Integrated hydrological modelling of wetlands for environmental management: the case of the Usangu wetlands in the Great Ruaha catchment

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Abstract

Knowledge of wetland hydrology and quantification of water inputs and outputs are prerequisites to understanding wetland environments and determining their vulnerability to change. To get a better understanding of the dynamics of wetland change in the Usangu Plains, a study was conducted to: a) investigate the effects of human interventions on the wetlands, and b) determine the amount of dry season inflow required to maintain environmental flows downstream of the wetlands. The study integrated hydrologic data, remote sensing and GIS techniques to study the dynamics and spatial response of the wetlands. A monthly water balance model was developed for the wetlands to determine the major components of the water budget. The results of the analyses indicate that the wetlands have changed appreciably in size over recent years and the inflow volumes have decreased with time as a result of increased human interventions. The dry season vegetated swamp cover, a major component of the swamp, decreased by 67% over the 16 years from 1984 to 2000. If this trend continues, it is possible that the wetlands will undergo a change, which will be extremely difficult to reverse. Downstream of the wetlands an environmental flow of 0.5 m^3/s was estimated. To maintain this outflow, the corresponding inflow volume into the wetlands was estimated to be 6.8 m^3/s. To achieve this, the available dry season water resource will have to be divided 20% for anthropogenic needs and 80% for the environment to feed the wetland. The study has demonstrated the need for integrated water resources management to balance the demands between different sectors and enable appropriate catchment interventions to ensure the sustainability of wetland resources.

Key words: *Wetlands, environmental flows, modeling, water balance, GIS, remote sensing, integrated water resources management*

Introduction

Wetlands exist in the landscape where the water balance ensures an adequate water supply at or near the surface (Price *et al.*, 2005). Therefore sustained wetland functioning requires proper land use and water management. To achieve this an integrated understanding of the spatial dynamics and hydrological balance of the wetland ecosystem among other factors is required. An important note is that, wetlands are linked through the hydrological system to upstream and downstream areas. What happens upstream will affect a wetland, while what happens in a wetland will affect the environment and people living downstream. As Abbot and Hailu (2001) argued, wetlands may be influenced by broad environmental changes, such as deforestation and climate change, driven by socio-economic factors, including national economic policies and local market conditions. Worldwide it has become evident that many aquatic ecosystems have changed as a result of modification of the flow regime caused by river regulation (Poff *et al.*, 1997; McCully, 2001; Tharme, 2003; Postel and Richter, 2003; Bunn and Arthington, 2002; and Brown and King, 2003). The modification of the hydrologic regime can indirectly alter the composition, structure, or function of aquatic, riparian and wetlands ecosystems through their effects on physical habitat characteristics, including temperature, oxygen content, water chemistry and substrate particle sizes (Dynesius and Nilsson, 1994; Richer *et al.*, 1996).

The importance of hydrology for the maintenance of wetlands is widely recognised. However, knowledge of the interlinkages between upstream land use and water diversions and the resulting impacts on wetland hydrology and spatial dynamics as well as the implications for downstream flows is still limited. Such information is required for informed decision-making and for influencing policy changes towards sustainable and "wise use" of wetlands. Hayashi and Rosenberry (2001) noted the need for understanding the linkages between adjacent uplands and wetlands because of their importance in maintaining the hydrological and ecological integrity of wetlands. Also Hill (2000) and Bedford (1999) both stressed the need for a catchment /landscape approach to understand upland-wetland linkages and the potential impact of individual and cumulative catchment disturbance on the receiving wetland. Therefore, an integrated understanding both upstream and downstream of the wetland is required.

This paper is based on the research undertaken to improve understanding of the spatial dynamics and the hydrology of the Usangu Plains wetlands within the Great Ruaha Catchment in Tanzania and the impact of increased upstream water diversions for anthropogenic activities on wetlands and the downstream. The work was divided into three parts: a) an analysis of land cover change between 1973 and 2000 using satellite imagery, b) an evaluation of changes in flow downstream of the wetland over the same time period, and c) an estimate of the dry season inflows required to maintain predetermined flows downstream of the wetlands.

Study area, materials and methods

Description of the study area

Location and topographical features

The Usangu Plains are located in the southern western part of Tanzania between longitudes 33°E and 35°E, and latitudes 8°S and 9°30'S (Figure 1). They form the upper catchment of the Great Ruaha River. This river, in turn, is a main tributary to the Rufiji river, the largest drainage basin in Tanzania, covering some 174 800 km^2, or about 18% of mainland Tanzania. The plains cover an approximate area of 15,560 km^2. The plains are flat and surrounded by the Poroto and Kipengere mountains in the Southern Highlands between Mbeya and Iringa, and Chunya mountains. They lie at an average elevation of 1100 m above mean sea level (amsl) while the surrounding hills are at average of elevation of 3000 m amsl. The Usangu wetlands are located at the center of the Usangu Plains. They comprise the western and eastern wetlands - joined by a narrow band of land along the river at Nyaluhanga and intermediate wetlands *(i.e., the Ifushiro swamp).*

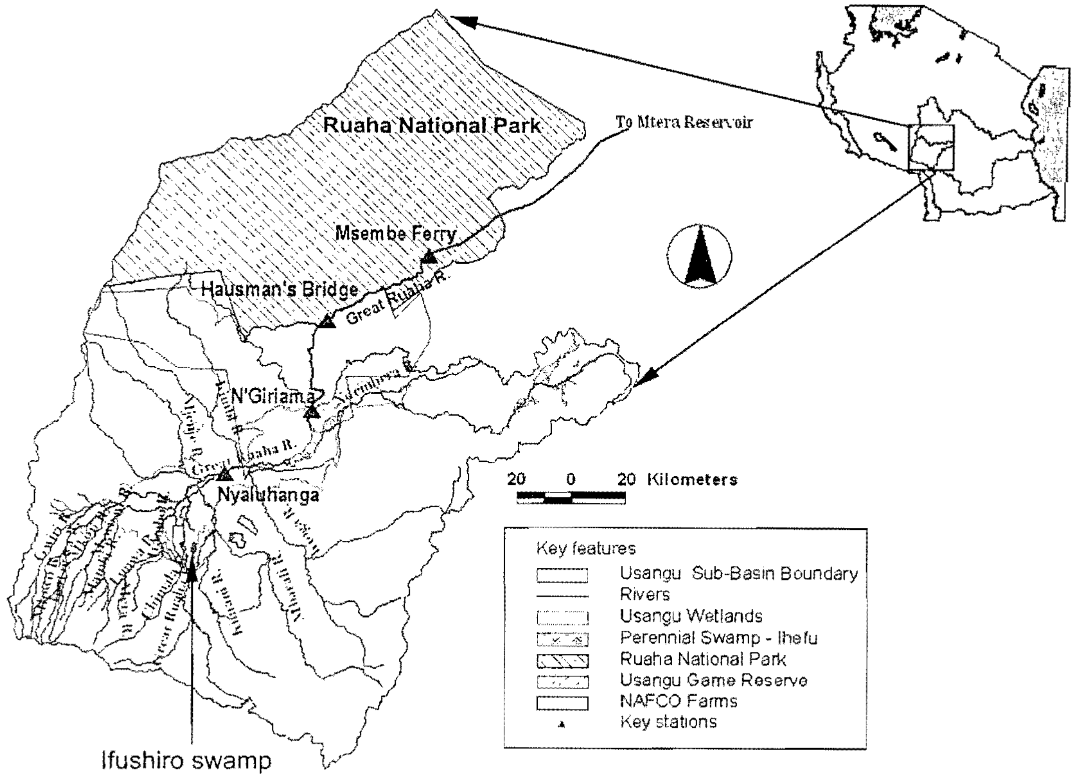

Figure 1: Map of Tanzania showing location of the study area

Drainage pattern

The major rivers (perennial) draining the Usangu Plains are the Great Ruaha, Mbarali, Kimani, Chimala and Ndembera. The first four account for 70% of measured average annual flow, while the Ndembera accounts for an additional 15% (SMUWC, 2001 a). The small rivers include Umrobo, Mkoji, Lunwa, Mlomboji, Ipatagwa, Mambi, Kioga, Mjenje, Kimbi, Itambo and Mswiswi rivers. Most of these rivers especially in the southwest, are perennial and so make zero contribution to inflows to Usangu wetlands in the dry season. The major water supplier to the Usangu wetlands is the Great Ruaha River (GRR), which flows as a single river after being joined by other rivers in the western wetland to supply the eastern wetland. A natural rock outcrop at N'Giriama controls the outflow from the eastern wetland. Downstream of the Usangu wetlands the GRR flows first through the Ruaha National Park (RNP) serving as the main source of water for the Park in the dry season. Thereafter, together with the Little Ruaha River and Kisigo River, the river supplies water to the Mtera and Kidtau hydropower reservoirs. .

Climate

The rainfall regime in the area is unimodal with a single rainy season from November to May. Rainfall is brought by monsoon winds associated with the biannual passage of the Inter-tropical Convergence Zone (ITCZ), although the spatial distribution of rainfall is also strongly influenced by topography. The rainfall distribution varies greatly across the catchment and rainfall amounts are strongly correlated to the elevation of the terrain with the higher areas receiving average annual rainfall ranging between 1 000 mm to over 1 600 mm. In contrast, rainfall on the Usangu Plains is low, ranging between 500 and 700 mm annually.

Land cover and land use

There is distinct variability in land cover/ use and vegetation patterns from highland to lowland areas including the wetlands. Miombo woodland dominates naturally throughout the highlands except at the higher altitudes. At higher altitudes (>2 000 m), there is remnant montane humid forest, giving way to afro-alpine vegetation (Hagenia forest, Erica, and Alpine grassland) at the highest elevations and on concave slopes (SMUWC, 2001 a). Cultivation is extensive in the lower (African plateau, 1 200-1 800 m), rolling hills of the northeast, in Iringa Region also within the slopping hills of the Mbarali sub catchment and the south-western part of the Mkoji sub catchment providing almost continuous cropping. The lowlands area – the Usangu plains (areas below about 1 100 m) may be divided into two broad areas — the wetland and the fans with different vegetation composition and characteristics. The Usangu wetland in the plains contains a mix of seasonally flooded open grassland (mbuga), seasonally flooded woodland, and a small perennially flooded swamp (*Ihefu*). The perennial swamp is dominated by water lilies and/or water chestnut (floating) including herbaceous vegetation. Also Vossia, which is indicative of unstable hydrological regime, has been found (Denny, 1985). The fans are alluvial deposits spreading from the base of the escarpments onto the plains. The southern fans are naturally occupied by thorny woodland and/or wooded grassland, with *Acacia tortilis, Commiphora spp.,* and *Lannea humilis.* However, this has been largely cleared and replaced by cultivation or secondary thorn bush. In the lower fans vegetation also grades into *Acacia kirkii* bush. *Acacia kirkii* bush mixed with open grasslands; the grass emerges with the rains but is rapidly removed by livestock, and for much of the year these 'open grasslands' appear as bare soil. The *Acacia tortilis — Commiphora* thorn bush is therefore less extensive and soon gives way to miombo-transitional vegetation types.

Water uses and users in the Great Ruaha River catchment

The Great Ruaha River Basin is a complex basin with diverse multi-sectoral water uses and users. A great population (about 80%) of the basin is sustained by irrigation and water-related livelihoods such as fishing and livestock keeping. Irrigation in the basin is the major activity and the largest water user, mainly during the dry season. The dry season irrigation is concentrated in upper courses of the rivers, irrigating high-valued crops such as green vegetables, onions, tomatoes, beans and maize. In contrast to the wet season, the dry season is a water scarce period associated with conflicts and disputes over access to water. During the dry season, villagers along the rivers in the mid catchments divert water to both fallow and cropped irrigated fields in plot-to-plot distribution and to the villages for consumptive domestic uses as well as for brick making. Downstream of the irrigation schemes, with the exception of the major perennial rivers, most rivers dry up. However, even the perennial rivers retain very minimal flows in the dry season. Since 1993, dry season flow in the GRR, has been so low that water levels in the eastern wetland (*Ihefu*) have dropped below the top of the rock outcrop at the outlet, with the result that flows downstream of the wetland have ceased completely. Failure in outflows from the Eastern wetland has resulted in extended periods of zero flow through the RNP (Table 1).

Table 1: Drying up of the Great Ruaha River for the period from 1994 to 2004.

Year	Date flow stopped	Date flow started	Period of no flow
1994	17 November	15 December	28
1995	19 October	23 December	65
1996	17 October	16 December	60
1997	20 September	22 November	63
1998	18 November	9 March 1999*	87
1999	21 September	20 December	90
2000	17 September	22 November	66
2001	12 November	23 December	41
2002	2 November	24 December	52
2003	21 September	16 January 2004**	104
2004	3 November	4 December	31

oxygen-depleted, nutrient-rich water that may be high in hydrogen sulphide, iron and manganese.

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

Impacts on sedimentation

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

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

Impacts on organisms and biodiversity

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

Impacts on primary production

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

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

Impacts on fish

Few fish are adapted to both lotic and lentic habitats. Consequently, the transformation of a river to a reservoir often results in the extirpation of resident riverine species. Downstream of dams, marked changes in fish populations occur as a consequence of blockage of migration routes, disconnection of the river and floodplain and changes in flow regime, physiochemical conditions (e.g. temperature, turbidity and dissolved oxygen), primary production and channel morphology. These changes may benefit some species but they generally have an adverse effect on the majority of native species.

The 1996 IUCN Red List of Threatened Animals includes 617 freshwater fishes (i.e. about 6% of the known number of freshwater species). Other researchers have speculated that globally between 20% and 35% of all freshwater fish are threatened (Staissny 1996). Although the loss of species is not solely a consequence of dams, they are one of the principal factors. It is estimated that half the fish stocks endemic to the Pacific coast of the USA have been lost in the past century to a large extent because of dam construction (Chaterjee 1998).

Impacts on birds and mammals

The importance of riparian corridors for birds and terrestrial animals has been demonstrated (e.g. Decamps *et al.* 1987). The creation of reservoirs has both positive and negative effects for aquatic and terrestrial species. The inundation of ecosystems inevitably leads to the loss of habitat and terrestrial wildlife. In tropical areas, flooding forests high in endemic species extirpates many and, in some circumstances, may result in species extinction. In contrast, in arid climates, reservoirs provide a permanent water resource that may benefit many species. In South Africa, the presence of reservoirs has greatly increased the availability of permanent water bodies, and has had a major effect on the distribution and numbers of waterfowl (Cowan and Van Reit 1998).

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

Environmental Protection

Options for environmental protection

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

- Avoidance measures result in no change to the existing environmental functioning of a particular area by avoiding anticipated adverse effects. For dams this means alternatives to dam construction such as demand management, water recycling, rainfall harvesting or alternatives to hydropower (e.g. solar, wind, thermal or nuclear). All alternatives have economic, social and environmental consequences that must be weighed against those arising from dam construction.
- Mitigation measures reduce the undesirable effects of a dam by modification of its structure or operation, or through changes to the management of the catchment within which the dam is situated. To date, mitigation is the most widely used approach to ameliorating the negative impacts of dams and a wide range of technical interventions has been developed (Tables 1 and 2). For example, making environmental flow releases to sustain downstream ecosystems is increasingly common. However, to be successful in a specific situation, mitigation measures require a great deal of understanding of complex processes and their interactions. Strategies are often of limited effectiveness, or may even result in undesirable effects, if detailed scientific and engineering studies are not conducted beforehand.
- Compensation measures compensate for effects that can neither be avoided nor sufficiently mitigated. Principal approaches include preservation of existing ecologically important areas (e.g. through the establishment of a national park) and rehabilitation of previously disturbed land either around reservoirs or some distance from the development in question.

Ideally, environmental protection measures are identified through an Environmental Impact Assessment so that adverse affects are minimised from the outset of a project. In many situations integrated approaches that incorporate changes in catchment management are essential for success.

Constraints to successful environmental protection

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

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

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

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

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

	Construction of shallow water habitat. Introduction of lake species into reservoir.	More than 1.5 million fish (i.e. salmon, rainbow trout and brook trout) were introduced into the Williston Reservoir in British Columbia, Canada (IEA 2000).
Terrestrial wildlife	Wildlife rescue. Enhancement of reservoir islands for conservation.	10,000 animals were rescued from drowning prior to the filling of the Afokaba reservoir on the Surinam River in South America (Nilsson and Dynesius 1994).

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

Issue	Mitigation measure	Example
Flow regime	Managed flow releases.	The Physical Habitat Simulation System (PHABSIM) has been used to compare options for minimising the in-stream ecological impacts of river regulation through compensation flow releases from the Derwent Valley Reservoir System in the UK (Maddock *et al.* 2001).
Thermal regime	Multi-level outlet works.	A multiple level outlet tower has been proposed for the Glen Canyon dam in the USA to mitigate the impact of cold water releases on trout (CGER 1996).
Water quality	Outlet works aeration. Multi-level outlet works. Turbine venting.	In the USA Duke Power has experimented with various approaches to increasing dissolved oxygen levels in turbine tailraces. At the Wateree Dam, turbine blades were modified to enable air to be drawn into the water through small holes in the turbine vanes. This produced a 3 mgl^{-1} increase in DO, without significantly impacting turbine performance (Sigmon *et al.* 2000).
Sedimentation	Addition of sediment to rivers. Managed flow releases. Shoreline stabilisation. Pumping offshore sediment to estuaries.	Gravel has been added to the River Rhine, since 1977 downstream of dams, to reduce erosion and maintain the channel morphology (Dister *et al.* 1990). On the Galuare River in France banks historically protected with rip-rap, are now being protected through the regeneration of a buffer zone of riparian woodland (Piégay *et al.* 1997).
Weeds/algal blooms	Mechanical cutting. Chemical control. Biological control. Flushing.	Mechanical harvesting of aquatic macrophytes was attempted on the River Otra in southern Norway, to control *Juncus bulbosus*. The approach was largely ineffective because of high operational costs and inadequate removal of submergent vegetation (Rørslett and Johansen 1996). Research has shown that algal blooms on the Murray River, Australia can be dispersed through a combination of flow management and reduction in water-levels behind weirs (Maier *et al.* 2001).
Fish	Freshets to stimulate fish migration. Improved design of turbine, spillways and overflows. Fish passes. Artificial spawning areas.	A vertical slot fish pass has been shown to be effective in enabling 24 species of fish, including barramundi (*Lates calcarifer*) to move upstream of the Fitzroy barrage in Australia (Stuart and Mallen-Cooper 1999). The hydropower dam in the Hunderfossen

	Hatcheries and fish stocking.	project in Norway was a barrier to migratory trout. A fish ladder was unsuccessful, because the primary constraint to fish migration was reduced downstream flows. Trout restocking also proved to be less successful than expected. An increase in minimum downstream flows at certain times of year to trigger migration has improved the situation (IEA 2000).
Terrestrial wildlife	Managed flow releases.	High flow releases were designed into the operation of the Itezhi-tezhi dam in Zambia. One reason for this was to preserve, through annual flooding, the high biodiversity of the internationally important Kafue Flats (McCartney 2002).

Compliance with commitments for environmental protection

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

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

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

Regular environmental auditing, by independent bodies, leading to certification, has been proposed for both existing and new dams (WCD 2000). Environmental management is a prerequisite for certification and the development of an ISO (International Organisation for Standardisation) standard for dam management is being contemplated (Giesecke *et al.* 2000). Compliance plans that specify binding arrangements for specific social and environmental commitments are one way of encouraging developers and operators to implement environmental protection measures (WCD 2000). In North America licensing of dams is an important mechanism for initiating environmental protection measures. Re-licensing (typically every 25 to 30 years) is now often made conditional on improved environmental protection, reflecting contemporary priorities.

Conclusion

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

A prerequisite for sustainable development is that future dam planning, construction and operation must become part of an integrated management effort that gives prominence to environmental protection. All the environmental impacts of a dam should be evaluated within the specific environmental, social and economic context of the catchment in which it is located. This requires inter-disciplinary thinking and basic understanding of the complex interactions between ecological and socio-economic systems. This is particularly true of environmental flow releases, where lack of hydro-ecological understanding remains a key constraint to successful implementation. There is an urgent need for further research to link abiotic processes and the impact of dams on these processes to ecological change and the socio-economic consequences.

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