader, 1999)

A two-dam complex, Sugarloaf and Yarra Brae was proposed for the Yarra River to provide water supply reserves for Melbourne. Main issues involved streamflow and water quality, vegetation and wildlife, social and recreational effects. The Yarra Brae would inundate significant ecological and recreational resources in addition to requiring relocation of 39 dwellings. After consultation, the Yarra Brae was replaced with a small weir to divert some water (73% of initial scheme) to Sugarloaf Reservoir. Continuing review led to elimination of the weir but provided for the diversion through placement of the intake within the existing river channel. Also, the effects of the surface pipeline were avoided by constructing a tunnel to transport the water.

5.2 Constraints to successful amelioration

Case studies show that amelioration interventions are successful in specific circumstances but are not effective in all cases. Constraints to successful implementation of amelioration arise for technical reasons and because of limitations in human, financial and institutional capacity.

Lack of scientific knowledge is at present the primary constraint on amelioration in both the developed and developing world. For most river ecosystems there is limited understanding of complex natural processes and the way that dams cause changes in abiotic steering variables that have wider effects on biota. Despite the research conducted to date, it is in many cases impossible to predict, even with site specific studies, what many of the precise impacts of a dam will be (see box 5.2).

Failures of mitigation measures generally stem from the lack of sufficient information needed during the design stage. Available descriptions of effective mitigation measures generally do not include the underlying assumptions or specifications that were used to design the measures. Without appropriate criteria and specifications for their design, it is highly probable that mitigation measures will not achieve the desired goals. Information needed to develop the necessary criteria and specifications includes species composition, habitat characteristics and the habitat requirements of the species. This information must be supplemented with adequate descriptions of the expected physical and chemical characteristics arising from the dam and operating regime.

To a large extent the effectiveness of amelioration depends on the capacity both of those people who determine which negative environmental impacts need to be alleviated and those who design and implement a particular amelioration strategy. In many parts of the world, the requisite professionals are unavailable or not proficient in the interdisciplinary working habits necessary for amelioration to be successful.

Often the responsibilities for planning, monitoring and regulation of dams are spread across a large number of institutions. Disparate organisation can result in problems relating to management co-ordination and the identification of responsibility. Very often the ecological and socio-economic monitoring required both for design prior to construction and afterwards to assess the effectiveness of amelioration measures is inadequate. Without such monitoring the assessment of compliance with existing legislation is very difficult. Furthermore, many countries, particularly in the developing world, have neither the necessary framework to ensure legal compliance nor organised civil society to enforce recommended amelioration measures. In such situations the contractual arrangement with the donor may be the major means for ensuring compliance. However, in the absence of a transparent, accountable system this arrangement is rarely successful.

Box 5.2 Anticipating and predicting ecosystem impacts

Over the last decades, increasing attention has been given to assessing the impacts of large dams on ecosystems. The WCD (2000) reported that in a sample of 87 dams the percentage of unanticipated impacts declined from 83% to 36% between the 1950s and 1990s. For less then 25% of those anticipated impacts mitigation was undertaken. About half of those projects recorded the effectiveness of mitigation, indicating that 40% of the implemented measures did not mitigate the impact. Thus, although ecosystem and species impacts of dams can increasingly be predicted, their mitigation is not fully undertaken, the effectiveness of mitigation is limited and the monitoring of mitigation can be much improved.

Experience of successful mitigation indicates that developing the scientific knowledge needed to mitigate and manage impacts involves significant financial resources. In many projects funds for conducting environmental impact assessments and for post project monitoring are often only a very small fraction of the total project costs and in many cases insufficient. Environmental impact assessments are very often viewed simply as an "add-on", a hurdle that has reluctantly to be overcome to enable the project to go ahead, but for as low a financial cost as possible.

To be successful, amelioration strategies require:

- good information and competent professional staff able to formulate complex issues, collect data and design option for decision-makers;
- an adequate legal frameworks and compliance mechanisms;
- sophisticated and transparent co-operation between design teams and all stakeholders;
- adequate long-term monitoring and evaluation of mitigation effectiveness;
- sufficient financial and institutional resources.

As the science base develops and the capacity gaps are filled the amelioration of negative dam impacts are likely to improve. However, this process will take several decades to be completed and requires continued public attention and politicat will to be persuit..

Table 5.1 Examples of measures to mitigate the impact of dams on ecosystems

Environmental issue	Mitigation measures that influence conditions	
	Upstream and in the reservoir	**Downstream of the dam**
Flow regime	-	Water releases from the dam to maintain downstream Environmental flow requirements
	-	Managed flood releases
Thermal regime	Changes to inlet structure configuration Artificial mixing by mechanical mixer Flushing to reduce residence times Artificial mixing by fountain jets or compressed air	Multilevel outlet works
Water quality	Catchment management Pre-impoundment clearing of reservoir Reservoir re-aeration Treatment of reservoir inflows Flushing to reduce residence times	Outlet works aeration Multilevel outlet works Turbine venting
Sedimentation	Catchment management	River feeding to Maintain morphology
	Debris dams Sediment flushing Utilisation of sediment density currents	Managed flood releases Shoreline stabilisation Pumping offshore sediment to estuaries
	Sediment dredging	
Plant Weeds	Harvesting (e.g. mechanical cutting) Chemical control (e.g. herbicides) Biomanipulation (e.g. introduction predator)	Harvesting Chemical control Biological control Flushing
Fish	Man-made spawning areas	Freshets to stimulate Fish migration
	Removal of sand bars across tributary mouths	Fish passes
	Construction of islands for shallow water habitat	Improved design of turbine, spillways and overflows
	Introduction of lake species into reservoir	Man-made spawning areas Hatcheries and fish stocking
Terrestrial wildlife	Wildlife rescue	Managed flood releases

5.3 Mechanisms for promoting the integration of amelioration strategies into large dam development

The integration of mitigation and compensation strategies into large dam developments has been motivated by four basic mechanisms at the international and national levels:

- *Public pressure for protection and enhancement of environmental resources;*
- Enactment of environmental agreements at the international level and statutes and regulations at the national and local levels;
- Requirements of multilateral and bilateral financial institutions as conditions of financial support;
- Corporate policy to maintain customer loyalties.

Public pressure

In many industrialised countries the principal mechanism for integrating amelioration measures into large dam developments stems from public demand for maintenance of, or improvement to, environmental quality. Often, commercial interests, particularly from fisher communities whose livelihoods are directly or indirectly affected by dams, drive the demand for rectification of those effects. With increased leisure time availability force in industrialised nations, demand for recreational opportunities led to demand for improving the aesthetic and recreational opportunities at large dams. Added to this popular demand is, the growing scientific evidence that environmental resources are finite and limited and efforts are needed to improve environmental conditions. Currently, public demand for protection and maintenance of environmental resources, expressed through a large number of NGOs, remains one of the primary driving forces for incorporating amelioration measures into new as well as existing dam projects.

National legislation and International Agreements

Public demand for improved environmental conditions and the protection of existing resources led to the adoption of environmental policies and enactment of various statutes and regulatory frameworks by national governments (Binnie, 1999; Cunningham and Saigo, 1999). Significant examples of these environmental laws are the National Environmental Policy Acts and similar laws passed by the governments of many industrialised nations (e.g. Australia, France, Germany, United Kingdom, and USA). Governments of many other nations have either passed significant laws and regulations and have set environmental policies or are in the process of doing so. In many cases, the government, through its establishment of environmental policies or enactment of environmental statutes and regulations has become a major mechanism for integrating avoidance, mitigation and compensation measures into resource developments.

> **Box 5.3 Five nature reserves established to compensate for Gariep and Vanderkloof dams in South Africa** (source Skinner, 1999)
> After constructing the Gariep and Vanderkloof dams on the Orange River, lands acquired to accommodate flood levels were excised and set aside for flora and fauna conservation. The reserves, occupying a total of 56,000 ha, are owned by the government. They are run by provincial Nature Conservation Authorities. The Oviston Nature Reserve remains one of South Africa's best game areas. Jointly the five reserves provide economic benefit to the area through exploitation for recreation. Opportunities include bird and game viewing, hunting, hiking, mountain-biking and 4x4 vehicle trips. The reserves cater for more than 170,000 visitors each year. According to the managers the reserves would not have evolved without the reservoirs. Major drawbacks to the reserves arise primarily from their linear configuration that complicates effective management.

The enactment of the environmental laws at the national level has expanded to the international level through a number of international treaties and agreements to protect significant ecological resources. Although not relating specifically to dams these agreements provide the context and justification for amelioration measures, since they commit the signatory nations to either protect or enhance their environmental resources or to develop programs that lead to sustainable development of those resources. These conventions and treaties include: Convention on Wetlands of International Importance Especially as Waterfowl Habitat (the Ramsar Convention), Convention on the Conservation of Migratory Species of Wild Animals, the UN Convention on Biological Diversity, UN Convention to combat desertification and UN framework Convention on climate change.

Policy and Requirements of International Institutions

The policies and requirements of many multilateral, bilateral and private investment institutions promote the integration of amelioration measures into large dam projects. These organisations (e.g. World Bank, European Union, AusAid, USAID) have developed, and are continuing to update policies regarding the integration of environmental considerations into projects that they are willing to support. Through these requirements and the respective conditions of loan agreements, developers and owners of water resource development projects are required to integrate mitigation and compensation measures into their developments.

Box 5.4 Decommissioning of the Edwards Dam, USA. (Source : American rivers 2000)
When in 1997 the Federal Energy Regulatory Commission (FERC) in the USA ordered the removal of the Edwards dam it cited the following compelling environmental considerations :

- power produced at the dam can easily be replaced by existing resources in the region;
- removal will provide 9 species of fish with continuous access to 17 miles of spawning habitat;
- removal will provide 4 species of fish that do not use fishways, with access to their entire historic range within the Kennebec river;
- wetland habitats, recreational boating and fishing will benefit;
- there will be no major environmental or social drawbacks.

The removal of the 7.4m high dam cost $2.9 million, and in July 2000, one year after breaching, an estimated two million alewives as well as striped bass, shad, sturgeon and Atlantic salmon have recolonised the river above the old dam site. The settlement that allowed removal of Edwards Dam also provided $4.85 million for associated fish restoration efforts in the basin, including river restoration projects and stocking of some fish species.

One of the constraints that is faced by these international financial institutions is that, once a dam is built and becomes operational, their ability to enforce implementation of effective mitigation or compensation programs is limited. Generally, the financial institutions must rely on the national legal framework and local institutional capacities to ensure that promised mitigation and compensation programs are implemented. To assist in strengthening national environmental capacities, many of the institutions are providing financial support to bring international expertise to national governments to assist in developing their regulatory frameworks and their capacity for reviewing and enforcing the regulatory framework.

"Good will" policies of developers

The desire to become perceived as an "environmentally friendly" corporation has led many developers to voluntarily incorporate amelioration measures into their projects. By adopting a mitigation and compensation policy, many developers seek support from certain consumer groups. The benefit for the company is improved image and greater acceptability of its products. They publicise their actions to solicit selection of their products in preference to that of competitors. Thus the costs of amelioration measures are perceived as investment to increase future profits. At this time, this voluntary integration of mitigation and compensation measures into large dam schemes is likely to be most achievable in more industrialised nations where consumers have the wealth and are willing to contribute to the increased cost. (Truffer, 1999a; Morris and Scarlett, 1996). It is likely that similar situations will become more prevalent in some developing nations in the future.

5.4 Mechanisms for funding amelioration strategies

The usual assumption for financing amelioration measures is that the organisation responsible for the development is responsible for financing because it is the developer that will reap the primary benefits of the project. If, the basic mitigation and compensation plan is enhanced to take advantage of other opportunities to or initiate additional environmental and social programs other funding could be available. This may not be served directly through the project but rather from additional funding from other sources. Ideally, these additional programs are incorporated through a participatory planning process during the planning and design of a large dam. More commonly, at least to date, these additional programs are incorporated at a later time after construction when the social, economic, and environmental conditions have stabilised and additional programs are identified.

Recently, determination of the economic value and resource utilisation has become a major focal point for determining the potential financial support for conservation and enhancement of environmental resources (Hagler-Bailly Canada, 1999; Aylward, 1999; Vorhies, 1999). The main thrust of the arguments is to translate the use of a resource into a revenue stream for use in environmental management. Often, the economic appraisal of a large dam fails to incorporate the potential excess costs or potential benefits that might be accrued to the project or to other projects within the basin. If these additional benefits or costs are incorporated into the benefit-cost ratio, the financial feasibility of a project is likely to change considerably and could provide additional revenue streams for environmental management programs.

To date several alternative financing mechanisms are available to acquire financial support for continuing environmental programs and to enable modification or expansion of amelioration measures. These include capitalisation of amelioration measures, funding from project revenues, government funding, bilateral and multilateral assistance, and a range of less explored options.

Capitalisation of amelioration measures

The basic mechanism for financing various amelioration measures into new dams is to incorporate the costs into the capital financing package for the project. The amelioration measures that are most readily incorporated into the capital costs of a project are those that are financed on a one-off basis such as fish passage facilities, minimum release structures, or multilevel intake structures. Other measures that can be incorporated into the capital cost include reservoir clearing, restoration and compensation for land disturbed or lost through inundation. It is now standard practice for the multilateral financial institutions (e.g. the World Bank and the Asian Development Bank) to include these costs in the financial arrangements with the developer.

This policy, however, is not as common for bilateral funding agencies and even less common for private investment groups. As a consequence, there may be considerable discrepancy between the environmental mitigation and compensation programs at different projects even within the same nation. National policies, supported by statutory and regulatory frameworks, are the primary mechanisms that provide the requirement for incorporating mitigation and compensation measures into the capital cost of the development.

Funding of compensation and management programs through project revenues

Capitalisation of amelioration costs is generally a one-off event occurring as part of the initial construction of the project. However, some amelioration measures require continued support throughout the life of the project or at least for some extended period of time. Other, unanticipated environmental effects may also become evident once the project becomes operational. In either case, a continued source of funding may be required. Examples of measures to support.

Beyond the construction period include management of terrestrial or aquatic resources such as wildlife preserves or fish management programs. Successful implementation of vegetation rehabilitation or restoration also requires a continued effort over an extended period, as does implementation of a watershed management program.

One mechanism for funding such programs is through the incorporation of an operating charge that is earmarked for environmental management programs. Such a funding mechanism may be established through, a fee for environmental management added to the tariff charged by the government or the utility. For example, tariff rates for the Ertan Hydropower Project in China were set by the Central Government and include a 0.1 fen per KWh surcharge for the environmental management program (Bizer, 2000). A second opportunity, arises where a privat, the owner agrees to contribute a portion of the revenues to either a governmental agency or to a contractor to implement and manage the mitigation

Table 5.2 Other potential sources of financial support (adapted from Bizer, 2000)

Global Environment Facility (GEF)

The goal of the GEF is to finance projects supporting the objectives of various international conventions including reduction of greenhouse gases, protection of biological diversity, protection of international waters and protection of the ozone layer. Generally, funds are available for mitigation or compensation of water resource developments (or other types of development) primarily when the affected habitats are shown to be of global significance. Consequently, such funding may be limited for specific projects but may be available for co-operative projects where incremental funding would enable broader application of a management or development concept (GEF 2000).

Debt for nature swaps

Debt for nature swaps are a potential source of significant funding for mitigation, compensation and environmental enhancement programs. In simple terms the concept entails debtor nations to exchange high interest loans for loans with lower interest rates on condition that the money saved is invested in environmental programs. Such programs have been effective in Peru, Bulgaria and the Philippines (Kaiser and Lambert, 1996). Of the funds that have been generated, no estimate is available of amounts specifically targeted for mitigation or compensation of effects of large dams.

Rents

This mechanism has been used particularly in national and international transboundary situations. Rent allocation stems from the benefits accrued to owners of facilities located downstream from projects. In particular, a storage reservoir constructed in the upper portions of a basin may significantly increase the benefits that may be accrued to the downstream projects as a consequence of further regulation of the riverflow. Consequently, it is possible that the owners of the upstream may derive a share of the revenues accrued to the owner of the downstream project through various contractual arrangements (Hagler-Bailly Canada, 1998). This mechanism is most commonly used within a national boundary but may also be imposed at the international level (e.g. the Columbia River Basin Treaty between USA and Canada). It is incumbent on the owner of the upstream development to allocate a portion of the revenue to environmental mitigation or compensation programs.

Taxes

The imposition of a tax earmarked for environmental management programs is a common mechanism for obtaining funding for compensation, rehabilitation and restoration efforts. Such taxing may be assessed directly on the water resource development either as tax on the revenues generated by the facility, a fixed resource use tax, or a fixed tax on the owner/developer regardless of the revenues generated by the facility (Hagler-Bailly Canada, 1998). The taxes may also be derived on a non-project specific basis in the form of general income taxes at the federal, state or local levels.These funds are then allocated to environmental management programs through the annual budgeting process of the government. Recently, some countries (e.g. Belize) have imposed entry taxes from foreign nationals that are earmarked for development and maintenance of recreational facilities including restoration and rehabilitation of natural resources within the country.

Royalties

In other sectors that rely on natural resources as the source of an end-product, financial support for both environmental and social programs has been derived through is the imposition of a royalty. "Owners" of the resource or the area where the resources are located, are paid a royalty or fee for the right to use or extract those resources. This method has been used extensively in the mining and petroleum sectors but to date has been used sparingly in the water sector (Hagler-Bailly Canada, 1998). Frequently, royalties are paid to governmental entities or representative organizations that represent the owners of the resources. These entities are then responsible for distributing the proceeds according to the various needs including distribution of funds for compensation, administration of the resources, as well as a variety of other governmental programs including environmental management.

User Fees

Funding of ongoing environmental management programs including rehabilitation and restoration, can be derived from the imposition of user fees at protected areas designed to preserve ecological conditions. Such fees (e.g. for entry, hiking , hunting or boating) can either be funneled into a general management fund or earmarked for specific components.

Funding through trusts

Compensation and restoration programs may be funded through targeted trusts and foundations. Several types of trusts have been established. These include project specific trusts, government trusts, advocacy group trusts and or compensation measure (NTEC, 1997). In either case, the surcharge for environmental funding is integrated into the operating expenses of facilities.

The amount of the surcharge in both cases is a negotiable component of the implementation process. Because the integration of an environmental surcharge into the tariff rate structure in essence affects the operating expenses of the project, the surcharge will affect the feasibility of the project and the amount must be determined to be acceptable (Hagler-Bailly Canada, 1998).

Government funding of amelioration measures

In countries with specific ministries and agencies established for environmental protection or nature conservation, the implementation of mitigation or compensation programs may be integrated into their jurisdiction. For existing dams, these measures are incorporated through an adaptive management of the facility. Often these programs have not been anticipated when dam is planned and constructed. Financial support for the programs must be derived from other sources. In some industrialised nations, this is achieved through ongoing funding of the natural resources ministries or agencies at various levels of government. For example, Switzerland and in the United States, federal, state or local agencies may establish and maintain parks and other recreational facilities along the margins of an impoundment through their annual budget allocation. Such facilities include management of significant ecological areas through organisations such as the National Park Service and the National Forest Service. Also, some elements are implemented and managed through the US Army Corps of Engineers (responsible for maintenance of navigable waterways), the Soil Conservation Service and other related agencies. At the State level, State Departments Natural Resources and State Park Departments may establish parks or manage the recreational fishery within the impoundment. At the local level, city and county park districts may also establish parks and other recreational facilities at an impoundment. Generally, these types of improvements to environmental conditions at a large dam facility are in addition to the basic mitigation and compensation plans of the developer and owner.

Multilateral and bilateral technical assistance packages

Both the World Bank Group, through the International Finance Corporation, and the Asian Development Bank, through its Technical Assistance Program, are able to fund many types of compensation packages. Recently, the World Bank has implemented a number of projects that are financed to provide resource management programs that are coupled with financing of water resource developments. For example, the World Bank is at present considering an environmental management project in the Lao PDR that would complement the guarantee for the Nam Theun 2 hydropower project. The coupling of resource management programs with capital development projects is an effective way of expanding the scope of an environmental or social improvement program outside the specific area affected by a water resource development. Other sources of funding have included grants and program development offered by the FAO, UNDP, UNESCO and the UNEP.

Bilateral agencies such as AusAID, JICA, DGIS, NORAD, and USAID provide funding packages to assist nations in developing the organisational framework for implementing resource management programs. In 1994, the governments of Mauritania, Mali and Senegal received financial assistance from the Dutch Development Aid Agency DGISfor a regional wetland development program to restore the ecosystem and elaborate a management plan for the lower delta of the Senegal River (Hamerlynck, et al, 1999; Vincke and Sow, 1994; Vincke and Thiaw, 1996). This program was conducted, in part, to assist in the mitigation of impacts associated with the development of the Senegal river project. This development involved construction of hydropower and water supply facilities and the construction of a barrage to prevent seawater intrusion. Among the achievements of this program was the establishment of a national park (Diawling National Park) and community-based management programs for the resources associated with the Senegal river facilities.

Other potential sources of financial support for environmental measures

A variety of other mechanisms for generating funds to use in managing environmental resources have been developed. Currently, international funding available through contributions of various nations in support of the implementation of international treaties and conventions, for example the Global Environment Facility (GEF 2000). More recently, funding for environmental programs has been obtained through various non-governmental organisations as well as corporate and private trusts. These sources of funding may be directly applied to a particular water resource development or may form the basis for environmental management at a broader level.

As indicated in Table 5.2, there is a range of sources that can provide funds for implementing ameliorating strategies. To access these the use of the generated revenues must be identified. In the negotiated agreements. The mechanisms listed can contribute significantly to implementing mitigation and compensation programs if benefits of mitigation ca be clearly shown.

Often, acquisition of funding through these mechanisms is made through third party participants in a water resource development rather than directly through the developer/owner of the facility. However, proponents of a water resource development, may increasingly seek assistance in financing environmental mitigation and/or compensation programs through one or more of these mechanisms.

5.5 Compliance with commitments to implement mitigation and compensation strategies

A difficult aspect of implementing mitigation and compensation strategies measures into large dams arises from the failure of developers/owners to comply with commitments and requirements. In many situations throughout the world, developers and owners may agree to various mitigation or compensation programs but then do not implement them during the construction or operation of the project. Often, they view the measures as unnecessary or do not have the capacity for their implemention . In such situations, some motivation for compliance with the agreements or a mechanism for redress of non-compliance is needed.

Requirements for, and enforcement of, implementation of mitigation and compensation programs associated with large dams should be implemented within the statutory and regulatory frameworks of nations. In many industrialised nations, regulatory frameworks and enforcement authorities have evolved to force developers and owners to comply with their commitments and requirements. This includes the implementation of environmental and social programs as a part of the authorization or re-authorization of the facilities. A principle components of this capacity is the effective monitoring of the performance of the development by independent third parties. Also required is an effective mechanisms for judicial redress when performance standards are not achieved. As a consequence, developers and wners can be held accountable for any lack of implementation.

In some developing countries, the lack of an authorization process, monitoring and judicial redress has led situations where mitigation measures have not been fully implemented (Onestini, 1999; Mott MacDonald, 1999). This is exacerbated by the lack of an effective enforcement procedure or appropriate national policies relating to environmental protection and nature conservation.

Until the capacities of nations are developed sufficiently, some international mechanism to independently monitor the performance of developers may be necessary. Additionally, an international mechanism for redress when environmental mitigation or compensation measures are not implemented may be desirable. Nations must voluntarily submit to such mechanism as some may be perceived it as an infringement on their sovereignty.

One possible mechanism for ensuring that a developer complies with mitigation and compensation commitments is to require the developer to establish a performance bond. The bond could be set up on the basis of individual components of the mitigation plan or on the whole plan. Such performance bonds are relatively standard practice in other sectors of the construction industry and provide significant motivation for complying with mitigation and compensation requirements. Such bonds might be a requirement of multilateral, bilateral or private financial institutions or could be administered by governments.

Another possible mechanism for ensuring compliance can be developed in collaboration with the insurance industry. A process is currently in place that requires developers to acquire insurance for risk associated with dam safety. Such policies might be expanded to include insurance against potential adverse effects to ecosystems through adjustments to the rate structures. In simple terms, by not implementing mitigation or compensation measures, the developer andowner would be required to pay significantly higher premiums to maintain the insurance. With implementation of effective mitigation or compensation measures, the developer and owner would realise a significant reduction in the premiums.

In the absence of an international convention or agreement that establishes mechanisms for compliance with needs forenvironmental protection, other compliance stimuli involve the establishment of policies within financial organisations. Both the World Bank and the Asian Development Bank have the capability of withholding funds if the developers/owners do not comply with commitments made as part of the loan agreements. However, this is limited to compliance with measures that are required during the construction period. Once a water resource development is constructed, the direct ability of the financial institutions to ensure developers and owners comply with mitigation programs is limited.

6. Conclusions and Recommendations

6.1 Synthesis of main findings

The most significant conclusions of the three wide-ranging reviews in this project, and summarised in this report, are presented below.

Freshwater ecosystems have comparatively high species diversity and provide essential goods and services

- Freshwater ecosystems have high species diversity compared to terrestrial and marine environments. Worldwide they contain 10,000 species of fish and 4,000 species of amphibians. Freshwater ecosystems harbour 40% of the world's fish species on less than 0.8% of the area of the world surface.

- Freshwater ecosystems provide valuable goods and services, such as food, timber, fish and clean water, that are essential to many rural and urban communities and societies. The total global monetary value of freshwater and wetland goods and services is estimated at USD 1.7 billion per year or 26% of the total global monitory value of ecosystem services.

- Freshwater and coastal species diversity and ecosystem functioning depend on critical river linkages between upstream and downstream areas, and river channels and floodplains.

Dams are globally significant human interventions affecting natural river flow processes

- Dams are globally significant human interventions in the hydrological cycle. Today, reservoir storage capacity equals 15% of the global annual rainfall and dams fragment 60% of the world's rivers. Only 23 % of the total river flow on the Northern Hemisphere remains unregulated.

- Dams have changed the natural flow and transfer processes along rivers, and have affected critical linkages between channels and floodplains. They have modified, through disruption of physical, chemical and biological processes, the habitat conditions to which ecosystems and species have adapted over thousands of years.

- 100,000s of small dams and 10,000s of large dams have been built during the 20th century and new dams will be constructed in the 21st century. Consequently, dam developers and owners together with societies at large will have to address the environmental impacts of dams together with their socio-economic consequences for many decades to come.

Dams have led to an irreversible loss of species and ecosystems

- There is much evidence that the response of ecosystems to dams has been multiple, varied, complex, but generally negative. The detailed nature of the impacts is difficult to predict and depends not just on the dam location, structure and operation, but also on local hydrology, sediment supplies, geomorphic constraints and the key attributes of the local flora and fauna.

- Dams have caused extinction and/or extirpation of fish and mollusc species and populations. 66 well documented cases from around the world have shown that reservoir creation and downstream changes resulting from dam construction have caused a 70% extinction of molluscs and a 53% extinction or extirpation of fish species on average.

- A common result of habitat change induced by dams is a decline in native species richness and a proliferation of non-native species.

- The creation of reservoirs has lead to the destruction of terrestrial habitats but also has, under specific conditions, induced the creation of shoreline marsh habitats often used by waterfowl.

Anticipation of the environmental impacts of dams has increased over time, but remains insufficient

- The impacts of dams on ecosystem and species have increasingly been anticipated over the last decades due to the increasing use of environmental impact assessments (EIA). A sample of 87 dams showed that between 1950 and 2000 the percentage of unanticipated impacts declined from 83% to 36%.

- The anticipation of environmental impacts has not resulted in detailed predictions of the effects of ecosystems and species, partly due to the lack of appropriate baseline data, incomplete scientific understanding of ecological interactions and insufficient attention.

Mitigation of environmental impacts of dams has been restricted and shown limited success

- A wide range of both technical and non-technical measures currently exists to avoid, minimise, mitigate and compensate for the negative environmental impacts of dams. However, access to detailed information on these is constrained by the absence of a comprehensive compendium of these measures.

- The anticipation of environmental impacts has, so far, not led to a high level of mitigation of these impacts. Of a sample of 87 projects where ecosystem impacts were anticipated, mitigation was carried out for less than 25% of the anticipated impacts.

- The results of the implementation of mitigation measures show the limited effectiveness of these measures. Several studies indicate that at least 35% of the implemented mitigation measures do not effectively mitigate the impact. This is sometimes due to technical reasons, but is also caused by a wide range of socio-economic and financial factors.

- Where avoidance, mitigation or compensation measures are implemented, insufficient monitoring of their effectiveness takes place. Of the above mentioned 87 projects, only about 50% recorded the effectiveness of implemented mitigation measures.

Mechanisms to promote and finance avoidance, mitigation and compensation of environmental impacts are still little used, but increasingly available

- Mitigation and compensation measures are increasingly built into new dam schemes based on better planning and design criteria, improved national legislation, wider public attention and increasing technical and institutional capacities.

- Limited efforts are directed towards the amelioration of adverse environmental effects at existing dams. To date, examples of such efforts are found primarily in developed countries where re-licensing of facilities is taking place or where public pressure and political will is exercised.

- The primary responsibility for financing avoidance, mitigation and compensation strategies lies with the dam developer and owner. It is increasingly recognised that the incorporation of avoidance, mitigation and compensation can enhance the project's sustainability and revenues.

- A wide range of financial mechanisms is currently available to finance avoidance, mitigation and compensation strategies. At present these are little known to most public, governmental, and development organisations, although they provide additional opportunities to be pursued separately or in partnership with a dam developer or owner.

6.2 Recommendations

The management of natural resources and particularly freshwater will be a key human endeavour in the 21st century. Most dams have been built to provide water to irrigated lands, households and industries, to produce power or to reduce the devastating effects of floods. To date, it is widely recognised that if development is to be sustainable, the effects of impoundments on ecosystems and species can no longer be ignored. The challenge is to enable human development in a manner that does not destroy the environment we depend upon, but maintains its functioning. Against this background the following recommendations are made.

Improve dam planning, development and operation

- Evaluate the construction of a dam against alternative options for water supply, irrigation and power production;

- Consider dam planning, development and operation only within the framework of river basin management and international/national/regional policies and legal and institutional structures;

- Make the planning and development of all new dams conditional to high quality Environmental Impact Assessments that include the definition of strategies to avoid, mitigate, minimise or compensate for all adverse environmental effects;

- Do not plan or build new dams in locations where they will negatively impact the habitats that are vital to the survival of internationally recognised rare, threatened, endangered or vulnerable species;

- Evaluate the operation of existing dams and, wherever possible, modify the facility and operating rules to protect ecosystems and environmental conditions, and preserve species diversity.

Increase financial support for avoidance, mitigation and compensation

- Expand the financial packages for the planning and construction of all large dams to include funds targeted specifically at avoidance, mitigation, minimisation and compensation of environmental impacts;

- Establish mechanisms to use dam revenues to retrofit existing facilities to mitigate and minimise existing ecosystem impacts and compensate for past losses of ecosystems and species.

Enhance information, knowledge and impact predictions

- Undertake fundamental research and assessments to establish the necessary baselines on freshwater biodiversity and ecosystem functioning to reduce the impact of dams on these processes and on species;

- Improve Environmental Impact Assessment (EIA) procedures to integrate avoidance, mitigation, minimisation and compensation strategies. In this context, ensure the EIA demonstrates how the project will be developed to:

    - Avoid adverse environmental effects through adjustments to project, location, size, and operating regime;

    - Mitigate for adverse effects through structural or operational measures and provide necessary information base to design and implement effective mitigation measures;

    - Compensate for residual effects including those that are not avoidable, or fully mitigable;

- Monitor and evaluate the effectiveness of the mitigation and compensation measures;
- Provide a mechanism for continuous adaptation of the mitigation strategy through the life of the project to enable mitigation or compensation of unanticipated effects, rectification of ineffective measures, and meeting of changing objectives of the local communities and resource managers;
- Propose funding and institutional arrangements to ensure implementation of the proposed avoidance, mitigation, minimisation and compensation measures and modification of the measures as necessary.

Improve performance and compliance

- Develop a prime focus of attention to the amelioration of the negative effects of existing large dams. Establish national and international mechanisms and capacities to review existing conditions and implement remedial measures to restore ecosystems damaged by dams.
- Set up and implement mechanisms to encourage, ensure or enforce compliance with commitments to carry out high quality EIAs and implement avoidance, mitigation, minimisation and compensation measures at dams. Possible mechanisms include:
- Continued assistance by multilateral and bilateral organisations to improve legal frameworks and institutional capacity in developing countries to design avoidance, mitigation, minimisation and compensation measures;
- Establishment of a system of environmental performance bonds that are coupled to implementation of avoidance, mitigation, minimisation and compensation measures;
- Co-operation of insurance agencies to adopt premium structures based on implementation of avoidance, mitigation, minimisation and compensation measures.

References

Acreman, M.C., Farquharson, F.A.K., McCartney, M.P., Sullivan, C., Campbell, K., Hodgson, N., Morton, J., Smith, D., Birley, M., Knott, D., Lazenby, J., Wingfield, R. and Barbier, E.B., 2000. Managed flood releases from reservoirs: issues and guidance. Report to DFID and the World Commission on Dams. Centre for Ecology and Hydrology, UK. 88 pp.

Agostinho, A.A., Julio, Jr., H.F. and Petrere, M. 1994. Itaipu Reservoir (Brazil): Impacts of the impoundment on the fish fauna and fisheries. pp. 171-184. *In:* I.G. Cowx. (Editor). *Rehabilitation of freshwater fisheries.* Fishing News Books, Oxford.

Agostinho, A.A. and Zalewski, M. 1995. The dependence of fish community structure and dynamics on floodplain and riparian ecotone zone in Parana River, Brazil. *Hydrobiologia* 303: 141-148.

Aylward, B. 1999. *Direct Payments, Transfers and Markets for Environmental Services.* A Paper for FAO. 31 pp + annexes.

Balogen, J.K. and Ibeun, M.O. 1995. Additional information on fish stocks and fisheries of Lake Kainji (Nigeria). pp. 1-18. In: R.C.M. Crul & F.C. Roest (Editors) *Current status of fisheries and fish stocks of the four largest African reservoirs,* CIFA Technical Paper 30, FAO, Rome.

Balon, E.K. 1974. *Fishes of Lake Kariba, Africa.* T.F.H. Publications, Inc., New Jersey. 144 pp.

Barbier, E.B. and Thompson, J.R., 1998. The value of water: floodplain versus large-scale irrigation benefits in Northern Nigeria. Ambio 27 (6) 434-440.

Blaock, H. and Sieckal, J.B. 1996. Changes in the mussel (Bivalvia: Unionoidea) fauna within the Kentucky portion of Lake Barkeley since impoundment of the lower Cumberland River. *American Malacological* Bulletin 12: 111-116.

Binnie, C. 1999. Personal Communication to Mr. J. Skinner, World Commission on Dams.

Bizer, J.R. 2000. Avoiding, minimizing, mitigating and compensating the environmental impacts of large dams. Report for IUCN/UNEP submission to World Commission on Dams.

Braimah, L.I. 1995. Recent developments in the fisheries of Volta Lake (Ghana). pp. 111-134. *In:* R.C.M. Crul & F.C. Roest (Editors) Current status of fisheries and fish stocks of the four largest African reservoirs, CIFA Technical Paper 30, FAO, Rome.

Casinader, R. 1999. Sugarloaf Dam, Australia: Note on environmental and social mitigation mechanisms in planning, design and construction. Personal Communication to Mr. J. Skinner, World Commission on Dams.

Cederholm, C.J., Kunze, M.D., Murota, T. & Sibatani, A. 1999. Pacific salmon carcasses: Essential contributions of nutrients and energy for aquatic and terrestrial ecosystems. *Fisheries* 24(10): 6-15.

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

Collier, M. Webb, R.H. and Schmidt, J.C. 1996. *Dams and Rivers: a primer on the downstream effects of dams.* US Geological Survey Circular 1126. 94 pp.

Cunningham, W. P. and B. W. Saigo. 1999. Environmental Science: A global concern, Fifth Edition. WCB/McGraw Hill, USA.

Dowidar, N.M. 1988. Productivity of the south eastern Mediterranean. pp. 477-498. In: M.I. El-Sabh & T.S. Murty (Editors) Natural and Man-Made Hazards, Reidel, Holland.

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).

Dynesius, M. and Nilsson, C. 1994. Fragmentation and Flow Regulation of River Systems in the Northern Third of the World. Science 266, 753-762.

Flatby, R. and T. Konow. 1999. Environmental Impact Assessments, Licensing Procedures and Terms of Licence (sic) – A Review of the Norwegian Experience. Proceedings of Workshop on Benefits of and Concerns about Dams – Case Studies. Pp. 69 – 76. International Commission on Large Dams, Antalya, Turkey.

Gourène, G., Teugels, G.G., Hugueny, B.,and Thys van den Auderaerde, D.F.E. 1999. Evaluation de la diversité ichtyologique d'un bassin ouest-africain après la construction d'un barrage. Cybium 23: 31-38.

Hagler Bailly Canada. 1998. Measuring and apportioning rents from hydro-electric power developments. Prepared for World Bank, Industry and Energy Department, Washington, DC, USA. 47 pp.

Hamerlynck, O., M. L. Baba, and S. Duvail. (In press). The Diawling National Park, Mauritania: Conflict and development around a newly established protected area. Submitted to Vida Sylvestre Neotropical.

Harper, P.P. 1992. La Grande Riviere : a subarctic river and a hydroelectric megaproject In: Calow, P. and Petts, G.E. (eds). The Rivers Handbook Vol 1, Blackwell Scientific Publications, Oxford. 411-425.

Helfman, G.S., Collette, B.B. and Facey, D.E. 1997. The Diversity of Fishes. Blackwell Sciences Massachusetts.

Hydro Quebec, 1999. Environmental Performance Report, 1999.

ICOLD, 1997. Position Paper on Dams and the Environment, Paris, International Commission on Large Dams.

IEA, 2000. Implementing Agreement for Hydropower Technologies and Programmes. Annex III Hydropower and the Environment: Present Context and Guidelines for Future Action, Paris, International Energy Agency.

Ishak, M.M. 1981. Effects of reservoirs on River Nile fisheries. ICLARM Newsletter 4: 11.

Jackson, P.B.N. 1989. Prediction of regulation effects on natural biological rhythms in south-central African freshwater fish. Regulated Rivers: Research and Management 3: 205-220.

Joffe, S. and Cooke, S. 1997. Management of the water hyacinth and other invasive aquatic weeds: issues for the World Bank. Report for the Rural Development Department of the World Bank.

Junk, W.J., Bayley, P.B. and Sparks, R.E. 1989. The flood pulse concept in river-floodplain systems in Doge, D.P. (ed.) Proceedings of the International Large River Symposium (LARS). Can. J. Fish. Aquat. Sci., 106, 110-127.

Kaiser, J. and A. Lambert. 1996. Debt swaps for sustainable development: A practical guide for NGOs. IUCN/SCDO/EURODAD, IUCN Gland, Switzerland, and Cambridge, UK. 72 pp.

Karenge, L.P. 1992. Inshore fish population changes at Lakeside, Kariba, between 1969-1991. M. Phil., University of Bergen. 61 pp.

Kavanagh, J. 1999. Feeding the forest. David Suzuki Foundation Newsletter, November 1999, pp. 6-7.

Kolding, J. and Karenge, L. In prep. Fish diversity, stability and disturbance in Lake Kariba 30 years after impoundment.

Kone, T. and Teugels, G.G. In press. Donnees sur la reproduction d'un tilapia estuarien (Sarotherodon melanotheron) isole dans un lac de barrage oeust africain. Aquatic Living Resources 12: 1-5.

Larsen, T. B. 1999. Norwegian Hydropower Resources: Use, management and planning. Proceedings of Workshop on Benefits of and Concerns about Dams – Case Studies. International Commission on Large Dams, Antalya, Turkey. 6 pp.

Machena, C. 1995. Recent developments in the fisheries of Lake Kariba (Zambia/Zimbabwe). pp. 41-79. In: R.C.M. Crul & F.C. Roest (Editors) Current status of fisheries and fish stocks of the four largest African reservoirs, CIFA Technical Paper 30, FAO, Rome.

Marshall, B.E. 1984. Lake Kariba (Zimbabwe/Zambia). pp. 105-153. In: J.M. Kapetsky and T. Petr (Editors) Status of African Reservoir Fisheries, CIFA Technical Paper 10, FAO, Rome.

Marshall, B.E. 2000. Fish introductions: the African experience and its relevance to Lake Nasser. pp. 145-153. In: J.F. Craig (Editor) Sustainable fish production in Lake Nasser: ecological basis and management policy. ICLARM Conference Proceedings 61.

McAllister, D.E, Craig, J.F., Davidson, N., Delany, S. and Seddon, M. 2000. Large dam impacts on freshwater biodiversity. A review for IUCN/UNEP. Submission to the World Commission on Dams 55 pp.

McAllister, D.E. 1991. Questions on the ocean impacts of James and Hudson Bay hydro projects. Sea Wind 5(3): 22-30.

McCartney, M.P., Sullivan, C and Acreman, M. 2000. Ecosystem impacts of large dams. A review for IUCN/UNEP. Submission to the World Commission on Dams 80 pp.

McCully, P. 1996. Silenced Rivers: the ecology and politics of large dams. Zed Books, London 350 pp.

MHSP. 1998. Upper Karnali (Nepal) Environmental Impact Assessment.

Moore, D and Driver, A. 1989. The conservation value of water supply reservoirs. Regulated Rivers: Research and Management 4, 203-212.

Morris, J and Scarlett, L., 1996. Buying Green: Consumers, Product labels and the environment. Policy Study No. 217. Reason Foundation, Los Angeles, CA, USA. 51 pp.

Mosquin, T. 1994. A conceptual framework for the ecological functions of biodiversity. Global Biodiversity 4(3): 2-16.

Mott MacDonald. 1999. Mitigating Large Dams. Communication to Department of Water Affairs and Forestry, Pretoria, South Africa. 12 pp.

Murray-Darling Basin Ministerial Council, 1995. An audit of water use in the Murray-Darling Basin. Canberra, 40pp.

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

Nam Theun Electric Consortium. (NTEC) 1997. Nam Theu 2 Environmental Impact Assessment. Submitted to World Bank.

Odum, E.P. 1963. Ecology. Holt, Rinehart and Winston, Inc., New York.

Onestini, M. 1999. Represa Hidroeléctrica Yacyretá: Impacto socio-ambiental y reclamos de la sociedad civil. Presentation at WCD Regional Consultation, Buenos Aires, Argentina. 22 pp.

Onta, I. R. Director, EastConsult. 1999. Personal Communication to Mr. J. Skinner, World Commission on Dams.

Petts, G.E. 1984. Impounded rivers: perspectives for ecological management. John Wiley and Sons, Chichester 326 pp.

Petr, T. 1967. Fish population changes in the Volta Lake in Ghana during its first sixteen months. Hydrobiologia 30: 193-220.

Petr, T. 1968. The establishment of lacustrine fish population in the Volta lake in Ghana during 1964-1966. Bulletin de l'Institut Fr. Afr. noire Tome XXX: 257-269.

Petr, T. 1971. Lake Volta - a progress report. New Scientist and Science Journal. pp. 178-180

Petr, T. and Reynolds, J.D. 1969. Fish population changes in the Volta Lake in 1968. FAO Technical Report.

Pielou, E.C., 1998. Fresh water.The University of Chicago Press, Ltd., London pp. 275.

Poddubny, A.G. and Galat, D.L. 1995. Habitat associations of upper Volga river fishes: effects of reservoirs. Regulated Rivers: Research and Management 11, 67-84.

Reimchen, T.E. 1995. Estuaries, energy flow and biomass extraction in Gwaii Haanas. Sea Wind 9(3): 24-26.

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

Rosa, L.P. Sikar, B.M., Sikar, E.M., Santos, M.A. 1997. A model for CH4 and CO2 emission mean life in a reservoir based on data from an Amazonian hydroplant – in Rosa, L.P. and dos Santos, M.A. Hydropower plants and greenhouse gas emissions, COPPE, 1997.

Skelton, P.H. 1987. South African Red Data Book - Fishes. pp. 199, Foundation for Research Development, Council for Scientific and Industrial Research. South African National Scientific Programmes Report 137, Pretoria, S. Africa.

Skinner, J. 1999. Gariep/Vanderkloof Compensation. Personal Communication to G. Bergkamp.

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

Stone, R. and K. Webster. 1999. Allocating water in the Harvey Basin, Western Australia: A case study in public consultation and multi-objective planning. Proceedings of Workshop on Benefits of and Concerns about Dams – Cast Studies. International Commission on Large Dams, Antalya, Turkey. 241 – 262.

Truffer, B. 1999a. Green electricity products and the sustainable use of water resources. Landau network – Centro Volta, Como, April 12-15, 1999.

Truffer, B. 1999b. Personal Communication to Mr. J. Skinner, World Commission on Dams.

Vincke, P. P. and P. A. Sow. 1994. La voie fonciere et administrative en appui a la voie ecologique et agricole pour une gestion decentralisee des resources naturelles dans le programme Apres-Barrages au Senegal. Tropicultura 12 (2): 50 – 54.

Vincke, P. P. and I. Thiaw. 1996. Protected areas and dams: The case of the Senegal River delta. Parks 5(2): 32-38.

Vorhies, F. 1999. Financing Protected Areas. IUCN Economics Unit. URL: http://economics .iucn.org. 39 pp.

Vorosmarty, C.J., Sharma, K.P., Fekete, B.M., Copeland, A.H., Holden, J., Marble, J., Lough, J.A. 1997. The storage and ageing of continental runoff in large reservoir systems of the world. Ambio 26, 210-219.

Wilcove, D.S., Rothstein, D., Dubow, J., Phillips, A., & Losos, E. 1998. Quantifying the threats to imperilled species in the United States. Assessing the relative importance of habitat destruction, alien species, pollution, overexploitation and disease. BioScience 48(8): 607-615

Zakova, Z., Berankova, D., Kockova, E., Kriz, P., Mlejnkova, H. and Lind, O.T. 1993. Investigation of the development of biological and chemical conditions in the Vir Reservoir 30 years after impoundment. Water Sci. Technol. 28 (6) 65-74.