Biodiversity Impacts of Large Dams

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Executive summary

Although occupying a smaller area compared to land and oceans, freshwaters 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). While only about 45,000 species of freshwater animals, plants and microorganisms have been scientifically described and named, scientists estimate that at least an additional million more species remain to be named.

Freshwater biodiversity is unevenly distributed. High numbers of species or endemics are found, for example, in the Amazon, Congo, Nile and Mekong basins. Such species-rich areas are called ‘hotspots’ and dominate other patterns or trends.

Already human uses of freshwater threaten the survival of freshwater, brackish, coastal and terrestrial biodiversity. The global level of threat for mainly terrestrial vertebrates is 11-25%, while for freshwater groups it is 13-65%. While this paper focuses on the impacts of large dams on freshwater biodiversity, the significant effects of large dams on terrestrial biodiversity should not be overlooked.

About 60% of the world’s river flow is regulated. There are more than 40,000 large dams and more than 100 dams with heights >150 m. Reservoirs cover a total area in excess of 500,000 km^2.

Dams and their associated reservoirs impact freshwater biodiversity by:

- Blocking movement of migratory species up and down rivers, causing extirpation or extinction of genetically distinct stocks or species.
- Changing turbidity/sediment levels to which species/ecosystems are adapted in the rivers affects species adapted to natural levels. Trapping silt in reservoirs deprives downstream deltas and estuaries of maintenance materials and nutrients that help make them productive ecosystems.
- Filtering out of woody debris which provides habitat and sustains a food chain.
- Changing conditions in rivers flooded by reservoirs: running water becomes still, silt is deposited, deepwater zones, temperature and oxygen conditions are created that are unsuitable for riverine species.
- Providing new habitats for waterfowl in particular for overwintering or in arid regions which may increase their populations.
- Possibly fostering exotic species. Exotic species tend to displace indigenous biodiversity.
- Reservoirs may be colonised by species which are vectors of human and animal diseases.
- Flood plains provide vital habitat to diverse river biotas during highwater periods in many river basins. Dam management that diminishes or stops normal river flooding of these plains will impact diversity and fisheries.
- Changing the normal seasonal estuarine discharge which can reduce the supply of entrained nutrients, impacting the food chains that sustain fisheries in inland and estuarine deltas.
- Modifying water quality and flow patterns downstream.
- The cumulative effects of a series of dams, especially where the impact footprint of one dam overlaps with that of the next downstream dam(s).
- Other human activities, including agriculture, forestry, urbanisation and fishing, although these are primarily land-based.

International agreements and organisations have established standards for minimising the negative impacts of human activities on biodiversity. Pertinent legal instruments include the World Charter for Nature, the Convention on Biological Diversity, and Agenda 21, while international organisations such as the World Bank, the World Business Council on Sustainable Development and the The World Conservation Union (IUCN), have contributed to the development of accepted standards. The standards involve conservation of species and ecosystems, the recovery of degraded ecosystems, the conser-

vation of ecological functions or processes, securing adequate information for decision making, adherence to the Precautionary Principle, and the adherence to high standards for environmental impact assessments. A short evaluation shows that many of the standards have been transgressed in the past.

A number of recommendations are made. They include:

- Avoid the coincidence of environmental impacts of dams with areas rich in biodiversity — 'hotspots'
- Avoid blocking migratory species
- Maintain natural seasonal and daily river flow cycles
- Maintain discharge volume as much as possible
- Sustain water quality — temperature, oxygen, sediment & other levels
- Avoid cumulative effects of dams — limit their number and proximity
- Take into account the impacts of other human activities when planning dams
- Apply high environmental impact assessment standards
- Involve environment staff early and at high levels in planning and construction
- Enhance delivery and conservation in extant dams
- Decommission ineffective dams & restore river ecosystems and species
- Use landscape management to make dams more effective and to protect biodiversity
- Establish protected areas to enhance the efficiency of dams and conservation of biodiversity
- Improve needed knowledge bases through research
- Explore and reduce the impacts of dams on terrestrial biodiversity

Freshwater species and ecosystems are among the most imperilled. Dams are a principal threat to freshwater diversity and that threat is largely mediated through loss of habitat frequently involving modifications to the natural flow regime and to blockage of migrations.

This offers a challenge to the dam construction and management community. Can this community make courageous and profound changes in their initiatives and, in so doing, find new opportunities for returns on corporate balance sheets and the Earth's biodiversity balance sheets?

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In memory of Don McAllister, who recently passed away.

Table of Contents

1 Introduction

This study investigates the interaction between dams and biodiversity particularly the impacts of large dams on freshwater organisms (see Oud & Muir 1997 for a definition of a large dam). In addition the following were analysed: biogeography, the application of techniques developed elsewhere in the planning and construction of dams, the minimising of dam impacts on biodiversity and the application of ecosystem-based management to enhance the performance of dams. As the analysis was carried out within a short time period it cannot be considered definitive. There have been many publications on the impact of dams on animal biodiversity although the data are weak in a number of areas including plants and small organisms.

Dams, including large dams, are constructed because of the potential benefits that they bring:

- Water for increased food production - 250 million hectares of agricultural land are under irrigation and use three-quarters of the water supply
- Generation of electric power without releasing atmospheric pollutants or greenhouse gases - hydropower contributes 20% of electricity production
- Control of floods.
- Drinking water. Of the Earth’s 6 billion people, 1.5 billion are without access to reliable sources of drinking water

The large expenditures involved with the construction and operation of large dams and the benefits for agriculture and power generation, are of considerable long-term economic importance.

Biodiversity

Biodiversity is considered at four levels: genetic; species; ecosystem and ecological function. Normally it is the indigenous or native components of biodiversity that are examined; exotic or alien species are a separate component, although interacting with the 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.

Perturbations to a species status can be measured in simple terms by reduced population sizes, extirpations (loss of populations from a part of the species range), or extinction (loss of all individuals of a species). Finer levels of species loss are provided globally by IUCN:

- Extinct (EX)
- Extinct in the Wild (EW)
- Threatened (Critically Endangered (CR) (Endangered (EN) (Vulnerable (VU)
- Under inadequate data: Data Deficient (DD)
- Under evaluated: Not Evaluated (NE)

Conserving habitats and ecosystems is the key to species conservation. Here habitat may be defined as the place where an organism lives or living space 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, 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 size and loss of habitat to extirpation. 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, *e.g.* freshwater mussel larvae (glochidia) are parasitic on the gills of fishes for part of their life cycle. In many cases specific fish hosts are required.

Status of the world's freshwaters

Revenga *et al.* (1998) describe the watersheds of the world, their ecological value and their vulnerability. The impacts to the freshwater environment by various activities or sectors are summarised in Table 1.1.

Table 1.1 Sector threats to freshwater environments

Sector	**Measure of threat**	**Impacts (Add to each, biodiversity loss)**
Agriculture	11% of land in crops, 26% in pasture. 3/4 of human water withdrawals, 250 million hectares under irrigation.	Runoff of toxic pesticides (fish kills); fertilisers and manure (eutrophication); soil (turbidity and siltation). Overgrazing (loss plant cover, bank stability).
Deforestation	50% of world's forests lost; widespread clearcut instead of selective harvesting.	Soil erosion (turbidity and sedimentation. Rapid runoff. Loss stream food/habitat (leaves, wood, insects). Changed hydrological cycles.
Dams	60% world's river flow regulated. 15% world's precipitation held in 500,000 km2 of reservoirs. Blocking of movement of local- and long-distance migrations in neighbourhood of dam.	Fish migrations blocked; stocks lost. Seasonal flows changed; flows reduced. 25 million km river habitat modified. Flood plains & deltas lost. Lowered fish production. Sediment/turbidity/nutrient changes. Running to still water.
Industry and urban areas	Release toxic substances, hormone blockers, untreated sewage. 1/4 of human water withdrawals.	Fish kills and advisories. Impaired reproduction. Eutrophication. Reduced flows.
Aquaculture and introductions	Escape of alien species. Pollution.	Competition with and loss of native biota. Spread alien pests and diseases. Loss of native habitats. Genetic pollution. Eutrophication.
Channelisation and levee construction	Simplification of river structure. 500,000 km of river altered for shipping.	Loss of habitats, flood plains and wetlands.
Fishing	Over-harvesting. Gear damage.	Reduced populations, loss of stocks, changed food webs, and habitat loss.
Acid rain	Reduction of pH (increase in acidity) of lakes and streams down to 4.5 or lower in thousands of water bodies in North America and Europe.	Reduction of populations or extirpation of species of molluscs, amphibians, fishes, etc. in water bodies. Development of skeletal abnormalities. Deposition of aluminium on fish gills.
Human population and *per capita* consumption	Doubled to 6 billion since 1975. Per capita consumption doubled since 1950.	Population/consumption rate increases magnify each sector impact above. Humans use 54% of geographically & temporally accessible water.

The table shows that indirect landscape and direct waterscape changes have had profound impacts on the freshwater environment including:

- River seasonal flow patterns (levelling)
- River flow volume (reduction)
- Accessibility of species to river segments (blockage of migrations)
- Input of organic matter (leaves, wood, insects) (reduced)
- Toxicity (increased)
- Turbidity & sediments (both increases & decreases to natural levels)
- Nutrient levels (increased).

Freshwaters, and especially rivers and wetlands, are amongst the world's most severely impacted and have received many of the direct effects of human activities. Long-term and quality data on river discharge patterns are poor. Historical hydrological data are rare for many rivers. However data from old air photos and satellite images, including the new Radarsat images, which can be made through clouds, offer a promising source of information in particular the extent of flooding in the river floodplains.

Table 1.2 Proportion of terrestrial and freshwater vertebrates globally threatened

Group	Proportion Threatened (%)
Mammals - all	25
Land birds	11
Waterfowl (freshwater)	13
Turtles, tortoises and terrapins	38
Crocodiles	43
Amphibians	25 (estimated)
Freshwater fishes	33 (estimated)
Freshwater mammals (freshwater dolphins and otters)	65

An analysis by Postel (1996) indicates that humans presently use 54% of the geographically and seasonally accessible runoff. Demands by the year 2025 may increase to more than 70% of accessible runoff. The existing and growing friction between countries over shared waterways shows that humans are already facing water shortages that are international in scope. Problems already exist at the national and local level between and within sectors such as agriculture, domestic users and industry. The fixed supply of water poses profound problems for how it will be shared by aquatic life and increasing demands of humans.

Status of the world's biodiversity

Assessing the status of biodiversity at the global level is difficult because the evaluation is incomplete and uneven. Birds are quite well assessed, oligochaetes poorly, and many microbiota not at all. The IUCN *Red Lists* ease the task by bringing together what is known and applying uniform criteria. However, summaries do not separate freshwater biota from biota in other environments. Table 1.2 summarises terrestrial and freshwater vertebrate data at the global level. The level of threat for dominantly terrestrial vertebrates is 11 to 25%, while the remaining values for groups occurring more frequently or uniquely in freshwater range from 13 to 65%. This gives a sense that, globally, freshwater species are more at risk than terrestrial species. Waterfowl are more threatened, 12.7%, than land birds, 10.8%. Similarly, freshwater mammals are more threatened, 65%, than all mammals, 25%.

Data for North American animals is more complete and the proportion of selected groups of animals at risk is given in Table 1.3. These data indicate that freshwater animals are much more at risk, 39 to 68%, than predominantly terrestrial ones, 15 to 17%.

Molluscs. Extinctions are a significant problem in terrestrial, freshwater and marine molluscs. Of all the species that became extinct since 1600 AD, 37% were mollusc species, which is more than any other group evaluated (birds 17%, mammals 14%, fish 14%, reptiles 3%, and all others 15%). These percentages refer to the total known globally. It should be made clear that the percentages are affected by the degree to which the group has been studied and the number of species in the group, *e.g.* the status of birds is better studied than that of molluscs, but there are more mollusc than bird species.

Table 1.3 The proportion of selected North American animals at risk (from Stein & Flack 1997)

Group	Proportion at risk (%)
Birds	15
Mammals	17
Freshwater fishes	39
Amphibians	40
Freshwater crayfishes	51
Freshwater mussels	68

The 1996 IUCN *Red List of Threatened Animals* lists 12 bivalves and 216 gastropods as extinct, and 114 bivalves and 806 gastropods as threatened, for a total of 228 extinct and 920 threatened terrestrial, freshwater and marine molluscs. About 18% or 145 of the threatened molluscs are spring molluscs. Data on threatened freshwater molluscs are given in Table 1.4).

Spring snails in the critically endangered category in Austria, Australia and United States are threatened by over-abstraction of water from their habitat or by pollution. African freshwater molluscs are threatened by decline in quality of water, pollution, damming, and increased sediment load.

Table 1.5 and 1.6 provide information on the status of North American and Australian freshwater molluscs (since the latter table was made, a further 66 freshwater species have been described, many from the family Hydrobiidae).

Wilcove *et al.* (1998) reviewed the threats to imperilled species in the United States. They found that the chief threats to freshwater molluscs were habitat degradation and loss, 97%, pollution, 90%, and alien species, 17%. The chief causes of habitat loss were water development, 99%, pollution, 97%, dams and other barriers to flow, 96%, and agriculture 64% (note that more than one threat can act on a given species so the threats do not add up to 100% although they indicate their relative importance). More recently in North America, alien zebra mussel invasions have become the major factor in loss of native mussel diversity (Ricciardi & Rasmussen 1999).

Table 1.4 Freshwater molluscs in the IUCN 1996 Red List of threatened animals

Risk category	Bivalves	Gastropods	Total molluscs
Extinct	12	14	26
Critically endangered	85	60	145
Endangered	24	86	110
Vulnerable	8	194	202
Near threatened	66	35	101
Data deficient	4*	104*	108*
Total listed	199	493	692

Fishes. The 1996 IUCN *Red List* of Threatened Animals lists 617 freshwater fishes (including euryhaline species); about 6% of the known number of freshwater species. The *Red List* has evaluated only a fraction of freshwater fishes, therefore a conservative estimate gives 20% as extinct, endangered or vulnerable, or more realistically 30-35% (Stiassny 1996).

Table 1.5 USA Federal register of threatened status of North American freshwater mollusc fauna (after Bogan 1998)

Category	Total bivalves	%	Total gastropods	%	Total freshwater
Taxa	300		601		901
Candidate taxa	61	20.3	173	28.0	244
Threatened taxa	5	1.7	0	0	5
Endangered taxa	57	19.0	9	1.5	66
Extinct taxa	35	11.7	42	7.0	77

In the United States, freshwater fishes have been threatened by water development (91%), dams, impoundments and other water barriers (64%), pollutants (55%) and agriculture (45%) (Wilcove *et al.* 1998).

Birds. According to the 1996 *Red List*, 1,107 species or 11% of all bird species are threatened and 104 are extinct. Amongst the more threatened of bird groups are the aquatic Gruiformes (rails and cranes) with 54 species, and the partially aquatic Coraciiformes (kingfishers and bee-eaters) with 11.5% threatened, while 18% of the Podicipediformes (grebes) are threatened. Extinct aquatic birds include the Colombian grebe (*Podiceps andinus*) and the Atitlan grebe (*Podilymbus gigas*). Thirteen per cent of globally threatened birds are (freshwater) water-birds. There are 90 species of critically endangered, endangered and vulnerable water-birds. This suggests that water-birds are slightly more threatened than land birds. Habitat loss and degradation are the key factors affecting threatened species. This is generally due to the loss and change through drainage and land reclaiming, converting natural wetlands into urban and industrial lands in Europe and into agricultural land in North America.

Table 1.6 Threatened status of the freshwater mollusc fauna in Australia (after Beesley et al. 1998)

Status	NSW	QLD	VIC	SA	WA	NT	TAS	Total
Taxa	42	56	37	34	31	27	42	178
Endemic to State	11	24	16	11	20	8	86	176
Threatened	1	13	5	9	1	0	60	88

NSW = New South Wales, QLD = Queensland, VIC = Victoria, SA = South Australia, WA = Western Australia, NT = Northern Territory and TAS = Tasmania

Plants. There are about 270,000 scientifically described species of vascular plants, but the true number may be in the order of 300,000-350,000 species (WWF & IUCN 1994). Two important documents on global plant biodiversity have been published in recent years, *Centres of plant diversity*, in three volumes (WWF & IUCN 1994, 1995, 1997), and the 1997 IUCN *Red list* of threatened pl*ants* (Walter & Gillett 1998). About 78% of the world's plants are tropical (the zone between the Tropic of Cancer and the Tropic of Capricorn). More than 40,000 plant species, about a quarter of the world's tropical plant diversity, occurs in Colombia, Ecuador and Peru, while Brazil has between 40,000 and 80,000 species. Tropical and subtropical (areas north and south of the tropics but outside of the temperate zone) Asia has at least 50,000 species and Southern Africa has 21,000 species of plants, of which 80% are endemic.

The *Red list* of threatened plants demonstrated that 32,112 species or 11.9% of the world's 270,000 vascular plant species, are threatened, and 374 or 14% are extinct. The counts are for terrestrial and aquatic species combined. Of these, 6,522 species are classed as endangered. Thirty-two countries have at least 5% of their native species threatened. The main countries (excluding small islands) having high proportions of threatened species, 11-29%, include the USA, Jamaica, Turkey, Spain, Australia, Sri Lanka, Cuba, Panama, Japan and Greece.

In the United States about half of the potentially extirpated species are either obligate or facultative native wetland species (LaRoe 1995). (The Ramsar Convention in 1971 adopted a wide definition for wetlands: areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres.) These wetland plant species may be affected by changes in the aquatic environment mediated by dams. Terrestrial species may be affected by reservoir flooding, de-watering downstream of dams; construction of transmission lines, access roads or canals or through lowered water tables.

Walter and Gillett (1998) list the numbers of species, the number globally threatened by category and the threatened percentage for each family of vascular plants. The status of selected freshwater plants based on their *Red List* is presented in Table 1.7.

Table 1.7 Status of selected families of freshwater plants

Family	% of threatened species
Water lilies, Ceratophyllaceae	16.7
Water lilies, Nymphaeaceae	8.0
Water poppies, Limnocharitaceae	31.6
Water plantains, Alismataceae	13.3
Reeds and sedges, Cyperaceae	7.0
Frog-bits, Hydrocharitaceae	14.0
Duckweeds, Lemnaceae	9.7

This small sample illustrates the level of threats, 7.0-31.6% in ‘water-loving’ plants is about as high as in all vascular plants (terrestrial and aquatic) 11.7%. The mean, 14.3, and the midpoint, 19.1, of this sample are both higher than the mean of the family values for terrestrial and aquatic plants combined. This suggests that freshwater plants are more threatened than land plants.
About half of the world’s wetlands have been lost over the past century (Myers 1997). In Asia more than 5,000 km^2 of wetland is lost every year due to agriculture, irrigation, dam construction, *etc*.

Large dams

Large dams are usually >15 m from foundation to crest. Dams of 10-15 m can also be defined as large dams if they meet the following criteria: crest length 500 m or more; reservoir capacity of at least one million cubic metres; maximum flood discharge of at least 2,000 m^{3}s^{-1}; ‘specially difficult’ foundation problems, or ‘unusual design.’ Major dams meet one or more of the following criteria: at least 150 m high; having a volume of at least 15 million m^3; reservoir capacity of at least 25 km^3; or generation capacity of at least one gigawatt.

There are 306 major dams in the world and 57 are planned in the near future (Revenga *et al.* 1998). Table 1.8 lists watersheds with more than five major dams.

Construction of large dams includes the creation of access roads, preparation of the reservoir,

Table 1.8 Watersheds with more than five major dams

Watershed	Number of dams
Paranà	14
Colombia	13
Colorado	12
Mississippi	9
Volga	9
Tigris and Euphrates	7
Nelson	7
Danube	7
Yenisey	6
Yangtze	6

excavation, construction of buildings and dams within and between river diversions, digging of canals and erection of power lines. Forested reservoir basins provide a particular challenge. Leaving some trees may provide fish habitat although leaving trees in any quantity may pose problems for future fishing, water quality and turbine safety. While most reservoirs tend to trap sediments, *e.g.* a new delta is being formed within Lake Nasser (Saad 2000), in some cases *e.g.* South Indian Lake Manitoba, (Bodaly *et al.* 1984), the exposure of clay soils to shifting reservoir water levels increases erosion and downstream sediment discharge.

The quantity of water discharged, when it is discharged during diel and seasonal cycles relative to the river's natural flow pattern and abiotic characteristics of the discharge such as temperature, oxygen, turbidity, and water quality significantly affect downstream biodiversity.

The value of biodiversity

Globally terrestrial and aquatic ecological functions have been calculated to be minimally worth US$33 trillion per year, almost twice the value of the global gross national product, some $18 trillion (Costanza *et al.* 1997), although the figure contains the value of some biological resources as well as functions. Costanza *et al.* (1997) indicated that the annual per hectare total global flow value of inland water systems, US$6,579 x 10^9 exceeded that from all other non-marine ecosystems combined - US$5,740 x 10^9. Ecological functions, although not ordinarily included in gross global or national/domestic products nevertheless make significant contributions to economies. Freshwater ecosystems are economically more valuable than terrestrial ones. In many developing countries, fishes, including those from freshwater make a notable contribution in animal proteins to an otherwise carbohydrate-based diet. In the Amazon, the *per capita* consumption rate is 67 $kgyr^{-1}$ higher than in many areas (Chao *et al.* 1999). In Tonie Sap, Cambodia, 100,000 tonnes of freshwater fish are caught annually, which source alone would provide a per capita 10 $kgyr^{-1}$.

Biodiversity has many kinds of values and potential benefits for humans and the world as a whole. Before it is diminished, those responsible may well wish to consider the Precautionary Principle and take action to conserve it before components of it are permanently lost, even when the evidence for loss is not as strong as might be desired. That approach is advocated by the Convention on Biological Diversity.

2 Patterns of freshwater biodiversity

Although freshwaters comprise only 0.8% of the surface area of the world and they have fewer species than other systems, Table 2.1 shows that freshwaters contain more species per unit area than terrestrial and marine environments. This is particularly notable for fishes.

Table 2.1 Species richness of the world's major environments

Environment	Area of world surface %	No. living species %	Richness: %species/%area
Freshwater	0.8	2.4	3.0
Terrestrial	28.4	77.5	2.7
Marine	70.8	14.7	0.2
Symbiotic	N.A.	5.3	N.A.

Global biodiversity patterns in the three study groups, molluscs, fishes and vascular plants is presented in Table 2.2. Transitional ecosystems such as estuaries and land-water interfaces are not presented.

The total number of species (species richness) is only one measure of biodiversity. Other measures include species abundance. For example molluscs can form significant proportions of the benthos; 80% of the biomass of the River Thames at Reading is composed of freshwater unionid mussels (Berrie & Boize 1992). Holcík (1999) states that long term investigations in the Czech and Slovak Republics show a large biomass of fishes per unit area. In the mountains, the mean fish biomass varies from 27-80 kg ha^{-1}, in foothill streams from 90-500 kg ha^{-1} and in the lowland streams from 300-600 kg ha^{-1}, while in human-made lakes it varies from 65-200 kg ha^{-1}. Diversity indices, which measure the relative richness, evenness, rarity and abundance, require quantitative sampling and at present there are little data for aquatic ecosystems.

Longitudinal gradients

Species richness can change from the headwaters to the river mouth. This may be related to changes in stream order, water temperature, oxygen, current, turbidity and available nutrients. The small headwater streams may have low numbers of fishes that increase downstream as the number of available habitats increases. Further and larger downstream segments of the river may have moderate numbers of species because lower habitat variety, and river estuaries, where salinity varies, may also have moderate species numbers. Higher numbers of fish species are found in the Tennessee-Cumberland plateau drainage of the Mississippi, USA, than in the adjacent mainstream Mississippi; this may reflect more numerous habitats in the varied topography of the former, compared to the more constant gradient of the latter. Different species may characterise different river segments. Trout (*Salmo*) and sculpins (*Cottus*) may occupy headwaters, minnows and catfishes (Cyprinidae and Ictaluridae) mid-river sections, and euryhaline (salinity-level tolerant) species are found in the estuaries.

Freshwater molluscs generally increase from the headwaters to the river mouth. This again is related to an increase in habitats in the floodplain areas in the middle or lower reaches.

Latitudinal gradients

Latitude-longitude grids have the disadvantage that the size of their grid cells shrinks towards the poles, a disadvantage in making comparisons of numbers of species if the study area spans several

Table 2.2 Number of species per environment in study groups (world counts)

Group	Total species	Land species	Freshwater species	Marine species
Molluscs[3]	95,500	24,500 26.0%	5,000[4] 5.0%	65,500 69.0%
Fishes	24,618	0[1] 0.0%	9,966[2] 40.5%	14,153 57.5%
Birds	10,100	9,043 89.6%	840 8.3%	217 2.1%
Vascular Plants[5]	270,000	194,400 72.0%	75,600 28.0%	<1.0%

1 The few species of fishes, like mudskippers and climbing perch edwell out of water intermittently, or for short periods, are ignored.

2 The 499 or 2.0% of fish species that move between the sea and freshwater are omitted.

3 To keep the table compact the midpoint values for marine, terrestrial and freshwater were used.

4 Of the freshwater molluscs 4,000 or 80% are found only in rivers.

5 Number of aquatic plants calculated on the basis of the proportion in USA and Canada (Reaka-Kudla et al. 1997).

degrees of latitude. It is generally accepted that the number of species tends to increase from the poles to the tropics. Arctic waters can therefore be expected to contain fewer species than ones in the tropics. In many freshwater lakes in the Arctic there is only one fish species, the Arctic charr, *Salvelinus*

Figure 2.1 Plant biodiversity hotspots in South America

Table 2.3 River basins and sub-basins with the highest number of native species per unit area (in descending order) and the number of associated large and major dams (Revenga et al. 1998)

River or sub-basin	Number of large or major dams
Kapuas, Indonesia, Borneo	0
Rio Negro-Amazon, northern South America	0
Chao Phrysa, Thailand	3
Hong, China	3
Xing Jiang (Hsi Chiang), China	7
Lake Victoria-Nile, Africa	1
Susquehanna, United States	124
Ohio-Mississippi, United States	711
Mekong, Cambodia, Laos, etc.	4
Alabama-Tombigbee, United States	103
Orinoco, northern South America	10
Lake Ontario, United States and Canada	2
Madeira-Amazon, South America	0
Magdalena, Colombia	5
Uruguay, South America	2
Hudson, United States	53
Fly, New Guinea	0
Yalu-Jiang, North Korea and China	3
Yangtze, China	17
Parana-Paraguay, South America	0

alpinus. The greatest freshwater fish diversity is found in Southeast Asia, tropical South America and central Africa although many fishes have not been scientifically described. Brown (1994) demonstrated the latitudinal trends in African freshwater molluscs which decreased in diversity from the tropics towards the Mediterranean and southern Africa.

Moist-arid gradients

McAllister *et al.* (1986) found that species diversity of North American fishes was related to a measure of 'aridity'. Data indicated that more species were found in moist compared to arid areas. The study showed at what critical level of moisture fish diversity began to increase rapidly.

Although arid areas may be poor in species, desert springs or other water bodies may be rich in endemic organisms, for example, there are vast numbers of endemic spring-snails and fairy shrimps in the arid west regions of the USA.

'Hotspots': areas rich in species and endemics

'Hotspots' are geographic areas rich in species. 'Hotspots' often dominate over latitudinal and other gradients as shown for plants (Fig. 2.1) and animals (Fig. 2.2). McAllister *et al.* (1997) listed countries that are rich in absolute numbers of aquatic species and in the number of species per unit area. There

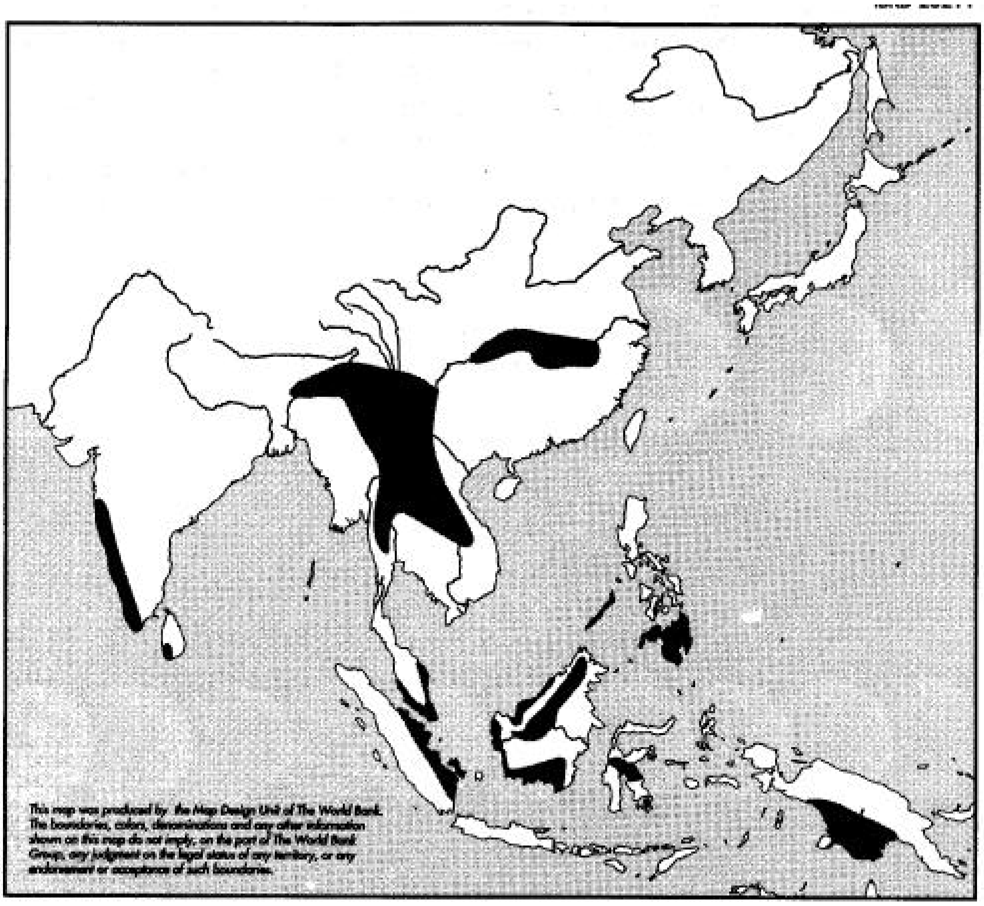

Figure 2.2 Animal biodiversity hotspots in Southeast Asia

is some evidence that 'hotspots' for different groups of freshwater organisms are correlated, for example McAllister *et al.* (1997) found that the numbers of amphibian and fish species in 12 'mega-diversity' countries were highly correlated (r=0.937). Revenga *et al.* (1998) catalogued the number of fish species, endemic bird areas and percentage area of wetlands for most of the world's primary watersheds. From this was determined the twenty richest basins (Table 2.3). The number of species varies with size of basin; generally larger basins have more species.

Global 'hotspots' of freshwater mollusc species include the Mobile Bay and Tennessee River basin faunas in the United States (North America has the richest freshwater mollusc faunas in the world); the lower Mekong River of southeast Asia (160 species of which 72% are endemic; the upper Mekong has been studied by the Chinese although data are not available); the northern Western Ghats, India (71 species, 18% endemic); the Lower Uruguay River and Rio de la Plata (93 species, 37% endemic); lower Zaire (96 species, 25% endemic); Lake Tanganyika (83 species, 64% endemic); Balkans region (190 species, 95% endemic); Lake Baikal (nearly 180 species, about 67% endemic). Note that the freshwater molluscs display very high levels of endemism. Alfonso and McAllister (1994) used an equal-area grid to show geographic patterns of freshwater molluscs, marine fishes and terrestrial mammals in the region surrounding the Great Whale River Hydroelectric Project (Fig. 2.3). Their approach helped to identify gradients in species numbers and determine any 'hotspots' in species including endemics.

Global, regional and national 'hotspots' are often the dominating feature in geographic patterns of biodiversity. Hence it is vital that they should be taken into account in evaluating prospective dam sites. However more accurate identification of freshwater 'hotspots' is needed. If a standardised method was used for different groups it would assist in identifying common underlying factors and assist in application of the data to environmental impact analyses.

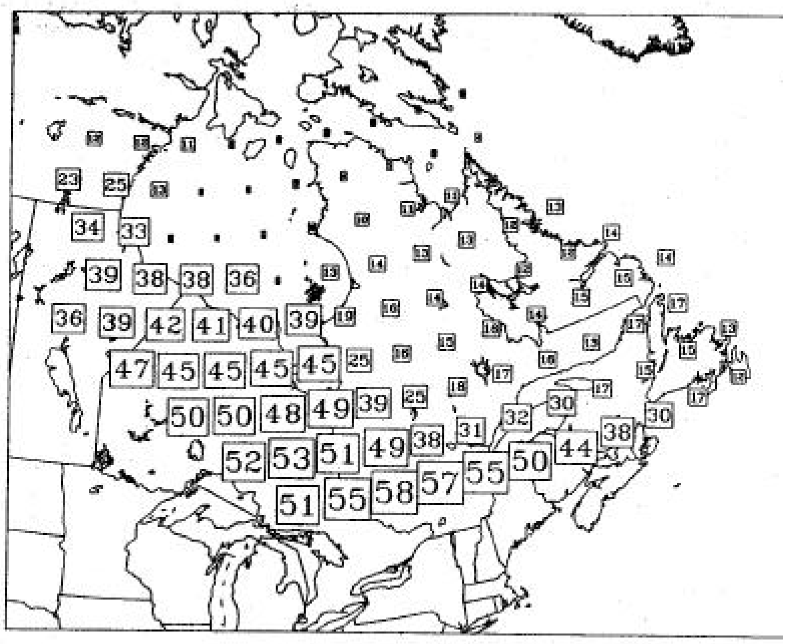

Figure 2.3 Plot of fish species on log-log axes

From data provided by Revenga *et al.* (1998), the 11 most species-rich watersheds were determined (Table 2.4). Kottelat and Whitten (1996) gave 298 species (equal to 37.0/ 100,000 km^2) for the Mekong watershed instead of 244 by Revenga *et al.* (1998). The number of fish species per 100,000 km^2 is given in the table although a better method is to plot the species and area data on log-log axes and see which basins lie above a line of best fit (Fig. 2.3) (Groombridge 1992; McAllister *et al.* 1997).

In Table 2.4 the Nile River and Lake Victoria watersheds were combined (Revenga *et al.* 1998 listed them separately). This results in a value inflated by a few percent for those species shared between the river and the lake. The Lake Victoria sub-basin has 343 species and 121 species/100,000 km^2, while the rest of the Nile watershed has only 129 species and 4 species/100,000 km^2. The difference in diversity is due to the rich flock of endemic cichlids in Lake Victoria (now largely extinct due to the introduction of the predatory Nile perch, *Lates niloticus*).

The Amazon, Congo, Nile, Paraná and Yangtze watersheds are the most species rich, with the Amazon far ahead of the others. When area is taken into account, the Indonesian Kapuas and Thailand Chao Phryas watersheds are significantly richer. However area correction will not cover ‘hotspots’ lying partly within a basin any more than they will within a country. Using Revenga *et al.*’s (1998) data for sub-watersheds shows this quite clearly. The Rio Negro, sub-watershed of the Amazon has 600 species with 83 per 100,000 km^2, the Ohio sub-watershed of the Mississippi has 281 species and 57 per

Table 2.4 Number of fish species in the world's 11 most species-rich primary watersheds

Watershed/continent	Number of fish species	Number of species/100,000 km2
Amazon, South America	3,000	49
Congo, Africa	700	13
Nile-Lake Victoria, Africa	432	12
Mississippi, N. America	375	12
Paraná, South America	355	14
Yangtze, Asia	322	19
Kapuas, Indonesia, Asia	320	360
Orinoco, South America	318	33
Xi Jiang (Pearl), Asia	290	71
Mekong, Asia	244	30
Chao Phrya, Thailand	222	124

100,000 km^2, while Lake Victoria, a sub-watershed of the Nile, has 343 species and 121 species per 100,000 km^2.

Using as closely-spaced geographic grid as the data will permit, would provide the most precise localisation of species or endemic species ‘hotspots’. ‘Hotspot’ analysis can be a useful tool in evaluating potential impacts of different dam sites.

Phylogenetic and ecological diversity

Species are the most common units used in evaluating biodiversity. Yet species are only one unit in a hierarchy: Since families are more distinct genetically, ecologically and behaviourally, and generally have a more ancient origin than species, many taxonomists and conservationists would give a higher priority to conservation of the sole species representing a family than to one of a family with numerous species.

Alien (exotic) species

Disturbed environments created by dams can foster populations of alien species and that diversions associated with dam projects may enable the invasion of such species. In the environmental assessments of dams, alien species should be separated from indigenous ones, and not tabulated in measurements of local indigenous biodiversity. In general, dam projects should not foster the introduction of alien species.

3 Impacts of dams on biodiversity

Species movements up and down stream

There are a number of different migratory patterns of river-dwelling species. These include the well-known anadromous fishes *e.g.* salmon and hilsa (Fig. 3.1) and the catadromous fishes such as eels. Adults of anadromous species migrate up rivers to spawn and the young descend, while the reverse occurs with catadromous species. But many other freshwater fishes move up rivers or their tributaries to spawn, while the glochidia larvae of freshwater mussels 'hitch rides' on host fishes. To help counteract the drift downstream of their larvae, some aquatic insect adults such as mayflies and stoneflies fly upstream to lay their eggs (Hynes 1970). Dams block these migrations to varying degrees. However most waterfowl are able to fly over dams. Reservoirs provide waterfowl habitat and may aid longer migrations by providing 'stopover' sites. Waterfowl is used in the present study to cover all wetland bird families (*e.g.* in the Ramsar Convention), including divers, grebes, cormorants, Anatidae (swans, geese, ducks), coots and rails; "shorebirds" (synonymous with waders); and some other wetland bird families notably gulls, terns, herons and egrets.

The blockage of fish movements upstream can have a very significant and negative impact on fish biodiversity. Many stocks of Salmonidae and Clupeidae have been lost as a consequence. In the Columbia River, USA, more than 200 stocks of anadromous, Pacific salmonids became extinct. Sturgeon populations in the Caspian Sea rely on hatcheries, mainly in Iran, since Russian dams block natural spawning migrations. Hydroelectric dams in the Amazon basin have halted the long distance upstream migration of several species of catfishes and interrupted the downstream migration of their larvae. On the Araguaia-Tocantins River basin, Brazil, several species of migrating catfish have been drastically reduced in abundance as a result of dams; catches in the downstream fisheries have been reduced by 70%.

McDowall (1992, unpublished information) noted that diadromous fishes (those that migrate at regular phases of their life history between freshwater and the sea, comprise about 250 species, <1.2% of all fishes species but form 3% of those classed as endangered. He observes that amongst them are species of great importance to fisheries, out of proportion to their number. Due to their occupation of connected habitats through which passes are needed at two or more life history phases, they pose special problems for conservation. In particular the diversity of habitats used, the extensive areas occupied, the spatial separation of the habitats and the need for fish passage between them. Fishways must be designed to assist not only upstream and downstream migrations of large, fast-swimming migrants such as salmon that can pass substantial barriers, but also those of the lesser-known climbers like eels and gobies that require continuous dampened surfaces on which to move.

Holcík (1999) stated that while dramatic declines in migratory species such as lampreys, sturgeons, salmons and clupeids were well known in European rivers, other fishes, the so-called resident or non-migratory fishes which perform in-stream movements require attention. These include the European minnow, *Phoxinus phoxinus*, the Japanese sculpin, *Cottus pollux*, the grayling, *Thymallus thymallus* and Balon's ruffe, *Gymnocephalus baloni*. Even small-sized species such as the white bream, *Abramis bjoerkna,* were found to migrate up to 60 km from the place they were tagged. Some of these small-sized species are among the most endangered. Damming can contribute towards their decline as in the unique and critically endangered percid, the asprete, *Romanichthys valsanicola*, endemic to the Arges River in Romania (Craig 2000). Artificial barriers also lead to the dramatic decline of the endangered cyprinid fish, *Anaecypris hispanica* in Iberia.

In general, a river is a one-way system for molluscs, as many molluscs can only move downstream by drifting or being dislodged by flood events and moved downstream. But some species with a larval form can move significant distances upstream with the aid of a third party, *e.g.* host fish during the larval stage.

Movement of matter up- and down-stream

Nutrients. Conventionally, rivers have been regarded as the one-way transfer of matter downstream. Experiments by the Fisheries Research Board of Canada several decades ago showed that removal of spawned out sockeye salmon carcasses from streams reduced the growth of fry in the following year. Recently there has been greater appreciation that migrating species carry nutrients upstream. Reimchen (1995) proposed that intensive coastal catches of Atlantic salmon 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

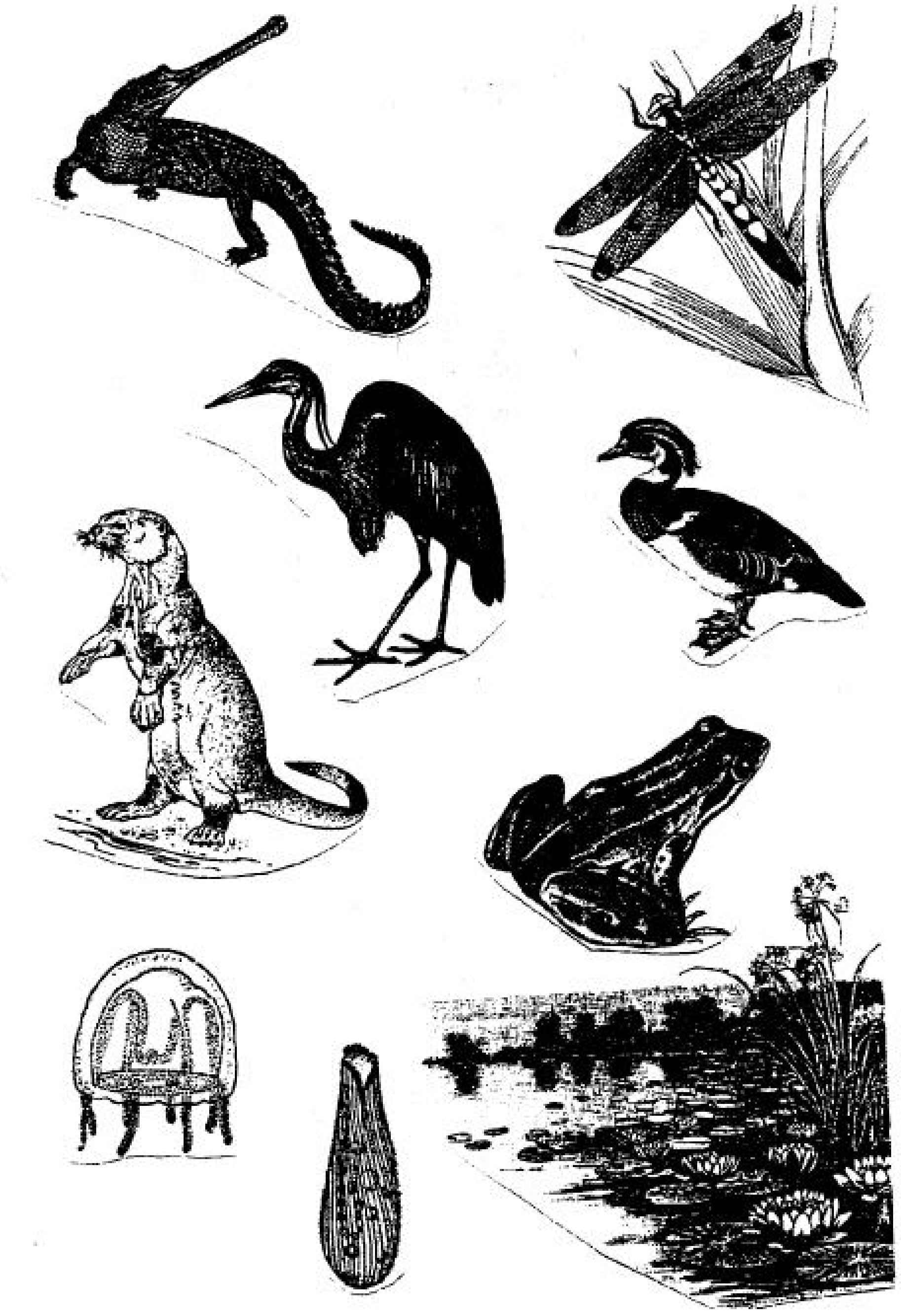

Figure 3.1 Some migratory freshwater species

(Kavanagh 1999). Data from 45 watersheds in British Columbia suggests that up to half the nitrogen stored in giant old-growth trees originates from sockeye salmon, using the nitrogen isotope N_{15} as a tag. The largest source of N_{15} is in the ocean. Cederholm *et al.* (1999) reviews the contribution of Pacific salmon carcasses to the flow of nutrients and energy for aquatic and terrestrial ecosystems. 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 the algae and other plants. 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, 8% of the pre-dam level. The decreased production could be self-perpetuating, since small stocks produce lower amounts of in-stream nutrients for themselves, as well as other species. To a degree fertilisation from the lower riparian vegetation will also affect fish productivity. The fall of insects, leaves and twigs into streams, which serves as direct or indirect food can be expected to decline, as riparian vegetation growth diminishes.

There is no reason to suppose that the upstream transport of nutrients is restricted to anadromous salmonids. It can be expected that andromous hilsa in southeast Asia, Arctic whitefish of the genera *Coregonus* and *Stenodus*, lampreys such as *Petromyzon marinus*, and New Zealand retropinnids such as *Stokellia anisodon* would also transport nutrients upstream during their spawning migrations.
Turbidity. Reservoirs trap suspended particles, reducing turbidity downstream. Many species are adapted to natural turbidity. For example turbid water catfishes have small eyes, refined senses of smell and touch in their sensitive barbels. The turbid water helps conceal the fish and other biota from visual predators like birds. When normally turbid water becomes clear below dams, the indigenous species may find themselves at a disadvantage. Other animal species may move in, filter feeders and aquatic vegetation may flourish. Sediment burrowing species may find their habitat has diminished. Flood plain ecosystems and deltas may no longer be replenished by the annual transport of sediment. Silt and increased turbity, above natural levels, can interfere with primary production (Arthington & Welcomme 1995). In the Mekong River system, silt levels increased following deforestation. This resulted in siltation of the river, lakes and swamps threatening the river fisheries.

Large organic debris (LOD). This consists of branches and tree trunks that fall into the river because of age, storms, beaver activity and eroded banks (Maser & Sedell 1994; Bryant & Sedell 1995; Stevens 1997). Numerous organisms feed on LOD which is often the first link in the food chain. Trees can also play a complex role in creating habitats *e.g.* they divert, slow and speed up current flow, they shelter a variety of biota from currents and predators and create feeding stations. On land, LOD helps stabilise slopes and reduces erosion, and is converted into humus which helps hold water and moderates the runoff. In estuaries, along shores of lakes and coastal areas LOD functions as a source of food, energy and habitat.

In the Santilla River, Georgia wood represented 4% of the total habitat, yet supplied 60% of the invertebrate biomass and 78% of the drifting invertebrates (Bryant & Sedell 1995).
Dams tend to ‘sieve out’ LOD. The logs and branches may become waterlogged and sink, drift onto the shore or are removed by booms or other systems designed to protect turbines. If the integrity of downstream ecosystems is to be maintained, then LOD input must be sustained.

Lateral impacts

Species and materials may move laterally away from the river, extending the effect of river changes to a band of varying width, parallel to the river.

Watering wildlife. As long as there is sufficient river flow below the dam, wildlife such as deer, antelope and elephants will come to the water, especially in the dry and hot season for drinking. Hippopotamuses will use water of sufficient depth as a day-time refuge, emerging to forage at night. Many birds may fly in to drink. These lateral movements can extend to several kilometres from the river. The reservoir itself, however, may serve as a source of water during the dry season or droughts, to wildlife living within range.

Watering terrestrial vegetation. Water release protocols can lower water tables lateral to the rivers which may affect vegetation there. According to LaRoe (1995) riparian ecosystems along most major western rivers of the U. S. have changed as a result of water development and flood control. Losses of riparian forest downstream of dams have been reported throughout western North America. Cottonwood-willow stands are being replaced by non-native woody species such as Russian olive and tamarisk. This may result in diminished LOD input.

Loss of riverbank forests. The extinction of species may be related to the loss of gallery forests adjacent to rivers which became submerged following dam construction. The land-snail, *Anthinus albolabiatus,* was formerly endemic to gallery forest adjacent to the Uruguay River but became extinct after the formation of the Salto Grande Dam, Uruguay (Mansur unpublished information). This factor is of concern with regard to proposed dam projects in South Africa, where much of the remaining forest is preserved on the steep sides of valleys, which are also suitable sites for dam construction.

Maintaining populations and gene flow. The main stem of a river performs two related ecological functions to biota in tributaries. Periodically, populations of a tributary stream species, particularly fish, may go extinct and may be restocked from nearby rivers. Secondly individuals, as described above, may ascend a non-home tributary and contribute to the resident population's genetic diversity. For example salmonids are known to home to their natal streams for spawning, using celestial and olfactory cues. A small percentage of migrants are known, through tagging studies, to stray into adjacent tributaries or rivers. Straying can serve to repopulate streams and also contribute to the genetic diversity of populations through gene flow.

A single dam and more significantly multiple dams along a given river interfere with the genetic bridging function of the mainstem. Thus dams on the main stem can influence species diversity in lateral tributaries, even though there may be no changes in water flow or quality characteristics. In the Murray River, Australia, river regulation has lead to the separation of billabongs (oxbow lakes) from the main channel habitat and thus for many molluscs in particular freshwater gastropods. Since river regulation was introduced some mollusc species have become extinct.

Oxbows, wetlands and springs. Oxbows, ponds, lakes and wetlands are often isolated in the floodpain from the river's main stem. These may be replenished with water, biota, sediment and nutrients during natural, seasonal floods. Levelling out of river discharge has been known to prevent these periodic linkages with the mainstem. Most of the 50 species of fishes (many endangered) in the Austrian Danube, depend on the connection between the river and its backwaters (Schiemer & Spindler 1989; Balon & Holcík 1999).

Transmission lines. Transmission lines affect biodiversity on land. The use of herbicides to control plant growth under power lines probably reduces native plant diversity in favour of weed species, which are often exotic. Baker (1999) reported that power lines corridors can serve as refuges for rare species. Tree trimming may provide a haven for native 'sun-loving plants'. Shrub communities may flourish under power lines and provide habitat for nesting and migratory birds. Only nine snoutbean plants were thought to exist in all of Kentucky, USA. However an East Kentucky Power Plant Corporation (EKPC) study showed that about two thousand specimens survived under their power line. EKPC adjusted their mowing schedule and removal of woody plants and educated other utilities about protecting native plants. Utility rights of way may harbour rare birds, amphibians, reptiles, tree snails, mammals and other species.

Upstream

Above the reservoir. Water quality, flow and seasonality of flow are not normally disrupted in the upstream area above the reservoir so impacts are generally less than for the reservoir and downstream areas. Nevertheless, the dam and the reservoir affect migratory movements of species into and out of this upstream area. The genetic exchange with downstream segments is reduced or prevented. A study was made of molluscs upstream in a braided river that enters a reservoir on the River Inn in Austria (Foeckler *et al.* 1991). Data shows that there was a decline of 10 species upstream of the reservoir. This was due to channelisation of the braided area, an increase in the overall river gradient and a consequent reduction in the active floodplain area. The extirpation of freshwater mussel populations upstream of the dam construction at Lake Pepin on the Mississippi River, USA, was due to the lost migratory fish host species, skipjack herring, *Alosa chrysochloris* (Eddy & Underhill 1974).

Reservoirs. In the construction of reservoirs, the clearing of vegetation, movement of earth and rock, the presence of humans and machinery, bringing in construction materials, use of explosives, noise, and reducing or cutting off river flow and increasing turbidity, will affect biodiversity. Removal of forests or other vegetation over a wide area, excavation, earth and rock movement and reduction in river flow are the most significant. Some of the on-site activities are mirrored in off-site disturbances such as the mass displacement of earth and rocks and road building.

During reservoir filling the river and any associated wetland areas become inundated. Riffles, runs and pools of the river are lost beneath the rising waters, leading to the extirpation (or extinction) of habitat sensitive riverine species with tightly defined niche requirements. Fishes in rivers are generally well adapted to flowing water. Similarly molluscs are often restricted to specific habitats within the river system, *e.g.* some species are bottom-dwelling filter feeders, others live in weeds at the edge of the channel.

The transformation of a river to a reservoir therefore poses a problem for the resident, mainly riverine species that are not adapted to the new conditions. Lacustrine fishes have been introduced into reservoirs in a number of cases *e.g.* Lake Kariba although this may pose new problems. In eastern Canada, lakes and streams, which have emerged fairly recently from glaciation, contain a number of fish species able to dwell in both habitats. However some species like the longnose dace, *Rhinichthys cataractae*, and rainbow darter, *Etheostoma caeruleum*, are adapted to running water only.

Table 3.1 Factors affecting the life cycle stages of unionid molluscs (amended after Chesney & Oliver 1998). Items highlighted in bold are directly impacted (after impoundment) and those in italics indirectly

Factor	Life cycle stages affected
Exploitation (pearl fishing, shells for buttons or seeding)	Adults
Fish host stock size	Glochidium
Mussel stock size	Fertilisation, glochidium numbers
River bed	Adults, juveniles
Flow regime	Fertilisation, glochidium infection,settlement, juvenile and adult
Suspended solids	Adults, breeding and brooding
Eutrophication	Adults, juveniles
Nitrogen	Adults, juveniles
Phosphate	Adults, juveniles
Dissolved oxygen	All stages
Conductivity	Adults, juveniles
Calcium	Adults, juveniles
pH (acidity)	Adults, juveniles
Interstitial particulates	Juveniles
Interstitial water chemistry	Juveniles
Industrial pollutants	All stages
Pesticides	All stages

Molluscs generally show a drop in species richness from pre- to post-impoundment. Unionid mussels are exposed to a number of changes in the reservoir impoundment (Table 3.1). The most important ones include: changes in the fish host population size (needed for the glochidia stage of the mussel larvae), reduction in the mussel population size (fertilisation success), eutrophication (affecting adult and larvae) and dissolved oxygen levels (low levels of oxygen in the profundal zone would eliminate mussels from that zone). Eutrophication can limit the interstitial habitat of post-glochidial juveniles. Raised nitrate and phosphate levels are especially deleterious to juveniles. Organic debris can clog benthic interstitial spaces. Some of these effects can extend downstream of the dam. Table 3.1 shows the environmental and biotic factors which influence the various stages in the life cycle of unionid mussels.

Extinction of 38 out of 42 taxa of molluscs in the Mobile Bay, Alabama, USA, basin occurred when the big river shoal fauna were covered by deep standing water in the impoundments and subsequently buried under increased siltation (Bogan 1998). However molluscs may comprise an important part of the benthic fauna of some reservoirs. In the man-made Lake Kariba, molluscs made up nearly the entire biomass of the benthic animals (prosobranchs 4.1% and bivalves 95.8%) (Machena & Kautsky 1988).

In the Tennessee River Basin, U.S., several molluscs are under threat of global extinction following the construction of dams and the subsequent regulation of flow. A number of gastropods of the family Pleurocercidae are under threat as they persist on clean-swept shoal areas below dams on the river (Bogan 1998) and three other species have been extirpated from the river (Haage & Thorp 1991). Over 85 mussel species were known in the Cumberland River of the upper Ohio-Tennessee River basin prior to the construction of impoundments and locks between 1916 and 1923 (Blaock & Sieckel 1996). In Kentucky portion of the lower Cumberland, for example, there were 25 species in 1911, 15 in 1981 and only 4 in 1994, for a total of 21 extirpations.

Extensive mussel beds contribute to the health of rivers by their filtration power. Reductions in those beds reduces this ecological function. However replacement mollusc faunas have developed in some African reservoirs.

River sections with steep gradients or escarpments sometimes offer optimal conditions for locating hydroelectric and other dams. However, those locations may provide special fast-water habitats for species with only scattered distribution, or local endemics. In some cases species may multiply following construction of a dam. The status of a freshwater pulmonate, *Bulinus truneatus*, changed from rare to common in Lake Volta, Ghana. This led to an increase in the level of urinary schistomiasis infections in the region (Brown 1994).

Williams *et al.* (1989) listed 12 darter species (family Percidae) as endangered or threatened, and 9 of special concern in Tennessee, USA, a state which has many dams due to the activities of the Tennessee Valley Authority. The species of darter found in streams, now flooded by reservoirs in the Tennessee River system (Neves & Angermeier 1990), had well defined river run and pool niche requirements. In Texas, USA, the filling of a reservoir was involved in the extinction of the spring-dwelling Amistad gambusia, *Gambusia amistatensis* (Miller *et al.* 1989).

In some tropical reservoirs the overall number of fish species has increased, although several riverine species have disappeared, *e.g.* Lakes Kariba, Zambia and Zimbabwe, and Ayame, Côte d’ Ivoire, (Kolding & Karenge unpublished information; Gourène *et al.* 1999). Tilapias of the family Cichlidae are usually the most successful in these lakes.

The extent of entrainment of larval and juvenile fishes in hydroelectric turbines varies according to flushing duration, depth of extraction and species present (Walburg 1971; Travnichek *et al.* 1993). Passage through turbines of young anadromous salmonids, en route downstream, is a well-known source of mortality. In the catadromous eels, family Anguillidae, it is the downstream migrating adults which are killed by the turbines.

Reservoirs promote waterfowl and many dams have substantial populations. The type of shoreline, shallow, with fringing vegetation, supports greater species diversity and larger numbers compared to steeply shelving mostly deep water sites. A substantial number of dammed sites support nationally or internationally important waterfowl assemblages. In more arid areas, creating dams increases numbers of birds able to remain all year round in otherwise largely seasonally dry places. The presence of a dam has substantively altered the migration phenology and distribution of some species.

Of 957 Ramsar sites (Frazier 1999) 25% had natural lake types and 10% had artificial wetland types; 78% of the latter were dammed sites. Some of the Ramsar sites with dams supported internationally important waterfowl populations, though these sites were small in number compared to natural wetlands. The significance of such artificial wetlands for waterfowl is difficult to interpret. Nevertheless some dammed sites did prove suitable for large waterfowl assemblages.

A study of natural lakes and dammed reservoirs in Switzerland (Table 3.2) showed that waterfowl species diversity was considerably higher on natural lakes than on dammed lakes. Nevertheless there is considerable overlap in the number of species on the two types of water bodies. The most common five species were the same on natural lakes and dammed lakes, common coot, tufted duck, mallard, pochard and great crested grebe (Fig. 3.2). Damming of rivers has increased the number of open water sites available to wintering waterfowl.

Table 3.2 Waterfowl species diversity in Switzerland

	Natural lakes	Dams
Number of sites	8	6
Number of species per site	14-30	11-20
Total number of species	33	23

The United Kingdom is of major importance for wintering waterfowl which use the Eurasian-African flyways. Because of its relatively mild winters, its wetlands seldom freeze over, and, in severe winter weather in continental Europe, it additionally serves as a cold weather refuge for waterfowl species. Table 3.3 lists the number of natural and artificial wetlands in the UK which support internationally important numbers of wintering birds.

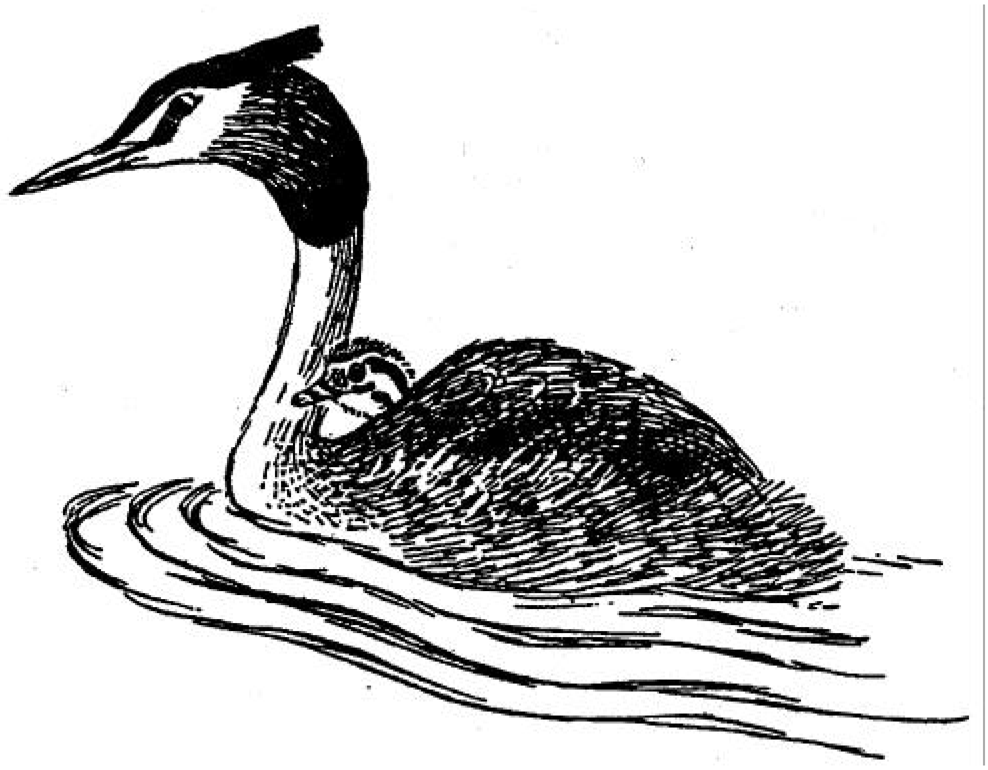

Figure 3.2 Great crested grebe (*Podiceps Cristatus*)

Table 3.3 Natural and artificial wetlands in the UK with internationally important numbers of wintering waterfowl

Wetland type	Estuaries and coasts	Inland wetlands	Dams and reservoirs
Sites with > 20,000 waterfowl: Ramsar criterion 3			
Number of sites	42	12	3
Average number internationally important species present	4.7	2.8	2.0
Other sites with 1 or more internationally important species: Ramsar criterion 6			
Number of sites	15	49	8
Total number of sites supporting internationally important species	52	60	11

Table 3.3 shows that estuaries and natural inland waters are of great international importance for wintering waterfowl. Estuaries and coasts tend to have higher numbers of species because they attract waders as well as waterfowl, while inland systems generally support only wildfowl in internationally important numbers. A much smaller number of artificial wetlands are of international importance for wintering waterfowl. Only 11 support one or more internationally important populations and only three have large overall wintering populations >20,000 waterfowl.

For several species a large proportion of nationally important lakes are artificial ones: 40% or more of important sites are artificial for eight waterfowl: little grebe, great crested grebe (Fig. 3.2), great cormorant, gadwall, northern shoveller, pochard, tufted duck and common coot. A further analysis showed 27 species on five natural lakes in the UK, as compared with 33 species on artificial lakes, in contrast to the situation in Switzerland. On the negative side was the fact that two exotic species, the Canada goose and the ruddy duck were present on dammed lakes. Those species have expanding populations and are of conservation concern.

Much of South Africa is arid and has few natural permanent water bodies. Almost all permanent water bodies are dammed sites constructed for water storage. There are at least 517 major reservoirs and numerous small, farm dams. The presence of these new wetlands has had several consequences. At least 12 impoundments support major and important concentrations of waterfowl. Suitable conditions have been provided for the Pelecaniformes (pelicans, darters and cormorants), 70% of the global population of the South African shelduck during moulting, and refuges for species of national conservation concern such as the pink-backed pelican, *Pelecanus rufescens*, and the Caspian tern, *Hydroprogne caspia*. Negative impacts in overall waterfowl assemblages in southern Africa are due to the loss of many of the former natural marshes and riverine habitats through reduction in river flow, removal of seasonal flow variability and consequent changes in sediment movement and channel stability. In addition poor dam management may cause sudden major releases of water, causing major downstream floods in areas that have had little or no flood activity for years. That can affect species that use unvegetated river banks and sand banks between river channels.

Running compared to still water impacts. The construction of reservoirs converts lotic (running) into lentic (still water) habitats. Species dependent on running water will diminish or disappear. In almost all cases, the diversity of fish species will drop (McCully 1996). Reservoir fisheries are one of the frequently claimed benefits of impoundments. The changes in catches following impoundment are variable. However the catches in new reservoirs frequently go through a “boom and bust” cycle (Welcomme 1995), with catches initially increasing following filling of the reservoir and then declining. Therefore impact assessments of dams should be based on the long term catches.

The shore-edge (marginal) ecosystem also changes. A study of the Upper Mississippi River, USA (LaRoe 1995), an area with many dams, showed that open water and marsh habitats generally increased between 1891 and 1989, although at the expense of grass-herb, woody terrestrial, and agricultural habitats. For example, in ‘Pool 8’, open water and marsh increased from 3,600 hectares in 1891 to 9,500 hectares in 1989.

The edges of new reservoirs are often exposed to erosion, while deeper areas are sedimented. In the Upper Mississippi River sedimentation rates of one to three cm per year have been measured (LaRoe 1995). Erosion was more prevalent in shallow areas and sedimentation at deeper depths, the processes converging between 0.9-1.5 m.

Creation of new sublittoral and profundal zones. Water oscillations in the littoral zone reduce its suitability for species requiring stable conditions. Some mobile species, such as shorebirds, may find this habitat suitable for feeding.

The nature of the deeper or profundal zone will depend on the climate, preparation of the reservoir prior to filling and other factors. In boreal and arctic areas the deeper waters are normally cooler than the surface waters and this provide habitats for both warm- and cool-loving species. If the trees and other vegetation are not cleared from the reservoir, then decomposition commonly leads to low oxygen levels in the profundal zone usually only suitable for anoxic microorganisms.

Weeds, exotics and diseases. The changed or fluctuating conditions in the reservoir may lead to opportunities for weed or exotic species *e.g.* the water hyacinth, *Eichhornia crassipe*.

Increases in the number of mollusc-borne diseases following dam construction in various countries. For example at least four genera of mollusc-borne human diseases have increased as a result of impoundments in Thailand (Woodruff & Upatham, 1992).

Following the construction of Lake Volta Ghana, the gastropod, *Bulinus truneatus* colonised the lake, replacing *Bulinus globosus* and other species which were not able to withstand the lake-level fluctuations. This lead to an increase in the level of urinary schistomiasis in villages around the lake (Brown 1994). The stocking of fishes for anglers in Texas, USA, reservoirs has resulted in the introduction of exotic “floater” freshwater mussel groups, transported as glochidia on the fish hosts (Howells *et al.* 1996).

Mercury. Mercury is in a harmless inorganic form in many soils (McCully 1996). Bacteria which feed on decomposing matter in a new reservoir transform the mercury into methyl mercury which passes up the food chain from plankton to fishes and those species that feed on fishes, including humans. Biomagnification results in higher mercury levels as mercury ascends the food chain (Rosenberg *et al.* 1997). In the La Grande Phase of the James Bay, Canada, hydro project it was found that reservoir fish became contaminated with mercury at levels exceeding World Health Organisation (WHO) standards (Dorcey *et al.* 1997). Sixty-four percent of the Cree living in the La Grande estuary had blood mercury levels far exceeding WHO standards (McCully 1996). Mercury can also negatively affect wildlife that prey on mercury-contaminated fishes. Loons are severely affected by mercury pollution. Sport fishing also plays a role in the local economy, and mercury contamination creates unfavourable publicity.

Sedimentation. Reservoirs tend to serve as sediment traps since river velocities and carrying capacity for particles decrease in reservoirs (McCartney *et al*. 1999). However sometimes fluctuating water levels in reservoirs erode the shores and add to the turbidity of the reservoir discharge. Sedimentation can degrade habitat both in the reservoir and below the dam, as well as reduce storage capacity. Many of the molluscan extinctions in the Mobile Bay, USA drainage, following multiple impoundments, were due to siltation (Bogan 1998). The degree of tolerance to silt cover depends on the species of mollusc. Suspended silt may reduce the feeding efficiency of filter-feeding bivalves and other species.

About 50 km^3 of sediment, nearly 1% of global reservoir capacity, was estimated in 1997 to be trapped behind dams. Keeping sediments flowing through reservoirs will benefit both reservoir life and the life of downstream ecosystems such as flood plains and deltas. Many of the existing potential solutions, such as dredging and sluicing, have economic or environmental limitations.

Downstream
In the downstream segment, most of the impacts of a dam are negative. In a preliminary assessment of 66 case studies of the impact of dam construction on fishes, based on qualitative information, 73% of the impacts were negative and only 27% were positive. About 55% of the impacts were below the dam and linked to fish migrations and to floodplain access.

In the distribution of molluscs along a 240 km stretch of the Little River in Oklahoma, USA there were mussel extinction gradients downstream from large impoundments (Vaughan & Taylor 1999). With increasing distance from the dam there was a relative increase in mussel species richness and species abundance. Only those stretches furthest from the dam contained the relatively rare species. Richness declined below each successive dam, with a multiplier effect.

Overall volume of flow. Some reservoirs have been filled by cutting off all or almost all flow downstream of the dam, *e.g.* Cabora Bassa, Mozambique (Jackson 1989) with the consequent loss of organisms. Large aquatic species such as sturgeons, crocodiles and dolphins require minimal flows in which to navigate and feed. Such species may be affected by reduced flows including a reduction in the area of habitat utilised. This may lead to smaller populations, reduced growth rates and, where populations are already at risk, extirpation or extinction.

A certain level of downstream flow is needed to maintain a minimum volume and area of habitat, oxygen concentration and other 'desirable' in-stream conditions and avoid lethal temperatures. Normal seasonal flow patterns are a key to maintaining river biodiverstiy. Balancing reservoirs may help avoid pulse discharges, delay peak discharges and reduce them to an ecologically acceptable level and guarantee a certain minimum discharge (Moog 1993).

Constructing dams just above large tributaries can moderate changes to downstream flow patterns. If the tributary has a similar seasonal flow cycle to the mainstem, then the downstream flow pattern and seasonal cues will be less impacted than if the mainstem dam had been sited below the tributary.

Seasonal variability of flow and flood plains. The pattern of flow of a river undergoes a regular series of changes with the seasons. The patterns can differ profoundly from region to region *e.g.* in an Indian river the peak flow may be during the monsoon, in an Arctic river during snow-melt or ice break-up. The expansion and contraction of the river controls living space and access to particular habitats. It is to these profound seasonal patterns that the species in a drainage basin adapt. It is from river flow events that species take cues to migrate, spawn, *etc.* The rhythm of the river is thus tied intimately to the life of river species. Dams alter the natural flow of rivers as is shown in the Colorado River, USA, following construction of the Lake Powell River dam (Fig. 3.3).

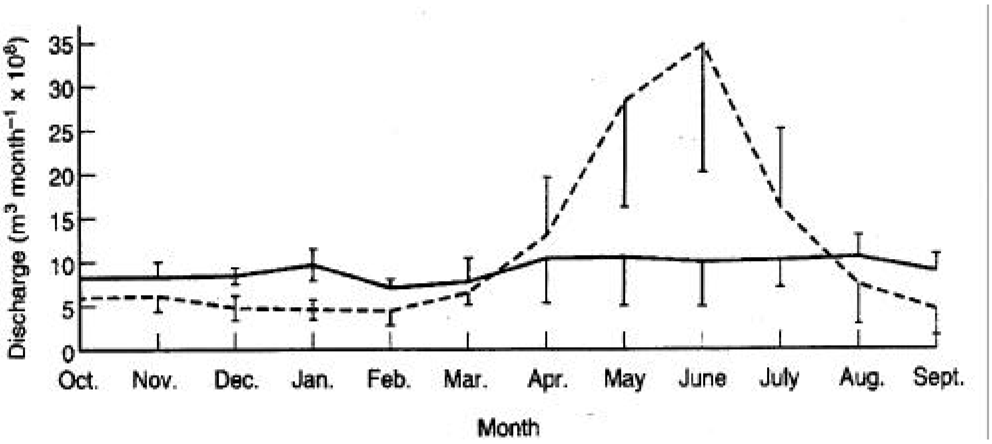

Figure 3.3 Discharge before (dotted line) and after (continuous line) dam construction in the Colorado River, USA

Some species are adapted to strongly seasonal flow regimes with flash flooding, as in certain river systems in Australia. Drastic declines in the molluscs of the Murray-Darling River system have been attributed to: predation and sediment disturbance by introduced fish such as the common carp, *Cyprinus carpio* (Fletcher *et al.* 1985), changes in flow patterns through intensive flow regulation after impoundments and possible changes in algae, bacteria and fungi, which form potential mollusc food sources.

A study by Almada-Villela (unpublished information) in the Naga Hammadi barrage area of the lower Nile, Egypt, showed the certain presence of 34 species and the questionable presence of an additional 3 species for a possible total of 37 species. Boulenger (1907) identified about 72 species in the Lower Nile. It was deduced that approximately 35 species have disappeared from the Lower Nile or have become very rare, since the construction of the Aswan High Dam and other dams and barrages in the Nile River.

Water table changes. Water diversion for irrigation may lower the downstream water table adjacent to the river. Further, the 'levelling out' of floods, may reduce seasonal recharging of the water table. The supply to springs, artesian flows and cave streams may also be affected.

Cave streams and some aquifers sometime have species characterised by reduced or absent eyes, loss of pigmentation and enhanced non-visual sensory systems. According to David Culver (personal communication) there are 1,300 described obligatory cave species in the United States alone, while the undescribed species probably number several times that value. Many cave organisms are restricted to a single cave or cave complex. Cutting off the cave water supply, either temporarily or permanently, may lead to extinctions. When selecting potential dam sites, planners should be alert to known cave dwelling speciesor check for the presence of unknown species.

Of the world's 110 described species of cave fishes, a high proportion are threatened. Proudlove (1997) reviewed the conservation status of hypogean (underground) fishes. The percentage of threatened hypogean fish species has risen from 18% in 1977 to 87% in 1996. Most of the species have very limited distribution. The primary threats are habitat degradation (*e.g.* quarrying and siltation due to dams and logging), hydrological manipulations (*e.g.* water removal for human consumption or irrigation and damming), environmental pollution (*e.g.* eutrophication and poisoning from agricultural and industrial runoff), overexploitation (capture for the aquarium trade) and introduced exotic animals.

Abiotic changes. In summer, in temperate lakes, solar radiation heats the eplimnion but not the hypolimnion. The hypolimnion is often anoxic. In the autumn the lake undergoes mixing and some heat is transferred to the bottom layers. Water discharge from the dam is usually below the epilimnion. Therefore in summer the water discharged into the river below the dam is colder and has less oxygen than normal and in winter it is warmer (Neves & Angermeier 1990). These physical changes can effect the biota for long distances down the river. Discharges from the reservoir are variable usually resulting from the requirements for hydroelectric power and not related to natural cycles. Flow below the dam can rapidly alter from almost standing water to torrential flows and water depth, water velocity, oxygen concentration, temperature, suspended solids, pollutants and chemical composition can change in a very short period of time.

Many of the effects experienced downstream of a dam are in reverse of those produced in the reservoir above them. Heat, silt, inorganic and organic nutrients retained in the lake are lost to the stream below. Large annual variations in water level in the reservoir results in a decrease in the annual variation in water level in the efferent river.

Inland deltas. As noted previously, dams trap sediments, diminishing the downstream supply. An inland delta and flood plain, including a network of oxbow lakes, in the middle Danube, was supplied by sediment during natural seasonal floods (Balon & Holcík 1999). The area produced an impressive harvest of trees, fishes and cereals. Biota included 65 species of fishes, 11 of amphibians, nine reptiles, 41 mammals and 242 birds. Construction of a series of dams, dredging the river channel and construction of a canal deprived the delta and flood plain of the annual supply of silt and resulted in severe alterations in the benthos and zooplankton communities as well as the change and decrease of species diversity and biomass. The inland delta was lost eliminating spawning, feeding and overwintering grounds for fishes. Amongst fish species lost from the affected area were the percids, *Zingel streber* and *Zingel*

zingel, both classed in the IUCN *Red List* as vulnerable, and the salmonids, *Hucho hucho*, classed by the IUCN *Red List* as endangered, and *Salmo labrax* m. *fario* (= *Salmo trutta* m. *fario)* (Holcík personal communication). The European beaver, *Castor fiber,* has left the territories influenced by the dam. The mean annual fish catch has dropped by 87%.

Anti-gradient, thermal transport. North-flowing rivers such as the McKenzie River, Canada, transport warmer water into the Arctic than that from local tributaries. This enables some species to range further north. The same phenomenon would occur in reverse in the Southern Hemisphere. Rivers flowing towards the tropics or down from higher cooler altitudes would permit cool water fishes to extend their ranges.

Dams or series of dams may affect anti-gradient thermal transport and the ranges of aquatic species which depend on them. However the thermal transport affects more than just the species in the river. In the Arctic the northern limits of the tree-line, appears to be extend adjacent to north flowing rivers, as well as next to large lakes which act as reservoirs of summer heat. It is not clear whether reducing the flow of anti-gradient thermally transporting rivers, or the effects of reservoirs and discharge from either epilimnion or hypolimnion will affect the downstream and lateral distribution of species. Analysis of data from Russian rivers with older dams might be useful.

Water basin connections

When waters of one basin are diverted into another, impacts can be expected from changes in volume and seasonality of flow. New biota from the source basin may invade the recipient basin and compete with the native species. If all the water is diverted from the source basin, this will obviously have serious impacts on any unique species or genetically different stocks.

Individuals washed down irrigation canals, especially if there is a drop from the impoundment, may no longer be able to return and may not be able to maintain viable populations in the new habitat. In the Nicola River, western Canada, considerable numbers of Pacific salmon fry pass down into irrigation ditches, depleting the river populations. Screen systems have been installed in Canada and the USA.

Estuarine and marine impacts

Many of the effects in estuaries are similar to those upstream, *e.g.* loss of habitat and changes in seasonal flow, turbidity and productivity. Water withdrawal on the North Caspian had the following effects (Rozengurt & Hedgepeth 1989): 1) the mean salinity increased from 8-11ppt; 2) the estuarine mixing zone was compressed and moved up to the delta; 3) the nutrient yield, especially phosphorus, and sediment load were reduced by as much as x2.5 and x3, respectively; 4) biomass of phytoplankton, zooplankton, and benthic organisms were decreased by as much as x2.5; and 5) a substantial part of the Volga flood plains that served as a nursery ground for many valuable fishes was transformed into drying swamps or desserts. This led to a progressive deterioration and significant decline in natural recruitment. Commercial catches fell by as much as three to five times for three sturgeon species, x10 for bream (*Abramis brama*), pikeperch (Stizostedion *lucioperca*), Caspian roach (Rutilus rutilus), and carp (*Cyprinus carpio*), and nearly x100 for the commercial fishery of Caspian herrings (*Alosa kessleri volgensis*). The sevruga, *Acipenser stellatus*, has been saved from extinction by release of fry reared in hatcheries over the last two decades.

Estuarine deltas. Deltas below impoundments tend to shrink, reducing habitats, because of the capture of sediments by impoundments. The Nile Delta, Egypt, has shrunk at a rate of 125 to 175 m yr^{-1} (Rozengurt and Haydock 1993), and more saline water has invaded inland. The Danube Delta, central Europe, shoreline is receding at a rate of up to 17 m yr^{-1}, threatening benefits from tourism to birdlife (Pringle *et al.* 1993). The delta support large populations of bird species that are generally widespread over Europe; some 170 species of birds breed in the delta, including pelicans, herons, ibises and terns. Impoundments upstream, including 7 major dams, on the 2,860 km long river, channelisation and the loss of the nutrient absorption capacity of upstream floodlands has meant nutrients and other pollutants are affecting delta water quality. Bird populations are at a fraction of their historical numbers. So although reservoirs may provide new habitat upstream their impacts on birds may be negative in the long-term.

Salinity, nutrients and reproduction. Decreased discharge rates can result in an increase in salinity in estuaries and change the composition of species in this zone. The effects of increased salinity on fishes of the Nile Delta, Egypt, has been documented by several authors. Abramovitch (1996), for example notes that out of 47 commercial fish species in the Nile prior to the construction of the Aswan High Dam, only 17 were still harvested a decade after its completion. The annual sardine harvest in the eastern Mediterranean has dropped by 83%, probably the effect of a reduction in nutrient-rich silt entering that part of the sea. The effect of lowered nutrient input is generally the greatest in the first year of life of the fishes.

Rivers can increase nutrient levels at river mouths by two processes: entrainment and transport. Satellite imagery can be helpful in evaluating the nutrient contribution of rivers. Reference to the October 1999 colour satellite photographs of nutrient levels show high levels at the mouths of the Yangtze, Mekong, Ganges, Indus and Volga in Asia, Amazon, Plate and Orinoco in South America, and moderate levels near the mouths of the Fraser and Columbia rivers in North America. The Colorado, Nile and Congo rivers have weak nutrient levels, the first two probably because of high abstraction rates from large reservoirs, leaving little discharge into the sea. A series of maps throughout the year should be consulted because of different seasonal discharge patterns.

Entrainment. The surface outflow of freshwaters in estuaries, results in a return current of deeper, nutrient-rich waters. These nutrients contribute to the high productivity of estuaries. Reduction of flow may therefore reduce import of nutrients. There are numerous impoundments in the North American Great Lakes and St. Lawrence River basin. It is estimated that the spring and summer runoff at the entrance to the Gulf of St. Lawrence has been reduced by between one third and one half (Neu 1975). Kerr and Ryder (1997) proposed that many decades of anthropogenic activity have altered the Laurentian Great Lakes ecosystem and the devastating changes that took place in the northwestern Atlantic ground fisheries can be related to this.

Coastal fish catches adjacent to deltas with large upstream volumes of impoundments have declined seriously from 1950 to 1990, *e.g.* the Egyptian Mediterranean to 18% and the western Black Sea, Sea of Azov and Caspian Sea to <3% of the original catches (Rozengurt & Haydock 1994). Based on world-wide experience, no more than 25-30% of the historical river flow to the estuary can be diverted without disastrous ecological consequences to the receiving estuary (Rozengurt & Haydock 1981). Economic losses in the Black, Azov and Caspian seas total about $3 billion per year (Rozengurt 1991).

Interaction with non-dam impacts

Dams often interact with the effects of other human activities. McAllister (1995) classes the potential interaction of human impacts as either neutralising, additive or synergistic He postulated that synergistic interactions, those where harmful affects were amplified, were more likely, considering that genomes by selection are adapted to a certain set of undisturbed natural environmental conditions. Species classed as endangered are more likely to become extinct. Factors to be considered include climate change (Watson *et al.* 1996) agriculture, forestry, industry and municipal effects (McAllister *et al.* 1997).

The impacts of dams on the biodiversity of molluscs, fishes and waterfowl are summarised in Tables 3.4, 3.5 and 3.6. Table 3.7 provides a summary.

Tables 3.4 and 3.5 show that upstream impacts are generally less than those in the reservoir or downstream. The exception to this generalisation is the migratory species that move up and downstream and use such movements to maintain genetic diversity (in a stock or the survival of a stock) or the survival of a species in that part of the basin, or in their entire global range.

For molluscs and fishes the change from running to still waters (and other related conditions) in a newly established reservoir is profound. Most species highly adapted to currents will be extirpated and the reservoir diversity will drop. The reservoir becomes stocked with ecologically flexible native species or with exotics. One exception is in African reservoirs where fish numbers may increase. Reservoir fishery harvests usually increase after impoundment, but then drop.

For waterfowl the situation is different. Reservoirs provide new habitat for over-wintering in cool regions and for residence in warm arid regions which have few natural water bodies. Thus new reservoirs can increase waterfowl populations, though their diversity will not be as high as that in natural lakes. The effects of impoundment on birds that existed in the reservoir basin and downstream of the dam have not been well studied.

Table 3.4. Dam impacts on freshwater molluscs

Case studies	Biodiversity increases	Biodiversity decreases	Source
Overall status			
N. American mussels - downstream and impoundments.	None noted.	Extinction curve, taking into account functionally extinct species is 4.2% per decade, result of all impacts including dams, but excluding zebra mussels.	Ricciardi & Rasmussen (1998).
USA mussels.	None noted, but alien zebra mussel and Asian freshwater clam populations are expanding.	Lead threats to 102 imperilled species are: habitat degradation - 97%, pollution - 90% and alien species - 17%. Habitat loss from: water development - 99%; pollutants - 97%, dams - 96% and agriculture - 64%, but these impacts are being overtaken by those of alien mollusc invasions.	Wilcove et al. (1998).
Mississippi Basin, USA.		Current decline of freshwater mussels in the Mississippi Basin will have a detrimental impact on the entire ecosystem as they play a vital role in sediment mixing and nutrient recycling. Given their dominance in terms of biomass, removal could have long-term effects, as yet unknown.	Stein & Flack (1996).
Upstream			
Nearctic			
Lake Pepin, Mississippi River, USA.		Demise of freshwater mussels due to host species (skipjack herring) movements being blocked by dam.	Eddy & Underhill (1974).
Palearctic			
River Inn, Austria.	One new freshwater mollusc recorded in river.	10 species lost due to changes in flow regime, increase in gradient. Loss of temporary habitats (Segmetina nitida, Viviparus connectus).	Foeckler et al.(1991).
Reservoirs			
African			
Lake Kariba, Zambezi River, Zambia and Zimbabwe.		Reservoir supports 7 species of the 25 gastropods known from the river system. Two species, Gabiella balovalensis and G. zambica; endemic to area. Under threat.	Brown (1994).
Lake Volta, Ghana.	Bulinus truncatus invades. Vector of urinary schistosomiasis.	Bulinus globosus populations decline, unable to use new habitat. Bivalves and prosobranchs dominate animal benthic biomass.	Machena & Kautsky (1988); Brown (1994).
Australian.			
Australia: overview.		Decline in species due to impoundments.	Walker (1985)
Murray-Darling River system, Australia.	One introduced non-native species of gastropod.	Decline from 18 gastropods to 1 native species due to 3 factors: changes in biofilms, predation by carp and flow regulation.	Sheldon & Walker (1993).
Murray-Darling River system, Australia.	Bivalve Velesunio ambiguus has increased in abundance.	Bivalve Alathyria jacksoni has declined in abundance.	
Lower Murray River system, Australia.	None noted.	Some molluscs become locally distinct because billabongs isolated when normal flooding stops.	Boulton & Lloyd (1991).

Nearctic			
Summary USA rivers.	None noted due to dams. Increase in range of two species, zebra mussel, Dreissena polymorpha and Asian freshwater mussel, Corbicula fluminals which are abundant where they occur and adversely impact native mussels.	294 species disappeared, decreasing 42-84% of pre-impoundment levels with an average loss of 70% of the fauna.	Bogan (1998).
Tennessee River, USA. overview		50% loss amongst 100 species.	Bogan (1998).
Mobile Bay basin, USA, overview.		Species richness: 38 of 42 extinctions, 90% when big river shoal fauna impounded, covered by deep water then silted.	Bogan (1998).
Mussel (Muscle) Shoals, Cumberland River, USA.		Species richness: Loss of very diverse fauna with over 70 species in 35 genera. Estimated decline: 50%.	Van der Schalie (1938); Williams et al. (1993).
Lake Berkely, Cumberland River, Kentucky, Ohio-Tennessee River basin, USA, established between 1916-23.	Species richness: 6 species (1981) and 5 species (2 new) 1994 survey.	Species richness: 10 species were extirpated. 1994 survey showed some new arrivals did not take. Species abundance: Most species now recorded at low % of total fauna (1.28-3.12%). Decline in overall diversity and predominance of a few species.	Blaock & Sieckel (1996).
Cumberland, Cumberland River, USA. Dam created 1952.		Species richness: loss of 43 species in dammed stretch. Decline from 59 to 16 species.	Neves (unpublished information).
Norris, Clinch River, USA. Dam created 1937.		Species richness: loss of 28 species in dammed stretch. Decline from 40 to 12 species.	Neves (unpublished information).
Demopolis, Tombigee River, Alabama, USA. Dam created 1954.		Species richness: loss of 21 species - decline from 50 to 29 species. 6 species present in river listed as endangered and 5 as candidates for Federal Register of protected species; all globally threatened. No decline in unimpounded sections in 1970s. Causes for decline: increased water depth, decreased current and loss of gravel substrate following siltation.	Williams et al. (1992); Neves (unpublished information).
Wheeler Dam, Tennessee River, USA.		Species richness: Loss of 42 species in dammed stretch - decline from 60+ to 18 species.	Neves (unpublished information).
Little River, Oklahoma, USA.	None noted.	Reduced mussel abundance with cumulative impact of multiple dams giving an overall mussel extinction gradient downstream from large impoundments. Only stretches furthest from the dam contain relatively rare species.	Vaughan & Taylor (1999).
Neotropical			
Yacyretá Reservoir (1600 km2. Parana River rapids, Argentina and Paraguay.	None noted.	Species richness: 3 of 7 taxa from this group of prosobranchs in the river (genus Aylacostoma) are extinct in the Wild (EW). Only extant in captive holdings of Argentine Museum of Natural Science. Increase in water depth changed the well-lit, clear bed with oxygenated water to dense growth of algae with muddy bottom.	Bertonatti (1999); Quintana (updates as pers. comm.).
Lateral effects			
Salto Grande Dam, Uruguay.		Species richness: Terrestrial gastropod (Athinus albolabiatus), formerly endemic to Gallery Forest next to Uruguay River has been proposed as Extinct for IUCN Year 2000 list following dam building	Mansur (unpublished information).

Asian (Oriental)			
Ubolratana (or Nam Pong) Dam, Thailand.	Species abundance increase of 3 species of prosobranch Bythnia funiculatus, B. siamensis and B. goniomphalos in subgenus Digniostoma which transmit Opisthorchis viverrini causing outbreaks of Opisthorchiasis. Can live at high densities, usually found in rice fields, canals, ponds and lake.		Woodruff & Upatham (1992).
Downstream			
Nearctic			
North American mussels - downstream and impoundments.	None noted.	Extinction curve, taking into account functionally extinct species, is 4.2% per decade - result of all impacts including dams, but excluding zebra mussels.	Ricciardi & Rasmussen (1998).
Mississippi Basin, USA.		Current decline of mussels in the Basin will have a detrimental effect on the entire ecosystem as they play a vital role in sediment mixing and nutrient recycling, and given biomass dominance, their removal could have long-term effects, as yet unknown	Stein & Flack (1996).
Lower Cumberland River, Kentucky, USA.	None noted.	21 of 25 mussel species disappeared between 1911 and 1994.	Neves (unpublished information).
Center Hill, Cany Fork, USA. Dam created 1948.		Loss of 32 species with impact 12 km downstream of dam - decline from 39 to 7 species.	Neves (unpublished information).
Demopolis, Tombigbee River, Alabama, USA. Dam created 1954.		No decline in impounded sections in 1970s.	Williams et al. (1992); Neves (unpublished information).
Mussel (Muscle) Shoals, Cumberland River, USA.		Loss of very diverse fauna with over 70 species in 35 genera. Estimated decline of 70%.	Van der Schalie (1938); Williams, et al. (1993).
Wolf Creek, Cumberland River, USA. Dam created 1952.		Loss of 35 species with impact 18 km downstream of dam - decline from 39 to 4 species.	Neves (unpublished information).
Palearctic			
River Inn, Austria.	None noted.	38 species lost due to changes in flow regime, increase in gradient: loss of temporary habitats, increasing pollution, glochidial fish host loss and increased siltation.	Foeckler et al. (1991).
Rivers of Franche Centé, France.		Declined from 48 to 39 species due to anthropogenic activity including hydropower developments.	Mouthan (1999).

Table 3.5. Overview of dam impacts on freshwater fishes

Case studies	Biodiversity increases	Biodiversity decreases	Source
Nearctic			
Overall USA status.	Alien species noted to be the third threat to freshwater biodiveristy.	Prime threats to freshwater biodiversity were: habitat loss - 94%, pollution (including siltation) - 66%, and alien species - 53%. Prime causes of habitat loss were: water development incl. dams - 91%, dams and other river barriers - 64%, and pollutants - 55%.	Wilcove et al. (1998).
Upstream			
Nearctic			
Columbia River, USA.	None noted.	*Acipenser transmontanus* endangered, numbers reduced. Dams prevent movement between riverine sections.	Beamesderfer et al. 1995.
Neotropical			
Parana River, Brazil.	*Prochilodus lineatus* increased by taking advantage of the connection between the reservoir and the floodplain above the reservoir.		Agostinho & Zalewski 1995.
Araguaia-Tocantins Basin, Brazil.	Increase in *Prochilodus nigricans, Semaprochilodus brama, Anodus elongatus* and *Pimelodina flavipinnis*.		Ribeiro et al. 1995.
Asian (Oriental).	None noted.	None noted.	
Palearctic			
Zahara-El Gastor Dam, Guadalete River, Spain.		In the long-term the three native species, *Barbus sclateri, Chondrostoma polylepis willkommii*and *Leuciscus pyrenaicus* have been almost entirely replaced by the exotic, *Micropterus salmoides*.	Ruiz 1998.
Bia Basin - Lake Ayame, Côte d'Ivoire.	Species number has recently increased from 44 to 65 including two exotics.	*Distichodus rostratus* and *Citharinus eburneenis* no longer present.	Gourène et al. 1999; Koné & Teugels in press.
Volta Lake, Ghana,	*Pellonula afzeliusi* and *Oreochromis niloticus* increased.	*Alestes baremose, Mormyridae* and others declined after dam closure.	Petr 1967, 1968, 1971; Petr & Reynolds 1969; Braimah 1995.
Kainji Lake, Nigeria.	Cichlidae, Cyprinidae and Bagridae increased in number in the lake compared to the River Niger.	Mormyridae, Cyprinidae, Citharinidae and Bagridae decreased. A loss of about 23 species formerly in the river that were not subsequently found in lake	Balogen & Ibeun 1995.
Lake Kariba, Zambia and Zimbabwe.	In ten years from closure, the number of species in the lake increased from 28 to 40. Mormyrids, cichlids and silurids increased. The characid, *Hydrocynus vittatus* also increased as did benthic species. *Synodontis zambezensis* is now the most abundant fish.	Several species of the Zambezi River such as *Opsaridium zambezense* and *Distichodus mossambicus* disappeared. Other early abundant species, *Clarias gariepinus, Labeo spp., Barbus spp.* and *Distichodus spp*. declined rapidly in the early 1960s. *Protopterus annectens* has now become extinct in the lake basin.	Balon 1974; Marshall 1984, 2000; Jackson 1989; Karenge 1992; Machena 1995; Kolding & Karenge unpublished information.

Australian	None noted.	None noted.	
Nearctic			
Colorado River, USA.		In the Kenney Reservoir, White River, exotic fish became dominant (90%) over native species. This has been a feature of many of the reservoirs on the Colorado River system.	Stanford & Ward 1986; Martinez et al. 1994.
Tennessee River, USA.		In the Norris Reservoir 35 species disappeared including four families, Petromyzontidae, Anguillidae, Cottidae and Cyprinodontidae, and several genera and species of Cyprinidae and Percidae.	Neves & Angermeier 1990.
Neotropical			
Tucurui Dam, Araguaia-Tocantins River Basin, Brazil.	Richness (217 species) not affected.		Barthem et al. 1991; Ribeiro et al. 1995.
Asian (Oriental)			
Xianjiang Reservoir, Qiantang River, China.		The number of species decreased from 107 to 66-83 because the Xianjiang Dam blocked migrations.	Zhong & Power 1996.
Paleoarctic			
Sainte Croix Reservoir, River Verdon, France.	The original, 8 native, riverine species colonised the lake. Stocking increased this number to 17.	Three of the four most common species in the river, *Chondrostoma toxostoma, Leuciscus cephalus* and *Barbus fluviatilis* declined, in particular in the downstream area of the reservoir.	Brun et al. 1990.
Kerkini Lake, Greece.		Six of the 21 species in the lake disappeared or became very low in number. These included *Silurus glanis, Barbus plebejus cyclolepsis, Anguilla anguilla* and *Abramis brama. Perca fluviatilis* and *Esox lucius* lost spawning habitat (destruction of reed beds and shallow water areas). Two exotics, *Lepomis gibbosus* and *Stizostedion lucioperca* now present.	Pyrovetsi & Papastergiadou 1992.
Volga, Russia.	The number of species in four major reservoirs increased from 44 to 48. Thirty nine species are resident. Nine species immigrated or were introduced but none of these reproduce naturally. They will probably disappear as stocking has discontinued.	Seven species, mainly anadromous rheophils, disappeared.	Poddubny & Galat 1995; Gertsev & Gertseva 1999.
Downstream			
African			
River Nile, Aswan High Dam, Egypt.		Total catch of *Sardinella spp.* declined by 90%.Forty seven species of fishes have disappeared in the lower Nile.	Ishak 1981; Dowidar 1988.
Central Delta of the Niger River, Mali.	Cichlidae, Clariidae and Centropomidae increased.	Decline in *Gymnarchus niloticus, Polypterus senegalus* and *Gnathonemus niger* (reproduction linked to the floodplain) and *Citharinus citharus* and *Clarotes laticeps* (feed in the flood plain).	Läe 1995.

South Africa.		Dams have prevented or disrupted the migrations of several vulnerable and rare species. They have also negatively affected the conditions required by rheophilic species. These include *Barbus serra, B. capensis, Labeo seeberi* (Olifants River system), *B. tenius* (Gourits and Keurbooms River systems), *Chiloglanis bifurcus* (Incomati River system - Braam Raubenheimer Dam on the Crocodile River), *Austroglanis sclateri* (Vaal-Orange system), *Hippocampus capensis* (dam on the Keurbooms River), *Syngnathus watermayeri* (dams on the Bushmans and Kariega Rivers), *Myxus capensis* (along the east coast of southern Africa) *Chiloglanis emarginatus (*Fig Tree and Morgensen Dams, Pangold River system) and *Opsaridium zambezense* (eastern Transvaal, Swaziland and Natal).	Skelton 1987.
Australian			
Australian rivers in general.		Those impacted by dams include: *Maccullochella macquariensis* and *Maccullochella sp.* both endangered, and *Prototroctes maraena*, vulnerable.	Wager & Jackson 1993.
Thomson River, Victoria, Australia.	The diversity of fish has not changed.		Gippel & Stewardson 1995.
Lower River Murray, Australia.		In the river system 15-16 species of fish are threatened and 5 are vulnerable. Flow regulation is implicated because floods are essential for reproduction.	Walker & Thoms 1993.
Murray-Darling River system, Australia.		Fish diversity decreased with increase in water regulation.	Gehrke et al. 1995.
Nearctic			
Colorado River, USA.		*Ptychocheilus lucius* reduced in the Green River catchment and the White River (Taylor Draw Dam). Endangered species are: *P. lucius, Gila elegans, G. cypha,* and *Xyrauchen texanus*.	Holden & Stalnaker 1975; Carlson & Muth 1989; Martinez et al. 1994; Stanford & Nelson 1994.
Columbia River, USA.		More than 200 stocks of anadromous salmonids have become extinct. The state of the 214 native, naturally spawning stocks of Pacific salmon, steelhead and sea-run cutthroat trout (*Oncorhynchus spp.*) from the Pacific north-west are: endangered = one, facing high = 101 or moderate =58 risk of extinction or are of special concern =54. Eighteen of the high risk stocks may already be extinct.	NPPC 1987; Williams et al. 1989; Riggs 1990; Nehlsen et al. 1991; Wissmar et al. 1994; Devine 1995; Losos et al. 1995; Ryman et al. 1995; Independent Scientific Group 1999.
Missouri River, USA.		*Hybopsis meeki,* special concern, has had much of its habitat eliminated. Low species diversity below the Garrison Dam due to the discharge of cold, hypolimnion water from Lake Sakakawea.	Hesse et al. 1989; Williams et al. 1989; Wolf et al. 1996.
Tennessee River, USA.		In the South Fork Holston River 43 species were found before impoundment compared to 17 collected in the tailwater of the operating dam. Thirty two species were sampled before construction of the Watauga and Wilbur dams compared to 13 in the tailwaters after impoundment.	Neves & Angermeier 1990.
Neotropical			
Parana River, Brazil.		Dams on the river have obstructed the migration of some commercially valuable fish species including *Pseudoplatystoma corruscans* and *Salminus maxillosus*. Two other commercially important species, *Piaractus mesopotamicus* and *Brycon orbignyanus* were eliminated after the dam was closed.	Lowe-McConnell 1987; Agostinho et al. 1994; Agostinho & Zalewski 1995.

Araguaia-Tocantins River Basin, Brazil.	Richness (190 species) was not significantly affected. Migration of *Hypophthalmus spp.* not directly interrupted by the Tucurui Dam.	Ten previously abundant species drastically reduced. Long distance migrations of *Prochilodus nigricans, Anodus elongatus, Brachyplatystoma flavicans, B. filamentosum, Phractocephalus hemiliopterus* and *Pinirampus pirinampu* interrupted by the dam.	Ribeiro et al. 1995.
Amazon River.		Hydroelectric dams in the Amazon Basin interrupt the migrations, both upstream by adults and downstream by larvae, of the catfish *Brachyplatystoma filamentosum*, *B. flavicans, B. vaillanti, Goslinia platynema* and *Lithodoras dorsalis*.	Barthem et al. 1991.
River Sinnamary - Petit Saut, French Guiana.		Decrease in the number of taxa of juveniles from 51 to 48. Species richness (of all age groups caught by gill netting) in general declined from pre-dam through filling to the stabilisation period (54 species pre- to 47 post-impoundment). There were 34 species common to both pre- and post-impoundment, 20 species present before the dam but not after and 13 not found before but captured after. *Pterengraulis atherinoides* (Engraulidae) and *Triportheus rotundatus* (Characidae) practically disappeared after dam closure.	Ponton & Copp 1997; Ponton & Vauchel 1998; Merona & Albert 1999.
Asian (Oriental)			
Ganges River, India.		Dams, e.g. the Farakka Barrage, have nearly eliminated the anadromous *Hilsa ilisha* (Clupeidae) in the riverine stretches. Other major carp species reduced (50% of 1964 levels) in the lower Ganges.	Jhingran & Ghosh 1978; Natarajan 1989; Dudgeon 1992, 1995. Temple & Payne 1995.
East River, tributary of the Pearl River, China.		*Macrura reevesii* and *Clupanodon thrissa* migrations blocked by dams and fish virtually disappeared by 1970. *Cirrhinus molitorella,* also affected.	Liao et al. 1989.
Qiantang River, China.		*Macrura reevesii* eliminated from the river.	Zhong & Power 1996.
Gezhouba Dam, Yangtze (Changjiang) River, China.		*Acipenser sinensis* migrations affected.	Zhong & Power 1996.
Chenderoh Dam, Perak River, Malaysia.		Decline in *Probarbus jullieni* (Cyprinidae).	Dudgeon 1992.
Paleoarctic			
Rhône River, France.		Dams on the river have reduced access to spawning grounds of *Alosa alosa, Acipenser sturio* and *Petromyzon marinus*. Biodiversity has been reduced because of loss in habitat variation resulting from river regulation.	ruget 1992; Crivelli personal communication.
Upper Rhône - Bregnier-Cordon, France.	Chondrostoma nasus, usually considered sensitive to river engineering, increased in abundance. Diversity increased in the lotic habitats.		Penaz et al. 1995.
River Gudbrandsdalslagen, Norway.		Smolt production of the Hunder strain of brown trout, *Salmo trutta*, has been permanently reduced.	Aass 1993.
Jeziorsko, Warta River, Poland.		The anadromous *Vimba vimba* and the rheophilous *Chondrostoma nasus* disappeared.	Penczak et al. 1998.
Volga, Russia.		*Alosa kessleri volgensis* virtually disappeared from the Volga - North Caspian	Rozengurt & Hedgpeth 1989.
Valparaiso Dam, Rio Tera, Spain.	Salmo trutta persisted.	Cobitis calderoni, Leuciscus carolitertii, Rutilus arcasii, Gobio gobio and Barbus bocagei disappeared after impoundment.	Garcia de Jalon & Sanchez 1994.

Lake Vänern, Sweden.		Two thirds of large-sized stocks of Salmo trutta have become extinct in <100 years due to migratory obstructions.	Ros 1981.
Cow Green Reservoir, England.	Environmental changes brought about by water regulation improved conditions for Cottus gobio and Salmo trutta below the dam.		Crisp et al. 1983.

Table 3.6. Overview of dam impacts on waterfowl

Case studies	Biodiversity increases	Biodiversity decreases	Source
Upstream			
Global overview.			
800 Ramsar sites.	Five regularly support > 20,000 waterfowl; 6 support > 1% of biogeographical population.	Not evaluated, but number of Ramsar sites involving dams with internationally important waterfowl populations is small compared to natural wetlands.	Davidson & Delany, Personal observations.
Palearctic			
Switzerland wintering waterfowl.	232-4,272 birds on reservoirs with overall diversity of 23 species and 753-88313 on natural lakes with overall diversity of 33 species.	Not evaluated.	Davidson & Delany, Personal observations.
UK wintering waterfowl.	Three reservoirs support >20,000 waterfowl and 8 support 1 or more internationally important species (natural wetlands: 12 and 49 respectively).	Not evaluated.	Davidson & Delany, Personal observations.
African			
South African waterfowl	At least 12 reservoirs support major and import. concentrations. Adds habitat to dry landscape.	Only one area studied- 2 of 13 waterfowl present before inundation disappeared, including 1 Red Data species, 2 decreased in abundance, 7 little change, and 2 common species increased in abundance.	Davidson & Delany, Personal observations.
Downstream			
Palearctic			
Danube Delta in Romania and Ukraine.	None noted.	Populations of many of the 160 species of waterfowl down to a fraction of their historical numbers, due to habitat decline, in part from upstream impoundments and channelisation.	Pringle et al. (1993)

Table 3.7. Overall summary of dam impacts

	Biodiversity increase	Biodiversity decrease
Upstream		
Mollusc.	None noted.	Decrease in freshwater molluscs.
Fishes.	None noted	Decrease in migratory species.
Waterfowl.	Not evaluated.	Not evaluated.
Reservoir		
Molluscs.	Increases not noted except species abundance, especially where molluscs dominant in benthos.	In 66 cases around the world, an average of 70% of species were lost. Extinction or extirpation rates of up to 50% or even 90% are reached in rich faunas.
Fishes.	Increase in overall diversity noted only in some African reservoirs.	On most continents overall fish diversity declines despite the frequent invasion of a few exotic species.
South African waterfowl	At least 12 reservoirs support major and import. concentrations. Adds habitat to dry landscape.	Only one area studied- 2 of 13 waterfowl present before inundation disappeared, including 1 Red Data species, 2 decreased in abundance, 7 little change, and 2 common species increased in abundance.
Waterfowl.	Reservoirs increase populations, providing new habitats, sometimes in significant numbers of important species.	Diversity of waterfowl tends to be higher on natural water bodies than reservoirs. Delta populations of birds may suffer impacts from lowered water quality, delivery of sediments and other results of upstream impoundments and channelisation.
Downstream		
Molluscs.	None noted.	Moderate to drastic declines with extirpations (up to 84%) and extinctions.
Fishes.	27% of 66 cases reservoir/downstream were positive.	In 77% of the 66 reservoirs/downstream impacts were negative, but with most (53%) being downstream.
Waterfowl.	None noted.	One Red Data waterfowl disappeared below a South African dam; Many of the populations of 160 species of water-birds down to a fraction of their historical numbers, in part from upstream impoundments and channelisation.

The impounding of rivers has terrestrial impacts on 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 ecology is tied to that of estuaries in the transport of silt, nutrients and seasonally different volumes of river discharge. This is important in the physical maintenance of delta and coastal habitats and the nutrient-based estuarine food chains. The nutrient plume of rivers can extend far out to sea. So regulation of rivers can influence even ocean species and ecosystems.

Cumulative effects

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. Table 1.8 shows that there are 10 basins with 6 to 14 major dams.

The Itaipu Reservoir, Brazil, is sited below a floodplain and hence enhances migratory fishes. The species inhabit the floodplain, then, when mature, migrate down into the reservoir (Agostinho *et al.* 1994; Agostinho & Zalewski 1995). However, the floodplain will disappear when a new dam being built will cause it to go underwater.

In James and Hudson Bay, Canada, river basin impoundments discharge 50% more water in winter than in the pre-dam era. This has a number of ecological effects in the estuaries and seawards (McAllister 1991).

If the dams reservoirs are used for irrigation water supply, then the volume of flow will become progressively attenuated, as in the Colorado River, USA, where the mouth is virtually waterless.

Dam effects relative to other sectors
There is no doubt that many human activities, other than dams, are degrading freshwater ecosystems and have, at times, contributed to the extirpation or extinction of individual freshwater species. However the examples shown in Tables 3.4 and 3.5 indicate that dams have caused the extirpation or extinction of numerous stocks and species of molluscs and fishes.

In a study of extinction rates of North American freshwater fauna, Ricciardi and Rasmussan (1999) showed that the mean rate of extinction in freshwater fauna (fishes, crayfish, mussels, gastropods and amphibians) was 0.5% per decade, while in terrestrial and marine groups (birds, reptiles, land and marine mammals), the rate was 0.1% per decade. That is extinction is proceeding five times faster in freshwater than on land in North America. The authors point out that in 1990 only about 40 rivers >200 km remained free-flowing.

Status of species at the global level are not as completely evaluated. The level of threat for predominantly terrestrial vertebrates is 11 to 25%, while for more aquatic vertebrates it is 13 to 65% (Table 1.2).

Prospects for freshwater biodiversity

The present analysis has focused on what is known on biodiversity and the impacts of dams on three groups, molluscs, fish and birds. Three questions remain outstanding: how complete are the data, what does the data imply for other groups of animals, plants and microorganisms, and what are the prospects for freshwater biodiversity and its relationship to dams?

Completeness of study data. There is a lack of data from many of the developing countries where much of the world's biodiversity is located. In most countries, developed and developing, monitoring of the environment, following baseline studies, is geographically uneven and infrequent. Species may be declining or have even become extirpated or extinct without human awareness. The problem may be worse for the smaller, non-commercial or low profile species. Environmental impact assessment reports are often difficult to secure, they do not enter into the published literature, and their data may not be reliable.

Better estimates of biodiversity status come from areas such as North America, Europe and Australia, involve vertebrates, vascular plants, or a few other high profile groups, and have been tracked by international environmental organisations such as IUCN's Species Survival Commission or the Nature Conservancy. Tracking status is more effective when the taxonomy of a group is fully resolved. Tracking extinctions is important as a measure of the loss of biodiversity although most resources should be invested in monitoring the status of populations. Detecting a decline early provides greater options for reversing loss.

Implications of data for biodiversity as a whole. The lack data for many of the world's taxonomic groups and geographic areas means that it is necessary to make an estimate the world's freshwater biodiversity loss by applying assumed rates of loss to the number of freshwater species.

The mean of globally freshwater threatened species (Table 1.2) is 36%. In the USA Stein and Flack (1997) estimated it to be 40%. If a midpoint value of 38% is applied to the 44,000 scientifically described freshwater species, then 16,720 species of animals, plants and microorganisms are threatened. Similarly applied to the 1.5 million species, scientifically described and yet to be described, then the number of threatened species is 570,000.

Prospects for freshwater biodiversity in relationship to dams. Data from Revenga *et al.* (1998) suggests that the preponderance of the large dams already constructed are in watersheds outside the tropics (Cancer and Capricorn). It is predicted that tropical locations for dams will be given preference in the next century. The tropics are 'home' to much of the richest freshwater biodiversity (Fig. 2.4). One of the main considerations of dam impacts on biodiversity is placement in regard to species-rich areas. Priority must be given to ensure that the environmental impact of dams does not overlap with biodiversity ‘hotspots’.

In areas rich in biodiversity and productive biological resources, it is also important to take into account the cumulative impact of dams. Two or more dams may have either serious cumulative or synergistic impacts.

4 Standards for minimising negative impacts on biodiversity

As a result of the continuing erosion of biological diversity, the inter-governmental community has, through a variety of mechanisms, adopted a set of standards for minimising harmful impacts on biodiversity. These standards, which have been adopted in legally binding documents by almost all governments, are far more exacting and demanding than is generally recognised. In this section of the report, we review these internationally agreed standards, because they are the most appropriate biodiversity benchmark against which to assess the impacts of the dam construction industry.
World Charter for Nature.

The World Charter for Nature was adopted by consensus by the UN General Assembly in 1982. It provides the high-level guiding principles that should govern human responsibility for biodiversity. Its states that activities which might have an impact on nature shall be controlled, and the best available technologies that minimise significant risks to nature or other adverse effects shall be used; in particular:

- Activities which are likely to cause irreversible damage to nature should be avoided;
- Activities which are likely to pose a significant risk to nature shall be preceded by an exhaustive examination; their proponents shall demonstrate that expected benefits outweigh potential damage to nature, and where potential adverse effects are not fully understood, the activities should not proceed;
- Activities which may disturb nature shall be preceded by assessment of their consequences, and environmental impact studies of development projects shall be constructed in advance, and if they are to be undertaken, such activities shall be planned and carried out so as to minimise potential adverse impacts.

These guiding principles have been reaffirmed in a succession of formal intergovernmental agreements.

Convention on Biological Diversity
The Convention on Biological Diversity (CBD) was signed by 156 States in June 1992, and by September 1999 175 countries had ratified the Convention. The Preamble to the CBD starts with similar sentiments to those in the World Charter for Nature. The objectives of the CBD are the conservation of biological diversity, the sustainable use of its components, and the fair and equitable sharing of the benefits arising out of the utilisation of genetic resources.

Article 8 of the CBD identifies the in-situ conservation measures that Parties should seek to carry out. Article 14 addresses impact assessment and minimising adverse impacts, *inter alia* in Section 1 (a): 'Introduce appropriate procedures requiring environmental impact assessment of its proposed projects that are likely to have significant adverse effects on biological diversity with a view to avoiding or minimising such effects and, where appropriate, allow for public participation in such procedures'.

Other agreements
A very similar set of standards relating to impacts on biodiversity is included in **Agenda 21**, which was adopted by consensus at the UN Conference on Environment and Development in June 1992. Chapter 15 on Conservation of Biological Diversity states that: processes and activities with significant impacts on biological diversity should be identified; action should be taken for the conservation of biological diversity through the *in-situ* conservation of ecosystems and natural habitats; and that the rehabilitation and restoration of damaged ecosystems and the recovery of threatened and endangered species should be promoted.

The Convention on the Conservation of Migratory Species of Wild Animals (CMS), adopted in 1979, states, among its fundamental principles, that: 'the Parties acknowledge the need to take action to avoid any migratory species becoming endangered'. This principle is of particular importance for the current report, since migratory freshwater species have suffered particularly serious adverse affects from large dams.

At the national level, numerous laws, action plans, and conservation programmes have enshrined the principles contained in the documents quoted above.

World Bank

The World Bank's Operational Policy 4.04 on Natural Habitats requires that comprehensive analysis should demonstrate that overall benefits from a project outweigh the environmental costs before significant conversion of natural habitats is allowed, unless there are no feasible alternatives for the project and its siting. The World Bank Environment Department study, the Impact of Environmental Assessment (1997) reported some positive trends but also a wide range of quality in the biodiversity sections of Environmental Impact Assessment (EIA) reports

Corporate sector

The World Business Council for Sustainable Development and the IUCN have prepared: *Business and biodiversity. A guide for the private sector* (WBCSD and IUCN 1997). This explains the Biodiversity Convention, issues and opportunities for the private sector, and describes how companies can engage with biodiversity issues.

Hydro-Québec, Canada, a major hydro-power company, is moving into wind-generated power. The company has co-published a report on biodiversity and hydroelectricity (HQ and GDG 1999).

Government sector

Some governments have high environmental protection standards. The United States Environmental Protection Act was a pioneer in establishing standards not in outlawing killing endangered species but in protecting their habitat.

Work on a California dam in 1996 included substantive pro-active environmental activities. Endangered frogs were relocated. Flooded habitat had to be replaced and artificial ponds which would be self sustaining were created with large reed beds for amphibians and birds. There were stiff penalties for any construction worker moving outside the terms and conditions of site work, including loss of job and financial penalties. Training videos were produced which even visitors to the site had to watch.

Accepted standards

A few key points can be distilled from the documents quoted in this section. These are as follows:

- Species and ecosystems have intrinsic value. They should be conserved in their own right, as well as to provide benefits to humans.
- Every effort should be made to minimise the risk of the extinction of species.
- Urgent steps should be taken to bring about the recovery of threatened species.
- High priority should be given to securing the recovery of degraded habitats and ecosystems.
- Essential ecological functions or processes should be conserved.
- Natural resources should be used sustainably.
- There is concern that biodiversity continues to be lost at a rapid rate.
- Attempts to conserve biodiversity are hampered by inadequate information.
- Lack of information should not be an excuse for lack of conservation action — the Precautionary Principle
- Environmental impact assessments should be thorough, be given sufficient time, and be carried out in an open and transparent fashion
- Activities that have potential impacts on biodiversity should be the subject of prior environmental impact assessments.
- Activities that are likely to have particularly serious negative impacts on biodiversity should not be permitted.
- Staff training about biodiversity conservation in project environmental standards and objectives is needed
- In the absence of good information on the likely impacts of particular actions, the precautionary principle should apply.

It is important to realise that the above list summarises the points that have been agreed by the global community through formal inter-governmental mechanisms.

Environmental impact assessment standards
UNEP and Wetlands International have been promoting economic and environmental impact assessment. Dorcey *et al.* (1997) provide a checklist for key potential environmental and social impacts caused by large dam projects. The public expects high standards for environmental impact surveys (EIA), an expectation not always met. Standard most frequently breached are:

Lead time. EIAs should begin long before any construction, especially in geographic regions where biota are poorly known. Lead time should permit sampling through at least one annual cycle, preferably more to allow for natural variability. Biodiversity monitoring should be continued through the construction phase.

Expertise. Taxonomic knowledge is required. Similar expertise is required in ecological, life history, fishery and other aspects. It is desirable to complement academic expertise with local indigenous and traditional knowledge.

Open process. Draft and final EIA studies should be freely available locally, nationally and internationally with sufficient lead-time before public hearings and final approval processes.
Voucher specimens. Representative voucher specimens of flora and fauna collected should be deposited in national or regional museums.

‘**Arm’s’ length’ analysis.** EIA’s should not be conducted by the firms engaged in building the dam, nor their subsidiaries.

Follow-up. One-, five- and ten-year follow-up biodiversity studies, by an organisation other than the one which carried out the EIA, should be performed. These test EIA predictions and provide data for planning future dams. EIAs should consider what are alternative uses of the site, in addition to current usage and the planned dam. What are the costs and benefits of the various options, including items that do not enter the normal market such as subsistence fishing? What is the lifetime of the various options? In some cases dam capacity has been significantly reduced in less than 10 years, in other cases dams are functioning at good capacity several decades after their construction. Can sedimentation be mitigated by engineering solutions *in situ* (dredging and draining sediments) or reduced *ex situ* by biological management of the drainage basin? What are the biodiversity effects of these various options? If heavy sediment deposition is impossible to avoid, is this a factor in possible elimination of this dam site?